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Research Article

The Impact of Goodwill Recognition and Goodwill Impairment on the Increasing Holdings of Block Shareholders

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There is a large amount of goodwill recognition and goodwill impairment. These characteristics would trigger stock price fluctuation. Hence, stakeholders will increase holdings to mitigate the volatility of stock prices. According to the data in regard to the Chinese A-share nonfinancial listed companies from 2007 to 2020, we study the reaction of block shareholders after goodwill recognition and goodwill impairment, respectively. Our findings are as follows: (1) goodwill recognition leads to increasing holdings of block shareholders; (2) goodwill impairment also leads to increasing holdings of block shareholders when there is a large amount of goodwill impairment. We also take state ownership into consideration: compared to state-owned firms, private firms show a much stronger positive relation between goodwill recognition and level of increasing holdings of block shareholders, but there is no significant relation between goodwill impairment and increasing holdings of block shareholders in state-owned firms. These empirical results provide us with abundant evidence that block shareholders would increase shareholdings when there is goodwill recognition due to private information of positive future expectation in M&A. Meanwhile, block shareholders would stabilize stock price via increasing shareholdings when goodwill is impaired.

1. Introduction

Goodwill refers to the difference between the consideration paid by the listed company in the process of acquiring the target asset and the fair value of the identifiable net assets of the acquired party. During the accounting period when the merger is completed, goodwill is included in the financial statements of the listed company. According to the statistics of Chinese Stock Market Accounting Research (CSMAR) database, the proportion of companies with goodwill recognition (GR) on the balance sheet date in China's listed companies has increased from 28.72% in 2007 to 55.02% in 2019, and the net goodwill had also increased from 37.629 billion yuan (5.141 billion dollars, according to the exchange rate in the end of 2007) in 2007 to 1306.963 billion yuan (202.238 billion dollars, according to the exchange rate in the end of 2019) in 2019. It can be seen that the scale of companies with GR and the scale of goodwill among listed companies has increased rapidly year by year. If the GR brings stock price fluctuations of the company, it will affect the stability of the entire capital market directly. GR from corporate M&A is closely related to the performance of listed companies, and it is usually seen as having a positive influence on firm value [1]. According to the theory of merger efficiency, M&A generate merger goodwill, increase synergies, and improve company's value [2]. As the insider of the company, the shareholders have private information concerned of future value of the firm. They have positive expectations on the firm's future value. Consequently, they would increase their holdings after GR in order to max their wealth.

After the listed company recognized goodwill, along with the company's production and operation activities, the value of the goodwill gradually shifts. When the future economic benefits of the acquired asset for the merger of the listed company are far lower than its book value that is included in the financial statements, goodwill is impaired. Goodwill impairment (GI) is seen as a negative message to the stock market. In January 2020, Zhongsheng Pharmaceutical hit the lower price limit at the same day after announcing a GI of

740 to 780 million yuan (114.022 to 120.185 million dollars, according to the exchange rate in January 2020). In January 2020, Global Info Tech's stock price dropped 10.15% after announcing a GI of 645 million to 794 million. There is a prevailing issue that stock prices dive soon after GI. As the owners of firms, block shareholders have a great intention to stabilize the stock price to prevent fire sale because of investors' scared sentiment. Fire sale would induce stock price plunging and dry-up of liquidity. Thus, stabilizing stock price would keep the market value of firm in a reasonable level, and it also avoids stock price crash. Hence, block shareholders will increase their holdings. A great deal of longing prevents the stock prices' dropping persistently; meanwhile, shareholders' longing is a positive signal in stock markets, which can allay panic of external investors. In general, block shareholders would increase their position to stabilize the stock price soon after GI.

To stay in step with International Financial Reporting Standards (IFRS), Chinese Accounting Standards for Business and Enterprises (ASBE) set the rules of GR in 2006 as follows. After GR, firms must test whether they should make goodwill impairment in a regular base. When the target firm of M&A would bring down the value of the original firm, they need to make goodwill impairment and adjust the book value in time. Goodwill impairment brings negative expectation in regard to firm's value. Additionally, the slow growth rate of the Chinese economy and the depression of the world economy deepen the negative expectation of GI. Along with the rapid growth of GR due to large amount of M&A, the risk of GI might bring severe economic blow.

To cope with the underlying risk of GI, Chinese Security Regulatory Commission (CSRC) issued "No.8 Tips of Accounting Supervision Risk, Goodwill Impairment" in November 2018. It requires related department need to strengthen the supervision of GI. CASC (China Accounting Standards Committee) issued "Feedback from the Advisory Committee Members on Some Issue Documents of Accounting Standards Advisory Papers" in January 2019, and it recommended goodwill amortization. But goodwill amortization is not adopted for the following reason. If goodwill increases on regular basis in the future, amortization would damage the authenticity. Meanwhile, IFRS also considered goodwill amortization. However, there is no evidence showing that amortization is a suitable way to improve the quality of financial reports. Hence, International Accounting Standards Board released "Business Combinations—Disclosures, Goodwill and Impairment," which suggested carrying out impairment of goodwill instead of amortization. Hence, ASBE might retain the current method of impairment according to IFRS.

GI might be a warning of increasing risk of firms in the future, which means a negative expectation of future growth. As an insider of the company, block shareholders have a more accurate judgment on the company's intrinsic value and performance prospects. Block shareholder transactions contain more judgments about the economic situation and future trends [3], and their transactions are informative [4–6]. Shareholder transaction decisions will have a significant impact on the market. Therefore, we first study the reaction of block shareholders after GR according to the data from 2007 to 2019 in the Chinese stock market. GR and GI send different messages to external investors, as GR is a positive signal while GI is a negative signal. Although, theoretically speaking, both GR and GI cause increasing position of block shareholders, they have different mechanisms. GR appears in M&A, and M&A usually drives stock prices up [2]. Hence, block shareholders increase their position to max their private wealth. However, GI is a signal of declining of future firm revenue, and it drives stock price down. Hence, block shareholders increase their position to stabilize stock price according to signal theory [7]. After we establish the relation between GR and block shareholder's behaviour as well as GI and shareholder's behaviour, respectively, we shift our focus on influence of firms' characteristics to this very relation. We study the difference between privately owned firms and state-owned firms. The large number of state-owned firms is an issue with the Chinese characteristics. The first shareholders of state-owned firms are standing for the country, and these shareholders value political perspective much more than private wealth, and there is a difference between shareholders' behaviours of state-owned firms and privately owned firms, respectively [8]. Therefore, facing GI and GR, state-owned firms' block shareholders might react differently with privately owned firms' block shareholders. We focus on the difference via subsample panel data regression.

The rest of this paper is organized as follows: Section 2 presents the hypothesis of this research. Section 3 discusses the research methodology. Section 4 presents the main empirical results. Section 5 presents the difference between privately owned firms and state-owned firms. Section 6 draws the conclusions.

2. Hypothesis

2.1. The Impact of GR on the Increasing Holdings of Block Shareholders. Different scholars have different research conclusions on the relationship of goodwill and company value. One view is that with the GR from M&A, the company's stock price will gradually rise. Goodwill has a positive impact on company profitability and market value [9]; goodwill can increase the company's stock price significantly [10, 11]. Another view is that with GR brought about by M&A, the company's stock price will decline day by day. Firstly, the company may only consider short-term performance without long-term vision and fail to evaluate the acquired company properly. As a result, the company may recognize goodwill blindly leading to merger premiums and overestimation of goodwill; secondly, when goodwill is overestimated, if the company's resources cannot be effectively integrated after the merger, which will further increase the financial burden of the acquirer, so it will reduce the company's value. Therefore, the goodwill of listed companies will affect company value adversely [12]. Huang and Tang [13], Wei and Zhu [14], and Zheng et al. [15] found that high goodwill will reduce the company's future performance significantly.

As a product of a company's premium M&A, goodwill is the potential economic value of the merged party's future excess returns to the merging party [16]. According to the theory of M&A efficiency, as well as the concept of excess returns, M&A can change the efficiency of both parties, generate synergy effects, achieve complementation of resources, and bring future expected excess returns to the company, thereby enhancing the company's value [1, 2]. In addition, goodwill also reflects the acquirer's recognition of the acquired company's value, which can be used as a positive signal. At the same time, block shareholders, as the company's insiders, have a better understanding of the company's internal realities and information. If block shareholders are optimistic about the company's business prospects, they are more willing to increase their holdings to release internal good information that they are optimistic about the company's future development trend to the outside world. And the behaviour of the increasing holdings of block shareholders can also be used as a positive signal to attract more external investors and increase personal income. According to the M&A arbitrage concept, due to the price of the M&A has difference, when the stock price of the acquirer relative to the acquired party is overvalued, the insiders of the companies of both parties may carry out arbitrage behaviours and obtain excess returns [17, 18]. In other words, when M&A activities generate goodwill, insiders will use their own information advantages to obtain immediate benefits by increasing the shareholdings [19].

Due to the existence of certain "economic rationality," whether it is the extensional development brought about by large-scale M&A or the high-quality development brought about by value mergers, it is expected that they will bring excess returns to the company. Therefore, with the GR brought about by M&A, the stock price rises accordingly [10]. Insiders are more optimistic about the company's future development trend, and block shareholders choose to increase their shareholding accordingly. According to the explanation of signal transmission motivation [20], compared with external investors with a lack of information, as insiders of the company, block shareholders have unique information advantages and understand the company's operating conditions and development prospects fully, in order to promote the company's development and enhance their own interests, block shareholders usually adopt the behaviour of increasing holdings to send positive signals to external investors and show their recognition of the good prospects in the future. Therefore, if the company's M&A activity generates GR during the current period, block shareholders are more inclined to increase their shareholdings. Based on the discussion above, we formulate the following hypothesis:

Hypothesis 1. Compared with companies without GR, block shareholders of companies with GR are more inclined to increase their shareholdings.

Hypothesis 2. Compared with companies with less GR, block shareholders of more GR companies in the current period are more inclined to increase stock holdings.

2.2. The Impact of GI on the Increasing Holdings of Block Shareholders. Scholars hold different views on the research between GI and company value fluctuations. One view is that GI, as a potential crisis derived from the goodwill of company's M&A, is regarded by investors as a signal of declining in the company's stock price [21], which has an adverse effect in the company's future development. GI has been shown to be negatively correlated with stock market performance [22]. The lower the stock price, the more GI is accrued [23]. Lu and Sun [24] and Lin and Yang [25] found that GI will reduce the company's financing ability, the company's stock price, and the stock return rate and destroy the company's value. Therefore, GI can be used as an intuitive economic reflection of the deterioration of the economic environment, the downturn in the stock market, and the crisis of corporate performance [26].

Due to the limited ability of external investors to obtain the company's internal information, when they learn that the company's goodwill has been impaired, they will have a negative psychology, to reduce their expectations on the stock price, and have an adverse impact on the company [27]. Another view is that the company's provision of GI will not have an adverse effect on the stock price. On the one hand, the company may have problems with resource integration in the short term after the merger, GI caused by the failure of M&A to achieve the promised performance has become more common, and the degree of market response has become flat. On the other hand, the company may conduct earnings management for the provision of GI, the company's information is relatively low in truthfulness [23]. Additionally, the GI test has a certain degree of subjectivity; therefore, external investors may have doubts about GI by the company's disclosed, and they do not believe that GI can reflect the company's financial status and future development prospects truly [28, 29], so the provision of GI may not cause a decline in stock prices.

The essence of GI is the economic loss caused by the acquirer's failure to complete the promised performance in high-value M&A. Therefore, the company's behaviour of accruing goodwill impairment may reduce the company's value to a certain extent. At this time, as the company's insiders, block shareholders have a better understanding of the company's true financial capabilities and future development due to information asymmetry with external investors. Based on the needs of company development and personal interests, they are more inclined to use the potential information advantage of symmetry and cover up the unfavourable news for the company's development and personal interests [30, 31] so as to mitigate the negative impact of GI on the company. Besides, adopting increasing holdings conveys the company's "good" signal to the outside world so as to affect the judgment of external investors from stabilizing investor confidence. Accordingly, the "good" signal may inspire external investors chasing behaviour, which is helpful of maintaining the company smooth operation [32]. Therefore, GI of the company is related to the increasing holdings of block shareholders closely.

According to the signalling motivation [20], if the company's provision of GI is less, as an insider, the block shareholder has a better understanding of the company's situation and may have the information that the postmerger company's development is good. In order to further increase the stock price and obtain personal income, block shareholders may choose to increase their shareholdings to send signals to the outside world, implying that the company is operating well and has a bright future. Therefore, the behaviour of the increasing holdings of block shareholders is regarded by external investors as a good performance of the company's future development. However, since less GI has a lesser impact on the company, the tendency of the increasing holdings of block shareholders is not obvious. When there are more provisions for GI, the stock market is sluggish, the stock price is undervalued [33], and the company is even facing risks. In order to help the company overcome difficulties and maintain stable operations, the company's block shareholders usually choose to increase stock holdings to save the company and stabilize market confidence [34]. Simultaneously, perhaps the company has a "big bath" surplus behaviour, and block shareholders still maintain the company's future development. External investors generally recognize that the behavior of increasing the holdings of major shareholders is of signal significance, so major shareholders are more motivated to signal to the outside world that they still have expectations of the company, accordingly individuals can gain benefits while attracting more investors to the company.

Due to the price difference of M&A activities, when the stock price of the acquiring party relative to the acquired party is overvalued, the insiders of the companies of both parties may carry out arbitrage behaviours on this M&A transaction so as to obtain excess returns in the future. Behaviour of M&A arbitrage can obtain excess returns based on the cash acquisitions in the US market from 1971 to 1985 [35]. Goodwill is a manifestation of the value of excess income obtained by the acquirer, and the amount of goodwill means the size of the arbitrage opportunities. When the goodwill is recognized in the current period of M&A activities, the more goodwill is recognized in the current period of the merger, the greater the price difference of this merger is, and insiders will use their own information advantages to increase the proportion of shareholdings to ensure personal income. That is, the larger the scale of goodwill, the stronger the motivation of block shareholders to increase their holdings for arbitrage. Therefore, we formulate the following hypothesis.

GI is a potential crisis derived from the goodwill of a company's M&A [36], which means that the company's future development trend is poor, and it is often regarded by investors as a signal of the company's share price decline. Thus, impairment is negatively correlated with stock market performance [37]. At the same time, the provision of GI indicates that the company's forecast of future performance is declining, which may have a further attack to the stock price. Therefore, as an intuitive economic reflection of the company's performance decline, GI may have an adverse impact on the company [27]. Once the GI provision occurs, the stock price is more likely to fall. GR and the scale of GR may make block shareholders more inclined to increase stock holdings; when the value of goodwill is depressed with the company's business activities and GI is accrued, if the degree of GI is different, it may also have different effects on the tendency of the increasing holdings of block shareholders.

For companies with a low degree of GI, the financial status is relatively good [26], the impact of GI on the company's stock price is limited, and block shareholders do not need to use a signalling mechanism to stabilize the market. At this time, the motivation to increase shareholdings is small. Moreover, the appropriate disclosure of GI helps the market recognize that companies have made relatively sufficient disclosures of financial information and performance expectations, and financial statement data can more truly reflect the company's financial and operating conditions. Although GI means that it may take some time for the company's performance to recover, there are still good expectations for the future. Therefore, when the company's GI provision ratio is low, the tendency of the increasing holdings of block shareholders is limited.

For samples with a high degree of GI, the tendency of the increasing holdings of block shareholders may be more pronounced. When the degree of GI is high, poor performance expectations will lead to more negative information about the company. If a large amount of negative information flows into the market, it may cause a stock price collapse [38]. Under the premise of information asymmetry, management is more inclined to hide negative news in order to pursue its own interests [39]; block shareholders will choose to increase their stock holdings supporting management, which passes on the "good" signal to the outside world to boost investor expectations [40] and stabilize market confidence. External investors recognize generally that the behaviour of the increasing holdings of block shareholders has signal significance, and that stable shareholding can obtain significant and positive excess returns and increase confidence for the company's future development [41]. Therefore, with the more GI recognized by the company, the greater the tendency of block shareholders to increase their holdings. In summary, we formulate the following hypothesis:

> *Hypothesis 3.* The more GI accrued in the current period, the stronger the tendency of the increasing holdings of block shareholders.

3. Methods

3.1. Sample and Data Sources. The data used in this study consists of China's A-share nonfinancial listed companies from 2007 to 2020. In order to make the data more effective, during the sample selection process, the following screenings were performed: (1) excluding data with GR or GI reserves being 0 at the same time; (2) excluding block shareholders increasing holdings/total shares smaller than 0.01%; (3) excluding enterprises listed in 2017 and after; (4) excluding companies with missing data on major variables; and (5) excluding data in 2020. The outbreak of COVID-19 in 2020 will have a severe impact on the Chinese stock market, which will affect the scale of GR and the scale of GI; the relationship between the decision of block shareholders and GR and GI may be more affected by COVID-19. To control the influence of extreme values, all continuous variables in the sample data are processed with winsorize (1%–99%). A total of 12,888 observations from 2073 companies were obtained. The data in this paper are derived from the WIND database, the CHOICE database, and the CSMAR database; and the study uses EXCEL and STATA13.0 to collate the data and perform statistical analysis.

3.2. Variables and Models

3.2.1. Variables. The dependent variable is SI (SI is the tendency of the increasing holdings of block shareholders). SI refers to the tendency of the increasing holdings of block shareholders. The block shareholders include the investors holding more than 5% of the shares or the top ten shareholders of a listed company, who will take the decision of continuing to purchase the company's shares through the secondary stock market according to the information advantage. In particular, although the block shareholder is an insider, the transaction behaviour of the block shareholder's increase in holdings is not consistent with insider trading. Insider trading may be illegal or legal. Illegal insider trading focuses more on the use of major events that affect stock prices that are unknown in advance for trading, and the trading purpose is for obtaining short-term excess returns. The legal insider trading focuses more on the company's intrinsic value and future performance, and the trading purpose is to obtain long-term excess returns. Because strong regulatory systems can significantly limit the risks of insiders using undisclosed information [42], and insider trading has significant long-term excess return effect [43], the trading decision of increasing their shareholding basically complies with the regulatory framework. In order to test the influence of GR and GI on SI, this paper represents SI from two aspects. Firstly, the virtual variable that is whether block shareholders increase their holdings (SIV) is taken as the first-aspect dependent variable, which reflects whether the holdings' proportion of block shareholders has been increased. The virtual variable explores the logical relationship between GR and SI; GI and SI initially. Secondly, in order to analyse the quantitative relationship specifically between GR and SI; GI and SI, the quantitative indicators of SI are taken as the second aspect of dependent variables. Based on the research of Li et al. [38], the changes of the increasing holdings of block shareholders (SIQ); that is, the cumulative number of changes in holdings of block shareholders in the current period/total shares is selected as the dependent variable in this paper. SIQ reflects SI from the angle of quantity. The larger the index, the stronger the SI.

The independent variables are GR and GI. GR is expressed in two aspects: whether to recognize goodwill (GRV) and the degree of goodwill recognition (GRQ). Among them, GRV is a dummy variable, used to verify the logical relationship between GRV and SIV. Based on the research of scholars such as Li et al. [38] and Deng and Mei [44], the added goodwill in this period/total assets (GRQ) is used as independent variables to reflect the scale of GR brought by corporate M&A, used to verify the logical relationship between GRQ and SIQ.

At the same time, according to the research of Hu and Li and other scholars [45], this paper takes the provision for goodwill impairment in the current period/total assets (GIQ) as an independent variable to reflect the scale of GI by enterprises in the current period; these quantitative indicators analyse the relationship between GIQ and SIQ concretely.

GR and GI impact on SI, which is bound to be affected by the enterprise characteristics and the financial situation. For example, the scale of the enterprise (ES) affects the corporate development, which in turn affects SI [46, 47]; the net cash flow generated from operating activities/total shares (OC) can reflect the ability of generating cash flow out of capital. The stronger OC is, the greater SI is [48]; the size of the board of supervisors (BS) (in Chinese corporations, board of supervisors is a department that supervises the daily operation of firms on behalf of stakeholders. Board of supervisors is set to avoid abusing power of managers and block shareholders) measures the effect of company internal governance [49, 50], providing positive information for the increasing holdings of block shareholders; the lower the price-to-book ratio (PB), the lower the risk [51], and the investment value becomes higher; the long-term capital debt ratio (LCD) reflects the company's long-term capital structure [52] and also affects the holdings scale of the block shareholders; the cost and charge margin (CCM) can measure the agency costs between managers and shareholders: the better the performance of managers, the higher the SI [53]. Therefore, as previously mentioned, this paper takes ES, OC, BS, PB, LCD, and CCM as control variables. And year and industry are introduced as control variables. The definitions of variables are shown in Table 1.

3.2.2. Models. The following regressions model are established to verify the above assumptions.

Model 1. It tests hypothesis 1, which verifies the relationship between GRV and SIV:

$$\mathrm{SIV} = a_0 + a_1 \times \mathrm{GRV} + \sum(\alpha_i \times X_i) + \varepsilon. \qquad (1)$$

Model 2. It tests hypothesis 2, which verifies the relationship between GRQ and SIQ:

$$\mathrm{SIQ} = a_0 + a_1 \times \mathrm{GRQ} + \sum(\alpha_i \times X_i) + \varepsilon. \qquad (2)$$

Model 3. It tests the hypothesis 3, which verifies the relationship between GIQ and SIQ:

$$\mathrm{SIQ} = a_0 + a_1 \times \mathrm{GIQ} + \sum(\alpha_i \times X_i) + \varepsilon. \qquad (3)$$

Among them, a_0 represents the constant, a_1 represents the coefficient of the independent variables, α_i represents the coefficient of the control variables, X_i represents the control variables, ε represents the random error term, and the meaning of the rest of variables is shown in Table 1.

Table 1: Variable definitions.

Variable dimension	Variable name	Proxy	Definition
Dependent variables	Whether block shareholders increase their holdings	SIV	Increased holdings in the current period, recorded as 1; without increased holdings in the current period, recorded as 0
	The changes of the increasing holdings of block shareholders	SIQ	The cumulative number of changes in holdings of block shareholders in the current period/total shares
Independent variables	Whether to recognize goodwill	GRV	Added goodwill in this period is recorded as 1; without added goodwill in this period is recorded as 0
	Degree of goodwill recognition	GRQ	The added goodwill in this period/total assets
	Degree of goodwill impairment	GIQ	Provision for goodwill impairment in the current period/total assets
Control variables	Enterprise size	ES	LN (total assets)
	Operating cash flow	OC	The net cash flow from operating activities/total shares
	Board of supervisors	BS	The number of supervisory board
	P/B ratio	PB	Current value of the closing price of the current period/(total value of owner's equity in the end of this period/the value of paid-in capital for the end of current period)
	Long-term capital debt ratio	LCD	Total noncurrent liabilities/(total owner's equity + total noncurrent liabilities)
	Cost and charge margin	CCM	Total profit/(operating costs + sales expenses + management expenses + financial expenses)
	Years	Year	Annual dummy variable. When the company is in the year, take 1; otherwise, take 0
	Industry	Ind	Industry dummy variables. When the company is in this very industry, take 1; otherwise, take 0

4. Results

4.1. Descriptive Statistics and Correlation Analyses. Table 2 shows descriptive statistics like the mean, minimum, median, maximum, and standard deviation of each statistical indicator. The mean of SIV is 0.2419, which is greater than the median of 0, and the standard deviation is 0.4282, indicating that SIV has a skewed distribution and a large degree of dispersion. SIQ presents the same characteristics. The mean of GRV is 0.2037, which is greater than the median of 0, indicating that the distribution of goodwill is biased. Moreover, the maximum of GRQ is 0.2866, and the mean is 0.0115. This further shows that from the overall sample of GR, the degree of GR caused by M&A of some companies is relatively high, and the level of goodwill is relatively close, and the smaller companies also account for a certain size in the overall sample. The distribution of the degree of GIQ is biased, indicating that some companies have accrued a large amount of GI, which affects the company's operating performance. In summary, it can be seen that in the overall sample, GR is common relatively, and a considerable number of companies recognized goodwill on a large scale, and GI caused by GR should not be underestimated. Compared with the biased and discrete degree of the company's GR and provision of GI, the increasing holdings of block shareholders also have similar characteristics. After the company recognized the goodwill, the adjustment effect of the provision of GI on SI is also complicated. The following will verify the correlation between GR and SI; GI and SI.

The Pearson correlation results are presented in Table 3, as well as the results of the significance test performed to detect whether there is collinearity between the variables in the table. In the total sample, GRV and GIQ; GRQ and GIQ are significantly positively correlated; it can be seen that for the company with an increase in GR, it may also increase the degree of GI. This means that if the company recognized goodwill during the merger, there is a possibility of subsequent impairment, and the greater the GR, the larger subsequent calculation of the scale of GI. Therefore, companies that recognized high amounts of goodwill will have the risk of "explosion" of goodwill. GRV and SIV are correlated positively and significantly, indicating that if the company recognized goodwill, block shareholders might be more inclined to increase stock holdings. GRQ and SIQ are correlated positively and significantly, indicating that as the scale of the company's recognized goodwill increases, SI may gradually increase. The above results verify the research hypotheses 1 and 2 preliminarily. GIQ is correlated significantly and negatively with SIQ, indicating that the larger the company's provision for GI, the more SI may decrease. Hypothesis 3 has not been verified yet, but since other influencing factors of the dependent variable are not controlled at this time, further regression analysis is still needed. The correlation coefficients among other variables are also reasonable. The correlation coefficients among most control variables are not high; however, they are correlated significantly. A few control variables have correlation coefficient values higher than 0.3, so all variables are tested by VIF. The result shows that the highest VIF is 2.05, and the rest are between 1 and 2, indicating that the collinearity is not serious, the variable definitions are more reasonable, and the regression results are more credible.

Table 2: Descriptive statistics.

Variables	N	Mean	Minimum	Median	Maximum	Std. deviation
SIV	12888	0.2419	0	0	1	0.4282
SIQ	12888	0.0105	0	0	0.2060	0.0308
GRV	12888	0.2037	0	0	1	0.4027
GRQ	12888	0.0115	0	0	0.2866	0.0435
GIQ	12888	0.0017	0	0	0.0795	0.0093
ES	12888	22.3207	19.9415	22.1355	26.2981	1.2846
OC	12888	0.4009	−2.1470	0.2970	3.5683	0.8005
BS	12888	3.5674	2	3	7	1.0475
PB	12888	3.4699	0	2.7054	15.8395	2.7545
LCD	12888	0.1498	0	0.0833	0.7054	0.1674
CCM	12888	0.1307	−0.5617	0.0991	0.9162	0.1905

Table 3: Correlation analysis.

	SIV	SIQ	GRV	GRQ	GIQ	ES	OC	BS	PB	LCD	CCM
SIV	1										
SIQ	0.6040***	1									
GRV	0.0401***	0.0200**	1								
GRQ	0.0681***	0.0570***	0.5206***	1							
GIQ	−0.0112	−0.0209**	0.0575***	0.0319***	1						
ES	0.0662***	0.0851***	0.0623***	−0.0606***	−0.0470***	1					
OC	0.0521***	0.0276***	−0.0235***	−0.0331***	−0.0526***	0.2271***	1				
BS	−0.0067	0.0158*	−0.1033***	−0.0971***	−0.0611***	0.2671***	0.1177***	1			
PB	0.0246***	−0.0084	0.0090	0.0558***	−0.0158*	−0.3645***	−0.0324***	−0.1004***	1		
LCD	0.0143	0.0479***	−0.0227***	−0.0731***	−0.0258***	0.5551***	0.0645***	0.2061***	−0.1527***	1	
CCM	0.0055	−0.0100	0.0303***	0.0578***	−0.2869***	−0.0255***	0.1248***	−0.0178**	0.1089***	−0.1270***	1

Note. $^{***}p < 0.01$, $^{**}p < 0.05$, and $^{*}p < 0.1$.

4.2. Hypothesis Tests

4.2.1. Regression Results of Hypothesis 1. Table 4 is the empirical results of Model 1. Columns (1) and (2) in the table show the relationship between GRV and SIV. Column (1) shows that the coefficient of GRV is positive and significant at the 1% level when the control variables are not considered; column (2) shows that the coefficient of GRV is significant and positive at the 5% level when the control variables are considered; the results support Hypothesis 1. According to the above empirical results, if goodwill is recognized in the current period, block shareholders of companies with GR are more inclined to increase their shareholdings.

Table 4: Regression results of Hypothesis 1.

Variables	Model 1	
	(1) SIV	(2) SIV
GRV	0.0312** (0.011)	0.0249** (0.043)
ES		0.0684*** (0.000)
OC		0.0060 (0.338)
BS		−0.0126 (0.272)
PB		0.0132*** (0.000)
LCD		−0.2855*** (0.000)
CCM		0.0574* (0.054)
Constant	0.2217 (0.122)	−1.2704*** (0.000)
Year and industry	Included	Included
Observations	12888	12888
R-squared	0.0169	0.0252

Note. p statistics are in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, and $^{*}p < 0.1$.

4.2.2. Regression Results of Hypothesis 2. Columns (1) and (2) in Table 5 show the impact of GRQ on SIQ. Excluding the data that without GR in the current period, there are 2625 observations in the sample of GR in the current period. Column (1) shows that the coefficients of GRQ and SIQ are significant and positive at the 1% level when the control variables are not considered; column (2) shows that the coefficients of GRQ and SIQ are still significant and positive at the 1% level when the control variables are considered, which supports Hypothesis 2. According to the above empirical results, the more GR of the company in the current period, the stronger the SI.

The empirical results of Model 1 and Model 2 show that the goodwill will stimulate block shareholders to increase their holdings; and during the accounting period for recognizing goodwill, the company will allocate and redistribute related resources after the merger. When a company's resources can be used in related businesses at low cost during allocation and redistribution activities, the synergies based on M&A come into play, and the company's development prospects may be better. Among the samples which recognized goodwill in the current period, the synergies brought about by M&A will more significantly encourage block shareholders to tend to increase their shareholdings. When the company recognized goodwill, the

Table 5: Regression results of Hypothesis 2.

Variables	Model 2	
	(1) SIQ	(2) SIQ
GRQ	0.0559*** (0.000)	0.0550*** (0.000)
ES		0.0053 (0.301)
OC		−0.0026 (0.118)
BS		−0.0040 (0.315)
PB		0.0004 (0.387)
LCD		−0.0438*** (0.005)
CCM		−0.0005 (0.937)
Constant	−0.0469** (0.013)	−0.1501 (0.200)
Year&industry	Included	Included
Observations	2625	2625
R-squared	0.0500	0.0638

Notes. p statistics are in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, and $^{*}p < 0.1$.

higher GRQ means the higher the M&A premium, the greater the space for future investment returns, and the stronger the SI.

4.2.3. Regression Results of Hypothesis 3. As a signal that investors believe that the company's stock price will fall, GI may have a further impact on the company's stock price. Based on the company's stable development and personal long-term income, block shareholders are usually more inclined to choose to increase their shareholdings to send positive signals to the outside. Taking into account the above correlation analysis results, GI and SI show a negative correlation. This paper further verifies the moderating effect of different degrees of GI on SI after the company recognizes the goodwill. Since GRQ and GIQ are continuous variables, this paper will group the samples of companies that have accrued GI according to the degree of impairment to verify the moderating effect. Taking GIQ as the measurement standard, there are a total of 1820 data. Referring to Brogaard et al. [54], the samples are evenly divided into three groups; grouping results is 607, 607, and 606 pieces of data from low to high. Table 6 shows the empirical results of Model 3. Among the samples with high degree of GI in the current period, GIQ and SIQ are significant and positive.

According to the empirical results in Table 6, in the samples with low degree of GI and medium degree of GI, the correlation between the two is not significant. This paper believes that the reason for this result is that when GI is small, the impact on the performance of the stock in the secondary market is limited, so block shareholders do not need to send signals to stabilize the stock price by increasing their holdings. Only when the company accrues large-scale GI, the investor's strength reflects the risk of stock price decline or stock price collapse, thereby affecting the decision of block shareholders to increase their holdings. The empirical result supports Hypothesis 3, indicating that the higher the degree of impairment, the more significant the impact of the degree of GR on SI.

4.2.4. Robustness Tests

(1) *Substitution Variable Method.* The increasing holdings of block shareholders have the role of a weather vane, which has an important impact on the fluctuation of the stock market. Among the shareholders who hold more than 5% of the shares or rank in the top ten, the shareholders who hold more shares are generally more stable and will not be easily replaced. Moreover, shareholders with more shares have more opportunities to participate in the company's business decision-making and may respond to goodwill risks more promptly, which plays a decisive role in smoothing the company's goodwill risks and stabilizing market expectations. Thus, in order to test the robustness of the research results, we use the new dependent variable SIV*. (SIV* is whether top three shareholders increase their holdings.) Also, we use SIQ* (SIQ* is the cumulative number of changes in holdings of the top three shareholders in the current period/total shares.) to replace SIQ. Regression analysis is performed using Models 1–3, and almost all the results in Table 7 are still significant.

(2) *Instrumental Variable Method*. This paper adopts the panel data instrumental variable method to solve the influence of missing variables on the research results. GI mainly comes from the size of the asset premium brought about by M&A. The higher the performance commitment is set during M&A, the higher the asset premium becomes, also the higher the degree of GI would generate in the future. This paper uses the performance commitment multiple, that is, the performance commitment in the current period/ total assets as the instrumental variable. Firstly, a one-stage regression is carried out on the degree of GI and the performance commitment multiple in the same period. The regression results show that they are correlated significantly. Then, a two-stage regression is performed on the performance commitment multiple and SIQ. The regression coefficient is still significant and positive, indicating that the main hypothesis of GIQ and SIQ is still valid after controlling the endogenous problem (Table 8).

(3) *Sample Grouping Method.* Taking into account the result that GI is negatively related to SI in the above correlation analysis results, it may be that the samples with lower impairments partly cover the results of the samples with higher impairments. After the degree is divided into three equal parts in the regression analysis, GI of the high-impairment group is correlated positively with the increasing holdings of block shareholders, indicating that the different degree of impairment of listed companies will have the different adjustment mechanism on SI, and there is typical trend characteristics in high-impairment group. The more GI is accrued, the stronger the SI. Thus, in order

Table 6: Regression results of Hypothesis 3.

Variables	Model 3		
	Low impairment	Medium impairment	High impairment
GIQ	7.8020 (0.438)	2.0522 (0.494)	0.0288* (0.051)
ES	−0.0098 (0.509)	0.0142 (0.284)	0.0152** (0.011)
OC	−0.0009 (0.831)	0.0068 (0.105)	0.0079** (0.047)
BS	0.0032 (0.369)	0.0324 (0.152)	−0.0020 (0.691)
PB	−0.0034* (0.070)	0.0005 (0.633)	0.0009 (0.155)
LCD	−0.0440 (0.260)	0.0456 (0.488)	−0.0227 (0.220)
CCM	−0.0003 (0.989)	0.0146 (0.534)	−0.0002 (0.888)
Constant	0.2508 (0.444)	−0.4282 (0.148)	−0.3195** (0.014)
Year and industry	Included	Included	Included
Observations	607	607	606
R-squared	0.0553	0.2183	0.1564

Notes. p statistics are in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, and $^{*}p < 0.1$.

Table 7: Robustness test: replacing the dependent variable.

Variables	SIV*		SIQ*		SIQ*	
	(1)	(2)	(3)	(4)	(5)	(6)
GRV	0.0333*** (0.006)	0.0265** (0.029)				
GRQ			0.0516*** (0.000)	0.0509*** (0.000)		
GIQ					0.0075 (0.569)	0.0261* (0.063)
ES		0.0710*** (0.000)		0.0052 (0.277)		0.0125** (0.022)
OC		0.0049 (0.417)		−0.0026* (0.097)		0.0077** (0.040)
BS		−0.0167 (0.112)		−0.0038 (0.330)		−0.0033 (0.476)
PB		0.0124*** (0.000)		−0.0003 (0.454)		0.0007 (0.224)
LCD		−0.2825*** (0.000)		−0.0421*** (0.006)		−0.0174 (0.301)
CCM		0.0580** (0.047)		−0.0018 (0.775)		−0.0004 (0.828)
Constant	0.2448* (0.093)	−1.2833*** (0.000)	−0.0239** (0.032)	−0.1268 (0.249)	−0.0038 (0.460)	−0.2579** (0.030)
Year and industry	Included	Included	Included	Included	Included	Included
Observations	12888	12888	2625	2625	606	606
R-squared	0.0171	0.0254	0.0465	0.0605	0.0802	0.1549

Notes. p statistics are in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, and $^{*}p < 0.1$.

Table 8: Robustness test: panel instrumental variable regression.

Variables	Model 3	
	One-stage	Two-stage
GIQ		0.6852* (0.055)
Controls	Included	Included
Constant	0.2122*** (0.000)	−0.4504*** (0.001)
Year and industry	Included	Included
R-squared	0.2833	0.0210
F-value	50.22***	
Wald chi^2		418.70***
Observations	2280	2280

Notes. p statistics are in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, and $^{*}p < 0.1$.

to test the robustness of the research results, the following steps are carried out: regrouping the samples of GI in the current period, reducing the scope of high-impairment groups further, and verifying the adjustment mechanism of the impact of GI on SI. According to GIQ from low to high, first, select 546, 728, and 546 pieces of data base on the ratio of 30%, 40%, and 30% in the 1820 group of samples, and then select 728, 728, and 364 pieces of data base on the proportions of 40%, 40%, and 20%, respectively, to reduce the range of the high-impairment group gradually, and perform panel fixed-effects regression. According to the regression results, in the low-impairment group and the medium-impairment group of the two classifications, GIQ has a positive or negative impact on SIQ insignificantly, indicating that when the company's provision for GI is low, the scale of GI has not a consistent effect on SI, while in the high-impairment group of the two classifications, there is a significant positive correlation between GIQ and SIQ, and the more rigorous the classification standard of the high-impairment group, the higher the significance between GIQ and SIQ. The results of Hypothesis 3 are verified (Table 9).

5. State-Owned Firms and Privately Owned Firms

Studies have found that the nature of the company's property rights will affect the behaviour of the increasing holdings of block shareholders [8, 55]. The behavioural decisions of block shareholders are inevitably affected by

Table 9: Robustness test: grouping samples.

Variables	Model 3	
	(1) SIQ	(2) SIQ
GIQ	0.0284* (0.054)	0.0486** (0.024)
ES	0.0159* (0.059)	0.0347** (0.040)
OC	0.0107** (0.032)	0.0216** (0.029)
BS	−0.0021 (0.679)	0.0106 (0.115)
PB	0.0008 (0.276)	0.0016 (0.275)
LCD	−0.0200 (0.390)	−0.0397 (0.436)
CCM	−0.0003 (0.885)	−0.0007 (0.866)
Constant	−0.3263* (0.080)	−0.8138** (0.030)
Year and industry	Included	Included
Observations	546	364
R-squared	0.1294	0.3959

Notes. p statistics are in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, and $^{*}p < 0.1$.

Table 10: State-owned firms versus privately owned firms: the influence of GR.

Variables	State-owned company		Privately owned companies	
	(1)	(2)	(3)	(4)
GRQ	0.0762 (0.231)	0.0647 (0.255)	0.0541*** (0.000)	0.0573*** (0.000)
ES		0.0429** (0.020)		0.0002 (0.967)
OC		−0.0030 (0.164)		−0.0036 (0.109)
BS		−0.0019 (0.806)		−0.0011 (0.708)
PB		−0.0006 (0.788)		0.0003 (0.558)
LCD		−0.0978** (0.032)		−0.0317** (0.050)
CCM		−0.0029 (0.946)		0.0006 (0.919)
Constant	−0.0065 (0.647)	−0.9726** (0.022)	−0.1320*** (0.000)	−0.1282 (0.286)
Year and industry	Included	Included	Included	Included
Observations	567	567	2058	2058
R-squared	0.0860	0.1398	0.0716	0.0816

Notes. p statistics are in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, and $^{*}p < 0.1$.

Table 11: State-owned firms versus privately owned firms: the influence of GI.

Variables	State-owned companies		Privately owned companies company companies	
	(1)	(2)	(3)	(4)
GIQ	−0.0196 (0.721)	0.1960 (0.376)	0.0067 (0.615)	0.0273 (0.102)
ES		0.1067** (0.020)		0.0132** (0.028)
OC		0.0090 (0.505)		0.0058 (0.140)
BS		−0.0185 (0.238)		0.0019 (0.497)
PB		0.0004 (0.174)		0.0006 (0.311)
LCD		−0.1456 (0.259)		−0.0142 (0.332)
CCM		0.0099 (0.848)		0.0004 (0.843)
Constant	−0.0044 (0.623)	−2.3069** (0.020)	0.0138 (0.274)	−0.2872** (0.031)
Year&industry	Included	Included	Included	Included
Observations	83	83	523	523
R-squared	0.1197	0.4835	0.1006	0.1674

Notes. p statistics are in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, and $^{*}p < 0.1$.

political factors, and the increase in holdings is probably not entirely motivated by financial motives [56, 57]. The nature of the property rights of state-owned enterprises has brought political advantages, making them insufficiently pay attention to efficiency and risk [58, 59]. Therefore, block shareholders of state-owned firms are less willing to obtain economic benefits through increased shareholding [60]. The data on the increase of holdings by block shareholders of Chinese listed companies also showed that the increase of holdings by block shareholders of state-owned enterprises is very consistent with the coordination of government policies, while block shareholders of privately owned enterprises mostly increase their holdings for economic benefits [57].

The motivation of the increasing holdings of block shareholders of non-state-owned listed companies are economic factors mostly; while the majority of state-owned companies' block shareholders increase their holdings to cater to or respond to the call of national policies [51], that is, block shareholders increase their shareholdings due to political factors mostly. When the size of GRQ is different, will the size of GRQ make the difference when we consider the difference between state-owned firms and privately owned firms?

Among the 2625 observations, Table 10 uses Model 2 to verify the different results of state-owned listed companies and non-state-owned listed companies. Among them, columns (1) and (2) reflect that when state-owned listed companies recognize different degrees of GR, SI is not significant. However, columns (3) and (4) reflect that SI has increased significantly with the increase in GRQ in non-state-owned listed companies. Since GR is a positive signal of the company's future performance, block shareholders of state-owned listed companies do not need to increase their holdings based on political motives. Table 10 verifies the political motivation of the increasing holdings of block shareholders of state-owned companies, and the economic motivation of the increasing holdings of block shareholders of non-state-owned listed companies. It also verifies the signalling motives of the increasing holdings of block shareholders further. Table 11 presents the empirical results of difference between state-owned firms and private-owned firms in regard to the influence of GI. It appears that when we run subsample regression, GI has no significant influence on block shareholders' behaviour.

6. Conclusions

In recent years, China's A-share market has shown the typical characteristics of high goodwill and high GI/total assets or GI/net assets, which have brought fierce discussions on goodwill risks inside and outside the market. The stock price fluctuations from goodwill risks are threatening the stability of the entire capital market. Therefore, goodwill risk has become the focus of the current work resolving major risks and has become an important issue in the Chinese economy gradually. As an insider of the company, block shareholders usually have the same interest trend with the company, and they have information advantages compared with external investors. External investors are more likely to agree with the company information transmitted by block shareholders. Therefore, the behaviour of the increasing holdings of block shareholders can alleviate the company's goodwill risk effectively by sending positive signals to the outside world. Therefore, our paper focuses on discussing the relationship between GR and SI, and the adjustment mechanism of the degree of GI on SI. On this basis, further research is carried out to verify the different effects of GR on SI from the perspective of property rights heterogeneity. Our research has shown the following:

(1) If goodwill was recognized in the period of M&A, block shareholders were more inclined to increase their shareholdings. The more GRQ in the current period, the stronger SIQ.

(2) When listed companies make provision for GI, only block shareholders tend to increase their shareholdings in the high-impairment group, indicating that block shareholders will significantly and positively adjust the impact of GRQ on SIQ in the higher-impairment companies.

(3) Block shareholders of state-owned listed companies choose to increase their holdings based on political motives and block shareholders of non-state-owned listed companies based on economic motives. During the accounting period of GR, since GR is a positive signal of the company's future performance, block shareholders of state-owned listed companies do not need to increase their holdings based on political motives, while block shareholders of non-state-owned listed companies have strong economic motivation that strengthens their well-being anticipating and obtains future benefits by increasing their holdings, which verified the signalling motives of the increasing holdings of block shareholders further.

Our findings enriched the relationship between GR, GI, and SI, especially the relationship between the higher degree GI and SI. However, as in all empirical research, our findings have several limitations. Firstly, trading conflicts and COVID-19 might amplify the risk of GR and GI, which might have great influence on accounting rules in regarding of goodwill. In consideration of the relevant requirements of accounting information, firms probably need to carry out the current impairment method of goodwill. But there might be difference in the relation between GR, GI, and block shareholders' behaviour under trading conflicts and COVID-19. Secondly, GR and GI used in the paper may be influenced by the macroeconomics; their changes may be synchronized with SI because of the macroeconomics.

Data Availability

The data used to support this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Research Article

Is the Improvement of CSR Helpful in Business Performance? Discussion of the Interference Effects of Financial Indicators from a Financial Perspective

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To achieve sustainable business operations, corporate betting on the implementation of social responsibility has become a trend of global concern. Therefore, companies that pay attention to and invest many resources in corporate social responsibility (CSR) have gradually become critical strategies for business operations. This strategy has a substantial effect on business performance, especially regarding the financial impact. This study aims to explore the effect of CSR improvement on financial performance, return on assets (ROA), return on equity (ROE), size, debt ratio, and asset turnover on its interference. A total of 346 items of data from Taiwan companies that have won the "CommonWealth Corporate Citizenship Award" from 2012 to 2018 were analyzed via descriptive statistics and hierarchical regression methods to determine the influence and adjustment of various factors layer by layer. CSR, firm size, debt ratio, and asset turnover have a significant prediction on ROA. CSR, firm size, and turnover have a significant prediction on ROE. Firm size and debt ratio have a significant negative moderation effect on CSR to ROA. The debt ratio has a significant negative moderation effect on CSR to ROE. This study concludes that CSR has a significant impact on business performance. CSR affects ROA moderated by firm size and ROA and ROE moderated by debt ratio. This study puts forward practical and future research suggestions for the relevant units to promote CSR development.

1. Introduction

Social attention on corporate social responsibility (CSR) has gradually shifted from developed countries to developing countries in recent years. Society hopes that multinational companies and local companies will be required to incorporate CSR as the business philosophy and value of the company. Porter and Kramer argue that corporations and society's mutual dependence implies that both business decisions and social policies must follow the principle of shared value, with choices benefiting both sides. Even though heightened corporate attention to CSR has not been entirely voluntary [1], the companies need to readjust their attitude towards CSR to improve their corporate image, gain reputation, and increase their profits. CSR has become an outstanding science, highly valued by academics, practical circles, and government units. Today, countries worldwide advocate the sustainable development goals (SDGs) as set by the United Nations at the 2015 Earth Summit Rio, Brazil. Then, according to a report from Better Business, Better World (BSDC) in 2017, it is estimated that, by 2030, there will be at least 12 trillion US dollars in annual global revenue and 380 million employment opportunities related to the SDGs. The report results show that the implementation of the United Nations Global SDGs has become a global development trend and has also become the development trend of future business opportunities for enterprises. The CSR concept has become a relevant component of modern business and risk management, as it ensures the successful functionality of a company [2].

The new millennium brings a new uncertain environment into business, along with intense pressure in companies to improve and establish new company strategies that allow CSR, which has become one of the management strategies of most enterprises, not only to increase market participation and obtain a significant level of company performance but also to survive in a market that gets more globalized and competitive by time [3], and it has also become the central axis of the long-term development of enterprises. Newman et al., using a representative sample of more than 5,000 Vietnamese enterprises to explore the firm-level productivity effects of CSR, showed that CSR behavior might bring rewards [4]. However, it is undeniable that CSR is already a necessary task for modern enterprise management.

According to Carroll, the concept of CSR began to be mentioned at least as early as the 1930s [5]. CSR has gradually become more critical as the years change, and its definitions have become more diverse [6]. Taiwan CommonWealth Magazine established the Corporate Citizenship Index in 2007 and began conducting "Corporate Citizenship" surveys. It refers to the United Nations Program, the OECD, the US Dow Jones Index, and other international indicators and evaluation methods and divides the measurement of CSR into four facets: corporate governance, corporate commitment, social participation, and environmental sustainability. Corporate governance mainly measures the independence of the internal board of directors and the transparency of corporate information disclosure. Enterprise commitment refers to the company's commitment to the consumers, the care and training of its employees, and its investment in innovation and research and development. Social participation mainly measures whether the company has long-term investment or involvement in specific social issues and positive influences. Environmental sustainability involves investigating whether companies have adopted specific goals and methods in environmental protection and energy conservation management [7].

Financial performance is one of the methods to calculate business performance; the most commonly used indicators are return on assets (ROA), return on equity (ROE), or other indicators that measure the performance of a company's market value [8]. Dewi and Monalisa investigated the relationship between CSR, ROA, and ROE [9]. This study tries to use financial performance to measure business performance and aims to determine the impact of CSR on business performance through financial indicators. Based on the empirical evidence of previous studies, this study found that most of the financial performance measures of the studies were measured on basic accountancy. Therefore, this study selects the most commonly represented financial performance indicators of the company's operating performance as the indicators of business performance, which are ROA and ROE. In past research, there have been many demonstrations of the relationship between CSR and business performance. Patel and Misra obtained 340 responses from senior executives/managers working in multinational firms and found that CSR influences organizational performance when exercised towards external stakeholders [10]. The relationship between CSR and business performance will vary with research perspectives or measurement methods. The research of Hasan et al. demonstrated that the link between corporate operating performance and CSR would be affected by other regulatory factors [11]. Chatterjee and Wernerfelt's study indicates that the firm size will impact its strategic form. The larger the size of an enterprise is, the easier it is to raise funds. The size of an enterprise will affect its financing, which affects its operating performance [12]. The firm size is directly proportional to CSR. The larger the enterprise, the higher the CSR index [13]. McWilliams and Siegel's research proves that the debt ratio will affect the performance of CSR on the business performance of enterprises [14]. McGuire, Sundgren, and Schneeweis pointed out that the impact of asset turnover on business performance means that the company is operating well and represents an efficient use of resources [15]. Shen and Chang indicated that the better the asset turnover, the better the resources and operating conditions of the business [16]. From the research above, ROA and ROE are the effects of critical financial indicators that were discussed. Size of an enterprise, debt ratio, and asset turnover have a moderating effect on the impact of CSR on business performance. Therefore, this study explores the influence of enhancing CSR on ROA and ROE by moderating firm size, debt ratio, and turnover.

CSR is like a chameleon that changes its color according to its context [17]. In summary, CSR has become a global enterprises consensus and an indispensable condition for corporate growth or stability. The CSR would affect business performance, and business performance is an indicator of corporate effectiveness, which can assist companies in determining whether the adopted strategies, organizational structure, execution ability, and effectiveness allow them to reach the preset goals or help them to develop inspection targets for higher goals [18]. This study hopes that exploring CSR can help companies improve business performance, and, through the implementation of CSR, they can achieve the joint development of enterprises and society. ROA and ROE measure the business performance in the above study. At the same time, to make the analysis results more convincing, this study takes firm size, debt ratio, and turnover as the adjustment variables. The specific research objectives of this study are as follows:

(1) To investigate the impact of CSR, firm size, debt ratio, and turnover on ROA and ROE

(2) To investigate the impact of CSR on ROA and ROE regulated by firm size, debt ratio, and turnover

2. Materials and Methods

2.1. Research Framework. This study mainly explores the relationship between CSR and business performance. This study uses two financial indicators, ROA and ROE, as contingency terms. CSR is an independent variable, while firm size, debt ratio, and turnover rate are the adjustment variables. The research framework constructed is shown in Figure 1.

2.2. Research Subject. This study used Taiwan as an area of research. The Corporate Citizenship Index from Taiwan CommonWealth Magazine is one of Taiwan's most

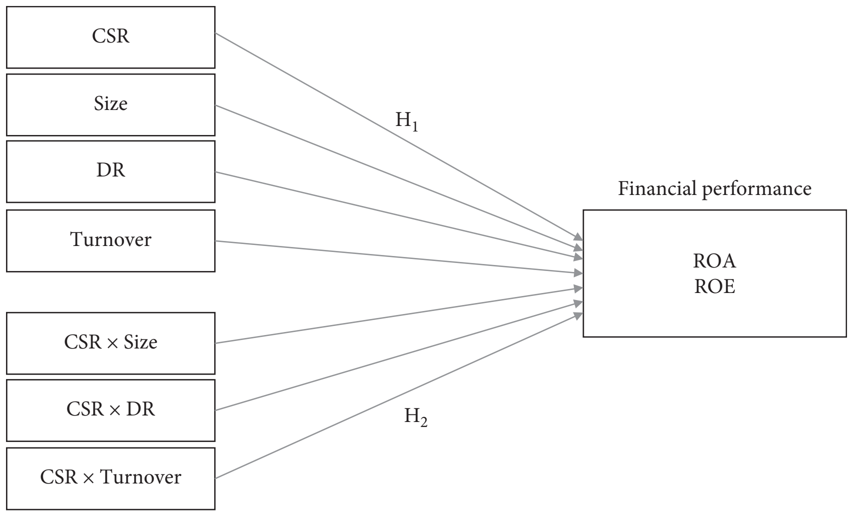

Figure 1: Research framework of CSR on ROA and ROE. CSR: corporate social responsibility; DR: debt ratio; ROA: return on assets; ROE: return on equity; H_1: hypothesis 1; H_2: hypothesis 2.

representative corporate social responsibility awards. The research object of this study was the enterprises that have won the CommonWealth Corporate Citizenship Award as the research sample. Taiwan CommonWealth Magazine was founded on June 1, 1981, and mainly reports news about Taiwan's economy and finance, business operations, and industry trends. It regularly launches surveys on corporate areas and people's livelihoods, including the Corporate Citizenship Index.

The survey and evaluation of the CommonWealth Magazine were divided into three stages. More than 2,000 recommended publicly issued companies and foreign companies were evaluated through expert review to 30 selected large-scale companies with revenues exceeding 10 billion, ten backbone enterprises with revenues below 10 billion, and ten foreign companies ranking the best corporate citizens in Taiwan.

In the first stage, companies from the public offering companies supervised by the Taiwan Financial Supervisory Commission (FSC) that have made profits for three consecutive years are selected. The Taiwanese foreign investors recommended by experts and scholars were invited to participate in the survey. In the second stage, a total of 118 short-listed companies were selected: 54 large-scale enterprises, 27 medium-scale enterprises, and 37 foreign-funded enterprises. In the third stage, judging, comprising twelve judges with credibility and social prestige, decided the rank of top 50 corporate citizens. A total of 572 companies were selected from 2012 to 2018. 111 foreign and 80 small companies were deleted, and 381 were left for financial analysis.

The firm size, debt, and turnover sample was taken from the Taiwan Economic Journal (TEJ) database. This study uses TEj's IFRS financial statements as aggregated sample data. In order to make the data obtained by this research more convincing, this research adopts the IFRS financial statements compiled by TEJ as the sample data. Taiwan officially entered the first year of IFRS in 2012. Therefore, the sample period of this study is selected from 2012 to 2018, a total of 7 years. After screening this research data, 35 companies with uneven financial information were excluded, and the final sample observations totaled 346. The diversity of samples that accorded with the emphasis of the research method did not cause the research results to be biased due to the concentration of the sample data attributes. The detailed description of measuring variables is shown in Table 1.

2.3. Research Tool and Analysis

2.3.1. Operational Definition and Variable Measurement. The SPSS 18.0 statistical software was used in this study to analyze the data, and then mainly descriptive statistics were used to analyze the current situation and hierarchical regression analysis to discuss the impact of each factor layer by layer. ROA and ROE act as dependent variables, while CSR acts as an independent variable, and firm size, debt ratio, and turnover act as the adjustment variables to identify the impact of CSR on business performance. The measurements of CSR, firm size, debt ratio, and turnover were obtained from the evaluation data of the CommonWealth Corporate Citizenship Award, and each piece of sample data was obtained from the TEJ financial database. CSR is divided into four dimensions: corporate governance, corporate commitment, social participation, and environmental sustainability. The scores of each dimension account for 25%, and the total score is up to 10 points. The scale of enterprises is divided into large and medium enterprises, the debt ratio is debt divided by total assets, and the turnover is net operating income divided by average total assets. The significance level was set at $\alpha = 0.05$.

2.3.2. Empirical Model. This study mainly investigated the relationship between the independent variable CSR and the dependent variable business performance. This study used

Table 1: Measuring variables.

Variable	Measurement
Dependent variables	
ROA	Net income/total assets
ROE	Net income/average shareholders' equity
Independent variable	
CSR	Index of Common Wealth Corporate Citizenship Award
Moderating variables	
Size	Large enterprises = 1; medium enterprises = 0
Debt ratio	Total debt/total assets
Turnover	Net operating income/total average assets

Regression Model 1 to test whether CSR significantly impacts ROA and Regression Model 2 to test whether CSR significantly impacts ROE. The regression equation of this study is divided into two sections. The first section is the regression formula without the interaction term, and the second section is the regression formula with the interaction term.

The first section is

$$\begin{aligned} \text{ROA}_i &= \beta_0 + \beta_1\text{CSR}_i + \beta_2\text{SIZE}_i + \beta_3\text{DR}_i + \beta_4\text{TURNOVER}_i + \varepsilon_i, \\ \text{ROE}_i &= \beta_0 + \beta_1\text{CSR}_i + \beta_2\text{SIZE}_i + \beta_3\text{DR}_i + \beta_4\text{TURNOVER}_i + \varepsilon_i. \end{aligned} \tag{1}$$

The second section is

$$\begin{aligned} \text{ROA}_i = {} & \beta_0 + \beta_1\text{CSR}_i + \beta_2\text{SIZE}_i + \beta_3\text{DR}_i + \beta_4\text{TURNOVER}_i + \beta_{12}\text{CSR}_i \times \text{SIZE}_i + \beta_{13}\text{CSR}_i \times \text{DR}_i + \beta_{14}\text{CSR}_i \\ & \times \text{TURNOVER}_i + \varepsilon_i, \\ \text{ROE}_i = {} & \beta_0 + \beta_1\text{CSR}_i + \beta_2\text{SIZE}_i + \beta_3\text{DR}_i + \beta_4\text{TURNOVER}_i + \beta_{12}\text{CSR}_i \times \text{SIZE}_i + \beta_{13}\text{CSR}_i \times \text{DR}_i + \beta_{14}\text{CSR}_i \\ & \times \text{TURNOVER}_i + \varepsilon_i. \end{aligned} \tag{2}$$

3. Results

3.1. Current Analysis of Research Variables. This section mainly analyzes via descriptive statistics to understand the distribution. The analysis results in Table 2 show that, based on the samples used in this research, all the companies have won the CommonWealth Corporate Citizenship Award; the maximum CSR score sample is 9.50, and the minimum is 7.17. The overall CSR score is high. The debt ratio in the sample shows an extensive range. The maximum value is 96.78, the minimum value is 6.43, and the average is 53.41. It means that companies with CSR are not necessarily low in debt ratio, and most have won the Corporate Citizenship Award; hence, it can be seen that the debt ratio shows a middle-to-upward trend. The maximum value of the turnover is 3.01, and the minimum value is 0.18, which indicates that the turnover of the winning companies has remained below 3.01. The maximum value of ROA in the sample is 33.22, and the minimum value is −13.95, indicating that companies performing CSR may not have higher ROA and companies with negative ROA may not perform well in CSR. The maximum ROE in the sample is 67.78, and the minimum value is −23.49, which indicates that the ROE level does not indicate that the implementation of CSR is not exemplary.

Through Pearson's correlational analysis in Table 2, it is revealed that the correlation between debt ratio and ROA is as high as −.54 ($p < 0.05$), indicating that there is a significant negative correlation between debt ratio and ROA. The correlation between turnover and ROA is as high as −.20 ($p < 0.05$), indicating a significant negative correlation between turnover and ROA. Besides, the scale of an enterprise is a dichotomous variable, and the scale-related correlation coefficient is the two-point series correlation. Based on the above, it can be known that the company debt ratio that implements CSR may not be low. The ROA and ROE may also show negative numbers.

3.2. The Impact of CSR on ROA. From Table 3, the first section variable has a significant explanatory power on the dependent variable, $R^2 = 0.34$, $F\,(4{,}341) = 44.32$, and $p < 0.05$. The ROA is representing the performance of the enterprise. ROA is affected by four variables, which account for 34.2% of the variation in the strain term. Among the four variables, CSR contributed the most ($\beta = 0.19$, $t\,(341) = 4.11$, $p < 0.05$), followed by turnover ($\beta = 0.18$, $t\,(341) = 3.93$, $p < 0.05$), firm size ($\beta = -0.11$, $t\,(341) = 2.37$, $p < 0.05$), and debt ratio ($\beta = -0.48$, $t\,(341) = -10.33$, $p < 0.05$). It shows that CSR and turnover mainly create the contribution of the first section. Through the standardized regression coefficient (β), CSR

Table 2: Descriptive statistics for each variable.

	Descriptive statistics				Correlation coefficient	
Variable	Mean	SD	Minimum	Maximum	ROA	ROE
CSR	8.33	0.46	7.17	9.50	−0.14**	−0.10**
DR	53.41	22.54	6.43	96.78	−0.54*	−0.15*
TURNOVER	0.84	0.62	0.18	3.01	−0.20*	−0.19*
ROA	5.97	5.95	−13.95	33.22		
ROE	12.14	9.98	−23.49	67.78		

*$p < 0.05$.

Table 3: Hierarchical regression model of ROA.

Module internal variable		First section			Second section			VIF
		β	t	p	B	t	p	
Independent variable	CSR (A)	0.19	4.11*	0.001	0.38	4.00*	0.001	4.70
	SIZE (B)	−0.11	−2.37*	0.018	−0.15	−3.07*	0.002	1.24
	DEPT RATIO (C)	−0.48	−10.33*	0.001	−0.46	−9.92*	0.001	1.17
	TURNOVER (D)	0.18	3.93*	0.001	0.14	2.98*	0.003	1.25
	(A) × (B)				−0.23	−2.46*	0.014	4.49
	(A) × (C)				−0.11	−2.33*	0.021	1.15
	(A) × (D)				−0.06	−1.13*	0.259	1.26
Model summary	(R^2, F, ΔR^2)	0 (0.34, 44.32*, 0.34*)			(0.37, 28.19*, 0.03*)			

*$p < 0.05$. CSR: corporate social responsibility; β: path coefficients; t: t-test; VIF: variance inflation factor.

and turnover positively impact ROA, while the firm size and debt ratio have a negative impact on ROA. The following is the standard regression model for overall fit:

$$\text{ROA} = 19 * \text{CSR} - 0.11 * \text{SIZE} - 0.48 * \text{DR} + 0.18 * \text{TURNOVER}. \tag{3}$$

In the second section, after the interaction terms of CSR and various variables were put into the model, the explanatory power of the model reached $R^2 = 0.37$, $F\ (7{,}338) = 28.19$ ($p < 0.05$). Zone explanatory power increase was $R^2 = 0.027$, F change $(3{,}338) = 4.74$ ($p < 0.05$), and the increment of the display section is statistically significant. The three interaction terms are "CSR × turnover" ($\beta = -0.06$, $t\ (338) = -1.136$, $p = 0.26$), "CSR × debt ratio" ($\beta = -0.11$, $t\ (338) = -2.33$, $p < 0.05$), and "CSR × firm size" ($\beta = -0.23$, $t\ (338) = -2.5$, $p < 0.05$). Through the standardized regression coefficient (β), the interaction term between CSR and debt ratio has a negative impact on ROA, the interaction term between CSR and firm size has a negative impact on ROE, and the interaction term between CSR and turnover has no significant effect on ROA. The following is the standard regression model for overall fit:

$$\text{ROA} = 38 * \text{CSR} - .15 * \text{SIZE} - .46 * \text{DR} + .14 * \text{TURNOVER} - 0.23 * \text{CSR} * \text{SIZE} - 0.11 * \text{CSR} * \text{DR} + 0.06 * \text{CSR} * \text{TURNOVER}. \tag{4}$$

3.3. The Impact of CSR on ROE. From Table 4, the first section variable has significant explanatory power on the dependent variable, $R^2 = 0.08$, $F\ (4{,}341) = 7.44$, $p < 0.05$. The ROE is representing the performance of an enterprise. ROE is affected by four variables, which account for 8.0% of the variation in the strain term. Among the four variables, turnover contributed the most ($\beta = 0.23$, $t\ (341) = 4.12$, $p < 0.05$), followed by CSR ($\beta = 0.17$, $t\ (341) = 3.02$, $p < 0.05$) and, last, firm size ($\beta = -0.12$, $t\ (341) = -2.14$, $p < 0.05$). It shows that the contribution of the first section is mainly created by turnover and CSR. Through the standardized regression coefficient (β), the turnover and CSR positively impact ROE, the firm size has a negative impact on ROE, and the debt ratio has no significant impact on ROE. The following is the standard regression model for overall fit:

$$\text{ROE} = 0.17 * \text{CSR} - 0.12 * \text{SIZE} - 0.08 * \text{DR} + 0.23 * \text{TURNOVER}. \tag{5}$$

In the second section, after the interaction terms of CSR and various variables were put into the model, the explanatory power of the model reached $R^2 = 0.10$, $F\ (7{,}338) = 5.29$ ($p < 0.05$). Zone explanatory power increase

Table 4: Hierarchical regression model of ROE.

Module internal variable		First section			Second section			VIF
		β	t	p	β	t	p	
Independent variable	CSR (A)	0.17	3.02*	0.003	0.29	2.60*	0.010	4.70
	SIZE (B)	−0.12	−2.14*	0.033	−0.15	−2.52*	0.012	1.24
	DEPT RATIO (C)	−0.08	−1.43	0.153	−0.06	−1.07	0.285	1.17
	TURNOVER (D)	0.23	4.12*	0.001	0.20	3.45*	0.001	1.25
	(A) × (B)				−0.15	−1.39	0.166	4.49
	(A) × (C)				−0.11	−1.97*	0.049	1.15
	(A) × (D)				−0.03	−0.56	0.574	1.26
Model summary	(R^2, F, ΔR^2)	(0.080, 7.44*, 0.08*)			(0.10, 5.29*, 0.02)			

*$p < 0.05$. CSR: corporate social responsibility; β: path coefficients; t: t-test; VIF: variance inflation factor.

was $R^2 = 0.018$, F change (3,338) = 2.37 (p = 0.08), showing that the investment of the second section interaction term can effectively increase the interpretation of the model by an additional 1.8%; that is, the section increment is statistically significant. The three interaction terms are "CSR × turnover" ($\beta = -0.03$, t (338) = 0.56, p = 0.57), "CSR × debt ratio" ($\beta = -0.11$, t (338) = −1.97, $p < 0.05$), and "CSR × firm size" ($\beta = -0.15$, t (338) = −1.39, p = 0.17). Through the standardized regression coefficient (β), the interaction term between CSR and debt ratio has a negative impact on ROE, and the other interaction term has no significant effect on ROE. The following is the standard regression model for overall fit:

$$\begin{aligned} \text{ROE} = {} & .29 * \text{CSR} - .15 * \text{SIZE} - .06 * \text{DR} + .20 * \text{TURNOVER} - .15 * \text{CSR} * \text{SIZE} \\ & - .11 * \text{CSSR} * \text{DR} - .03 * \text{CSR} * \text{TURNOVER}. \end{aligned} \tag{6}$$

From Figure 2, the relationship between CSR and ROE is affected by adjusting the debt ratio. Then, according to the slope, it can be realized that low debt ratio enterprises will have a significant increase in ROE as CSR increases; that is, the lower the debt ratio is, the more effectively the relationship between CSR and ROE can be adjusted.

4. Discussion

This study draws a reference with the comparison analysis of adjustment analysis proposed by Jaccard and Turrisi to understand further the relationship of the explanatory power of the interaction term reaching a significant part [19]. From Figure 3, the relationship between CSR and ROA is affected by the adjustment of firm size. Then, according to the slope, it can be observed that medium-scale enterprises will have a significant increase in ROA as CSR increases; that is, the smaller the size of the enterprise, the better the relationship between CSR and ROA. Besides, the relationship between CSR and ROA is also affected by the adjustment of the debt ratio. According to the slope, it can be observed that the low debt ratio enterprise will increase the ROA as CSR increases (Figure 4); that is, the lower the debt ratio is, it can effectively adjust the relationship between CSR and ROA.

It can be seen that CSR and turnover are important influencing factors in business performance; the explanatory power is 34.2%. When the interaction term is input, the district explanatory power is 36.9%, and the input of the interaction term can effectively improve the model's extra 2.7% predictive power, indicating that the ROA has many critical influencing factors. This analysis's results show that CSR will positively affect the ROA. The result is similar to the research results of scholars, such as from previous studies [14, 20, 21]. The ROA will change with the level of CSR; the higher the company performs CSR, the higher the result of ROA is.

Regarding the adjustment variables, the relationship between the firm size and the debt ratio with the ROA showed a significant and negative impact; the relationship between the turnover and the ROA showed a significant and positive impact. Then, through the interaction term, the relationship of the firm size and debt ratio between CSR and ROA will have a regulating effect. The result that the firm size will have an adjustment effect echoes the research point of Chatterjee and Wernerfelt [12]. In addition, the debt ratio will have an adjustment effect, which echoes the result of McWilliams and Siegel (2000) that the debt ratio will affect the company's business performance [14]. From Figure 3, it can be seen that the straight line of the medium-scale enterprises is significantly increased from the lower left to the upper right. Representing the medium-scale firm, the implementation of CSR has a better effect on ROA here than in the large-sized firm. Then, from Figure 4, it can be realized that companies with lower debt ratios have higher slopes than those with higher debt ratios, which indicates that CSR performance by companies with lower debt has a better effect on ROA than that by companies with higher debt ratios.

From Figure 2, the relationship between CSR and ROE is affected by adjusting the debt ratio. Then, according to the slope, it can be seen that low debt ratio enterprises will have a significant increase in ROE as CSR increases; that is, the

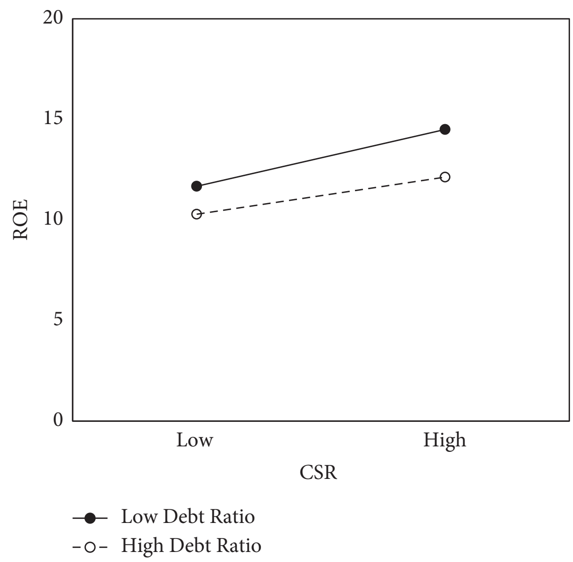

Figure 2: Cross diagram of CSR and debt ratio of ROE.

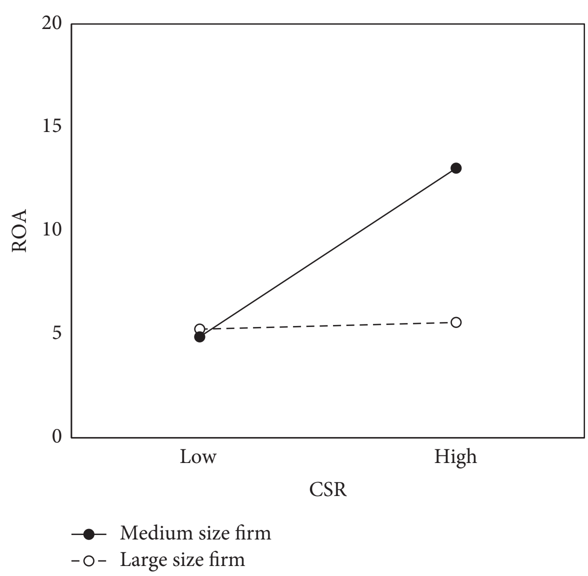

Figure 3: Cross diagram of CSR and size of ROA.

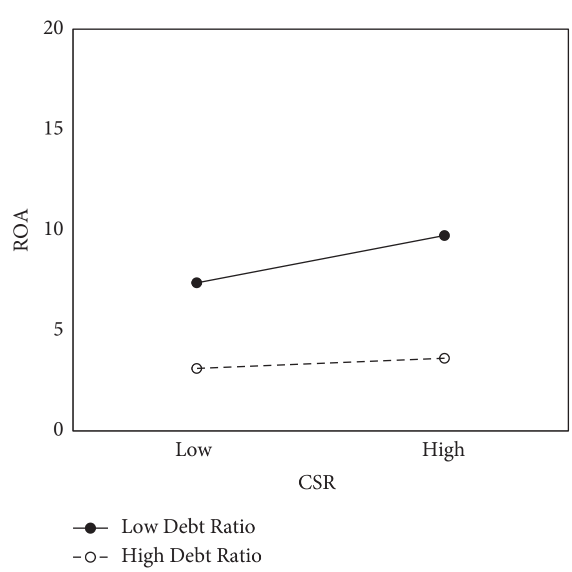

Figure 4: Cross diagram of CSR and debt ratio (DR) of ROA.

lower the debt ratio is, the more effectively the relationship between CSR and ROE can be adjusted. It also can be noted that CSR and turnover are important influencing factors in business performance, where explanatory power is 8.0%. When the interaction term is input, the district explanatory power is 9.9%; the input of the interaction term can effectively improve the model's extra 1.8% predictive power, indicating that ROE has many critical influencing factors. This analysis's result shows that CSR will positively affect ROA. The result is similar to the research results of scholars such as Moskowitz, Bowman and Haire, Liu et al., and Nieh et al., who proved that ROE would change with the level of CSR [22, 23].

Regarding the adjustment variables, the relationship between the firm size and ROE showed a significant and negative impact, while the relationship between the turnover and the ROE showed a significant and positive impact. Then, through the interaction term, it can be found that the relationship of debt ratio between CSR and ROE will have a regulating effect. The result that the debt ratio will have an adjustment effect echoes the research point of Nakamura [24]. The research results of Nieh et al. further validate the analysis results of this study; that is, the debt ratio has a regulating effect between CSR and ROE [23]. From Figure 2, it can be noted that companies with lower debt ratios have higher slopes than those with higher debt ratios, which indicates that CSR performance by companies with lower debt ratios has a better effect on ROE than that by companies with higher debt ratios.

5. Conclusions

This study concluded that CSR has a significant impact on business performance, and firm size and debt ratio have a moderating effect on CSR. The hierarchical regression analysis found that CSR and turnover positively and significantly impact ROA, while the firm size and debt ratio have a negative and significant impact on ROA. This result shows that CSR is an essential factor that directly affects whether an enterprise makes full use of its assets. Furthermore, the hierarchical regression analysis found that CSR and turnover have a positive and significant impact on ROE, while firm size has a negative and significant impact on ROE, and the debt ratio did not reach a significant predictive power on ROE. This result shows that turnover has the most significant influence; it is an essential factor that directly affects the company's operating capacity and is essential for shareholders to measure whether it is worth continuing to invest. Enterprises should strive to improve the fulfillment of CSR. This research first suggests that companies should focus on the fulfillment of CSR regardless of the firm size, the level of the debt ratio, and whether the asset turnover rate is good or not. Enterprises still need to rely on social resources to achieve sustainable operations, take from society, and feedback to society to form an excellent cycle to avoid an imbalance between supply and demand.

Firm size has a significant negative regulatory effect on the impact of CSR on ROA. In verifying the adjustment effect, the results of this study show that the effect of firm size has a significant negative adjustment effect between CSR and ROA. The larger the firm's size, the weaker the relationship between CSR and ROA. The medium-scale firm can enhance the effectiveness of its ROA by enhancing CSR. Based on the research results, this research suggests that the medium-scale firm should implement more CSR to help to increase the ROA. The empirical evidence of this research proves that low-scale enterprises will have a substantial increase in the ROA as CSR. Then, the large companies still show an upward trend in the relationship between CSR and ROA.

In verifying the adjustment effect, the results of this study show that the effect of debt ratio has a significant negative adjustment effect between CSR and ROA. That is, the larger the debt ratio, the weaker the relationship between CSR and ROA. The debt ratio has a significant negative regulatory effect on the impact of CSR on ROE. This result shows that the debt ratio has a significant negative adjustment effect between CSR and ROE in verifying the adjustment effect. That is, the larger the debt ratio, the weaker the relationship between CSR and ROE. This research is expected to analyze the impact of CSR on business performance and explore how companies can further help corporate growth through CSR. The empirical results prove that the promotion of CSR will have an impact on business performance. In addition, the empirical results show that firm size and debt ratio have a regulating effect on the relationship between CSR and ROA. The debt ratio has a regulating effect on the return on the relationship between CSR and ROE. Enterprises should pay attention to the influence of the debt ratio when implementing CSR. According to the research results, the relationship between CSR and ROA is affected by the debt ratio adjustment. Therefore, this research suggests that companies should pay attention to controlling the corporate debt ratio when fulfilling CSR. If the debt ratio is too high, it will affect the use of corporate funds and thus affect corporate profitability.

Data Availability

All data generated or analysed during the study are included in this published article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Su-Shiang Lee and Chih-Wei Lin were responsible for conceptualization of the study, Wei-Peng Tan and Chih-Wei Lin were responsible for methodology, Wei-Peng Tan and Chih-Wei Lin developed the software, Su-Shiang Lee and Tso-Yen Mao validated the study, Wei-Peng Tan and Chih-Wei Lin performed formal analysis, Wei-Peng Tan and Chih-Wei Lin were involved in investigation, Wei-Peng Tan and Chih-Wei Lin wrote the original draft, Tso-Yen Mao and Chih-Wei Lin reviewed and edited the article, and Su-

Shiang Lee supervised the study. All authors have read and agreed to the published version of the manuscript.

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Research Article

A Network-Based Approach to Study Returns Synchronization of Stocks: The Case of Global Equity Markets

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The synchronization in financial markets has increased during the rise of global markets. Nevertheless, global shocks provoke high levels of returns synchronization that jeopardize market stability. Using correlation-based networks, regressions, and VAR models, we measure and estimate the effect of global synchronization on the world equity markets of North America, Latin America, Europe, Asia, and Oceania between July 2001 and April 2020. We find that our measure of global stock synchronization is dynamic over time, its minimums coincide with significant financial shocks, and it shrinks to its minimum levels, indicating that the returns of global markets are moving in a synchronized way. Also, it is a significant and positive factor of regional synchronization. Regional markets react heterogeneously to global synchronization shocks suggesting both local and global factors are sources of synchronization. Our work helps market participants who need to measure, monitor, and manage the synchronization of returns in a parsimonious, dynamic, and empirically tractable way. Our evidence highlights the necessity of including synchronization as a risk factor to assess the decision-making criteria of a broad range of market participants ranging from regulators to investors. To policy-makers, governments, and central banks, our work is a call to incorporate events of high global synchronization into the radar of hazards of the whole market stability.

1. Introduction

During recent decades, we have witnessed the emergence of global financial markets. Greater economic openness and increasing integration fostered financial integration, a higher interconnectedness in capital markets, and a greater size and complexity of the financial systems. As a result, the global financial market becomes a "complex system" highly interconnected with cross-border interconnections and interdependencies, where shocks easily amplify and quickly turn into global events. Studies on interconnectedness show its dual impact on systemic risk; it could improve financial robustness when it contributes to absorbs shocks, but it could also generate contagion when propagates shocks among the components of a financial system [1–3].

During financial turbulences, risk appetite fades provoking that the liquidity of risky assets practically disappears, transforming them into a generalized herd-like behavior, where investors desperately seek risk-free assets to take refuge. (For example, between February 15 and March 23 of 2020, the world witnessed violent falls in the financial markets; the S&P500 index accumulated falls of 35.33%; and the reference price for WTI oil fell by 58.13%, extending its fall to USD 17.27 during April. Likewise, during the same period, the interest rates of the 10-year bonds of the United States Treasury fell by 80.60%, reaching an all-time minimum of 0.3137% annually.) These behaviors are similar among world financial markets, reflecting that uncertainty and volatility are ubiquitous characteristics of capital markets during global shocks. Moreover, this uncertainty regarding the future performance of financial markets is not novel for the market. As past episodes have shown, it changes the volatility of the returns of financial assets, risk management, and asset pricing, affecting consumption, savings, and investment decisions in the economy [4]. For instance, the COVID-19 outbreak turned into a global shock that simultaneously affected most of the world economies. From a financial stability perspective, this shock negatively impacted the valuations of financial assets such as stocks and bonds. In addition, it generated the well-known flight to quality and liquidity hoarding effects typically observed in global capital markets during past episodes of financial turmoil [3, 5].

The complex relationship between financial markets and their constituents and their connectedness patterns and structures attracted the attention of academics, regulators, and market practitioners for its effects on market risk, systemic risk, and business cycle risk. After the 2007-8 financial crisis, financial markets have been studied through network-based models, focusing initially on the study of cascading effects on the financial sector [2, 5, 6]. Initial models depicted well how the structure of the financial network can lead to cascades of default under contagion and are capable of estimating the probability and impact of its occurrence. However, a deeper understanding and measuring of how shocks are amplified and propagated through financial networks of assets is still required. In this work, we study the phenomenon of equity markets returns' synchronization that especially emerges when the stock market is faced with sharp downtrends, causing that a large number of participants in the market suffer severe losses at the same time, a behavior that quickly propagates to the entire market [7]. This phenomenon was particularly present during the Subprime Crisis in 2008 and the initial stages of the COVID-19 outbreak in 2020.

Synchronization or co-movement of returns is a particularly relevant phenomenon in stock markets since contagion generates a significant change in market volatility and stock's correlation coefficients [8]. For a broader viewpoint [1], the synchronization of equity returns is critical to the financial system. In this sense, economic structural similarities of countries and regions, coupled with global factors, explain financial markets' co-movement and generate financial contagion on a large scale [9]. Moreover, evidence indicates that interconnections among financial markets vary over time, being an uneven phenomenon among countries and regions [10].

The Subprime Crisis revealed that networks of obligations, for instance, banks [11], or assets between financial agents, for example, mutual funds [12], are possible elements behind the co-movement of financial assets and the stability of financial markets. This phenomenon is crucial under the conditions such as a significant concentration of assets in a few financial institutions and during financial shocks. For instance, Lavin, Valle, and Magner [13] found that similarities in mutual funds' portfolio strategies become a potential factor of disturbance with implications on the stability of the network conformed by stocks and funds. This evidence suggests that synchronization of returns is a highly complex phenomenon with no single cause; on the contrary, as we witness during the past financial turmoil of the pandemic outbreak, its occurrence relates to multiple factors [9, 14, 15].

We analyze the synchronization of returns from a regional and global market viewpoint. Our paper studies co-movement and not integration because we focus on shedding light on how equity market correlations dynamically vary among periods of financial stability and instability. Historical financial turmoil episodes show that all these events share some structural properties and that not all markets react equally when global returns' co-movement skyrocket in terms of how the synchronization phenomenon evolves and spreads among global equity markets. The following research questions are not fully covered in how the synchronization phenomenon evolves and spreads among global equity markets. First, is it possible to gauge the aggregate level of synchronization of market returns? Second, how does global stock market synchronization affect regional markets? Third, do variations in the global stock market synchronization uniformly affect regional markets? And finally, does regional equity markets' synchronization typically move with or against the global equity markets' synchronization?

We contribute to the literature by studying this phenomenon in an appropriately parsimonious, dynamic, and empirically tractable way using correlation-based networks methods coupled with time-series analysis and VAR models. First, we tackle the previous research questions measuring the global synchronization of equity returns of 27 world equity markets indices from July 2001 to April 2020. Second, we build asset correlation trees of global and regional equity networks using planar filtering methods such as minimum spanning trees and Planar Maximally Filtered Graphs [16]. Third, we study the global synchronization effect on regional markets applying structural VAR and impulse-response function analysis. Fourth, exploring the dynamic quantification of the synchronization of returns at a broad market level, we help to monitor this phenomenon by estimating a global measure of synchronization that helps explain the regional co-movement of regional equity markets. Finally, we facilitate the task of monitoring synchronization risk by providing a sensitivity measure of each regional market to changes in the global market synchronization.

Specifically, we apply the length of the minimum spanning tree (MSTL) as a measure of synchronicity of returns for the regional markets (MSTLR) of North and Latin America, Europe, Asia, and Oceania. Similarly, we estimate the MSTL for the global equity market network (MSTLG) formed by the 27 equity markets that conform to the latter regional markets. After this, we organize our empirical strategy on three steps:

(1) We dynamically measure with MSTL the degree of synchronization at both regional (MSTLR) and global (MSTLG) levels.

(2) We econometrically test whether the global synchronization measure (MSTLG) is relevant in synchronizing regional markets (MSTLR) of North and Latin America, Europe, Asia, and Oceania.

(3) We empirically analyze whether global synchronization (MSTLG) levels affect the stock market's synchronization of the regional markets and contribute to generating future unequal synchronization among them.

Our main results show that the global synchronization of stock returns measured by the MSTLG dynamically captures changes in the global equity correlation network structure, especially during calms and during crisis times. For instance, the MSTLG reaches its minimum values during financial turmoil, evidencing the most significant level of synchronization among the global equity stock markets' returns. On the other hand, during periods of mild volatility, the MSTLG reaches its maximum values, indicating a low level of co-movement among global equity returns.

Similarly, we find different levels of synchronization sensitivity among regional markets. The co-movement sensitivity of each regional equity market due to variations on the global synchronization measure is unequal. This evidence would suggest the presence of regional factors that also influence the synchronization of the regional equity returns. These findings hold when applying robustness tests. The results remain unchanged when we apply specific controls and use the Planar Maximally Filtered Graph Length (PMFGL) as another global synchronization measure of returns instead of the MSTL.

Finally, we study the synchronization impact of global or world synchronization on the behavior of world regional markets. Using structural VAR and impulse-response function analysis, we find evidence that suggests the presence of Granger causality. Moreover, this predictability seems to go from the global network of returns towards the regional returns networks. These results suggest that the global synchronization of the equity market generates a contemporary and future regional equity synchronization of returns. In other words, the global synchronization of equity returns acts as a relevant factor explaining the variation of the co-movement of returns at regional market levels.

Our evidence has practical implications for practitioners and regulators. This work shows that an increase in the global synchronization of stock returns is the forerunner of a future rise in the synchronization of returns of regional markets. In addition, this result would imply a greater systemic risk and lessen portfolio diversification benefits [17]. Similarly, our measure of global synchronization would serve to set critical value limits that would allow market participants to anticipate future regional and global markets' synchronization spurs. Finally, our results highlight the relevance of global and local factors that would fuel synchronization events [9] and the importance of proper regulation of financial markets that alleviate the potential hazards of high synchronization periods.

The paper is structured as follows: Section 2 depicts the literature and connects it with the main hypotheses. Section 3 reviews the methodology. Section 4 discusses the main methods applied and shows the data. Section 5 presents the empirical findings. Finally, Section 6 concludes and extends our findings.

2. Literature and Hypotheses

2.1. Literature Review. Systemic risk jeopardizes the capital markets' stability and proper functioning, reducing market confidence and willingness to take risks. Diverse methodologies have been applied to monitoring and quantifying it. Among the most applied methods are equity-correlation-based measures [18], conditional value at risk (CoVaR) approach [19], copula functions [20], marginal expected shortfall analysis [21, 22], and cross-correlation coefficient-based analysis [23]. These approaches mainly focus on the relationships between financial institutions and the financial system.

As the interconnections on capital markets rise, the necessity of considering the interconnectedness and interactions that underlies the financial system as a whole perspective arises too. The complexity of interconnections and the size of the financial markets promote the ample use of network methodologies to quantify risks and identify the transmission of risks among sectors, countries, and markets. Moreover, understanding complex systems' behaviors are enhanced through network methods since they allow modeling the indirect effects in the interconnections of their components or entities [24].

The network literature initially focused on network attributes' implications and their relationships with financial systems' stability and fragility [25, 26]. Similarly, many studies explored how the links' distribution affects the systemic reaction to shocks and how the connectivity of critical nodes or hub nodes could destabilize and even cause the entire network to collapse [3, 27, 28]. Other relevant topics included transaction networks of financial assets, portfolio selection, risk management, overlapped portfolios, integration of financial markets, and financial crises [29–32].

Network methods initially employed correlation-based networks. The minimal spanning tree (MST) [30], the Planar Maximally Filtered Graph (PMFG) [33], the correlation threshold network [34], and the partial correlation-based network [35] are the most extensive methods. MST and PMFG apply Pearson correlation coefficients to build asset networks considering the level of similarity in the price changes for a given pair of assets. In contrast, partial correlation-based networks estimate partial correlations to measure whether other assets influence the relationship between this pair of assets. Pearson correlation-based networks methods are applied to study financial markets, the MST being the most frequent method used for its simplicity, robustness, and clarity to visualize asset trees properties and their linkages [35].

The structure of the asset network of financial markets reveals useful taxonomies for analyzing financial markets as a complex system. Mantegna [29] models US equity market structures using MST and PMFG, finding clusters between the Dow Jones index components. Onnela et al. [31], analyzing the correlation networks of the stocks belonging to the S&P500 index, show dynamic clusters whose existence is not exclusive due to industrial sectors but due to psychological and economic factors captured through the asset network. They find that the normalized tree length of the MST (MSTL) is dynamic over time and reaches minimums during financial crises, showing that the power of diversification in the market relates to the evolution of the MSTL asset network over time. Li et al. [36] found that during crises, the topology of the asset tree changes, the MST becoming more starlike and compact and this network becoming less resilient to shocks and more prone to systemic risk. Despite the widespread use of these methods as tools for studying relationships and interactions within financial markets, their main drawback is that the topological constraints for constructing these networks do not always possess apparent economic or statistical grounds [37, 38].

As interest in the phenomenon of financial market interconnections increases, new methodologies have developed to delve into the mechanisms of spillover and contagion. Spillover analysis method surge founded on econometric-based networks is classified into the following groups: (a) Granger-causality networks or mean-spillover networks [1]; (b) variance decomposition frame-based networks or volatility spillover networks [39] and GARCH model-based networks [40]; and (c) risk spillover networks that include the tail-risk driven networks [41–43] and the extreme risk networks [38]. In general terms, these methods can model the complexities of the interconnectedness phenomena present in capital markets and identify their possible spillover paths associated.

Network methods improve traditional statistical analysis of complex systems. For example, econometric methods study the direct effects on the relationships of the entities of a system. However, when coupled with networks, it is feasible to enrich the dynamic modeling of financial markets by estimating, for instance, the distance between two entities or nodes and how likely an indirect effect is between them [39]. Mainly, through network methods, it is possible to study the synchronization of returns in financial markets.

The ubiquity of the synchronization of returns is a phenomenon with multiple origins and implications. Glasserman and Young [5] found that, at present, the returns synchronization observed in the financial markets is more recurrent than before because of the growing interconnectedness of the world financial system. This issue is critical in a risk management context, because diversification does not properly protect portfolios against risk during high synchronization episodes. Ample evidence shows that, during the Subprime Crisis, the diversification advantage from portfolio management disappears due to increased synchronization of assets' returns [17, 44, 45]. Bury [46], Zhao et al. [47], and Gao and Mei [48] found that correlations are time-varying and synchronization of returns rises during crises. Higher synchronization periods tend to occur precisely when investors mostly need the help of diversification as a tool to lessen the adverse effects of financial shocks on their portfolios [31].

As the focus of our paper is the study of synchronization within global equity markets, we use the MST method. As mentioned, this is an excellent technique for studying the structure of financial time-series correlation networks and very useful for identifying the structure of financial time-series correlation networks [31, 49, 50]. Moreover, even though there are more sophisticated techniques to measure synchronization based on oscillators [51, 52] or phase synchronization [53, 54], the returns cross-correlation matrix is, in essence, the information of co-movement between signals, easy to compute and from which one can extract not only topological properties of the correlation network but also coupling behavior of time-varying signals.

From an economic and financial viewpoint, various theories would explain the synchronization of returns. Factors related to financial exposures and economic and commercial links, coupled with dynamic complex network structures, have been studied [46, 51, 55]. For instance, interest rate parity models link the synchronization of returns to exchange rates; trade flow models connect them to exchange rates, and asset pricing models associate them with exchange rate variations that affect the supply/demand of financial assets. Roll [56] and Chow et al. [57] found a positive relationship between the US dollar and stock returns. Phylaktis and Ravazzolo [58] observe that stock prices and exchange rates are positively related. In the same vein, but connecting different financial markets, Ciner et al. [59] showed that oil shocks negatively impact stock returns, and during crises, gold transforms into a refuge asset. Recently, Raddant and Kennet [9] related the co-movement of financial markets to countries' economic structural similarities and alike global sectoral factors.

2.2. Hypotheses. Network methods complement traditional econometric analysis since they allow the inclusion of second-order effects and nonlinear interactions present on complex systems. For instance, modeling the synchronization of returns is crucial for understanding the financial markets' behavior and reaction to disturbances always present on capital markets.

In opposition to linear systems, complex systems are characterized among other factors, by being nonlinear because the change in the outputs is nonproportional to the change in the inputs, causing the system to appear chaotic, unpredictable, or even contradictory. Precisely, we have witnessed this kind of behavior during the outbreak of the pandemic in equity markets, in part due to the extraordinary measures taken by central banks and governments and in part also as a natural reaction of investors towards a flight to quality investing as a consequence of a diminished risk appetite. To mitigate markets turmoil, liquidity injections, repurchase of risky assets, and the explosive increase in fiscal spending have been applied globally. Unfortunately, these measures have been accompanied by unwanted higher synchronization in the global equity market.

Capital markets are characterized by numerous entities and various interaction rules, on several degrees with nonlinearities, that generate collective behaviors and comovements that stimulate asset and market interactions that finally influence pairwise returns correlations under a specific catalyst. This generalized phenomenon hinders the comprehension and modeling of the whole system, especially when shocks generate state changes in global financial markets that skyrocket returns' synchronization [46, 51].

From the viewpoint of the market participants and regulators, today more than ever, it is needed to measure, monitor, and anticipate global synchronization of the returns of financial assets, especially for most volatile ones such as stocks. Therefore, central banks, regulators, portfolio managers, and investors require estimation of synchronization of the global, regional, and local level in order to use this measure as a "seismograph" that can help them to assess the movements that different shocks provoke on the financial system and at the same time be able to foresee the future level of synchronization.

We consider the contribution of financial networks as a tool to monitor the level of synchronization of returns of global stock markets. Based on the purpose mentioned above, considering the research questions mentioned in Introduction and considering the level of global synchronization of equity markets as an exogenous variable that evolves accordingly to the positive and negative shocks that financial markets face, we establish the following hypotheses:

> Hypothesis 1 (H1): *the global synchronization of returns (MSTLG) is a statistically significant factor in explaining the synchronization of returns of regional markets (MSTLR) of North and Latin America, Europe, Asia, and Oceania.*
>
> We expect that the global synchronization of returns estimated from the global equity market network is relevant to explaining the regional synchronization of returns. This global network captures the collective behavior at the aggregate level of pairwise markets correlations. Our second hypothesis is the following:
>
> Hypothesis 2 (H2): *there are statistically significant differences in the degree of sensitivity of each regional markets´ synchronization (MSTLR) to changes in the global synchronization of returns (MSTLG).*
>
> We expect that changes in the global synchronization levels affect market's synchronization of each regional market unequally since multiple local and global factors coupled with economic and commercial links affect the co-movements of stocks.

3. Network Methods

We apply network methodologies to stock indexes to estimate the correlations of market returns and build the network of correlations [31, 60]. For this, we considered the closing price of the index i on the day τ as $P_i(\tau)$ and its returns as $r_i(\tau) = \ln P_i(\tau) - \ln P_i(\tau - 1)$ for a consecutive sequence of transaction days. To calculate the evolution of indices' synchronization, we used a vector of returns for a time window defined by the number of transaction days of month t. This vector of returns corresponds to r_i^t, such that the correlation between index i and index j in month t is

$$\rho_{ij}^t = \frac{\langle \mathbf{r}_i^t \mathbf{r}_j^t \rangle - \langle \mathbf{r}_i^t \rangle \langle \mathbf{r}_j^t \rangle}{\left[\langle \mathbf{r}_i^{t2} \rangle - \langle \mathbf{r}_i^t \rangle^2 \right] \left[\langle \mathbf{r}_j^{t2} \rangle - \langle \mathbf{r}_j^t \rangle^2 \right]}, \tag{1}$$

where $\langle \ldots \rangle$ indicates the average overall transaction days of month t. The result for each pair of indexes is a matrix $\mathbf{C}^t$ of $N \times N$ with values $-1 \leq \rho_{ij} \leq 1$. This matrix is equivalent to the adjacency matrix with weights of a completely connected network, in which the interconnection of each index is represented and in which the weights correspond to the correlations between each pair of indices.

To capture the relevant correlations in the index network, we filtered the entire network's weights, preventing the network nodes from being disconnected. This methodology corresponds to the MST [29], which delivers a subgraph-type tree structure, connected from the entire network, with N nodes and N-1 links, and whose path to connect all nodes is minimal. The MST reduces the entire network of N (N − 1)/2 links to a tree with N − 1 links [61].

The MST built with Prim's algorithm [62] connects the asset network's N nodes minimizing the distance traveled. Previous to this network, we transformed the correlations using a nonlinear transformation such that $d_{ij} = (2(1 - \rho_{ij}))^{1/2}$ represents the distance between the indices. A correlation $\rho_{ij} = -1$ indicates the maximum distance with $d_{ij} = 2$, while $\rho_{ij} = 1$ indicates a minimum with $d_{ij} = 0$. As a result, we obtained a matrix D^t, which summarizes the distances between the indices that describe the ultrametric properties of the taxonomy of an asset network [29, 63, 64].

We estimate the MST at D^t, describing the asset network's adjacency matrix by T^t, whose sum of links is minimal. The sum of the links calculated for each month t forms a time series. In this way, for the network of N nodes and N − 1 links, the normalized tree length (MSTL) is defined as

$$L(t) = \frac{1}{N-1} \sum_{d_{ij}^t \in \mathbf{T}^t} d_{ij}^t. \tag{2}$$

We generated a time-series MSTL_i (t) for each month t and market i, taking its variation as

$$\Delta L_i(t) = \ln(L_i(t)) - \ln(L_i(t-1)). \tag{3}$$

Finally, to properly model this series, we study the stationarity conditions of this time series applying standard procedures to include them in the econometric models [65, 66].

4. Empirical Approach

4.1. Econometric Model. Our paper analyzes the hypotheses related to the global synchronization of 27 equity markets and the synchronization observed in the regional markets of North and Latin America, Europe, Asia, and Oceania. According to this, we built the following time-series model to test the hypotheses of this study:

$$\Delta L_{it} = \alpha + d_m + \beta * X_{it} + \gamma * C_{it} + e_{it}. \tag{4}$$

The dependent variable ΔL_{it} is the MSTLR variation of region i ($i = 1$: America; 2: North America; $i = 3$: Latin America; $i = 4$: Europe, and $i = 5$: Asia-Oceania) in month t ($t = 1$ …216); α is the constant; d_m is a dummy month variable that captures unobserved temporary effects ($m = 1$, January,. . ., $m = 12$, December); β represents the coefficients of the independent variables related to the hypotheses; γ corresponds to the estimated coefficients for the control variables; X_{it} is the global MSTL variation (MSTLG); C_{it} are the control variables; and e_{it} corresponds to the error term. In addition, we include lags ΔL_{it-1} and ΔL_{it-2} to control the possible effects of autocorrelation. Finally, we include as an independent variable, the monthly variation (*varmstl_global*) of the length of the global minimum spanning tree (MSTLG) as the variable that captures the global synchronization of stock returns.

In this way, using the model of equation (4), we evaluate the following hypotheses previously depicted in Section 2:

Hypothesis 1 (H1): the global synchronization of returns (MSTLG) is a statistically significant factor in explaining the synchronization of returns of regional markets (MSTLR) of North and Latin America, Europe, Asia, and Oceania.

H_{0i}: $\beta_i = 0$ and H_{1i}: $\beta_i \neq 0$, for all $i = 1, 2, 3, 4$, and 5.

Hypothesis 2 (H2): There are statistically significant differences in the degree of sensitivity of each regional market's synchronization (MSTLR) to changes in the global synchronization of returns (MSTLG).

H_0: $\beta_1 = \beta_2 = \beta_3 = \beta_4 = \beta_5$ and H_1: $\beta_1 \neq \beta_2 \neq \beta_3 \neq \beta_4 \neq \beta_5$.

We applied heteroscedasticity and autocorrelation consistent (HAC) estimators to estimate our econometric models. In addition, we implement robustness tests to verify that the results of the econometric analysis are consistent when including different robustness checks (see Section 5.3). Finally, we apply structural VAR, impulse-response function analysis, and forecasting error variance decomposition methods to our core models to test the existence of Granger causality among global and regional synchronization of equity returns (see Section 5.3).

4.2. Control Variables. In this section, we explain the control variables included in the econometric model of Section 4.1. According to the literature, financial shocks impact economic growth and stock returns. Nguyen et al. [67] found that commodities impact stock returns due to their utilization in portfolio diversification and hedging strategies. They also indicate that this factor would explain the comovement of copper with global stock markets. Similarly, interest rates also have an impact on stock markets. For instance, Shiller and Beltratti [68] found a negative relationship between long-term interest rates and stock returns in US markets. Likewise, there is evidence of a link between stock returns and exchange rates. Roll [56] and Chow et al. [57] showed a positive correlation between the dollar value measured by a basket of foreign currencies and US stocks' returns.

Commodities also impact the behavior of stock returns, especially the high correlation between oil prices and stock returns. Park and Ratti [69] and Apergis and Miller [70] documented an intertemporal relationship between oil and stocks, the positive or negative impact being on stock markets dependent on the type of oil shock. Along the same lines, there is evidence of a relationship between gold prices and stocks' behavior. Ciner et al. [59] pointed out that gold has a shelter status because investors use it as a haven under shocks and high uncertainty levels.

Uncertainty also influences the behavior of equity returns. The literature evidences a relationship between stock returns, market volatility, and economic uncertainty. The CBOE VIX (Chicago Board Options Exchange Volatility Index) is the best gauge to forecast volatility of equities, and it is an indicator highly valued by investors as a measure of implied equity market uncertainty. Banerjee et al. [71] found a negative relationship between the S&P 500 performance and VIX evolution. They also observe that the VIX has a robust predictive capacity of future stock returns. Similarly, Antonakakis et al. [4] found a negative correlation between stock's performance and the VIX. They also indicate that increases in the volatility of returns reduce future returns and boost economic uncertainty.

Considering the above literature, we incorporate control variables in our econometric model of Section 4.1 to control the possible impact that the previous variables would have on the market's returns of the equity markets of our study, which could influence the behavior of our dependent variable. Accordingly, following Eberhard et al. [32] and Lavin et al. [13], the variables we consider as controls are the following: to consider the possible effect of volatility, we added the monthly volatility of each region (*sigma*); to incorporate the effect of the VIX, we added the monthly variation of the VIX index (*varvix*); to control the effect of the US dollar, we added the monthly variation of the US dollar (measured against a basket of 10 leading global currencies) (*varbdxy*); to consider the possible effect of the interest rates, we added the monthly variation of the 10-year Treasury bond rate (*vart10us*); to incorporate the possible influence of the gold, we included the monthly variation of the gold price (*varau*); and finally, to control the effect of raw materials, we added the monthly variation of the copper price (*varhg1*) and the monthly variation of the oil price (*varcl1*).

4.3. The Data. We used daily data collected from Bloomberg from July 2001 to April 2020, totaling 226 months, for 27 stock indexes from North America, Latin America, Europe, Asia, and Oceania. These indices are part of Bloomberg's top benchmarks for each stock market at the country and regional level. Table 1 exhibits the stock indices for each region. Table 2 shows monthly variations and describes the main descriptive statistics for the global MSTL (MSTLG) and regional MSTL (MSTLR).

When comparing the different estimates, North American and European markets have a coefficient of variation (CV) higher than the global average. In contrast, Latin America, Asia, and Oceania have a lower one. These results indicate that in terms of the variability of MST length, the North American and European markets show higher volatility (relative to the average) in their degree of synchronization of returns than the rest of the regional markets. Figure 1 also exhibits the time series of the MSTLG from July 2001 to April 2020. As can be seen, there are big swings during the period, with clear maximums and minimums that tend to repeat during the whole period.

Table 1: Indices by region.

Region	Indices
North America	S&P500, NASDAQ from the USA and TSX from Canada.
Latin America	IPC from Mexico, BOVESPA from Brazil, IPSA from Chile, MERVAL from Argentina, IGBVL from Peru, and COLCAP from Colombia.
Europe	FTSE from the UK, CAC from France, DAX from Germany, IBEX from Spain, MIB from Italy, AEX from Holland, OMX from Sweden, RTS from Russia, and SMI from Swiss.
Asia	NIKKEI from Japan, HANG-SENG from Hong Kong, KOSPI from Korea, TSE from Taiwan, JSE from Indonesia, KLCI from Malaysia, and ST from Singapore.
Oceania	ASX 200 from Australia and NZSE from New Zealand.

This table summarizes each region of study and its corresponding stock indices.

Table 2: Descriptive statistics of minimum spanning trees length by region (MSTLR) and global (MSTLG) measure.

	Global		North America		Latin America		America		Europe		Asia-Oceania	
	MSTL	Monthly variation %	MSTL	Monthly variation %	MSTL	Monthly variation %	MSTL	Monthly variation %	MSTL	Monthly variation %	MSTL	Monthly variation %
Mean	13.045	−0.151	0.786	−0.184	3.379	−0.059	4.539	−0.092	2.932	−0.229	4.813	−0.174
SD	1.949	14.93	0.191	30.127	0.574	18.681	0.778	18.809	0.683	25.228	0.772	16.53
CV	0.149	—	0.243	—	0.170	—	0.174	—	0.233	—	0.160	—
p25%	11.516	−8.72	0.641	−22.571	3.042	−11.167	4.046	−10.195	2.423	−16.151	4.219	−9.783
p50%	13.302	−0.325	0.766	1.735	3.999	−0.342	4.639	1.064	2.908	−1.444	4.805	0.160
p75%	14.598	10.137	0.914	19.520	3.785	11.124	5.158	10.477	3.441	16.518	5.434	9.869

This table summarizes the means of the minimum spanning trees lengths by region and global levels, their respective monthly variations, and their main statistics for the period July 2001–April 2020. SD: standard deviation; CV: coefficient of variation; p25%, p50%, and p75%: percentile 25%, 50%, and 75%, respectively.

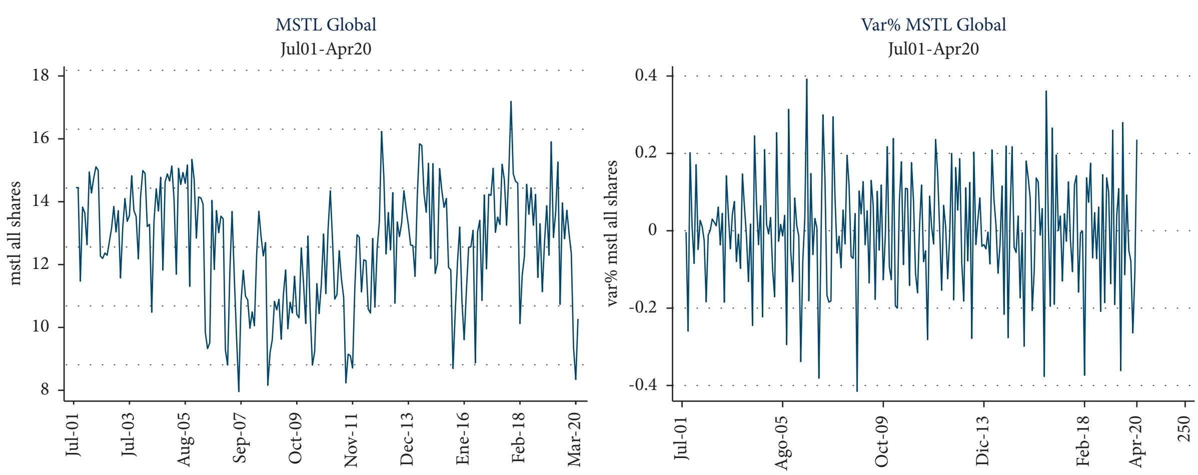


Figure 1: Global minimum spanning tree length (MSTLG). This figure represents the evolution and variation of the minimum spanning tree length for a total of 27 stock indexes in North and Latin America, Europe, Asia, and Oceania for the period July 2001–April 2020.

5. Empirical Findings

5.1. Descriptive Results. Considering our measure of global synchronization, in this section, we perform a brief comparison of the evolution of the MSTLG during the full-sample period and two periods of high turmoil in the financial markets, namely, the Subprime Crisis and the initial stages of the COVID-19 outbreak. The idea is to observe how our global synchronization measure behaves.

Figure 1 shows the monthly evolution and the monthly variation of the minimum spanning tree length for a total of 27 stock indexes in North and Latin America, Europe, Asia, and Oceania for the period July 2001–April 2020. As mentioned, this measure captures the global length of the MST asset conformed by the whole equity markets of our sample. In terms of the behavior of the MSTLG, we observe that the time series is dynamic over time, with clear cycles and pathways, reaching maximum levels near February 2018 and minimum levels near September 2017 and March 2020. In terms of the monthly variation of the MSTLG, we appreciate mild periods of change combined with high periods of fluctuations that broadly range from +40% to −40% monthly.

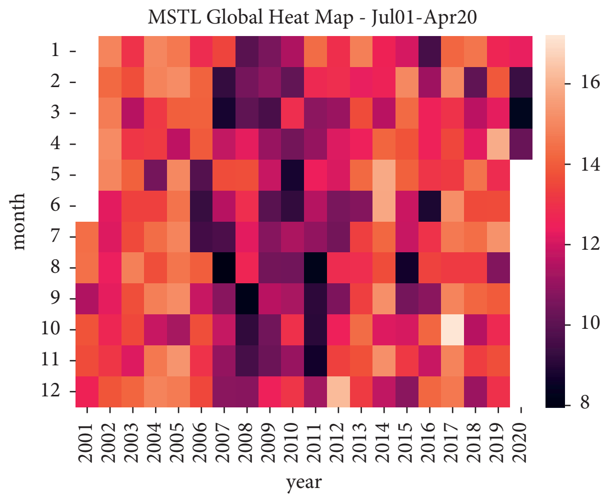


FIGURE 2: Global minimum spanning tree length (MSTLG) heat map. This figure represents the evolution of the minimum spanning tree length for a total of 27 stock indexes in North and Latin America, Europe, Asia, and Oceania for the period July 2001–April 2020. Black (khaki) color represents the minimum (maximum) values for the period.

Complementing the above evidence, Figure 2 depicts a heat map with the dynamic evolution of the MSTLG for the period July 2001–April 2020. Black (khaki) color represents the minimum (maximum) values for the period. We can observe the following:

(1) The global synchronization of the equity markets changes over time.

(2) The heat map illustrates that the minimum levels of the MSTLG coincide with shocks associated with the Subprime Crisis and the initial stages of the COVID-19 outbreak. This evidence suggests that two different shocks have a similar impact on the global synchronization of the equity returns of a broad sample of stock markets.

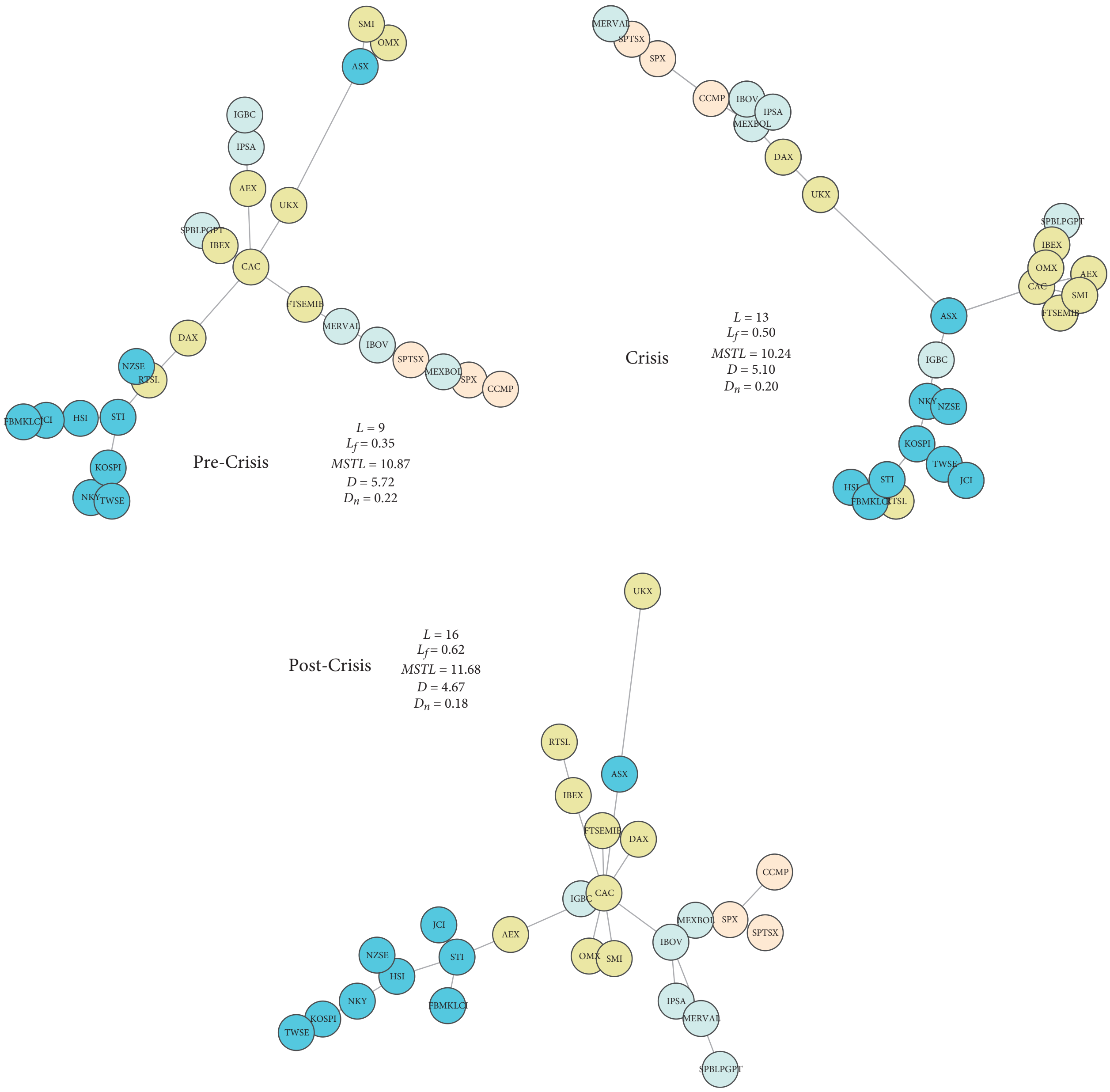
(3) The MSTLG shrinks to its minimum levels, indicating the returns of the global stock markets are moving in a synchronized way. Unfortunately, such aggregate behavior coincides with the worst periods in terms of performance and volatility of global stock markets.

In addition to the previous analysis, we perform network analysis to understand the structural changes within the asset trees that underlie the MSTLG during periods of high synchronization. Figure 3(a) shows nodes grouped according to their geographical region during the Subprime Crisis of 2008-9. In addition, we observe a persistent behavior on nodes in the same geographical sector remaining close to each other during and after the crisis (precrisis: January, February, and March 2008; crisis: September, October, and November 2008; and postcrisis: March, April, and May 2009). The shortening and lengthening of the MSTL do not break up the geographic node clusters, but it is present according to the analysis period.

We note that the Subprime Crisis caused important changes in the stock market synchronization. The length of the tree shortens from 10.87 to 10.24, while during the recovery from the crisis, the length increases from 10.24 to 11.68. Similarly, we observe that the structure of the trees is dynamic. Before the crisis, the tree has very long branches from several nodes joined sequentially, leaving only $L = 9$ terminal nodes with leaves, while in the postcrisis period, the tree has more star formations. As a result, more nodes appear as terminal nodes and more hub nodes; in this case, $L = 16$. We believe that this is relevant to the way information is transmitted throughout the financial network. The flow of information in a network with more star formations and hub nodes is different from a network with sequentially connected nodes. The average diameter of the tree D (the largest distance between any two nodes) also changes in the periods indicated. As expected, the diameter decreases (from 5.72 to 5.10), but it continues to do so even in the postcrisis period. Nevertheless, this decrease is due to the change in the tree's structure in which we see that the long rows of connected nodes give way in favor of more significant number of terminal nodes.

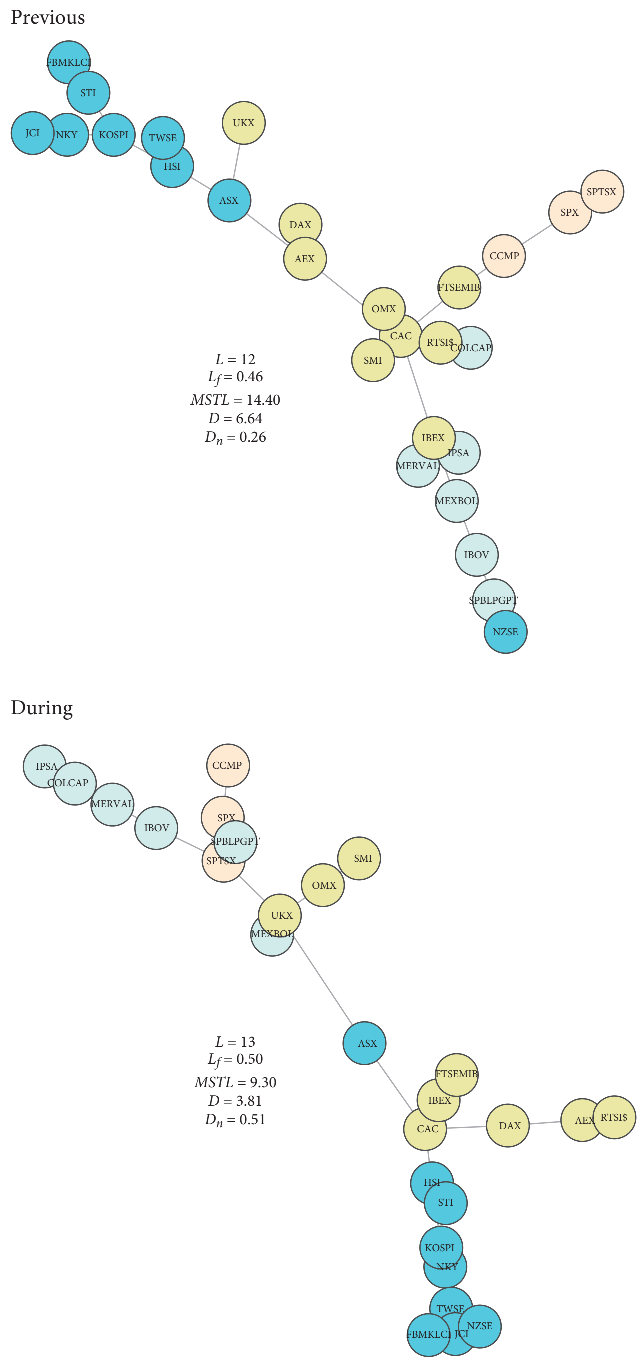
In the same way, we analyze how the network topology reacts during the initial months of the pandemic. Figure 3(b) shows the MST before (November 2019 to January 2020) and during the COVID-19 outbreak (February to April 2020). Like the Subprime Crisis, this shock does not seem to "disorder" the nodes, maintaining the network at a certain grouping level according to the region to which they belong. In any case, we observe a significant contraction of the distances (from 14.40 to 9.30). Unlike the Subprime Crisis, the trees' shape does not seem to change much: the number of terminal nodes before and during the COVID-19 outbreak is $L = 12$ and $L = 13$, respectively. However, the diameter also decreases significantly from 6.64 to 3.81. This reduction is due to the effect of this shock on financial markets and not a radical change in the network's topology.

In addition, we compare the effect of both shocks on the structure of the asset network. For this goal, we analyze the value of $\mathbf{L_f}$ and $\mathbf{D_n}$ between both asset trees. The first measure is the number of leaves divided by the maximum number of potential leaves (a starlike tree). The second measure is the diameter divided by the total number of edges. Table 3 summarizes these estimates. We can appreciate that the increase in $\mathbf{L_f}$ before and during both episodes was 8.7% and 30% for the Subprime Crisis and the COVID-19 outbreak, respectively. However, the decrease in $\mathbf{D_n}$ was 9.1% and 42.3%, respectively. In other words, on the one hand, the COVID-19 shock produced a significant topological change based on a relative increase in the number of leaves, while the Subprime Crisis produced an important topological change based on the diameter. Although the mechanisms that explain how and why both shocks affect the structure of the correlation networks differently are not precise, we know that both events' origin and basis are entirely different and both have different implications on the global financial and stock markets. Notwithstanding the previous results, from the viewpoint of the synchronization phenomenon, the previous results indicate that both episodes resemble each other, as the global synchronization increase in both periods.



(a)

Figure 3: Continued.



(b)

Figure 3: (a) Minimum spanning trees (MSTs) during the Subprime Crisis. This figure shows the resulting MST for three different periods. For comparison, we consider the quarters 6 months before and after where global markets fell sharply during Subprime Crisis: precrisis (January, February, and March 2008), crisis (September, October, and November 2008), and postcrisis (March, April, and May 2009). The color of the vertex represents different regions: (a) blue: Asia-Oceania, (b) light blue: Latin America, (c) light yellow: Europe, and (d) light salmon: North America. (b) Minimum spanning trees (MSTs) during the COVID-19 outbreak. This figure shows the resulting MST for two different periods. For comparison, we consider the quarter where global markets fell sharply during the COVID-19 outbreak and a quarter before: previous (November 2019 to January 2020) and during (February to April 2020) the outbreak. The color of the vertex represents different regions: (a) blue: Asia-Oceania, (b) light blue: Latin America, (c) light yellow: Europe, and (d) light salmon: North America.

5.2. Econometric Results. In this section, we resume the main results of the econometrics model presented in Section 4 that study our main hypotheses. As mentioned, H1 evaluates whether the global synchronization of returns (MSTLG) is a statistically significant factor in explaining the synchronization of returns of regional markets (MSTLR), while H2

Table 3: Descriptive parameters of the structure of the minimum spanning trees.

	Subprime Crisis		COVID-19 outbreak	
Period	L_f	D_n	L_f	D_n
Before	0.35	0.22	0.46	0.26
During	0.50	0.20	0.50	0.15
After	0.62	0.18	—	—

This table compares the means for L_f and D_n parameters of the MST trees during the Subprime Crisis and the COVID-19 outbreak. L_f: the number of leaves divided by the maximum number of potential leaves of the tree; D_n: the diameter divided by the total number of edges of the tree; periods of Subprime Crisis: precrisis: January to March 2008; crisis: September to November 2008; and postcrisis: March to May 2009. COVID-19 outbreak: before: November 2019 to January 2020; during: February to April 2020.

tests whether there are statistically significant differences in the sensitivity of each regional market (MSTLR) to variations in the global synchronization of equity returns (MSTLG).

Table 4 resumes the main results of the econometric estimations. First, we observe that MSTLG is a relevant factor for explaining the synchronization behavior of the regional markets under study (columns 1, 3, 5, 7, and 9). Second, as indicated by the coefficients associated with the variation of MSTLG (*varmstl_global*), there is a positive relationship between the variations in the global synchronization of equity returns and the variations in the level of regional synchronization associated with each regional market. Specifically, we can observe that the elasticities for North America, Latin America, America, Europe, and Asia-Oceania are 0.967, 0.858, 0.951, 1.083, and 0.772, respectively, all of them with $p < 0.001$. These coefficients suggest different levels of exposure to the risk of synchronization of global markets: the degree of linkage that a region has with the synchronization of returns on a global scale. Europe has a greater sensitiveness. A change of 1% in the global MSTL (MSTLG) causes a reaction of 1.08% in the synchronization of returns in European markets. Contrarily, for the Asia-Oceania markets, the impact is just 0.73%. The latter result suggests the lowest synchronization sensitivity among rest of the regional markets.

The above comparisons of regional sensitiveness regarding global synchronization are valid as long as the coefficients for each market are statistically different. Table 5, panel A, displays a statistical test of coefficient equality between models. As can we see, the evidence indicates Europe and Asia-Oceania have different elasticities suggesting that both regions would have different global synchronization exposures. On the contrary, North America and Europe exhibit similar elasticities suggesting that both regions respond similarly to changes in the global level of synchronization.

In addition, it is worth mentioning that the results of Table 4 are in line with the previous literature that indicates that the impact of regional stock volatility on returns co-movement is a relevant factor. As can we observe, there is a negative relationship between regional volatility and the synchronization of stock returns. The latter would occur because when regional volatility rises, a reduction in the regional MSTL develops as a consequence of a shock, indicating a higher level of correlation among regional stock markets, i.e., a higher regional synchronization episode emerges. These results are very interesting since a local volatility shock coupled with a global shock of synchronization would further increase the regional synchronization (columns 1 and 9).

5.3. Robustness Analysis. This section presents additional analyses to provide further insights and test the latter results' robustness. Accordingly, we apply three kinds of robustness analysis: (1) we control the possible impact of financial turmoil episodes; (2) we replace our global synchronization measure based on the length of the MST by the length of the PMFG; and (3) we study the influence of global synchronization on regional synchronization using VAR analysis.

5.3.1. Controlling Financial Shocks. During financial turmoil, the risk appetite practically disappears, giving space to liquidity hoarding and flight to quality. The above negatively impact risky assets, their returns, and their valuations. Accordingly, to evaluate the consistency of the results presented in the previous section, we apply robustness tests for controlling possible effects related to past financial shocks, such as the financial crisis of 2001, the Subprime Crisis of 2008-9, the financial turmoil of 2018, and the COVID-19 outbreak. During these episodes, the MSCI All Country World Index, a global free-float equity weighted index that includes both emerging and developed world markets, experienced negative accumulated returns from peak to valley, of −51%, −60%, −21%, and −34%. According to market practitioner's view, they entered a bearish territory because they fell more than 20%. For this reason, we include in the previous econometric models a dummy variable (*dum_shock* (The dummy shock takes the value of 1 for each month in the period from Mar-00 to Oct-02, Oct-07 to Apr-09, Jan-18 to Dec-18, and Feb-20 to Apr-20 and zero otherwise.)) to capture financial shock episodes. The idea is to corroborate that our results are not due to the financial turmoil during those specific bearish periods.

As Table 5, panel B, shows, the differences in the regional stock markets' sensitivity to changes in the global synchronization of the stock returns remain. In other words, during the analysis span, our results are consistent when controlling the unobserved effects of those above economic and financial shocks.

5.3.2. PMFG Length as a Measure of Global Synchronization. Our second robustness analysis tests whether our previous results hold when using a different measure to capture synchronization. We re-tested the econometric models, including

Table 4: MSTL models by regions.

	North America		Latin America		America		Europe		Asia-Oceania	
	(1) varmstl_nam	(2) varmstl_nam	(3) varmstl_lat	(4) varmstl_lat	(5) varmstl_ame	(6) varmstl_ame	(7) varmstl_eur	(8) varmstl_eur	(9) varmstl_asioc	(10) varmstl_asioc
varmstl_global	**0.967***** **(0.000)**		**0.858***** **(0.000)**		**0.951***** **(0.000)**		**1.083***** **(0.000)**		**0.772***** **(0.000)**	
sigma_nam	**−6.926***** **(0.005)**	**−9.311***** **(0.002)**								
sigma_lat			−1.412 (0.493)	**−5.478**** **(0.057)**						
sigma_ame					−1.974 (0.240)	**−6.780***** **(0.003)**				
sigma_eur							−2.413 (0.218)	**−7.188***** **(0.022)**		
sigma_asioc									**−3.576**** **(0.013)**	**−6.908**** **(0.013)**
Varvix	0.0374 (0.687)	**−0.291***** **(0.002)**	0.0656 (0.213)	**−0.258***** **(0.000)**	0.0660 (0.159)	**−0.274***** **(0.000)**	−0.143* (0.025)	**−0.522***** **(0.000)**	−0.0195 (0.694)	**−0.276***** **(0.000)**
Varbbdxy	−0.525 (0.616)	0.0405 (0.973)	**−1.161*** **(0.061)**	−1.148 (0.156)	**−0.998*** **(0.057)**	−1.000 (0.177)	0.746 (0.289)	**1.524*** **(0.098)**	−0.0264 (0.960)	0.214 (0.755)
vart10us	0.0527 (0.784)	0.144 (0.516)	−0.0620 (0.614)	0.0315 (0.844)	0.0434 (0.720)	0.139 (0.359)	0.0848 (0.587)	0.155 (0.443)	0.0356 (0.751)	0.0836 (0.503)
Varxau	−0.0914 (0.841)	−0.163 (0.762)	**−0.593**** **(0.033)**	**−0.684**** **(0.054)**	−0.304 (0.199)	−0.402 (0.223)	−0.0133 (0.964)	−0.0949 (0.804)	0.0952 (0.644)	−0.0801 (0.739)
varhg1	−0.0385 (0.868)	−0.0745 (0.773)	**0.290**** **(0.021)**	0.141 (0.444)	0.124 (0.248)	−0.0391 (0.823)	−0.0616 (0.744)	−0.231 (0.359)	−0.0740 (0.577)	−0.141 (0.506)
varcl1	−0.0282 (0.882)	−0.0365 (0.873)	0.0496 (0.678)	−0.0191 (0.892)	0.0161 (0.878)	−0.0402 (0.758)	0.111 (0.545)	0.115 (0.637)	0.00291 (0.976)	0.0223 (0.875)
L.varmstl_nam	**−0.444***** **(0.000)**	**−0.628***** **(0.000)**								
L2.varmstl_nam	**−0.212***** **(0.002)**	**−0.306***** **(0.000)**								
L.varmstl_lat			**−0.331***** **(0.000)**	**−0.582***** **(0.000)**						
L2.varmstl_lat			**−0.117**** **(0.027)**	**−0.235***** **(0.000)**						
L.varmstl_ame					**−0.302***** **(0.000)**	**−0.613***** **(0.000)**				
L2.varmstl_ame					**−0.0995**** **(0.031)**	**−0.276***** **(0.000)**				

Table 4: Continued.

	North America		Latin America		America		Europe		Asia-Oceania	
	(1) varmstl_nam	(2) varmstl_nam	(3) varmstl_lat	(4) varmstl_lat	(5) varmstl_ame	(6) varmstl_ame	(7) varmstl_eur	(8) varmstl_eur	(9) varmstl_asioc	(10) varmstl_asioc
L.varmstl_eur							**−0.277***** **(0.000)**	**−0.466***** **(0.000)**		
L2.varmstl_eur							**−0.142***** **(0.004)**	**−0.253***** **(0.000)**		
L.varmstl_asioc									**−0.237***** **(0.000)**	**−0.425***** **(0.000)**
L2.varmstl_asioc									**−0.191***** **(0.000)**	**−0.274***** **(0.000)**
_Cons	0.0702 (0.207)	**0.151***** **(0.001)**	**0.0495*** **(0.085)**	**0.117***** **(0.005)**	**0.0546**** **(0.014)**	**0.139***** **(0.000)**	0.0108 (0.730)	**0.121**** **(0.027)**	0.0437 (0.116)	**0.0962**** **(0.0022)**
N	184	184	184	184	184	184	184	184	184	184
R^2	0.599	0.473	0.698	0.462	0.776	0.505	0.708	0.476	0.711	0.441
Adj. R^2	0.547	0.408	0.659	0.396	0.747	0.444	0.670	0.412	0.673	0.372
F	17.29	10.45	17.95	10.83	28.22	12.16	23.84	11.43	27.08	9.779
LR-chi2 (1)		45.24		91.47		144.91		104.86		119.24
Prob > chi2		0.00		0.00		0.00		0.00		0.00

This table summarizes the results of the following model: $\Delta L_{it} = \alpha + d_m + \beta * X_{it} + \gamma * C_{it} + e_{it}$. ΔL_{it} is the variation of the MSTLR of region i in month t; α is the constant; d_m it is a dummy month variable that captures unobserved temporary effects; β represents the coefficients of the group of independent variables; γ corresponds to the estimated coefficients for the control variables; X_{it} is the variation of MSTLG; C_{it} are the control variables; and e_{it} is the error term. p values are given in parentheses. $^{*}p < 0.1$, $^{**}p < 0.05$, and $^{***}p < 0.01$. Bold values represent that the independent variable applied in the model is statistically significant.

Table 5: Comparison between coefficients of regressions by region.

	North America	Latin America	America	Europe	Asia-Oceania
			Panel A-without dummy shock		
North America	—	4.92 (0.0272)	2.42 (0.1208)	0.30 (0.5859)	9.28 (0.0025)
Latin America	—	—	1.35 (0.2465)	12.06 (0.0006)	0.90 (0.3426)
America	—	—	—	7.16 (0.0078)	5.90 (0.0157)
Europe	—	—	—	—	24.69 (0.0000)
			Panel B-with dummy shock		
	North America	Latin America	America	Europe	Asia-Oceania
North America	—	5.03 (0.0255)	2.50 (0.1146)	0.31 (0.5794)	8.54 (0.0037)
Latin America	—	—	1.37 (0.2422)	12.31 (0.0005)	0.83 (0.3630)
America	—	—	—	7.32 (0.0072)	5.36 (0.0187)
Europe	—	—	—	—	23.63 (0.0000)

This table shows the F-tests and p values (in parentheses) that compare the MSTLG coefficients between regression models shown in Table 4. The rows and columns of the table indicate the result comparison for each region. The null hypothesis indicates that there are no significant differences between the magnitudes of the estimated coefficients.

the variation of the length of the Planar Maximally Filtered Graph as an independent variable (The algorithm to find the PMFG [33] is similar to that used to find the MST, but unlike the latter, it produces a graph with 3N-6 edges, unlike MST that generates N-1 [72]. In this way, the PMFG retains a little more information than the MST.) (*varpmfgl*). Since the PMFG supports cycles in the network, the PMFGL will be higher than the MSTL. Because of this feature of including more information, it is interesting to compare the models that explain the synchronization phenomenon as a robustness measure. It is worth mentioning that we do not calculate the PMFG length for regions. As the PMFG includes the MST and the edges used to join the nodes in the PMFG are of minimum distance, therefore, the regional PMFG length will be the same as the length of the regional MST.

As we can see in Table 6, the principal results remain when we control the possible effect of financial shocks in conjunction with the length of the PMFG as a new estimate of global synchronization. Thus, we still observe the previous finding of a direct relationship between the global synchronization of equity markets and regional synchrony of returns. Moreover, similar to previous results, Table 6 shows that the sensitivity of the regional markets to changes on the global synchronization is dissimilar. For instance, North American and European markets have superior sensitivities compared to Latin American and Asian-Oceania markets.

5.3.3. VAR and IRF Analysis. Our last robustness analysis applies vector autoregression analysis (VAR) and impulse-response function (IRF) models to understand the interactions between the variables that capture synchronization at the regional markets and the effects of global synchronization on these variables. In the general form of the VAR model, the variables considered endogenous are *varmstl_nam, varmstl_lat, varmstl_ame, varmstl_eur,* and *varmstl_asioc*, while we incorporated the variable *varmstl_global* as an exogenous variable. In addition, we included the variable *varvix* to control for possible effects derived from implied volatility spillovers [73]. The VAR model is

$$Y_t = \sum_{k=1}^{K} A_k Y_{t-k} + \sum_{l=0}^{L} B_l X_{t-l} + e_t, \quad (5)$$

where Y_t is an nx1 vector of period t observations of endogenous variables; X_t is a vector of period t observations of the exogenous variables; and e_t is an nx1 residual vector. K is the number of lagged endogenous observations, and L is the number of lagged control observations. We set $K=4$ and $L=0$ based on the Akaike information criterion. The IRF function is

$$\begin{bmatrix} varmstl\_nam_t \\ varmstl\_lat_t \\ varmstl\_ame_t \\ varmstl\_eur_t \\ varmstl\_asioc_t \end{bmatrix} = \sum_{k=1}^{K} A_k \begin{bmatrix} varmstl\_nam_{t-k} \\ varmstl\_lat_{t-k} \\ varmstl\_ame_{t-k} \\ varmstl\_eur_{t-k} \\ varmstl\_asioc_{t-k} \end{bmatrix} + B_l * \mathrm{BM}_t + \begin{bmatrix} \varepsilon_{varmstl\_nam,t} \\ \varepsilon_{varmstl\_lat,t} \\ \varepsilon_{varmstl\_ame,t} \\ \varepsilon_{varmstl\_eur,t} \\ \varepsilon_{varmstl\_asioc,t} \end{bmatrix}. \quad (6)$$

Table 7 summarizes the results of the full-sample VAR. Again, we emphasize that we are not attempting to identify spillover effects, either the channels of transmissions by any means; on the contrary, we are just interested in studying the dynamic effects of the aggregate system (e.g., establishing if one variable helps forecast the other beyond a simple autoregressive benchmark). We organized our analysis in columns for each dependent variable and by

Table 6: Robustness models by regions.

	North America		Latin America		America		Europe		Asia-Oceania	
	(1) varmstl_nam	(2) varmstl_nam	(3) varmstl_lat	(4) varmstl_lat	(5) varmstl_ame	(6) varmstl_ame	(7) varmstl_eur	(8) varmstl_eur	(9) varmstl_asioc	(10) varmstl_asioc
varmstl_global	**0.935***** **(0.000)**		**0.848***** **(0.000)**		**0.938***** **(0.000)**		**1.063***** **(0.000)**		**0.747***** **(0.000)**	
varpmfgl_global		**0.838***** **(0.000)**		**0.766***** **(0.000)**		**0.837***** **(0.000)**		**0.992***** **(0.000)**		**0.712***** **(0.000)**
sigma_nam	**−9.925***** **(0.003)**	**−10.62***** **(0.002)**								
sigma_lat			−1.752 (0.477)	−2.266 (0.394)						
sigma_ame					−2.612 (0.262)	−3.393 (0.178)				
sigma_eur							−3.715 (0.109)	**−4.185*** **(0.069)**		
sigma_asioc									**−6.008***** **(0.001)**	**−6.409***** **(0.000)**
Varvix	0.0187 (0.831)	−0.0167 (0.849)	0.0586 (0.265)	0.0261 (0.602)	0.0584 (0.205)	0.0205 (0.675)	**−0.153**** **(0.018)**	**−0.180***** **(0.005)**	−0.0277 (0.584)	−0.0414 (0.390)
Varbbdxy	−0.537 (0.601)	−0.522 (0.621)	**−1.181*** **(0.059)**	**−1.243*** **(0.054)**	**−1.019*** **(0.052)**	**−1.087**** **(0.048)**	0.769 (0.282)	0.774 (0.316)	−0.0745 (0.887)	−0.106 (0.841)
vart10us	0.0386 (0.846)	0.0626 (0.755)	−0.0592 (0.637)	−0.0375 (0.781)	0.0437 (0.722)	0.0678 (0.606)	0.0809 (0.598)	0.109 (0.469)	0.0381 (0.720)	0.0524 (0.608)
Varxau	−0.120 (0.792)	−0.0762 (0.869)	**−0.615**** **(0.025)**	**−0.594**** **(0.041)**	−0.321 (0.175)	−0.298 (0.245)	−0.0421 (0.887)	0.00780 (0.979)	0.0526 (0.792)	0.0806 (0.671)
varhg1	−0.0366 (0.876)	−0.0606 (0.798)	**0.296**** **(0.019)**	**0.268**** **(0.035)**	0.126 (0.242)	0.0940 (0.393)	−0.0590 (0.748)	−0.0908 (0.622)	−0.0788 (0.542)	−0.0998 (0.447)
varcl1	−0.0469 (0.817)	−0.0603 (0.773)	0.0588 (0.633)	0.0489 (0.697)	0.0185 (0.865)	0.00615 (0.956)	0.121 (0.509)	0.112 (0.544)	0.00830 (0.931)	0.00388 (0.967)
dum_crisis	0.0981 (0.117)	**0.107*** **(0.094)**	0.0268 (0.347)	0.0309 (0.302)	0.0277 (0.298)	0.0353 (0.216)	0.0533 (0.223)	0.0579 (0.189)	**0.0565**** **(0.016)**	**0.0599**** **(0.015)**
L.varmstl_nam	**−0.450***** **(0.000)**	**−0.468***** **(0.000)**								
L2.varmstl_nam	**−0.215***** **(0.001)**	**−0.216***** **(0.001)**								
L.varmstl_lat			**−0.336***** **(0.000)**	**−0.365***** **(0.000)**						
L2.varmstl_lat			**−0.119**** **(0.026)**	**−0.126**** **(0.023)**						

Table 6: Continued.

	North America		Latin America		America		Europe		Asia-Oceania	
	(1) varmstl_nam	(2) varmstl_nam	(3) varmstl_lat	(4) varmstl_lat	(5) varmstl_ame	(6) varmstl_ame	(7) varmstl_eur	(8) varmstl_eur	(9) varmstl_asioc	(10) varmstl_asioc
L.varmstl_ame					**−0.309***** **(0.000)**	**−0.346***** **(0.000)**				
L2.varmstl_ame					**−0.103**** **(0.027)**	**−0.113**** **(0.021)**				
L.varmstl_eur							**−0.286***** **(0.000)**	**−0.302***** **(0.000)**		
L2.varmstl_eur							−0.146*** **(0.004)**	−0.136*** **(0.008)**		
L.varmstl_asioc									**−0.261***** **(0.000)**	**−0.267***** **(0.000)**
L2.varmstl_asioc									**−0.200***** **(0.000)**	**−0.195***** **(0.000)**
_Cons	**0.0935*** **(0.095)**	**0.105*** **(0.068)**	0.0483 (0.103)	**0.0577*** **(0.080)**	**0.0562**** **(0.019)**	**0.0691**** **(0.011)**	0.0629 (0.155)	0.0523 (0.277)	**0.0543*** **(0.057)**	**0.0607**** **(0.045)**
N	184	184	184	184	184	184	184	184	184	184
R^2	0.606	0.591	0.700	0.677	0.778	0.747	0.711	0.698	0.717	0.712
Adj. R^2	0.552	0.536	0.659	0.633	0.747	0.713	0.671	0.657	0.679	0.673
F	17.64	16.67	17.71	14.78	28.78	22.41	22.22	23.90	26.90	28.64

This table summarizes the results of the following model: $\Delta L_{it} = \alpha + d_m + \beta * X_{it} + \gamma * C_{it} + e_{it}$. ΔL_{it} is the variation of the MSTLR of region i in month t; α is the constant; d_m it is a dummy month variable that captures unobserved temporary effects; β represents the coefficients of the group of independent variables; γ corresponds to the estimated coefficients for the control variables; X_{it} is the variation of MSTL Global (PMFG Global); C_{it} are the control variables; and e_{it} is the error term. p values are given in parentheses. $^{*}p < 0.1$, $^{**}p < 0.05$, and $^{***}p < 0.01$. Bold values represent that the independent variable applied in the model is statistically significant.

Table 7: Vector autoregressive analysis.

	varmstl_nam			varmstl_lat			varmstl_ame			varmstl_eur			varmstl_asioc		
L1.varmstl_nam	−0.851*** (0.000)	−0.714*** (0.000)	−0.714*** (0.000)	−0.207** (0.012)	−0.098* (0.056)	−0.099* (0.055)	−0.204** (0.013)	−0.086** (0.050)	−0.087** (0.049)	−0.081 (0.492)	0.081 (0.232)	0.079 (0.241)	−0.107 (0.164)	0.000 (0.993)	0.000 (1.000)
L2.varmstl_nam	**−0.613*** (0.000)**	**−0.622*** (0.000)**	**−0.622*** (0.000)**	0.060 (0.514)	0.053 (0.355)	0.053 (0.357)	−0.023 (0.802)	−0.031 (0.531)	−0.031 (0.527)	0.056 (0.666)	0.046 (0.542)	0.045 (0.548)	−0.012 (0.893)	−0.019 (0.704)	−0.018 (0.707)
L3.varmstl_nam	**−0.472*** (0.001)**	**−0.441*** (0.000)**	**−0.446*** (0.000)**	−0.001 (0.993)	0.023 (0.686)	0.018 (0.754)	−0.009 (0.920)	0.017 (0.734)	0.013 (0.802)	0.020 (0.881)	0.056 (0.463)	0.034 (0.656)	−0.032 (0.709)	−0.009 (0.861)	−0.005 (0.924)
L4.varmstl_nam	−0.156 (0.203)	**−0.219** (0.018)**	**−0.220** (0.018)**	0.035 (0.667)	−0.014 (0.779)	−0.016 (0.758)	0.047 (0.568)	−0.007 (0.875)	−0.008 (0.855)	0.165 (0.156)	0.091 (0.172)	0.086 (0.198)	0.004 (0.959)	−0.045 (0.303)	−0.044 (0.315)
L1.varmstl_lat	**0.758** (0.030)**	**0.553** (0.036)**	**0.551** (0.037)**	**−0.892*** (0.000)**	**−1.055*** (0.000)**	**−1.057*** (0.000)**	−0.052 (0.823)	**−0.228* (0.067)**	**−0.230* (0.064)**	**0.589* (0.076)**	**0.347* (0.070)**	0.338* (0.074)	0.063 (0.773)	−0.097 (0.433)	−0.095 (0.441)
L2.varmstl_lat	**0.859** (0.035)**	0.316 (0.306)	0.322 (0.298)	−0.118 (0.663)	**−0.547*** (0.001)**	**−0.541*** (0.001***)**	0.409 (0.131)	−0.057 (0.697)	−0.052 (0.723)	**0.777** (0.044)**	0.136 (0.544)	0.162 (0.466)	**0.427* (0.091)**	0.005 (0.974)	0.000 (0.999)
L3.varmstl_lat	0.441 (0.272)	0.185 (0.541)	0.182 (0.547)	−0.332 (0.214)	**−0.534*** (0.001)**	**−0.537*** (0.001)**	0.134 (0.616)	−0.085 (0.551)	−0.088 (0.540)	0.508 (0.182)	0.206 (0.347)	0.194 (0.372)	0.215 (0.390)	0.016 (0.912)	0.018 (0.900)
L4.varmstl_lat	**0.708** (0.042)**	0.188 (0.479)	0.195 (0.464)	0.132 (0.570)	**−0.280* (0.054)**	**−0.273* (0.062)**	0.375 (0.106)	−0.072 (0.565)	−0.066 (0.601)	**0.635* (0.054)**	0.021 (0.914)	0.053 (0.781)	**0.378* (0.080)**	−0.027 (0.831)	−0.032 (0.796)
L1.varmstl_ame	−0.629 (0.159)	−0.367 (0.277)	−0.370 (0.274)	0.413 (0.165)	**0.621*** (0.001)**	**0.618*** (0.001)**	**−0.508* (0.089)**	**−0.282* (0.077)**	**−0.284* (0.074)**	−0.330 (0.436)	−0.020 (0.934)	−0.033 (0.891)	0.124 (0.655)	**0.329** (0.038)**	**0.331** (0.036)**
L2.varmstl_ame	−0.709 (0.166)	0.003 (0.993)	−0.002 (0.996)	−0.396 (0.245)	0.168 (0.433)	0.162 (0.449)	**−0.891*** (0.009)**	−0.279 (0.129)	−0.284 (0.122)	−0.775 (0.110)	0.065 (0.817)	0.041 (0.885)	−0.306 (0.336)	0.248 (0.174)	0.253 (0.167)
L3.varmstl_ame	−0.076 (0.882)	0.221 (0.565)	0.231 (0.550)	0.003 (0.993)	0.238 (0.260)	0.248 (0.241)	−0.457 (0.180)	−0.201 (0.267)	−0.193 (0.289)	−0.436 (0.367)	−0.085 (0.759)	−0.043 (0.877)	−0.104 (0.743)	0.127 (0.480)	0.120 (0.507)
L4.varmstl_ame	−0.508 (0.249)	0.114 (0.734)	0.109 (0.746)	−0.236 (0.421)	0.257 (0.164)	0.251 (0.173)	**−0.498* (0.091)**	0.036 (0.819)	0.032 (0.841)	**−0.788** (0.060)**	−0.053 (0.826)	−0.076 (0.753)	−0.400 (0.145)	0.084 (0.594)	0.088 (0.577)
L1.varmstl_eur	0.121 (0.190)	**0.187*** (0.007)**	**0.185*** (0.008)**	0.041 (0.505)	**0.093** (0.015)**	**0.092** (0.017)**	0.068 (0.273)	**0.124*** (0.000)**	**0.123*** (0.000)**	**−0.560*** (0.000)**	**−0.483*** (0.000)**	**−0.488*** (0.000)**	**0.102** (0.076)**	**0.153*** (0.000)**	**0.154*** (0.000)**
L2.varmstl_eur	0.166 (0.120)	**0.151** (0.061)**	**0.149** (0.064)**	0.098 (0.165)	**0.086** (0.050)**	**0.085* (0.056)**	0.110 (0.123)	**0.097** (0.011)**	**0.095** (0.012)**	**−0.388*** (0.000)**	**−0.406*** (0.000)**	**−0.414*** (0.000)**	**0.149** (0.024)**	**0.137*** (0.000)**	**0.139*** (0.000)**
L3.varmstl_eur	0.086 (0.421)	**0.138* (0.087)**	**0.137* (0.089)**	0.001 (0.990)	0.042 (0.343)	0.041 (0.354)	0.038 (0.591)	**0.083** (0.029)**	**0.082** (0.031)**	**−0.288*** (0.004)**	**−0.227*** (0.000)**	**−0.231*** (0.000)**	0.028 (0.676)	**0.068* (0.071)**	**0.069* (0.068)**
L4.varmstl_eur	**0.151* (0.098)**	0.112 (0.103)	0.113 (0.101)	−0.045 (0.455)	**−0.076** (0.044)**	**−0.075** (0.046)**	0.012 (0.843)	−0.021 (0.511)	−0.021 (0.523)	−0.067 (0.434)	**−0.113** (0.023)**	**−0.110** (0.025)**	0.065 (0.250)	0.035 (0.277)	0.034 (0.284)
L1.varmstl_asioc	0.178 (0.172)	**0.370*** (0.000)**	**0.373*** (0.000)**	**0.180** (0.039)**	**0.331*** (0.000)**	**0.335*** (0.000)**	**0.225*** (0.010)**	**0.390*** (0.000)**	**0.392*** (0.000)**	0.033 (0.789)	**0.260*** (0.000)**	**0.273*** (0.000)**	**−0.642*** (0.000)**	**−0.493*** (0.000)**	**−0.495*** (0.000)**
L2.varmstl_asioc	0.027 (0.863)	**0.244** (0.041)**	**0.244** (0.041)**	0.027 (0.795)	**0.199*** (0.002)**	**0.199*** (0.002)**	0.072 (0.490)	**0.258*** (0.000)**	**0.258*** (0.000)**	0.143 (0.336)	**0.399*** (0.000)**	**0.399*** (0.000)**	**−0.652*** (0.000)**	**−0.484*** (0.000)**	**−0.484*** (0.000)**
L3.varmstl_asioc	−0.124 (0.426)	0.055 (0.638)	0.055 (0.641)	0.038 (0.712)	**0.180*** (0.005)**	**0.180*** (0.006)**	0.034 (0.741)	**0.188*** (0.001)**	**0.188*** (0.001)**	−0.081 (0.582)	0.131 (0.126)	0.128 (0.130)	−0.412*** (0.000)	−0.273*** (0.000)	−0.272*** (0.000)
L4.varmstl_asioc	**−0.231* (0.082)**	0.035 (0.734)	0.032 (0.757)	**−0.175** (0.048)**	0.036 (0.521)	0.033 (0.560)	**−0.152* (0.087)**	0.077 (0.110)	0.074 (0.124)	−0.174 (0.167)	**0.140* (0.058)**	**0.127* (0.086)**	**−0.361*** (0.000)**	**−0.154*** (0.001)**	**−0.152*** (0.002)**
varmstl_global		**1.162*** (0.000)**	**1.145*** (0.000)**		**0.921*** (0.000)**	**0.902*** (0.000)**		**0.999*** (0.000)**	**0.982*** (0.000)**		**1.373*** (0.000)**	**1.292*** (0.000)**		**0.905*** (0.000)**	**0.919*** (0.000)**
Varvix			−0.022 (0.749)			−0.023 (0.538)			−0.020 (0.540)			**−0.099 (0.043)**			0.017 (0.583)
Cons	−0.005 (0.732)	−0.002 (0.870)	−0.002 (0.869)	−0.002 (0.834)	0.001 (0.933)	0.001 (0.935)	−0.003 (0.741)	0.000 (0.928)	0.000 (0.926)	−0.004 (0.782)	0.000 (0.995)	0.000 (0.990)	−0.002 (0.797)	0.000 (0.975	0.000 (0.973)
N	**221**	**221**	**221**	**221**	**221**	**221**	**221**	**221**	**221**	**221**	**221**	**221**	**221**	**221**	**221**
R^2	**0.444**	**0.684**	**0.684**	**0.362**	**0.753**	**0.753**	**0.370**	**0.821**	**0.822**	**0.288**	**0.764**	**0.769**	**0.342**	**0.788**	**0.788**
Chi2	**176.436**	**478.944**	**479.267**	**125.142**	**672.997**	**674.532**	**129.619**	**1015.371**	**1017.470**	**89.179**	**717.018**	**734.475**	**114.614**	**819.431**	**820.850**
P > chi2	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**

This table summarizes the results of the VAR analysis with monthly data and core specification from equation (5). p values are given in parentheses. $^{*}p < 0.1$, $^{**}p < 0.05$, and $^{***}p < 0.01$. Bold values represent that the independent variable applied in the model is statistically significant.

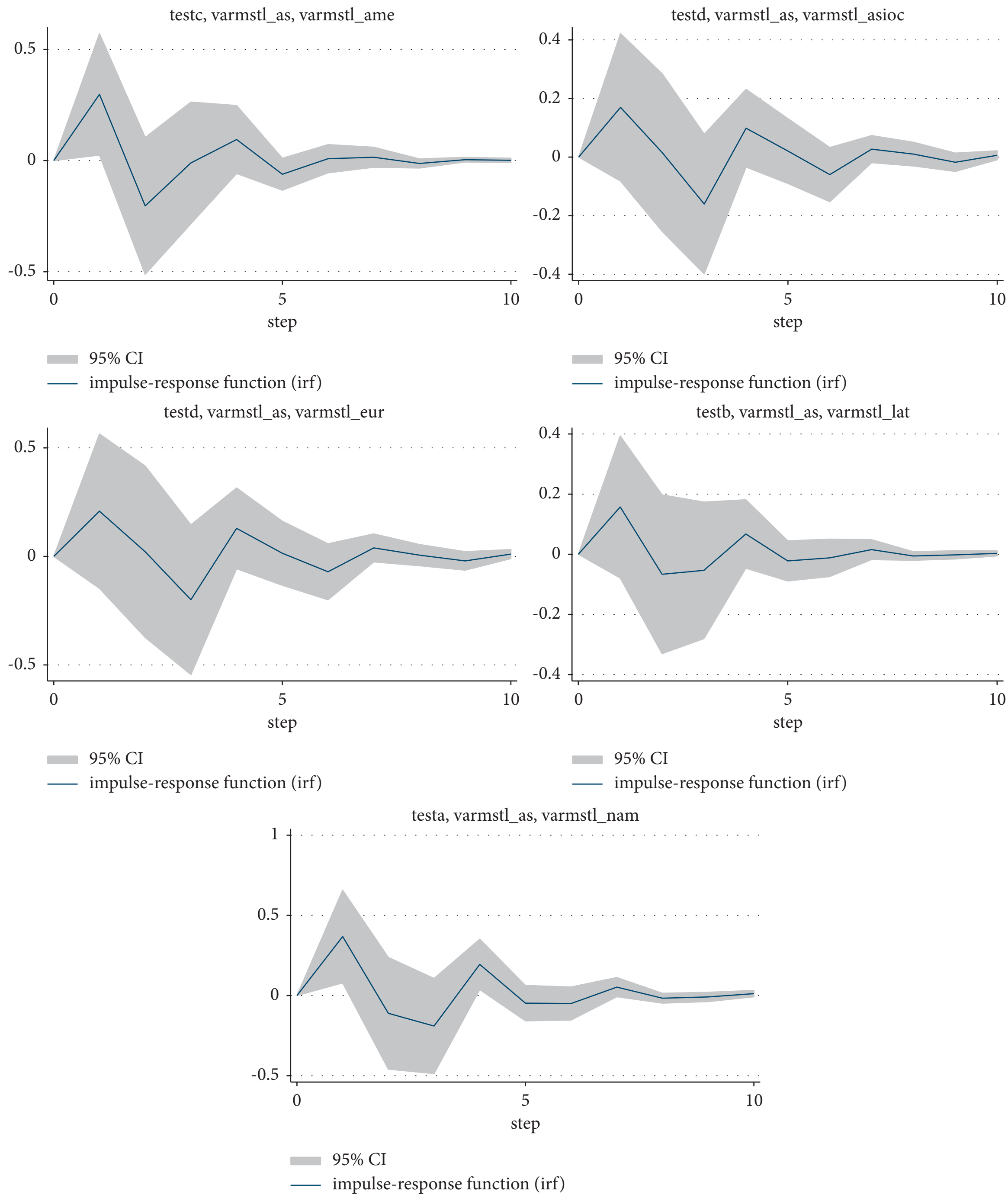


Figure 4: Impulse-response graphs. This figure depicts the impulse-response exercise from a shock in the global MSTL (varmstl_global) over the MSTL of North America (varmstl_nam), Latin America (varmstl_lat), America (varmstl_ame), Europe (varmstl_eur), and Asia-Oceania (varmstl_asioc).

rows for the lagged dependent variables and the exogenous variables.

The main results indicate relevant mutual influence in terms of synchronization of returns among regional markets. Asia and Oceania influence all the rest regions and itself; meanwhile, North America mainly affects itself and Latin America. Concerning the impact of the global synchronization over the regional markets, our evidence confirms a direct relationship between global synchronization captured by the variable *varmstl_global* and the synchronization exhibited by each regional market. Moreover, these results are robust when we control from possible effects derived by changes in the implied volatility that VIX captures.

In addition, to study the length of the synchronization episodes, we perform structural VAR analysis to capture the response after a shock of one standard deviation in the global MSTL. Figure 4 shows the impulse-response functions for each region. Consistent with our previous findings, we can

Table 8: Error variance decomposition.

	h	varmstl_global				varmstl_nam				varmstl_lat				varmstl_ame				varmstl_eur				varmstl_asioc			
		Oirf	S.E.	Fevd	S.E.	Oirf	S.E.	Fevd	S.E.	Oirf	S.E.	Fevd	S.E.	Oirf	S.E.	Fevd	S.E.	Oirf	S.E.	Fevd	S.E.	Oirf	S.E.	Fevd	S.E.
varmstl_global	0	**0.133**	0.006	0.000	0.000	**0.151**	0.014	0.000	0.000	**0.123**	0.009	0.000	0.000	**0.131**	0.008	0.000	0.000	**0.186**	0.012	0.000	0.000	**0.126**	0.008	0.000	0.000
	1	−0.053	0.009	**1.000**	0.000	−0.070	0.019	**0.406**	0.051	−0.053	0.012	**0.589**	0.042	−0.060	0.012	**0.702**	0.033	−0.073	0.016	**0.687**	0.035	−0.046	0.011	**0.690**	0.034
	2	−0.003	0.009	**0.963**	0.022	0.012	0.019	**0.330**	0.056	0.004	0.012	**0.535**	0.052	0.005	0.012	**0.618**	0.049	0.004	0.016	**0.653**	0.044	−0.011	0.011	**0.651**	0.044
	3	0.011	0.007	**0.952**	0.029	0.004	0.016	**0.325**	0.057	0.005	0.009	**0.520**	0.054	0.006	0.010	**0.601**	0.053	0.009	0.012	**0.646**	0.045	0.014	0.008	**0.646**	0.044
	4	−0.003	0.003	**0.946**	0.030	−0.005	0.009	**0.319**	0.056	−0.001	0.005	**0.516**	0.054	−0.002	0.005	**0.598**	0.053	−0.006	0.006	**0.636**	0.047	−0.001	0.004	**0.629**	0.048
	5	−0.002	0.002	**0.941**	0.033	0.003	0.006	**0.313**	0.057	−0.001	0.003	**0.512**	0.055	0.000	0.003	**0.592**	0.054	0.002	0.004	**0.632**	0.048	−0.005	0.004	**0.625**	0.049
varmstl_nam	0	0.000	0.000	**0.000**	0.000	**0.183**	0.009	**0.000**	0.000	0.000	0.007	**0.000**	0.000	**0.035**	0.005	**0.000**	0.000	−0.011	0.008	**0.000**	0.000	−0.017	0.006	**0.000**	0.000
	1	−0.019	0.008	**0.000**	0.000	−0.146	0.016	**0.594**	0.051	−0.023	0.011	**0.000**	0.000	−0.049	0.010	**0.050**	0.016	−0.017	0.014	**0.002**	0.004	−0.005	0.010	**0.012**	0.008
	2	0.012	0.009	**0.017**	0.015	0.031	0.018	**0.652**	0.056	0.021	0.011	**0.017**	0.015	0.022	0.011	**0.108**	0.034	0.010	0.015	**0.007**	0.008	0.007	0.010	**0.011**	0.007
	3	0.003	0.008	**0.023**	0.021	0.035	0.017	**0.651**	0.058	−0.007	0.010	**0.029**	0.025	0.005	0.010	**0.120**	0.041	0.007	0.014	**0.008**	0.011	0.000	0.009	**0.013**	0.009
	4	−0.006	0.005	**0.023**	0.020	−0.037	0.012	**0.654**	0.057	−0.002	0.007	**0.030**	0.026	−0.011	0.007	**0.119**	0.041	−0.010	0.009	**0.009**	0.011	−0.002	0.006	**0.012**	0.009
	5	0.002	0.003	**0.025**	0.022	0.012	0.008	**0.655**	0.058	0.004	0.004	**0.030**	0.026	0.006	0.004	**0.122**	0.042	0.003	0.005	**0.011**	0.013	0.000	0.004	**0.012**	0.009
armstl_lat	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	**0.103**	0.005	**0.000**	0.000	0.070	0.004	**0.000**	0.000	−0.044	0.008	**0.000**	0.000	−0.030	0.005	**0.000**	0.000
	1	0.005	0.009	0.000	0.000	0.004	0.015	0.000	0.000	−0.060	0.011	**0.411**	0.042	−0.046	0.011	**0.200**	0.026	0.044	0.015	**0.038**	0.014	0.018	0.010	**0.040**	0.014
	2	0.001	0.009	0.001	0.004	0.006	0.018	0.000	0.001	0.010	0.011	**0.424**	0.050	0.016	0.011	**0.209**	0.035	−0.016	0.015	**0.063**	0.026	0.008	0.010	**0.045**	0.020
	3	−0.004	0.008	0.001	0.004	−0.010	0.018	0.001	0.002	0.013	0.011	**0.415**	0.051	0.002	0.011	**0.211**	0.039	−0.005	0.014	**0.067**	0.030	−0.013	0.010	**0.047**	0.019
	4	0.001	0.005	0.002	0.005	0.006	0.012	0.002	0.006	−0.012	0.007	**0.416**	0.051	−0.006	0.007	**0.209**	0.039	0.011	0.009	**0.066**	0.029	0.003	0.006	**0.051**	0.023
	5	0.001	0.003	0.002	0.006	−0.001	0.008	0.002	0.007	0.004	0.004	**0.417**	0.052	0.003	0.005	**0.208**	0.039	−0.006	0.006	**0.067**	0.030	0.005	0.004	**0.051**	0.024
varmsl_ame	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.034	0.002	**0.000**	0.000	−0.007	0.008	**0.000**	0.000	−0.022	0.005	**0.000**	0.000
	1	0.004	0.009	0.000	0.000	−0.016	0.016	0.000	0.000	0.014	0.010	0.000	0.000	−0.013	0.010	**0.048**	0.006	0.003	0.015	**0.001**	0.002	0.018	0.010	**0.021**	0.010
	2	−0.008	0.009	0.001	0.003	0.012	0.018	0.003	0.006	−0.015	0.011	0.005	0.008	−0.005	0.011	**0.040**	0.009	−0.010	0.015	**0.001**	0.003	−0.009	0.010	**0.030**	0.017
	3	0.006	0.008	0.004	0.008	0.002	0.017	0.005	0.010	0.007	0.010	0.012	0.016	0.008	0.010	**0.039**	0.008	0.011	0.013	**0.003**	0.006	0.001	0.009	**0.032**	0.020
	4	−0.003	0.004	0.005	0.011	−0.011	0.011	0.005	0.010	−0.001	0.006	0.013	0.018	−0.005	0.006	**0.041**	0.011	−0.007	0.007	**0.005**	0.009	0.001	0.005	**0.031**	0.019
	5	0.001	0.002	0.006	0.011	0.009	0.006	0.006	0.010	−0.001	0.003	0.013	0.018	0.002	0.003	**0.041**	0.012	0.001	0.004	**0.005**	0.010	0.000	0.003	**0.031**	0.019
varmstl_eur	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.117	0.006	**0.000**	0.000	−0.056	0.004	**0.000**	0.000
	1	0.008	0.008	0.000	0.000	0.005	0.014	0.000	0.000	0.002	0.010	0.000	0.000	0.002	0.010	0.000	0.000	−0.056	0.014	**0.272**	0.031	0.040	0.009	**0.137**	0.022
	2	0.001	0.009	0.003	0.006	0.002	0.018	0.000	0.002	0.004	0.011	0.000	0.001	0.004	0.011	0.000	0.001	−0.009	0.015	**0.275**	0.037	0.007	0.010	**0.173**	0.034
	3	−0.007	0.008	0.003	0.006	−0.005	0.016	0.000	0.001	−0.006	0.010	0.001	0.002	−0.005	0.010	0.000	0.002	0.024	0.013	**0.274**	0.037	−0.026	0.009	**0.172**	0.032
	4	0.005	0.005	0.005	0.009	0.003	0.011	0.001	0.003	0.002	0.006	0.002	0.005	0.002	0.006	0.001	0.005	−0.009	0.008	**0.278**	0.039	0.013	0.006	**0.189**	0.038
	5	0.000	0.004	0.007	0.011	0.000	0.009	0.001	0.004	0.001	0.005	0.002	0.006	0.001	0.005	0.001	0.005	−0.006	0.007	**0.277**	0.040	0.004	0.005	**0.194**	0.041
varmstl_asioc	0	0.000	0.000	**0.000**	0.000	0.000	0.000	**0.000**	0.000	0.000	0.000	**0.000**	0.000	0.000	0.000	**0.000**	0.000	0.000	0.000	0.000	0.000	0.048	0.002	**0.000**	0.000
	1	0.017	0.009	**0.000**	0.000	0.035	0.015	**0.000**	0.000	0.025	0.010	**0.000**	0.000	0.029	0.010	**0.000**	0.000	0.007	0.014	0.000	0.000	−0.013	0.010	**0.100**	0.013
	2	−0.007	0.009	**0.014**	0.014	−0.019	0.018	**0.015**	0.013	−0.014	0.011	**0.018**	0.015	−0.014	0.011	**0.025**	0.017	0.011	0.015	0.001	0.003	−0.007	0.010	**0.090**	0.015
	3	−0.005	0.008	**0.016**	0.017	−0.010	0.017	**0.019**	0.019	−0.003	0.010	**0.023**	0.021	−0.008	0.011	**0.030**	0.023	−0.016	0.014	0.003	0.005	0.006	0.009	**0.090**	0.014
	4	0.007	0.005	**0.018**	0.017	0.019	0.012	**0.019**	0.017	0.008	0.007	**0.023**	0.020	0.013	0.007	**0.031**	0.022	0.006	0.008	0.007	0.011	0.001	0.006	**0.088**	0.015
	5	−0.003	0.003	**0.020**	0.019	−0.011	0.007	**0.023**	0.020	−0.005	0.004	**0.025**	0.021	−0.007	0.004	**0.036**	0.024	0.003	0.005	0.007	0.012	−0.003	0.004	**0.087**	0.015

This table summarizes the forecast-error variance decomposition results for July 2001 to April 2020. This table reports the results of forecast-error variance decomposition (percentage points) among MSTLG and MSTL of each region. The variance decomposition is based on the orthogonalized impulse-response function (OIRF) and Cholesky forecast-error variance decomposition (FEVD). Ordering is the following: MSTLG and each regional MSTL. Source: authors' elaboration.

Table 9: Total influence of global synchronization network.

Panel A: 1-month-ahead forecast-error variance decomposition								
	varmstl_as	varmstl_nam	varmstl_lat	varmstl_ame	varmstl_eur	varmstl_asioc	Total	Contribution from others
varmstl_as	1	0	0	0	0	0	—	0
varmstl_nam	0.406	0.594	0	0	0	0	—	0.406
varmstl_lat	0.589	0	0.411	0	0	0	—	0.589
varmsl_ame	0.702	0.05	0.2	0.048	0	0	—	0.952
varmstl_eur	0.687	0.002	0.038	0.001	0.272	0	—	0.728
varmstl_asioc	0.69	0.012	0.04	0.021	0.137	0.1	—	0.9
Contribution to others	**3.074**	**0.064**	**0.278**	**0.022**	**0.137**	**0**	**3.575**	
Contribution including own	**4.074**	**0.658**	**0.689**	**0.07**	**0.409**	**0.1**	**6.000**	
Panel B: 5-month-ahead forecast-error variance decomposition								
	varmstl_as	varmstl_nam	varmstl_lat	varmstl_ame	varmstl_eur	varmstl_asioc	Total	Contribution from others
varmstl_as	0.941	0.025	0.002	0.006	0.007	0.02	—	0.06
varmstl_nam	0.313	0.655	0.002	0.006	0.001	0.023	—	0.345
varmstl_lat	0.512	0.03	0.417	0.013	0.002	0.025	—	0.582
varmsl_ame	0.592	0.122	0.208	0.041	0.001	0.036	—	0.959
varmstl_eur	0.632	0.011	0.067	0.005	0.277	0.007	—	0.715
varmstl_asioc	0.625	0.012	0.051	0.031	0.194	0.087	—	0.913
Contribution to others	**2.674**	**0.2**	**0.33**	**0.061**	**0.205**	**0.111**	**3.581**	
Contribution including own	**3.615**	**0.855**	**0.747**	**0.102**	**0.482**	**0.198**	**5.999**	

This table summarizes the forecast-error variance decomposition results for the period 2001–2020 as percentage points among global MSTL and MSTL of each region. The variance decomposition is based on the orthogonalized impulse-response function and Cholesky forecast-error variance decomposition. Ordering is the following: MSTLG and each regional MSTL. Source: authors' elaboration.

observe that the MSTL in each region responds positively after a positive shock in the global MSTL (i.e., they tend to rise when the global MSTL rises and vice-versa). Moreover, in all cases, this response is significant in one period after the shock. Notably, in each region, the shock starts to be absorbed after the fifth period. These results would indicate that the duration of the synchronization phenomenon among global equity markets is not a short-term lived event.

Complementing the previous analysis, we perform an error variance decomposition for the full-sample period to assess the relevance of our global synchronization measure in terms of its influence on the synchronization of the regional markets. Table 8 shows how the orthogonalized disturbances contribute to the mean squared error (MSE) in the h-periods-ahead forecasts. We can notice the following:

(1) We observe that most MSTLs tend to be very autoregressive; in each MSTL, their lags explain a relevant part of the variance in the MSE. For instance, the MSTL lag of North America explains about sixty-five percent of the variance in the MSTL of North America; meanwhile, for markets like Europe and Asia-Oceania, the results are substantially lower.

(2) It is worth mentioning that the global MSTL explains an essential proportion of the variance in most cases. For example, for $h = 5$, it ranges from 31.3% for North America to 63.2% for the case of Europe.

(3) It is interesting to indicate significant heterogeneity among regional markets in terms of their exposure to global and local factors when episodes of global synchronization occur.

Finally, following Diebold and Yilmaz [74], we quantify the total influence of global synchronization on the world regional markets. (This framework permits studying total interdependence or total spillover effects between assets of the same nature and relies on the Cholesky-factor identification of VAR that generates a variance decomposition that can be dependent on the variable ordering. As mentioned, we consider the global synchronization as an exogenous variable and the regional synchronization as dependent variables; the ordering we apply is MSTLG and each regional MSTL. In order to determine individual or directional spillover effects and analyze different asset classes, see Diebold and Yilmaz [75] and Shaikh [76]). Table 9 exhibits the variance decomposition that results from contribution to the variance of the h-month-ahead synchronization forecast error of region i coming from innovations to synchronizations of region j. Panel A shows 1-month-ahead forecast-error variance decomposition. Panel B exhibits the same analysis for the fifth month. We can observe that 1- and 5-month-ahead contribution in terms of synchronization from the global network to regional networks is 86% (3.074/3.575) and 75% (2.674/3.581), respectively. These results highlight the crucial contribution that global synchronization exerts over the synchronization of regional markets.

In summary, our robustness analysis led us to think that the results of this section are consistent with our previous regression models:

(1) The VAR, impulse-response functions, and MSE variance decomposition suggest a Granger causality from the global MSTL to the regional MSTL

(2) This relationship is positive; i.e., more global synchronization precedes a more regional synchronization

(3) The capacity of the global MSTL to capture future episodes of synchronization seems to go beyond the own autoregressive measure of synchronization of the regional markets

6. Conclusions

Our research contributes to helping financial market participants in the task of measuring and monitoring synchronization risk. For this, we estimate the synchronization of global stock markets applying MST network methods to 27 world equity markets and use it as a proxy of the global synchronization phenomenon and as a factor for explaining the synchronization of the leading world regional equity markets. In the current financial context of high uncertainty, it is relevant to ask about the dynamic of the global equity market synchronization for its implications over systemic risk, especially after strong rallies in equity values after the COVID-19 outbreak when the risk of stock price corrections is higher. Therefore, the threat that novel emerging shocks affect financial markets and provoke new episodes of stock market synchronization is high.

Our main results evidence that the global equity market synchronization, measured by the length of the global MSTL (MSTLG), is dynamic over time, its minimum values coincide with relevant financial shocks, and it shrinks to its minimum levels, indicating that the returns of the global stock markets are moving in a synchronized way. Likewise, the changes in the topology of the global MST capture the impact of shocks of different natures on financial markets but have a similar impact on the assets' correlation, a behavior that finally provokes the synchronization phenomenon. In addition, our evidence indicates that global synchronization of the stock markets is a significant factor explaining the synchronization of the world regional equity markets during the last 20 years. Also, we find a positive relationship between the variations in the global synchronization of equity returns and the variations in the synchronization associated with the world regional markets. Finally, our results show different sensitivities among the regional equity markets to global equity synchronization variations.

Our evidence does not reject the hypothesis that the global synchronization of returns is a statistically significant factor in explaining the synchronization of regional markets' returns. Nevertheless, this evidence is crucial to understand the links between global and regional economic and financial factors, elements that rise due to business internationalization, lowered transaction costs, and growing international investments. This major interconnectedness and globalization are suitable for the development of the economies. However, in times of market turmoil, it can become a significant problem since the considerable increase in the synchronization of returns diminishes portfolio diversification's benefits and becomes an element of contagion.

In addition, we cannot reject the hypothesis that there are statistically significant differences among regional markets with the degree of sensitivity to the global synchronization of returns. On the contrary, we find a positive relationship between both variables, which suggests that when the global synchronization increases, the regional synchronization will increase too, and vice-versa. In conclusion, our results support the idea that the complex and interconnected nature of the present financial markets should motivate practitioners and regulators to revise and update beliefs regarding risk management to incorporate monitoring and management of the risk of synchronization as a priority.

Our research does not analyze the structural links between global and regional markets in terms of market synchronizations' spillover. Instead, we evaluate the impact of the global synchronization of stock returns on world regional markets and their sensitivity to this factor applying Pearson correlation-based network methods. A natural extension of our work relates to exploring the application of other networks methods, such as partial correlation networks [35, 74] in relevant assets in terms of assets under management (AUM) like bonds, commodities, and real estate, considering different economic sectors in both developed and developing countries. As well, it is a relevant deeper study using Pearson and partial correlation-based networks of the synchronization spillovers that arise due to structural interconnectedness present among different markets in terms of asset classes, regions, and sectors in order to gain a deeper understanding of the directional spillover inherent among financial assets and markets and their impact on systemic risk [75, 76].

One limitation of our study is the impact of the nonsynchronous trading effect (i.e., time zone differences) on global stock markets. Our focus is not to solve this problem because there is still no efficient way to deal with this problem [35]. Unfortunately, the option of working with weekly frequencies to eliminate the nonsynchronous trading effect causes the loss of valuable information on the daily activity of the markets as a problem. Nevertheless, this problem is more significant in the global MSTL series due to time zone differences, while in the regional MSTL series, this problem tends to be minimized. However, we conjecture that the nonsynchronous trading effect would tend to decrease when working with the first differences (variation of the global MSTL) and even more when estimating the coefficient of relationship between the variation of the global MSTL with the regional MSTL variations. Furthermore, Forbes and Rigobon [77] did not observe differences when implementing heteroscedasticity bias tests for contagion based on correlation coefficients using 2-day moving average correlation estimation windows and daily returns. Therefore, we believe it is necessary for future research to analyze potential methodological modifications that tackle the nonsynchronous trading effect.

Our work has many implications. First, it helps regulators, central banks, policy-makers, portfolio managers, and investors to measure, monitor, and manage the synchronization of returns. Second, as the benefits of international diversification diminishes when synchronization rises, risk management strategies founded on investing abroad require a revisit that incorporates this risk on the decision-making criteria. Third, global financial agents, such as investment banks, must innovate and develop new financial engineering products that help market participants to manage synchronization risk. Finally, markets regulators and policy-makers, as well as central banks and governments, need to incorporate these new perspectives and insights based on empirical evidence as input factors that conduct them to supervise the well-functioning of financial markets better, as well as to improve the coordination of the financial market before emerging global shocks again jeopardize the stability of capital markets.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Additional Points

(i) Using correlation-based network methods, such as minimum spanning trees (MSTs) and Planar Maximally Filtered Graphs (PMFGs), we study the impact of global synchronization of equity returns on the world equity markets of North America, Latin America, Europe, Asia, and Oceania. For this, we estimate the length of the MST and PMFG as a measure for the global synchronization phenomena using daily and monthly data between July 2001 and April 2020.

(ii) Our results evidence that the global synchronization of equity markets, measured by the length of the global MSTL, is dynamic over time, its minimum values coincide with relevant financial shocks, and it shrinks to its minimum levels, indicating that the global returns are moving in a synchronized way. Likewise, the changes in the topology of the global MST rightly capture the impact of shocks of different natures on financial markets, but that have a similar impact on the assets' correlation in terms of synchronization.

(iii) Using time-series regression analysis and structural VAR models, we find that the global synchronization of equity returns has a significant and positive impact on the contemporaneous and future synchronization of the world regional equity markets. Also, the reaction of the regional synchronization is unequal to variations in global synchronization levels. We find a wide heterogeneity response among regional markets to shocks in global synchronization levels.

(iv) Our results help financial market participants who need to measure, monitor, and manage the synchronization of returns. Likewise, our evidence shows the necessity of including synchronization as a risk factor to assess the decision-making criteria to policy-makers and regulators. Our work highlights the need to incorporate events of high global synchronization into the radar of hazards of market stability.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Multivariate CNN-LSTM Model for Multiple Parallel Financial Time-Series Prediction

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At the macroeconomic level, the movement of the stock market index, which is determined by the moves of other stock market indices around the world or in that region, is one of the primary factors in assessing the global economic and financial situation, making it a critical topic to monitor over time. As a result, the potential to reliably forecast the future value of stock market indices by taking trade relationships into account is critical. The aim of the research is to create a time-series data forecasting model that incorporates the best features of many time-series data analysis models. The hybrid ensemble model built in this study is made up of two main components, each with its own set of functions derived from the CNN and LSTM models. For multiple parallel financial time-series estimation, the proposed model is called multivariate CNN-LSTM. The effectiveness of the evolved ensemble model during the COVID-19 pandemic was tested using regular stock market indices from four Asian stock markets: Shanghai, Japan, Singapore, and Indonesia. In contrast to CNN and LSTM, the experimental results show that multivariate CNN-LSTM has the highest statistical accuracy and reliability (smallest RMSE value). This finding supports the use of multivariate CNN-LSTM to forecast the value of different stock market indices and that it is a viable choice for research involving the development of models for the study of financial time-series prediction.

1. Introduction

The study of datasets that vary over time is known as time-series data analysis. Time-series datasets keep track of measurements of the same component over time. To measure a company's performance, financial analysts use time-series data such as stock price fluctuations or profits over time [1]. At the macroeconomic level, the movement of the stock market index, which is a financial time-series statistic, is often associated as one of the key indicators in determining a country's economic situation, making it a crucial issue to be examined over time [2]. The stock market index's movement is determined by a variety of internal and external influences, including the domestic and foreign economic climate, the international situation, industrial prospects, and stock market operations, but it is mostly influenced by the stock market index's historical meaning [3, 4].

Previous research has also shown that complex relationships between series can be found in a variety of time-series data related to real-world processes in the economic and financial realms [3]. It has also been known that several time-series travel together over time because of these interrelationships. It is well understood, for example, that the movement of a stock market index in one country is influenced by the movements of other stock market indices around the globe or in that area. These findings are confirmed by the work of [3, 5–7].

However, most of the developed time-series forecasting methods are single-stand-alone algorithm that utilizes univariate time-series analysis, while little attention has been paid to prediction processes that use the dynamics of interactions between the observed series. In addition, projecting the course of movement of time-series values using only a single algorithm has some serious drawbacks, whether it is an econometric time-series forecasting model or a machine learning model like an artificial neural network. This is attributed to the high noise and volatility of financial time-series and the fact that the relationship between independent and dependent variables is subject to unpredictable shifts over time [8]. The concept also connects with previous research in the field of neural networks, which found that no one model always outperforms the others for all real-world problems [9]. Thus, in the current financial time-series data analysis and modeling phase, integrating the best algorithms to be able to take advantage of the different advantages possessed by each algorithm by creating an ensemble, which combines multiple forecasting models, has become a growth path [8–11].

Based on the outlined conditions above, two key problems in the field of financial time-series data prediction can be reported. The first is that there is no particular methodology that can often forecast the movement of financial time-series data with the greatest precision. Second, despite the fact that interdependencies between variables in financial time-series data are well-known (e.g., the movement of stock market indices is often determined by other markets), most forecasting models still rely on univariate analysis.

In line with this, the study's aim is to develop a time-series data forecasting model that combines the best features of multiple time-series data analysis models. The hybrid ensemble model developed in this study consists of two key components with distinct functions: (1) extracting important features from the observed time-series data and (2) predicting the value of the time-series data using the described features. To accomplish the first function, a Deep Learning model named the Convolutional Neural Network (CNN), which has been proven to have sound performance in feature extraction, is used, while the Long Short-Term Model (LSTM) is put into place to support the time-series forecasting process.

CNN and LSTM are deep learning neural networks that can learn arbitrarily complicated mappings from inputs to outputs and handle many inputs and outputs automatically. These are useful qualities for time-series forecasting, especially for situations with complicated nonlinear relationships, multivalued inputs, and multistep forecasting. These features are the reason why both models were chosen for this investigation. Furthermore, the proposed model applies a multivariate analysis technique to take advantage of the observed time-series data's relationship trend in forecasting their future values. It is anticipated that having such a structure would aid in improving the accuracy of financial time-series data prediction, especially for multiple parallel stock market indices.

This study uses regular stock market indices from four Asian stock markets, namely, Shanghai, Japan, Singapore, and Indonesia, to check the efficacy of the evolved ensemble model during the COVID-19 pandemic, which spans 242 trading days from January 1, 2020, to December 31, 2021. The data is divided into two parts: a training set of 170 trading days and a comparison set of 72 trading days.

The paper is organized in the following way. Section 2 discusses the research works that apply machine learning in a particular deep learning model in predicting the trajectory of various time-series datasets. The proposed ensemble of multivariate deep learning models that are utilized for multiple time-series prediction is outlined in Section 3, which will be followed by the experimental setting used in this research. Afterward, the results of the conducted trials are given and discussed, and the article ends with a conclusion and future work section.

2. Related Work

2.1. Deep Learning. Deep learning is a form of an algorithm in the machine learning area that [12] (1) uses a cascade of multiple layers of nonlinear processing units for feature, extraction, and transformation, where each successive layer uses the output of the previous layer as input; (2) learn in a supervised manner (e.g., classification) and/or unsupervised manner (e.g., pattern analysis); (3) capable of modeling different levels of representation according to different levels of abstraction; levels form a hierarchy of concepts.

Most modern deep learning models are based on neural networks, although they can also include propositional formulas or latent variables arranged in layers in deep generative models, such as nodes in deep belief networks and Boltzmann's machine [13]. In deep learning, each layer of the learning structure (in the sense of building a model) converts the input into a slightly more general representation (model). Primarily, the deep learning process learns in depth to be able to learn which features are optimally placed at a particular level by themselves. Of course, this does not eliminate the need for hand-tuning; for example, varying the number of layers and the size of the layers can provide different levels of abstraction [13, 14].

An artificial neural network with several layers between the input and output layers is known as a Deep Neural Network (DNN) [13, 15]. DNN discovered the right mathematical model for transforming linear and nonlinear inputs to outputs. The network traverses the layers, measuring the likelihood of each output. DNNs are capable of modeling nonlinear interactions that are complex. DNN architecture produces a composition model in which objects are expressed as layered primitive compositions. Additional layers allow feature composition of the lower layers, potentially modeling complex data with fewer units than a similarly performing shallow network [13].

2.2. Convolutional Neural Network (CNN). A DNN model that is commonly used in computer vision work is the Convolutional Neural Network (CNN) which has also been applied to acoustic modeling for automated speech recognition (ASR) [16]. The basic structure of CNN is given in Figure 1. CNN are inspired by biological processes [18, 19] because the patterns of connectivity between neurons resemble the organization of the visual cortex of animals. CNN is widely used in image and video recognition, recommendation systems, image classification, medical image analysis, and natural language processing. Findings from

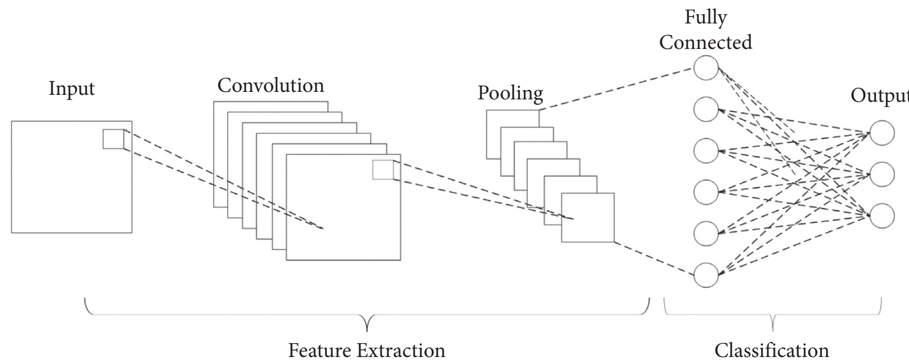


FIGURE 1: Illustration of the feature extraction process from image data to produce the final classification with a basic CNN architecture. The figure is recreated from [17].

previous research confirmed CNN's superiority in processing time-based flowing data [16, 18, 19].

CNN's main feature is the ability to process multichannel input data, so it is ideal for handling different time-series data with multiple inputs and outputs in this study [19–21]. However, there has not been much research into CNN's success in modeling and forecasting the movement of several time-series data values for deep learning models.

One of the main advantages of CNN is the local perception and weight sharing features, which can greatly reduce the number of parameters, thereby increasing the efficiency of the learning process. In terms of structure, CNN mainly consists of two parts, namely, the convolutional layer and the pooling layer. In this case, each convolution layer contains several convolutional kernels. After the convolution operation that occurs at the convolution layer, the important features of the data are extracted, which are accompanied by an increase in the feature dimensions. To solve this problem and reduce the burden on the training process, a layer of integration is added with the main objective of reducing the number of features extracted before finally producing the final result.

2.3. Long Short-Term Memory (LSTM). Aside from CNN, the Long Short-Term Memory model, also known as LSTM, is another well-known DNN model. The LSTM is a recurrent neural network subunit (RNN) [22], and the basic architecture is given in Figure 2. The LSTM algorithm is ideal for classifying, sorting, and making predictions from a single time-series dataset. Previous research has also shown that LSTM is capable of forecasting time-series data [23–26].

The computation process that occurs in the LSTM structure to calculate the predictive time-series data begins with the calculation of the output value from the previous time and the input value from the current time becomes an input to the forget gate, and the processing results from the forget gate are obtained through computation using the following formula:

$$f_t = \sigma\left(W_f \cdot [h_{t-1}, x_t] + b_f\right), \quad (1)$$

where the value range of f_t is (0, 1), W_f is the weight of the forget gate, b_f is the bias value applied to the forget gate, x_t is the input value for the current time, and h_{t-1} is the output value of the previous processing time.

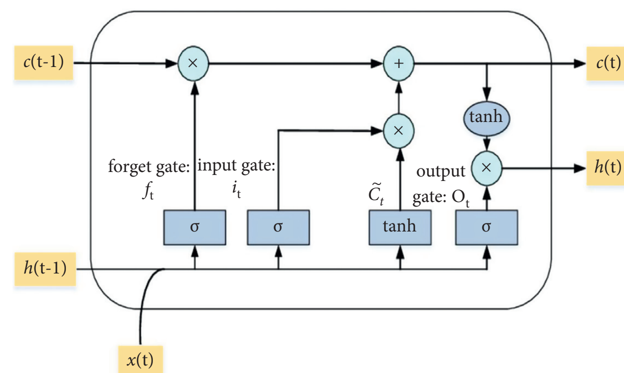


FIGURE 2: Basic architecture of LSTM when being used for time-series prediction in a supervised model. The figure is recreated from [22].

Furthermore, the output value from the previous time and the input value from the current time are also input to the input gate, and the output value and condition of the candidate cell at the input gate are obtained after calculation using the following formula:

$$i_t = \sigma\left(W_i \cdot [h_{t-1}, x_t] + b_i\right), \quad (2)$$

$$\tilde{C}_t = \tanh\left(W_c \cdot [h_{t-1}, x_t] + b_c\right), \quad (3)$$

where the value range of i_t is (0, 1), W_i is the weight of the gate input, b_i is the bias value of the gate input, W_c is the weight of the gate input candidate, and b_c is the bias value of the gate input candidate. The next stage in the LSTM model is the process of adjusting cell values or model parameters at this time carried out as follows:

$$C_t = f_t * C_{t-1} + i_t * \tilde{C}_t, \quad (4)$$

where the range of values for C_t is (0, 1). Then, at processing time t, the output value h_{t-1} and the input value x_t become the input for the output gate, and the output from the gate output is calculated using the following formula:

$$o_t = \sigma\left(W_0 [h_{t-1}, x_t] + b_o\right), \quad (5)$$

where the value range of o_t is (0.1), W_o is the weight of the gate output, and b_o is the bias value of the gate output. Finally, the final output value of the LSTM is generated by the output gate and is the result of the calculation using the following formula:

$$h_t = o_t * \tanh(C_t). \quad (6)$$

In this case, tanh is an activation function that can be tailored to the needs and characteristics of the problem to be resolved. Consequently, LSTM has the ability to process recorded data in a specific time sequence and therefore has been widely used in the process of analyzing and modeling time-series data [26, 27].

Both LSTM and CNN can be used to create deep learning models that can investigate complicated and unknown patterns in large and varied data sets. The idea was then designed to be able to combine different deep learning models, both CNN and LSTM-based, to create an ensemble. Since the findings of previous studies show that each model has different abilities to catch secret trends in the data, it is hoped that the solutions provided will be stronger and more detailed with this ensemble method.

2.4. CNN and LSTM for Financial Time-Series Prediction. The financial market is currently a noisy, nonparametric competitive environment, and there are two major types of stock price or stock market index forecasting methods: conventional econometric analysis and machine learning. Traditional econometric methods or equations with parameters, on the other hand, are notorious for being unsuitable for analyzing complex, high-dimensional, and noisy financial time-series results [28]. As a result, in recent years, developments in the field of machine learning have emerged as a viable option, especially for neural networks. Since it can derive data features from a vast number of high-frequency raw data without relying on previous information, neural networks have become a hot research path in the field of financial forecasting.

In 2017, Chen and Hao investigated stock market index prediction using a basic hybridized configuration of the feature weighted support vector machine and feature weighted K-nearest neighbor, resulting in enhanced short, medium, and long-term prediction capabilities for the Shanghai Stock Exchange Composite Index and Shenzhen Stock Exchange Component Index [29]. In 2017, Chong et al. released a thorough analysis of the use of deep learning networks for stock market forecasting and prediction [30]. According to the study's empirical results, deep neural networks will derive additional information from the residuals of the autoregressive model and improve the prediction accuracy. Hu et al. experimental findings from 2018 indicate that, while CNN is most widely used for image recognition and feature extraction, it can also be used for time-series prediction since it is a deep learning model, but the forecasting accuracy of CNN alone is relatively poor [31].

In 2019, Hoseinzade and Haratizadeh proposed a CNN-based tool that can be used to extract features from a variety of data sources, including different markets, to predict their future [17]. In addition, Zhong and Enke proposed that in 2019, hybrid machine learning algorithms can be used, as they have been shown to be effective in predicting the stock market's normal return path [32]. Nabipour et al. compared various time-series prediction techniques on the Tehran stock exchange in 2020 and found that the LSTM produces more accurate results and has the best model fitting ability [33]. Kamalov forecasted the stock prices of four big US public firms using MLP, CNN, and LSTM in 2020. These three approaches outperformed related experiments that predicted the trajectory of price change in terms of experimental findings [34]. In 2020, Liu and Long developed a high-precision short-term forecasting model of financial market time-series focused on LSTM deep neural networks, which they compared with the BP neural network, standard RNN, and enhanced LSTM deep neural networks. The findings revealed that the LSTM deep neural network has a high forecasting precision and can accurately model stock market time-series [23]. Moreover, Lu et al. proposed an ensemble structure of CNN-LSTM and proved that such model is effective when being applied to predict Shanghai Composite Index [31].

Additionally, Mahmud and Mohammed performed a survey on the usage of deep learning algorithms for time-series forecasting in 2021, which found that deep learning techniques like CNN and LSTM give superior prediction outcomes with lower error levels than other artificial neural network models [35]. Furthermore, their literature study discovered that merging many deep learning models greatly improved time-series prediction accuracy. However, Mahmud and Mohammed also conveyed that the performance of CNN and LSTM is not always consistent, with CNN outperforming LSTM at times and vice versa. In general, CNN tends to have superior predictive capacity when dealing with time-series data comprised of a collection of images, but LSTM appears to be superior when dealing with numerical data.

In conclusion, findings from previous studies show that using deep learning models such as CNN and LSTM for financial time-series prediction is successful. However, compared to LSTM, CNN has poorer prediction accuracy when applied to numerical time-series data due to its key characteristics, which include a high point in feature extraction. While at the same time, LSTM also has a weakness related to its capability of extracting the most valuable features from a data set when being compared to CNN. Consequently, constructing a composite or ensemble model that takes advantage of each combination model to overcome its weaknesses to increase time-series prediction accuracy is logical. Furthermore, based on findings from prior studies indicating cointegration between financial time-series data in a real-world environment, it is then reasonable to include a multivariate time-series analysis technique into the ensemble model. Therefore, the following are the major contributions of this work:

(1) Development of a new ensemble of multivariate deep learning approach named the multivariate CNN-LSTM that utilizes the superior feature of CNN and

LSTM model for simultaneous multiple parallel financial time-series prediction by considering the state of correlation between series into the forecasting process.

(2) Evaluation of proposed model by conducting experiments using data from real-world setting, i.e., four stock market indices from the Asia region, to confirm that constructing an ensemble model, which uses the core features of each model and incorporates multivariate time-series analysis, offers better forecasting accuracy, and is more suited for multiple parallel financial time-series forecasting by contrasting the evaluation indicators of proposed multivariate CNN-LSTM with stand-alone CNN and LSTM.

3. Multivariate CNN-LSTM Model

3.1. Multivariate Time-Series Analysis. When dealing with variables from real-world phenomena such as economics, weather, ecology, and so on, the value of one variable is often dependent on the historical values of other variables as well. For example, a household's spending expenses can be influenced by factors such as revenue, interest rates, and investment expenditures. If both of these factors are linked to consumer spending, it makes sense to factor in their circumstances when forecasting consumer spending. In other words, denoting the related variables by $x_{1,t}, x_{2,t}, \ldots, x_{k,t}$, prediction of $x_{1,t+h}$ at the end of period t may be represented by the following form:

$$\hat{x}_{1,t+h} = f_1\left(x_{1,t}, x_{2,t}, \ldots, x_{k,t}, x_{1,t-1}, x_{2,t-1}, \ldots, x_{k,t-1}, x_{1,t-2}, \ldots\right). \quad (7)$$

Similarly, a forecast for the second component may be dependent on all system's previous values. This equation can be used to express a projection of the k^{th} variable more broadly:

$$\hat{x}_{k,t+h} = f_k\left(x_{1,t}, \ldots, x_{k,t}, x_{1,t-1}, \ldots, x_{k,t-1}, \ldots\right). \quad (8)$$

There are several time-dependent variables in a multivariate time series. Each variable depends not only on its previous value but also on other variables. A multiple time-series $x_{k,t}$, $k = 1, \ldots, k; t = 1, \ldots, t$ is a set of time series where k is the series index and t is the time-point, and equation (8) expresses the prediction of $\hat{x}_{k,t+h}$ as a function of a multiple time series [24]. The main goal of multiple time-series analysis, like univariate time-series analysis, is to find appropriate functions $f_1, \ldots, f_q$, where q is the number of constructed functions that can be used to forecast the potential values of a variable with good properties. Learning about the interrelationships between a variety of variables is often of concern. For example, in a stock exchange environment with several markets, whether internationally or in a specific area, one may be interested in the possible effect of how these markets interact with one another.

This work explores further multivariate time-series analysis models by incorporating different state-of-of-the-the-art learning models originating from the machine learning arena, i.e., the deep learning model, to construct an ensemble model that can predict multiple financial time-series data simultaneously.

3.2. Multivariate CNN-LSTM General Concept. CNN and LSTM can be used to build deep learning models that could deeply study complex and hidden patterns in massive and diverse data stacks, including time-series data, especially from the financial sector [36, 37]. Empowering the advantages possessed by the two models to achieve the objectives of this study as presented in the Introduction, that is, to improve the accuracy of forecasting the movement of the stock market index, a time-series data forecasting model is created by combining CNN and LSTM, as well as including a multivariate time-series analysis method into the model to allow for simultaneous forecasting of parallel time-series using series correlation analysis.

In this case, the CNN-LSTM model built has different characteristics compared to most time-series data forecasting techniques, which generally work using a univariate analysis approach, where the CNN-LSTM model will utilize correlation information between series in making predictions. This is in line with the findings of various previous studies that a group of time-series data originating from a similar domain tends to have a relationship and influence each other. Therefore, information about the relationship between series should be used in the process of forecasting future conditions.

The built model is an ensemble of CNN and LSTM, which was referred to as the multivariate CNN-LSTM. In this proposed architecture, the time-series data will be reshaped to fit the input data structure that can be processed by the CNN structure and then the LSTM. The multivariate CNN-LSTM model consists of two main layers: the CNN layer, which has the main function of extracting the main features from the processed time-series data. The LSTM layer, which has the main function of calculating the final prediction result.

The CNN and LSTM ensemble models developed in this analysis are an extension of the framework used by Lu et al. in their study on stock price fluctuations on the Shanghai stock exchange [31]. Adjusting the input data structure to accommodate multiple parallel time-series data, parameter configuration at each layer, alteration of the training method parameters to match the characteristics of multiple parallel financial time-series data, and the inclusion of an LSTM layer to increase the prediction accuracy are all part of the update.

The structural diagram of the CNN-LSTM model is shown in Figure 3, where CNN and LSTM are the main components accompanied by an input layer, a 1-dimensional convolution layer (1D convolutional), a pooling layer, an LSTM (hidden) hidden layer, and layer full connection

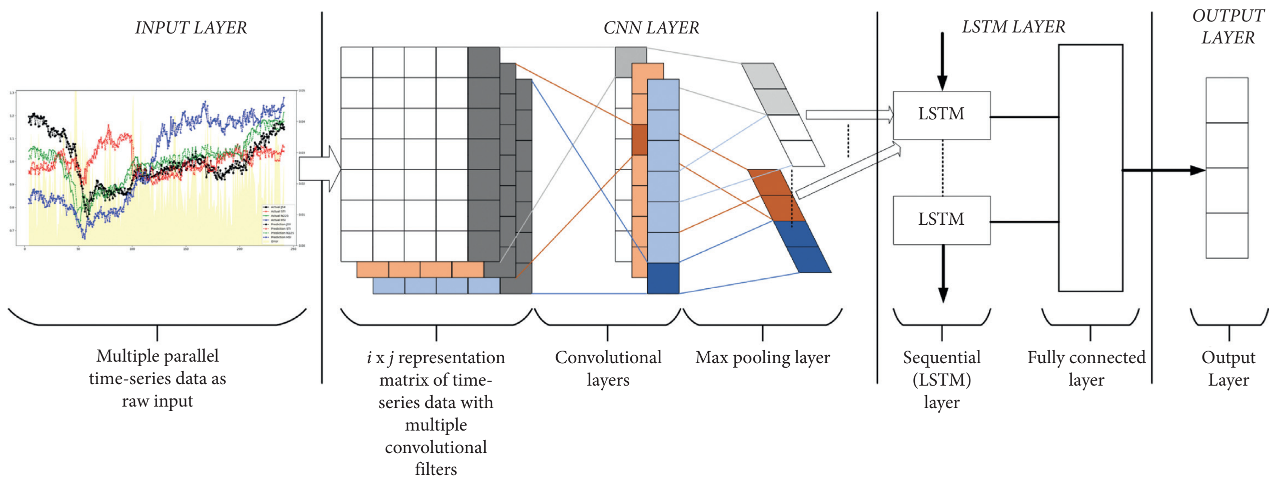


Figure 3: Architecture of the proposed multivariate CNN-LSTM for multiple parallel time-series prediction.

(full connection) which will issue the final result of the prediction.

3.3. Multivariate CNN-LSTM Learning Process. The stages of the training process and CNN-LSTM prediction on the time-series data are given as follows:

(1) The training stage begins with the training data input process. At this stage, the process of entering the data used for CNN-LSTM training occurs. The next step is to initialize the network parameters to determine the weight and bias value (if any) at the beginning of each CNN-LSTM layer. Then, it is continued with the process at the CNN layer where the input data sequentially passes through the convolution layer and the pooling layer at the CNN layer, followed by the extraction process for the input data feature, and produces an output value that will be the input for the LSTM layer. At the CNN layer, the feature extraction process mainly occurs from the input time-series data.

(2) Then, the output value from the CNN layer will enter the LSTM layer. In this LSTM layer, the prediction process mainly occurs in the observed time-series value, where the output value from the LSTM layer becomes the input for the full connection layer, which then produces the final predicted value. At this stage, the prediction training process is complete and then it is continued with the evaluation process of the training results where the error of the prediction results is calculated. The output value in the form of a prediction calculated by the output layer is compared with the actual value of the processed data group, and then the error value is calculated.

(3) The results of the evaluation serve as a reference for determining whether the stopping conditions for training are met. In this case, the training stop condition is that the predetermined number of training cycles (epochs) is reached, and the predictive error value is lower than a certain predetermined threshold.

(4) If based on the evaluation results, it is determined that the stop condition for training has not been achieved, then the calculated error value is propagated back to the previous layer and then adjusted the weights and bias values at each layer (back-propagation error) and return to the first step and repeat the training process. However, if any of the conditions of the stop condition for training are met, the training is completed, and the configuration of the entire CNN-LSTM network is saved.

(5) The next stage is testing the CNN-LSTM model that has been trained using the test data. This process begins by entering the test data used for prediction or testing data input into the saved CNN-LSTM model and then getting the output value (prediction result) as the final output of the CNN-LSTM training and prediction process.

(6) Measurement of the level of accuracy will be carried out by applying the calculation of the root mean square error (RMSE) value to see the amount of deviation between the actual value and the resulting predictive value.

4. Experiments Setting

4.1. Financial Time-Series Data. Multiple parallel financial time-series data were used in this study to represent an integrated structure in the stock exchange sector. The data is regular stock market indices gathered from four Asian exchanges: Shanghai, Japan, Singapore, and Indonesia, which spans 242 trading days from January 1, 2020, to December 31, 2020. Regular indices of the Shanghai, Japan, Singapore, and Indonesia exchanges will be predicted simultaneously using the historical values of the four observed series in this experiment. The data collection is split into two parts: a training set that includes the first 170 trading days and a test set that includes the last 72 trading days.

Since the four stock market indices have a wide range of values, the data collection is transformed, i.e., normalized as follows to help structure the training process and build an improved model:

$$y_i^j = \frac{x_i^j - \overline{x}^j}{s^j}, \tag{9}$$

where y_i^j is the standardized value of series j, x_i^j is the original input data value of series j, $\overline{x}^j$ is the average of the input data value of series j, and s^j is the standard deviation of the input data of series j. A snapshot of the data set is outlined in Table 1.

4.2. Model Evaluation. The root mean square error (RMSE) is used as the estimation criterion of the method to test the forecasting impact of multivariate CNN-LSTM in addition to univariate CNN and LSTM that will perform the prediction in an individual manner:

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\widehat{y}_i - y_i\right)^2}, \tag{10}$$

where $\widehat{y}_i$ is the predicted value at a particular time-point i and y_i is the actual value. Since the difference between the forecast and the original value is less, a lower RSME value means higher prediction accuracy. The RMSE is measured for each sequence and compared for each model under consideration. During the preparation and testing phase, a comparative review will be carried out.

4.3. Implementation of Multivariate CNN-LSTM. Table 2 shows the multivariate CNN-LSTM parameter settings for this experiment. It can deduce that the basic model is designed as follows based on the CNN-LSTM network's parameter settings: the input training set data is a three-dimensional data vector (None, 4, 4), where the first number 4 represents the time step size and the other number 4 is the input dimensions of four properties, which in this case are four stock market indices of Shanghai, Japan, Singapore, and Indonesia.

The data is first fed into a one-dimensional convolution layer, which extracts more features and produces a three-dimensional output vector (None, 4, 64), with 64 being the size of the convolution layer filters. The vector then joins the pooling layer, where it is converted into a three-dimensional output vector (none, 4, 64). The output vector then goes to the first LSTM layer for training; two layers of LSTM are put into place in this proposed structure to improve the accuracy of multiple variable predictions; after training, the output data with shape (None, 100) goes to the second LSTM layer to get the output values; 100 is the number of hidden units in both LSTM layers. Accordingly, Figure 4 depicts the basic structure of the proposed multivariate CNN-LSTM model.

5. Results and Discussion

After training CNN, LSTM, and multivariate CNN-LSTM with the processed training set data, the model is used to forecast the test set data, and the actual value is compared with the expected value for both phases, as seen in Figures 5 and 6. For the record, the CNN and LSTM models are trained separately using univariate analysis, while the multivariate CNN-LSTM is trained using multivariate analysis to achieve simultaneous multiple parallel time-series prediction.

Figure 5 displays graphics of the comparison between the predicted index values of the four stock markets observed with the original value at the training stage, while Figure 6 displays comparison charts at the testing stage. In general, from the two figures, it can be observed that the three models tested have the ability to predict the movement of the stock market index with a fairly good level of accuracy. However, more in-depth observations show that the graph of the prediction results generated by the LSTM model is better than that produced by the CNN model, and the graph of the prediction results from the multivariate CNN-LSTM model has the best results among the three. This happened consistently both at the training and testing stages as well as in the four stock markets.

Observing the yellow field on the graph can also be viewed as a guideline that the CNN-LSTM multivariate model does significantly more than the other two versions. The magnitude of the forecast error rate at any point in time is shown by the yellow region of the inn. As a result, it can be inferred that the smaller the field, the lower the cumulative error of prediction. Both Figures 5 and 6 demonstrate that the CNN-LSTM multivariate model's yellow region on the graph is smaller than the CNN and LSTM versions at both the training and testing levels. This supports the finding that of the three models studied, the CNN-LSTM multivariate model, which is an ensemble of the CNN and LSTM models, performs the best. In addition, the graph shows that the average error of the forecast outcomes is within a reasonable range.

In addition, given that the processed time-series data were in the coverage of the COVID-19 pandemic period, where the movements of various economic indicators became more uncertain, the CNN-LSTM multivariate model was also confirmed to have the ability to predict the value of financial time-series data with better performance. The largest difference between the predicted results and the original value occurs in the range of the 55^{th} trading day, which, if mapped to a calendar day, falls in early March 2020 when the COVID-19 pandemic begins to affect global economic conditions. However, after that, it appears that the value of the prediction error tends to decrease, which indicates the ability of the CNN-LSTM multivariate model to adapt to changes in the movement pattern of the stock market index value.

Paying more attention to the predictions of the four stock market indices made by the ensemble of the CNN-LSTM model, it is clearly seen that the proposed model can predict the movement of all four stock market indices with a

Table 1: Snapshots of daily stock market indices used as multiple financial time-series data.

Date	Shanghai		Japan		Singapore		Indonesia	
	Actual	Norm	Actual	Norm	Actual	Norm	Actual	Norm
02/01/2020	252.35	0.8085	23204.86	1.0221	8.49	0.9801	6283.58	1.1971
03/01/2020	258.36	0.8278	23575.72	1.0384	8.30	0.9580	6323.46	1.2047
06/01/2020	260.30	0.8340	23204.76	1.0221	8.25	0.9524	6257.40	1.1921
07/01/2020	261.46	0.8377	23739.87	1.0457	8.31	0.9591	6279.34	1.1963
08/01/2020	259.91	0.8328	23850.57	1.0505	8.22	0.9491	6225.68	1.1861
09/01/2020	266.31	0.8533	24025.17	1.0582	8.43	0.9735	6274.49	1.1954
10/01/2020	266.50	0.8539	23916.58	1.0535	8.42	0.9723	6274.94	1.1955
13/01/2020	271.54	0.8700	23933.13	1.0542	8.36	0.9657	6296.56	1.1996
14/01/2020	269.02	0.8619	24041.26	1.0589	8.36	0.9657	6325.40	1.2051
15/01/2020	271.15	0.8688	24083.51	1.0608	8.35	0.9646	6283.36	1.1971

Table 2: Parameters configuration for the proposed multivariate CNN-LSTM model.

Parameters	Values	Layer
Convolutional layer filters	64	CNN
Convolutional layer kernel_size	2	CNN
Convolutional layer activation function	Relu	CNN
Convolutional layer padding	Valid	CNN
Pooling layer pool_size	2	CNN
Number of LSTM layer 1 hidden unit	100	LSTM
Number of LSTM layer 2 hidden unit	100	LSTM
LSTM layer 1 and 2 activation function	Relu	LSTM
Time step	4	LSTM
Optimizer	Adam	Model fitting
Loss function	MAE	Model fitting
Epochs	1000	Model fitting

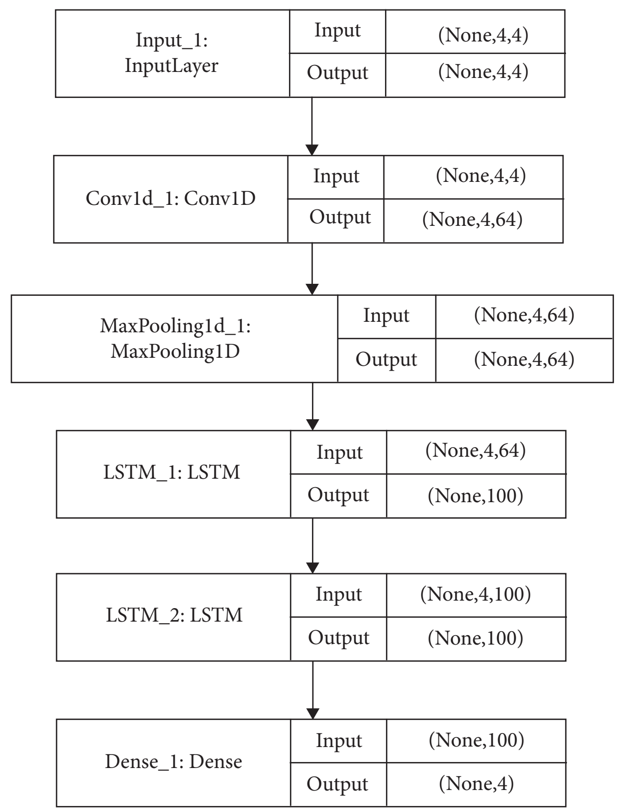


Figure 4: Basic structure of the proposed multivariate CNN-LSTM model for multiple time-series prediction with 4 features and 4-time steps for the prediction process.

high degree of accuracy. As the actual values of the four stock market indices is showing an increasing trend towards the end of the year 2020, the predictions made by the proposed model are demonstrating a similar manner as well. Therefore, these predictions can be utilized to help to make an investment decision, which in this case suggests that amid the COVID-19 pandemic period investing in the stock market can be considered worthwhile. This argument is in line with suggestions made by a financial analyst regarding some investing lessons from the pandemic, which states that (1) buy and hold could not have been truer than the past year; (2) the best time to invest is now, i.e., the time when COVID-19 vaccines become available; (3) the market is recovering gradually as the countries around the world are starting to have a grasp on COVID-19 pandemic [38].

Regarding the prediction's quality assessment, as previously stated, in this study, the performance of the three time-series data prediction models was also evaluated by calculating the RMSE value. RMSE calculations are carried out both at the training stage and at the testing stage as well. Additionally, to prove that the accuracy of financial time-series data predictions can be improved by building a CNN-LSTM ensemble structure that utilizes multivariate analysis techniques, the trial of the index prediction of the four stock markets using the CNN model and the LSTM model is carried out individually and based on analytical techniques univariate.

The comparison of RMSE values for each model and for each stage is shown in Figures 7 and 8 and details are outlined in Table 3. From the two graphs, it can be learned that the RMSE value for the CNN-LSTM multivariate model is the smallest in all indices, both at the training and testing stages. Thus, this fact confirms the theory, which states that combining various features and advantages possessed by different models or algorithms into an ensemble and using multivariate analysis techniques can provide better results in solving a problem, which in this case is to predict—index values of four stock markets in the Asian region.

Additionally, evaluation of predictions quality made by the proposed multivariate CNN-LSTM is also conducted by

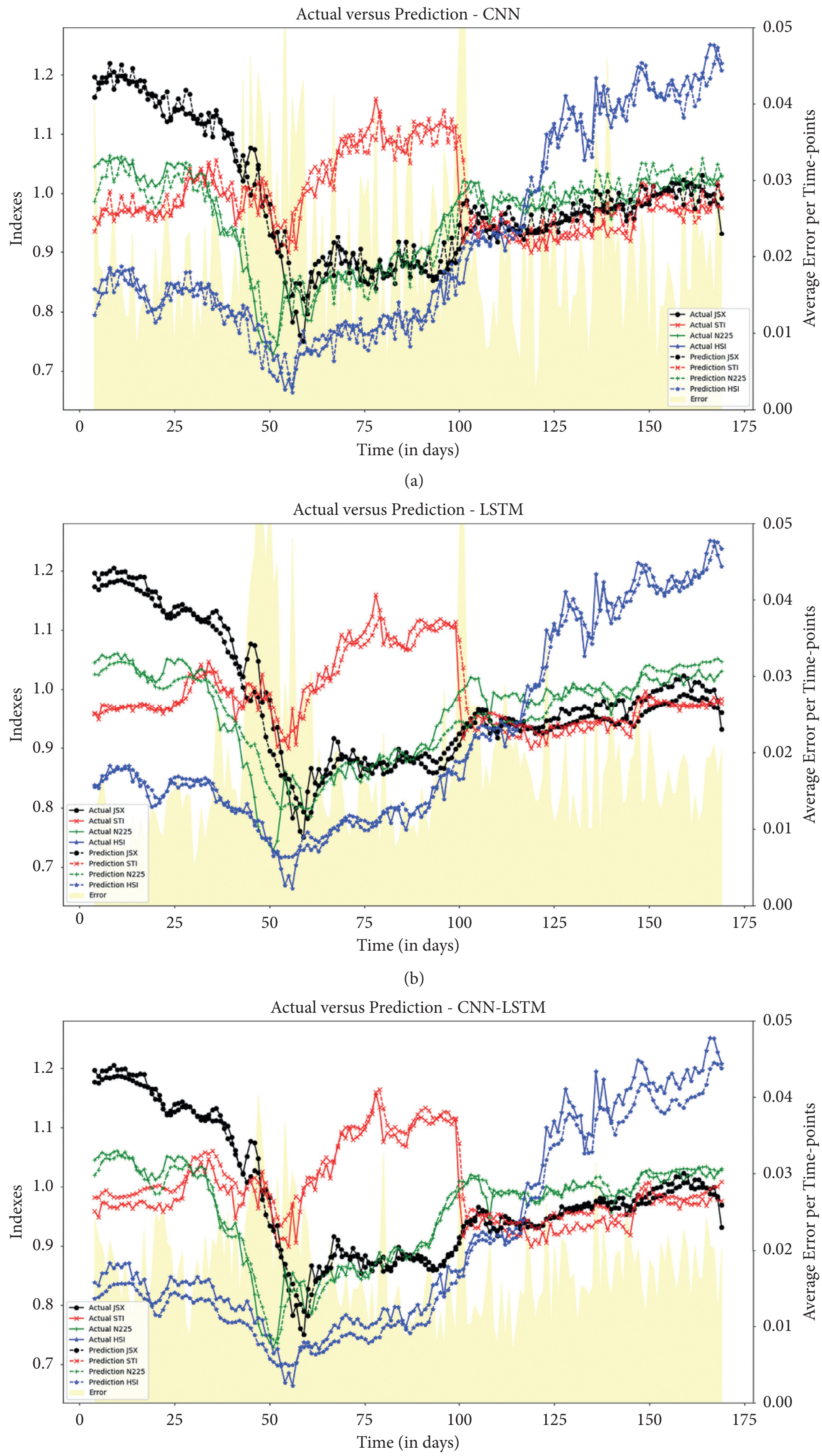
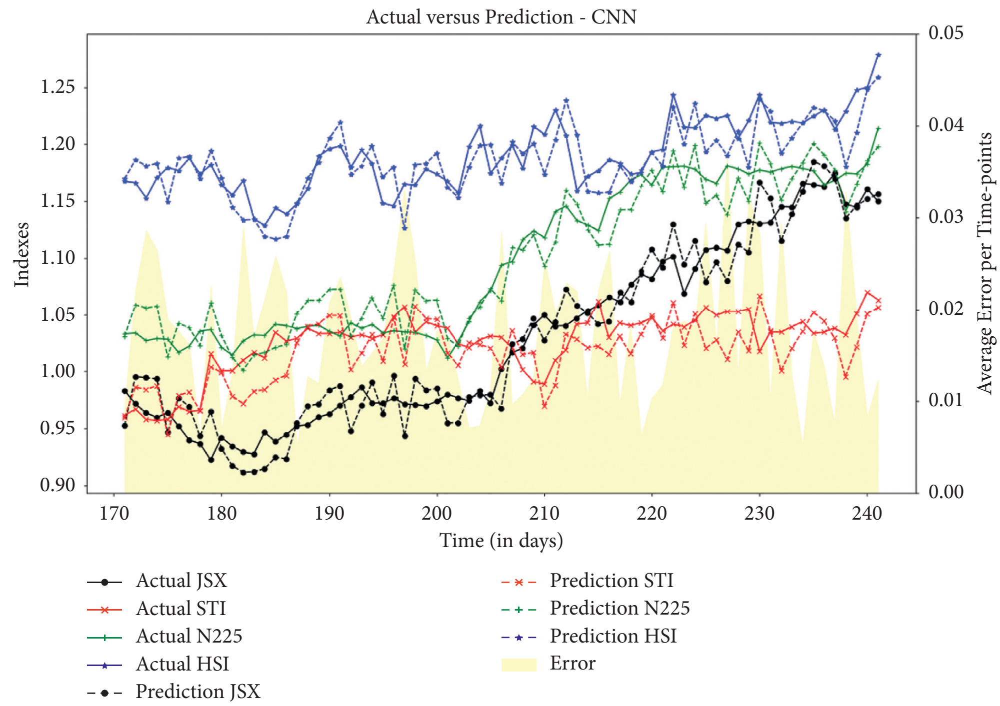
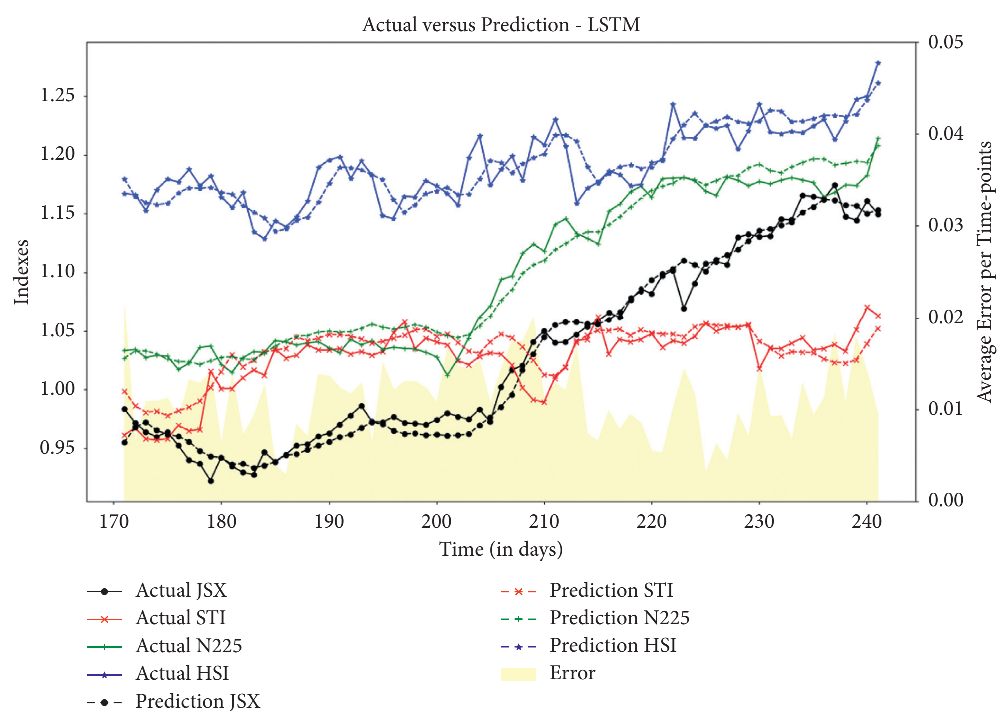


Figure 5: Comparison of the actual (solid line) and predicted values (dashed line) in the training phase (first 170 trading days of the year 2020): (a) by CNN Model, (b) by LSTM model, and (c) by the ensemble of CNN-LSTM.

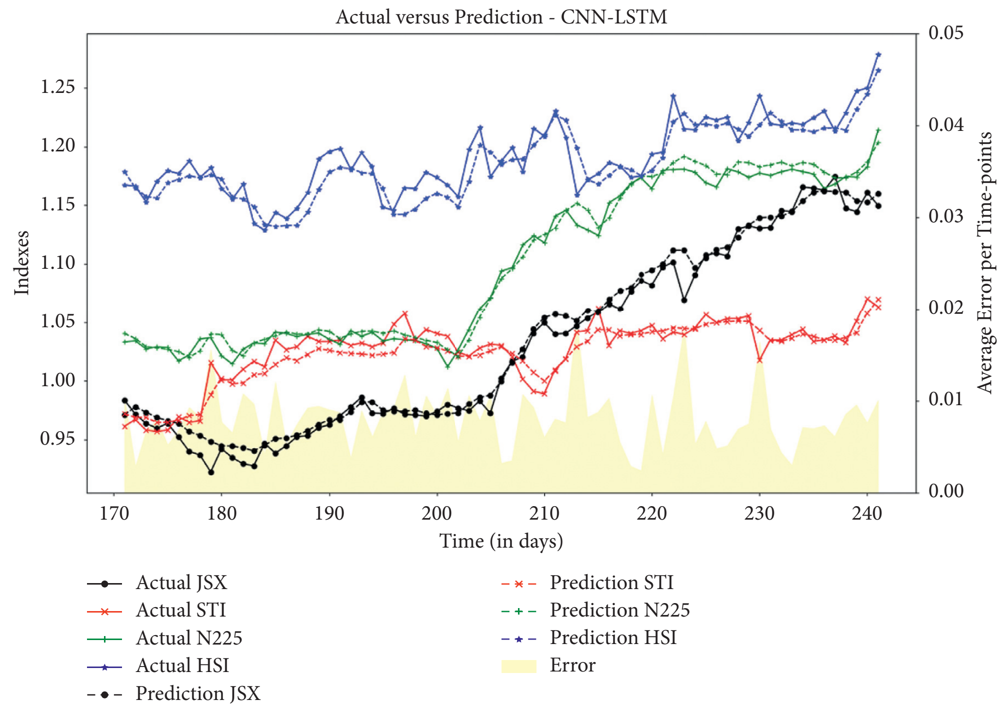


(a)



(b)

Figure 6: Continued.



(c)

Figure 6: Comparison of the actual (solid line) and predicted values (dashed line) in the testing phase (last 72 trading days of the year 2020): (a) by CNN Model, (b) by LSTM model, and (c) by the ensemble of CNN-LSTM.

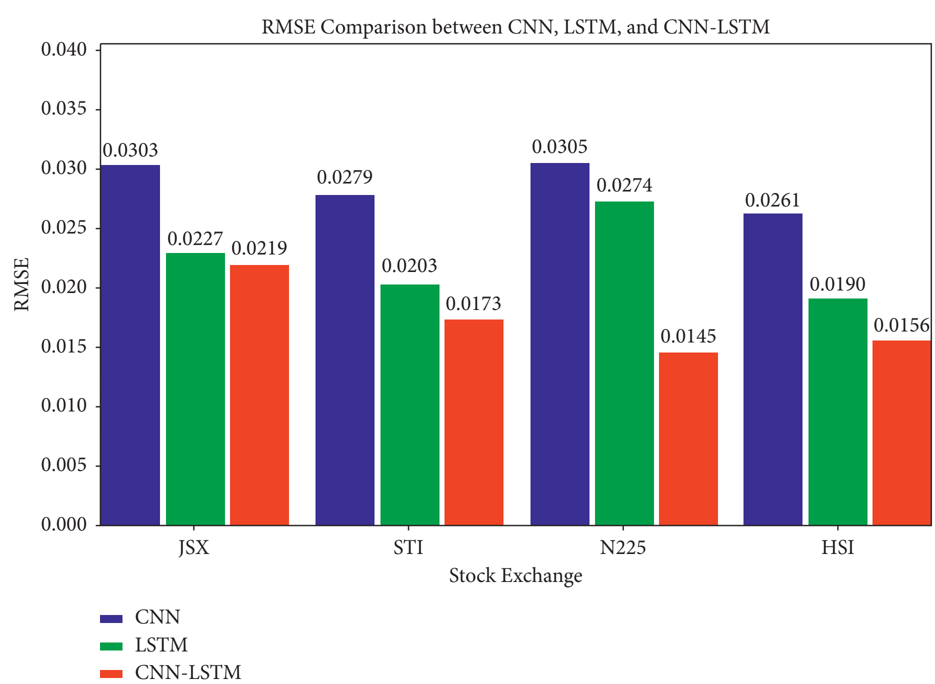


Figure 7: RMSE comparison between CNN, LSTM, and multivariate CNN-LSTM when predicting data in the training phase, i.e., the first 170 trading days of the year 2020.

comparing their descriptive statistics values with the actual values. The basic premise of such a comparison is that similar descriptive statistics values between series suggest that the data set is comparable as their basic nature is analogous. Descriptive statistics between actual and predicted values in the testing phase are given in Table 4.

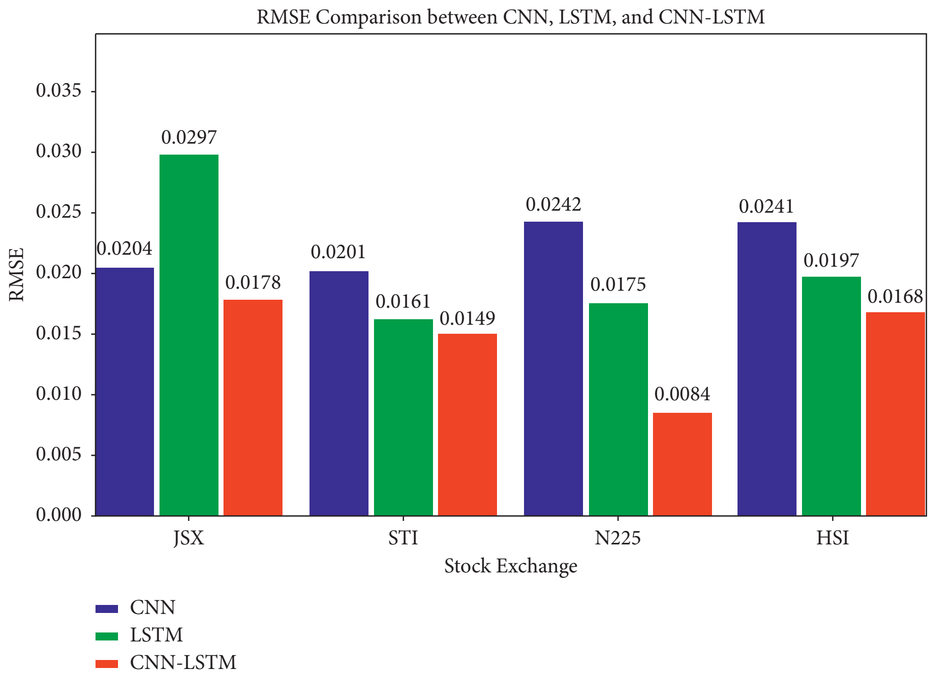


Figure 8: RMSE comparison between CNN, LSTM, and multivariate CNN-LSTM when predicting data in the testing phase, i.e., the last 72 trading days of the year 2020.

Table 3: Comparison of RMSE values between CNN, LSTM, and multivariate CNN-LSTM during training and testing phase.

Model	Shanghai (HSI)		Japan (N225)		Singapore (STI)		Indonesia (JSX)	
	Train	Test	Train	Test	Train	Test	Train	Test
CNN	0.0261	0.0241	0.0305	0.0242	0.0279	0.0201	0.0303	0.0204
LSTM	0.0190	0.0197	0.0274	0.0175	0.0203	0.0161	0.0227	0.0297
CNN-LSTM	0.0156	0.0168	0.0145	0.0084	0.0173	0.0149	0.0219	0.0178

Table 4: Comparison of descriptive statistics between actual and predicted time-series data produced by the proposed multivariate CNN-LSTM model in testing period, i.e., last 72 trading days of 2020. Note: Act = actual and Pred = predictions.

Descriptive statistics	Hang Seng (HSI)		Japan (N225)		Singapore (STI)		Indonesia (JSX)	
	Act	Pred	Act	Pred	Act	Pred	Act	Pred
Mean	1.1917	1.1802	1.0997	1.0853	1.0260	1.0221	1.0315	1.0421
Median	1.1872	1.1783	1.0956	1.0847	1.0336	1.0401	1.0093	1.0102
Standard deviation	0.0320	0.0296	0.0677	0.0643	0.0277	0.0291	0.0787	0.0766
Sample variance	0.0010	0.0012	0.0046	0.0043	0.0008	0.0071	0.0062	0.0058
Kurtosis	0.3295	0.3187	1.7725	1.7523	0.8161	0.8021	1.3399	1.3187
Skewness	0.3376	0.3152	0.1284	0.1179	1.1910	1.1876	0.3793	0.3685
Range	0.1497	0.1502	0.2022	0.2013	0.1132	0.1045	0.2520	0.2471
Minimum	1.1288	1.1256	1.0121	1.0097	0.9570	0.9613	0.9226	0.9197
Maximum	1.2786	1.2691	1.2143	1.2095	1.0702	1.0273	1.1746	1.1637
Confidence level (95.0%)	0.0075	0.0086	0.0159	0.0137	0.0065	0.0061	0.0185	0.0157

Comparative analysis between the descriptive statistics of actual and predicted values of four observed stock market indices as outlined in Table 4 indicates that both data set retain considerably similar values. This result confirms that both actual and predicted data set have similar basic nature and therefore can be concluded that the proposed multivariate CNN-LSTM model is capable of forecasting future values of financial time-series not only with good accuracy, in terms of relatively small RMSE values, but also with truthful basic nature.

6. Conclusions

This research proposes a multivariate CNN-LSTM model to forecast the value of multiple parallel financial time-series one stage in time based on the characteristics of the stock market index regular value time-series results (the next day). The technique used is multivariate time-series data forecasting, in which several time-series are predicted simultaneously by considering the condition of all observable series. CNN extracts features from the input data in the model, while LSTM studies the derived function data and performs the final step of estimating the performance of the stock market index the following day. This research uses applicable data from four Asian stock exchanges as training and test data to validate the experimental findings, namely, Shanghai, Japan, Singapore, and Indonesia. When compared with individual CNN and LSTM models, the experimental findings reveal that multivariate CNN-LSTM has the highest predictive precision and better efficiency (smallest RMSE value). This finding supports the assumption that incorporating relationships between variables into a prediction model will help with the multiple time-series problems of forecasting parallel movements of a set of time-sensitive variables that are related. As a result, multivariate CNN-LSTM can be used to predict the value of various stock market indices and can serve as a useful tool for investors when making investment decisions. Aside from that, multivariate CNN-LSTM is a viable option for research involving the construction of models for financial time-series data analysis. However, the existing model has a few flaws, including the fact that different data relating to external variables such as public opinion and national policy were not considered during the prediction period. In this regard, the future study work plan will focus on using more factors, both quantitative and qualitative in nature, as input into the prediction model and constructing a fully working investment-trading system based on the proposed model as well.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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Research Article

Optimal Time-Consistent Investment Strategy for a Random Household Expenditure with Default Risk under Relative Performance

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Considering the mind of rivalry between families, each family focuses not only on its own wealth but also on other families, especially neighbors. In this paper, we investigate the non-zero-sum mean-variance game between two families with a random household expenditure under the default risk and relative performance. Applying the stochastic control theory within the framework of the game theory, the extended Hamilton–Jacobi–Bellman equation equations are derived. By solving this equation, we obtain the Nash equilibrium strategies of the two families and the corresponding equilibrium value functions. We also provide a numerical example to analyze the effects of relevant parameters on Nash equilibrium strategy and on the utility loss due to the mind of rivalry.

1. Introduction

With the strengthening of household residents' financial awareness and the increasing abundance of financial products, families are increasingly focusing on the issue of optimal asset portfolio selection. Optimal investment portfolios have been widely studied in recent years. Hipp and Plum [1], David Promislow and Young [2], Milevsky et al. [3], Chen et al. [4], and Bayraktar and Zhang [5] consider the optimal investment for minimizing the ruin probability. Wang [6], Bo and Capponi [7], Delong [8], Yuan and Lai [9], and Li et al. [10] obtain the optimal investment strategy under maximizing the expected utility of terminal wealth.

And then the mean-variance criteria are another objective of great interest to insurers. In contrast to maximizing expected utility and minimizing ruin probability, mean-variance criteria allow insurers to minimize risk at an acceptable return. This approach takes not only the risk but also the returns into account. Due to its rationality and practicality, mean-variance has become a popular decision criterion in financial theory. The study of the mean-variance can be traced back to Markowitz [11]. Since then, there has been a certain amount of research on the optimization problem and its application in finance and insurance. For example, Li and Ng [12] introduce an embedding technique to transform the mean-variance problem into a stochastic linear quadratic control problem in a discrete-time model, which was extended to the corresponding continuous-time model by Zhou and Li [13]. The application of the mean-variance criterion to optimal reinsurance or/and investment can be found in Bäuerle [14], Bai and Zhang [15], and Bi and Guo [16]; however, they are all in the optimal strategy based on initial information, which is time-inconsistent. It is well known that the dynamic mean-variance criterion lacks iterated-expectation property, which leads to time-inconsistent in the sense that the Bellman optimality principle does not hold anymore. To this end, Björk et al. [17] solve the time-inconsistent problem by reconstructing stochastic control theory in the framework of game theory and obtain a time-consistent equilibrium strategy which is not only optimal at the current time but also optimal in the future. In recent years, there has been an increased interest in finding a time-consistent equilibrium strategy for the mean-variance portfolio problem, such as Zeng and Li [18], Li et al. [19], and Zhang and Liang [20].

Further, high-yield corporate bonds are becoming increasingly attractive to investors in today's financial markets. As a result, the optimal portfolio problem with defaulted securities has become an important area of research. Bielecki and Jang [21] consider the portfolio problem of investing wealth in credit risk assets, bank accounts, and stocks to maximize exponential utility maximization. Li et al. [22] investigate the DC pension management problem with a default bond under the CEV model and obtain an optimal time-consistent investment strategy. Zhao et al. [23] and Zhang and Chen [24] derive the optimal time-consistent investment and reinsurance strategies under default risk.

Similar to Yuan and Lai [9] and Li et al. [10], we study households with stochastic expenditure optimal investment strategies. Unlike them, we consider that households can invest in corporate bonds and study the optimal time-consistent strategy under the mean-variance. Further, relative performance concerns are prevalent, such as pension managers, insurers, and other firms, who are concerned not only with their absolute wealth but also with the gap between their wealth and that of their competitors. And considering that there is a mind of rivalry among families, and they not only focus on their own wealth but also on the wealth of other families, especially their neighbors; thus, we construct a non-zero-sum mean-variance game between two families under relative performance (see Espinosa and Touzi [25]). Applying the stochastic control theory in the game theory framework, we obtain the Nash equilibrium strategies of the two households and the corresponding equilibrium value functions, and in addition, we analyze the utility loss caused by the mind of rivalry.

The remainder of this paper is organized as follows. Section 2 formulates the mean-variance game between two families for a random household expenditure with default risk. In Section 3, by solving the extended HJB equation, we derive the time-consistent Nash equilibrium strategy and the corresponding equilibrium value functions. In Section 4, we provide a numerical example to simulate the influence of relevant parameters on the equilibrium strategy and give an economic explanation. Section 5 concludes this paper.

2. Problem Formulation

In this paper, we consider a complete probability space $(\Omega, \mathscr{F}, \mathbb{P})$ equipped with a right continuous and $\mathbb{P}$-complete filtration $\{\mathscr{F}_t\}_{t\in[0,T]}$, where $\{\mathscr{F}_t\}_{t\in[0,T]}$ represents the information of the market available up to time t. All stochastic processes introduced below are defined in the filtered probability space $(\Omega, \mathscr{F}, \{\mathscr{F}_t\}_{t\in[0,T]}, \mathbb{P})$.

Suppose that the financial market consists of three tradable assets: a risk-free asset, a risky asset, and a defaultable bond. The price of a risk-free asset satisfies the following process:

$$\mathrm{d}R(t) = rR(t)\mathrm{d}t, \quad R(0) = R_0, \tag{1}$$

where $r\,(>0)$ is the risk-free interest rate. The price $S(t)$ of the stock is given by

$$\mathrm{d}S(t) = S(t-)\left[\mu\mathrm{d}t + \sigma\mathrm{d}W_1(t) + \mathrm{d}\sum_{i=1}^{N(t)} Y_i\right], \quad S(0) = S_0, \tag{2}$$

where $\mu\,(>0)$ and $\sigma\,(>0)$ are the expected return rate and the instantaneous volatility, respectively. $\{N(t)\}_{t\in[0,T]}$, denoting the number of the price jumps that occur in the risky asset during time interval $[0,t]$, is a homogeneous Poisson process with an intensity λ; Y_l is the lth jump amplitude of the risky asset price; $\{Y_l, l = 1, 2, \ldots\}$ are i.i.d random variables with distribution function $F(y)$, finite first-order moment $E[Y_l] = \mu_Y$, and second-order moment $E[Y_l^2] = \sigma_Y^2$. Besides, we suppose that $\mathbb{P}\{Y_l \geq -1$ for all $l \geq 1\} = 1$ to ensure that the risky asset price remains positive. And we assume that $\mu + \lambda\mu_Y > r$.

Different from the price dynamics of the risk-free asset and risky asset which are defined under the real-world probability measure $\mathbb{P}$ directly, the price process of the defaultable bond is firstly given by the martingale probability measure $\mathbb{Q}$ and then turned into the price dynamics under the probability measure $\mathbb{P}$. Following Bielecki and Jang [21], the definition of the default process is given by $Z(t) = 1_{\{\tau\leq t\}}$, where τ is a nonnegative random variable representing the default time of the company issue the bond, 1 is an indicator which takes value one if the default occurs, and zero otherwise. That is, the default process $Z(t)$ is nondecreasing right continuous and has a jump at the random time τ. Furthermore, according to Driessen [26] and Duffie and Singleton [27], $Z(t)$ is supposed as the default process with a constant intensity $k^{\mathbb{P}}$ under the probability measure $\mathbb{P}$. Then, the martingale default process $K^{\mathbb{P}}(t)$ under probability measure $\mathbb{P}$ is given by $K^{\mathbb{P}}(t) := Z(t) - \int_0^t (1 - Z(u-))k^{\mathbb{P}}\mathrm{d}u$, where its differential form is $\mathrm{d}K^{\mathbb{P}}(t) = \mathrm{d}Z(t) - k^{\mathbb{P}}(1 - Z(t-))\mathrm{d}t$.

Then, the price process of the defaultable bond under the martingale probability measure $\mathbb{Q}$ is considered. Similar to Bielecki and Jang [21], the defaultable bond is assumed as a zero-coupon bond with the one-unit face value and maturity $\overline{T}$. Further, we assume that in the event that a default occurs, the insurer recovers a fraction of the market value of the defaultable bond just prior to default, and then, the post-default value of the defaultable bond is zero. The loss rate is denoted by ζ; then, $1-\zeta$ is the default recovery rate. In addition, we denote by $k^{\mathbb{Q}}$ the constant intensity of the default process under the martingale probability measure $\mathbb{Q}$, then $\vartheta = k^{\mathbb{Q}}\zeta$ is the risk-neutral credit spread, and then, we derive the following price process of the defaultable bond under the probability measure $\mathbb{Q}$:

$$p(t,\overline{T}) = 1_{\tau>t}e^{-(r+\vartheta)(\overline{T}-t)} + 1_{\tau\leq t}(1-\zeta)e^{-(t+\vartheta)(\overline{T}-t)}e^{r(t-\tau)}, \tag{3}$$

where $p(t,\overline{T})$ is a fictitious bond rather than a bond actually traded, and $T < \overline{T}$. That is, as Bielecki and Jang [21] and

Driessen [26] mentioned, the fictitious bond allows us to take into consideration the jump risk premium in the expected return of the defaultable bond. Applying Itô formula to the above expression, we derive

$$\mathrm{d}p(t,\overline{T}) = rp(t,\overline{T})\mathrm{d}t - \zeta e^{-(r+\vartheta)(\overline{T}-t)}\mathrm{d}K^{\mathbb{Q}}(t), \tag{4}$$

where $K^{\mathbb{Q}}(t)$ is a martingale default process under the martingale probability measure $\mathbb{Q}$.

Next, we need to transform the price process of defaultable bonds under the martingale probability measure $\mathbb{Q}$ into the real-world probability measure $\mathbb{P}$. Based on the above notations, by Girsanov theorem (see Kusuoka [28]), there exists a predictable process Δ such that the evolutions of the price process for the defaultable bond under real-world probability measure $\mathbb{P}$ as follows:

$$\mathrm{d}p(t,\overline{T}) = p(t-,\overline{T})\left[r\mathrm{d}t + (1-Z(t))\vartheta(1-\Delta)\mathrm{d}t - (1-Z(t-))\zeta\mathrm{d}K^{\mathbb{P}}(t)\right], \tag{5}$$

where $\Delta = (k^{\mathbb{Q}}/k^{\mathbb{P}})$ and $K^{\mathbb{P}}(t) = Z(t) - k^{\mathbb{Q}}\int_0^t (1-Z(u-))\Delta \mathrm{d}u$ is a $\mathcal{F}$-martingale under probability measure $\mathbb{P}$. Similar to Duffie and Singleton [27], the probability of default under the real-world probability measure $\mathbb{P}$ is lower than that under the martingale probability measure $\mathbb{Q}$, that is, $(1/\Delta) > 1$. According to Yu [29], equation (5) consists of two components: the first component is the return of a default-free bond. The second is the difference between the risk-neutral credit spread and the real-world credit spread provided that the default has not occurred by time t.

In addition, we assume that household expenditures include household consumption expenditures, transaction costs, and other expenditures. Thus, the family expenditure has stochastic property. We denote the family expenditure at the time t by $w(t)$ which is characterized by an arithmetic Brownian motion:

$$\mathrm{d}w(t) = \alpha\mathrm{d}t + \beta\mathrm{d}W_2(t), \quad w(0) = w_0 > 0, \tag{6}$$

where $\alpha(>0)$ represents the average expenditure. $\beta\mathrm{d}W_2(t)$ denotes expenditure subject to random factors, in which $\beta(>0)$ and $W_2(t)$ are positive constants and standard Brownian motion, respectively. And the correlation coefficient of $W_1(t)$ and $W_2(t)$ is denoted by ρ, i.e., $E[W_1(t)W_2(t)] = \rho t$. To simplify the calculation later, we assume that the expenditures are the same between the two households. In practice, the expenditures of the two households may be different, but it does not bring essential changes to the solution of the optimization problem but only increases the variables and parameters in the optimal solution.

Let $X_i(t)$ denote the wealth at the time $t \in [0,T]$ for family i, and $p_i(t)$ and $q_i(t)$ denote the amount at time t for family i invested in the risky asset and defaultable bond, respectively; then, the amount for family i invested in risk-free assets is $X_i(t) - p_i(t) - q_i(t)$. Define $\pi_i(t) = (p_i(t), q_i(t))$ as the strategy of family i at time t; thus, the dynamics of the wealth of family i under strategy π_i satisfies the following stochastic differential equation (SDE):

$$\begin{aligned}\mathrm{d}X_i^{\pi_i}(t) = {}& \left[rX_i^{\pi_i}(t) + p_i(t)(\mu - r) + q_i(t)(1-Z(t))\vartheta(1-\Delta)\right]\mathrm{d}t + p_i(t)\sigma\mathrm{d}W_1(t)\\ &+ \int_{-1}^{+\infty} p_i(t)yN(\mathrm{d}t,\mathrm{d}y) - q_i(t)(1-Z(t-))\zeta\mathrm{d}K^{\mathbb{P}} - w(t)\mathrm{d}t, \quad X(0) = X_0.\end{aligned} \tag{7}$$

Definition 1 (admissible strategy). For any fixed $t \in [0,T]$, a strategy $\pi_i = \{(p_i(t), q_i(t))\}_{t\in[0,T]}$ is said to be admissible if

(i) π_i is $\mathcal{F}$-progressively measurable

(ii) $E[\int_0^T ((p_i(u))^2 + (q_i(u))^2)\mathrm{d}u] < \infty$

(iii) The SDE (7) has a unique strong solution

For any initial state $(t, x_i, w, z) \in [0,T]\times\mathbb{R}\times\mathbb{R}\times\{0,1\}$, the corresponding set of all admissible strategies for family i is denoted by Π_i. When default has occurred, i.e., $\tau \le t$, we assume that $p(t-,\overline{T}) = 0$ and fix $p_2(t) = 0$ afterward. And we let z denote the initial default state, where $z = 1$ and $z = 0$ correspond to the postdefault cases $\tau > t$ and the predefault case $\tau \le t$, respectively.

Due to the mind of rivalry, each family is concerned not only with their own terminal wealth but also with the differences between them and other families, especially neighbors. Hence, we formulate this optimization problem as a non-zero-sum stochastic differential game among two households. Following Espinosa and Touzi [25], we define the relative performance $\widehat{X}_i^{\pi_i}(t)$ for family i as follows:

$$\widehat{X}_i^{\pi_i,\pi_j}(t) = (1-\kappa_i)X_i^{\pi_i}(t) + \kappa_i\left(X_i^{\pi_i}(t) - X_j^{\pi_j}(t)\right), \quad i \ne j \in \{1,2\}, \tag{8}$$

where $\kappa_i \in [0,1]$ captures the intensity of the family i's relative concern and measures his sensitivity to the performance of his competitors. Together with equations (7) and (8), we derive

$$\begin{aligned}
\mathrm{d}\widehat{X}_i^{\pi_i,\pi_j}(t) = &\left[r\widehat{X}_i^{\pi_i,\pi_j}(t) + (\mu - r)\left(p_i(t) - \kappa_i p_j(t)\right) + (1 - Z(t))\vartheta(1 - \Delta)\left(q_i(t) - \kappa_i q_j(t)\right) - (1) - \kappa_i w(t)\right]\mathrm{d}t \\
&+\left(p_i(t) - \kappa_i p_j(t)\right)\sigma \mathrm{d}W_1(t) + \int_{-1}^{+\infty}\left(p_i(t) - \kappa_i p_j(t)\right)N(\mathrm{d}t, \mathrm{d}y) \\
&-\left(q_i(t) - \kappa_i q_j(t)\right)(1 - Z(t))\zeta \mathrm{d}K^{\mathbb{P}}(t).
\end{aligned} \tag{9}$$

We assume that each family has mean-variance criteria and define the following value function for family i:

$$J_i^{\pi_i^*,\pi_j^*}(t,\widehat{x}_i,w,z) = \sup_{\pi_i\in\Pi_i}\left\{E_{t,\widehat{x}_i,w,z}\left[\widehat{X}_i^{\pi_i,\pi_j^*}(T)\right] - \frac{\gamma_i}{2}\mathrm{Var}_{t,\widehat{x}_i,w,z}\left[\widehat{X}_i^{\pi_i,\pi_j^*}(T)\right]\right\}, \tag{10}$$

where $E_{t,\widehat{x}_i,w,z}[\cdot]$ and $E_{t,\widehat{x}_i,w,z}[\cdot]$ are the conditional expectation and variance given $\widehat{X}_i^{\pi_i,\pi_j}(t) = \widehat{x}_i$, $w(t) = w$, and $Z(t) = z$ for $(t,\widehat{x}_i,w,z) \in [0,T]\times\mathbb{R}\times\mathbb{R}\times\{0,1\}$, and $\gamma_i > 0$ is the risk-aversion coefficient of family i.

Problem 1. In the classical non-zero-sum stochastic differential game, we find a Nash equilibrium $(\pi_i,\pi_j) \in \Pi_i \times \Pi_j$ such that

$$J_i^{\left(\pi_i^*,\pi_j^*\right)}(t,\widehat{x}_i,w,z) \geq J_i^{\left(\pi_i,\pi_j^*\right)}(t,\widehat{x}_i,w,z), \quad i \neq j \in \{1,2\}. \tag{11}$$

Because there exists a nonlinear function of the expectation of terminal wealth in the objective functional (10), the optimization problem is time-inconsistent. In fact, time consistency cannot be ignored for a rational decision-maker who aims to seek an equilibrium strategy that is optimal at a time and still can be optimal as time goes forward into the future. Hence, we shall define the following time-consistent equilibrium strategy according to Björk et al. [17].

Definition 2. Consider an admissible strategy π_i^* for family i, which can be informally viewed as a candidate equilibrium strategy. And choose arbitrarily a fixed $\widehat{\pi}_i \in \Pi_i$, a real number $\varepsilon(>0)$, and a given initial point $(t,\widehat{x}_i,w,z) \in [0,T]\times\mathbb{R}\times\mathbb{R}\times\{0,1\}$; the strategy π_i^ε for family i is defined as follows:

$$\pi_i^\varepsilon = \begin{cases} \widehat{\pi}_i(u,\widehat{x}_i,w,z), & (u,\widehat{x}_i,w,z) \in [t,t+\varepsilon)\times\mathbb{R}\times\mathbb{R}\times\{0,1\}, \\ \pi_i^*(u,\widehat{x}_i,w,z), & (u,\widehat{x}_i,w,z) \in [t+\varepsilon,T]\times\mathbb{R}\times\mathbb{R}\times\{0,1\}. \end{cases} \tag{12}$$

If

$$\liminf_{\varepsilon\downarrow 0}\frac{J_i^{\left(\pi_i^*,\pi_j^*\right)}(t,\widehat{x}_i,w,z) - J_i^{\left(\pi_i^\varepsilon,\pi_j^*\right)}(t,\widehat{x}_i,w,z)}{\varepsilon} \geq 0, \tag{13}$$

we call that π_i^* is an equilibrium strategy of family i and the equilibrium value function of family i is given by $J_i^{(\pi_i^*,\pi_j^*)}(t,\widehat{x}_i,w,z)$.

3. Nash Equilibrium Strategies

In this section, we derive the Nash equilibrium strategy between two families. According to Definition 2, the equilibrium strategy above is time-consistent. We aim to seek an equilibrium strategy (π_1^*,π_2^*) and the corresponding to equilibrium value functions. To give the extended HJB system and verification theorem conveniently, we define a variational operator. Let $C^{1,2,2}([0,T]\times\mathbb{R}\times\mathbb{R}\times\{0,1\})$ denote a space of any function $\varphi(t,\widehat{x}_i,w,z)$ which $\varphi(t,\widehat{x}_i,w,z)$ itself and its derivatives $(\partial\varphi/\partial t)$, $(\partial\varphi/\partial\widehat{x}_i)$, $(\partial^2\varphi/\partial\widehat{x}_i^2)$, $(\partial\varphi/\partial w)$, $(\partial^2\varphi/\partial w^2)$, and $(\partial^2\varphi/\partial\widehat{x}_i\partial w)$ are continuous on $[0,T]\times\mathbb{R}\times\mathbb{R}\times\{0,1\}$. For any function $\varphi(t,\widehat{x}_i,w,z) \in C^{1,2,2}([0,T]\times\mathbb{R}\times\mathbb{R}\times\{0,1\})$, the variational operator is defined as follows:

$$\begin{aligned}
\mathscr{L}^{\left(\pi_i,\pi_j\right)}\varphi(t,\widehat{x}_i,w,z) = &\frac{\partial\varphi}{\partial t} + \left[r\widehat{x}_i + (\mu - r)\left(p_i(t) - \kappa_i p_j(t)\right) - (1 - \kappa_i)w\right. \\
&\left.+ (1 - z)\vartheta\left(q_i(t) - \kappa_i q_j(t)\right)\right]\frac{\partial\varphi}{\partial\widehat{x}_i} + \alpha\frac{\partial\varphi}{\partial w} + \frac{1}{2}\left(p_i(t) - \kappa_i p_j(t)\right)^2\sigma^2\frac{\partial^2\varphi}{\partial\widehat{x}_i^2} + \frac{1}{2}\beta^2\frac{\partial^2\varphi}{\partial w^2} \\
&+ \rho\beta\sigma\left(p_i(t) - \kappa_i p_j(t)\right)\frac{\partial^2\varphi}{\partial\widehat{x}_i\partial w} + \lambda E\left[\varphi\left(t,\widehat{x}_i + \left(p_i(t) - \kappa_i p_j(t)\right)y,w,z\right) - \varphi(t,\widehat{x}_i,w,z)\right] \\
&+ k^{\mathbb{P}}(1 - z)\left[\varphi\left(t,\widehat{x}_i - \left(q_i(t) - \kappa_i q_j(t)\right)\zeta,w,1\right) - \varphi(t,\widehat{x}_i,w,0)\right].
\end{aligned} \tag{14}$$

Before finding the equilibrium strategy, the following theorem gives the verifications for the extended HJB equation corresponding to Problem 1.

Theorem 1. *(verification theorem). For Problem 1, we assume that there exist two real-valued functions* $V_i(t,\widehat{x}_i,w,z)$, $g_i(t,\widehat{x}_i,w,z)\in C^{1,2,2}([0,T]\times\mathbb{R}\times\mathbb{R}\times\{0,1\})$ *satisfying the following extended HJB equations:*

$$\begin{cases}\sup_{\pi_i\in\Pi_i}\left\{\mathscr{L}^{\pi_i,\pi_j^*}V_i(t,\widehat{x}_i,w,z)-\frac{\gamma_i}{2}\mathscr{L}^{\pi_i,\pi_j^*}g_i^2(t,\widehat{x}_i,w,z)+\gamma_i g_i(t,\widehat{x}_i,w,z)\mathscr{L}^{\pi_i,\pi_j^*}g_i(t,\widehat{x}_i,w,z)\right\}=0,\\ \mathscr{L}^{\pi_i^*,\pi_j^*}g_i(t,\widehat{x}_i,w,z)=0,\\ \pi_i^*=\arg\sup_{\pi_i\in\Pi_i}\left\{\mathscr{L}^{\pi_i,\pi_j^*}V_i(t,\widehat{x}_i,w,z)-\frac{\gamma_i}{2}\mathscr{L}^{\pi_i,\pi_j^*}g_i^2(t,\widehat{x}_i,w,z)+\gamma_i g_i(t,\widehat{x}_i,w,z)\mathscr{L}^{\pi_i,\pi_j^*}g_i(t,\widehat{x}_i,w,z)\right\},\\ V_i(T,\widehat{x}_i,w,z)=\widehat{x}_i,\\ g_i(T,\widehat{x}_i,w,z)=\widehat{x}_i,\end{cases}\tag{15}$$

then $E_{t,\widehat{x}_i,w,z}[\widehat{X}_i^{\pi_i^*,\pi_j^*}(T)]=g_i(t,\widehat{x}_i,w,z)$, $J_i^{(\pi_i^*,\pi_j^*)}(t,\widehat{x}_i,w,z)=V_i(t,\widehat{x}_i,w,z)$, *and* π_i^* *is an equilibrium strategy of family i.*

Proof. The proof of the verification theorem can be adapted from Theorem 5.2 in [17], and thus the proof is placed in Appendix A. □

Theorem 2. *For Problem 1, the optimal time-consistent Nash equilibrium strategies for family* $i(\neq j\in\{1,2\})$ *are given by*

$$\begin{aligned}p_i^*(t)=\frac{e^{-r(T-t)}}{1-\kappa_i\kappa_j}&\left[\frac{r(\mu-r+\lambda\mu_Y)+(1-\kappa_i)\gamma_i\rho\beta\sigma\left(e^{r(T-t)}-1\right)}{\gamma_i r\left(\sigma^2+\lambda\sigma_Y^2\right)}\right.\\&\left.+\kappa_i\frac{r(\mu-r+\lambda\mu_Y)+\left(1-\kappa_j\right)\gamma_j\rho\beta\sigma\left(e^{r(T-t)}-1\right)}{\gamma_j r\left(\sigma^2+\lambda\sigma_Y^2\right)}\right],\end{aligned}\tag{16}$$

$$q_i^*(t)=\frac{e^{-r(T-t)}}{1-\kappa_i\kappa_j}\left[\frac{\vartheta}{\gamma_i\zeta^2k^{\mathbb{P}}}-\frac{1}{\gamma_i\zeta}+\frac{c_i(t)-\overline{c}_i(t)}{\zeta}+\kappa_i\left(\frac{\vartheta}{\gamma_j\zeta^2k^{\mathbb{P}}}-\frac{1}{\gamma_j\zeta}+\frac{c_j(t)-\overline{c}_j(t)}{\zeta}\right)\right]1_{\{\tau>t\}},\tag{17}$$

and the equilibrium value function of family i is

$$V_i(t,\widehat{x}_i,w,z)=\begin{cases}e^{r(T-t)}\widehat{x}_i+B_i(t)w+C_i(t), & z=1,\\ e^{r(T-t)}\widehat{x}_i+\overline{B}_i(t)w+\overline{C}_i(t), & z=0.\end{cases}\tag{18}$$

Moreover, the expectation and variance of the terminal value corresponding to the equilibrium strategy for family i are as follows:

$$\begin{aligned}E_{t,\widehat{x}_i,w,z}&=\begin{cases}e^{r(T-t)}\widehat{x}_i+b_i(t)w+c_i(t), & z=1,\\ e^{r(T-t)}\widehat{x}_i+\overline{b}_i(t)w+\overline{c}_i(t), & z=0,\end{cases}\\ \mathrm{Var}_{t,\widehat{x}_i,w,z}&=\begin{cases}\frac{2}{\gamma_i}\left[C_i(t)-c_i(t)\right], & z=1,\\ \frac{2}{\gamma_i}\left[\overline{C}_i(t)-\overline{c}_i(t)\right], & z=0,\end{cases}\end{aligned}\tag{19}$$

where $B_i(t), b_i(t), c_i(t), C_i(t), \overline{B}_i(t), \overline{b}_i(t), \overline{c}_i(t), \overline{C}_i(t), c_j(t)$, and $\overline{c}_j(t)$ are given by (B.18)–(B.20), (B.40)–(B.42), (B.45), and (B.47), respectively.

Proof. See Appendix B.

If $\kappa_1 = \kappa_2 = 0$, then the model degenerates to the case where the competition factor is not considered; i.e., there is no psychological widespread between the two families; we have the following corollary. □

Corollary 1. *When $\kappa_1 = \kappa_2 = 0$, the optimal time-consistent Nash equilibrium strategies for family $i(\neq j \in \{1,2\})$ are as follows:*

$$\widetilde{p}_i^*(t) = e^{-r(T-t)}\left[\frac{r(\mu - r + \lambda\mu_Y) + \gamma_i\rho\beta\sigma\left(e^{r(T-t)} - 1\right)}{\gamma_i r\left(\sigma^2 + \lambda\sigma_Y^2\right)}\right], \tag{20}$$

$$\widetilde{q}_i^*(t) = e^{-r(T-t)}\left[\frac{\vartheta}{\gamma_i\zeta^2 k^{\mathbb{P}}} - \frac{1}{\gamma_i\zeta} + \frac{c_{i0}(t) - \overline{c}_{i0}(t)}{\zeta}\right]1_{\{\tau>t\}}, \tag{21}$$

and the equilibrium value function of family i is

$$\widetilde{V}_i(t, x_i, w, z) = \begin{cases} e^{r(T-t)}x_i + B_{i0}(t)w + C_{i0}(t), & z = 1, \\ e^{r(T-t)}x_i + \overline{B}_{i0}(t)w + \overline{C}_{i0}(t), & z = 0. \end{cases} \tag{22}$$

Moreover, the expectation and variance of the terminal value corresponding to the equilibrium strategy for family i are as follows:

$$\widetilde{E}_{t,x_i,w,z} = \begin{cases} e^{r(T-t)}x_i + b_{i0}(t)w + c_{i0}(t), & z = 0, \\ e^{r(T-t)}x_i + \overline{b}_{i0}(t)w + \overline{c}_{i0}(t), & z = 1, \end{cases}$$
$$\widetilde{\mathrm{Var}}_{t,x_i,w,z} = \begin{cases} \dfrac{2}{\gamma_i}\left[C_{i0}(t) - c_{i0}(t)\right], & z = 1, \\ \dfrac{2}{\gamma_i}\left[\overline{C}_{i0}(t) - \overline{c}_{i0}(t)\right], & z = 0, \end{cases} \tag{23}$$

where

$$B_{i0}(t) = b_{i0}(t) = \overline{B}_{i0}(t) = \overline{b}_{i0}(t) = -\frac{1}{r}\left(e^{r(T-t)} - 1\right), \tag{24}$$

$$\begin{aligned} c_{i0}(t) = &-\left(\alpha - \frac{(\mu - r + \lambda\mu_Y)\rho\beta\sigma}{\sigma^2 + \lambda\sigma_Y^2}\right)\frac{1}{r^2}\left(e^{r(T-t)} - 1\right) \\ &-\left(\alpha - \frac{(\mu - r + \lambda\mu_Y)\rho\beta\sigma}{\sigma^2 + \lambda\sigma_Y^2}\right)\frac{1}{r}(t - T) - \frac{(\mu - r + \lambda\mu_Y)^2}{\gamma_i\left(\sigma^2 + \lambda\sigma_Y^2\right)}(t - T), \end{aligned} \tag{25}$$

$$\begin{aligned} C_{i0}(t) = &\left(\alpha - \frac{(\mu - r + \lambda\mu_Y)\rho\beta\sigma}{\sigma^2 + \lambda\sigma_Y^2}\right)\left[-\frac{1}{r^2}e^{r(T-t)} - \frac{1}{r}(t - T) + \frac{1}{r^2}\right] \\ &+ \frac{\gamma_i\beta^2}{2}\left(1 - \frac{\rho^2\sigma^2}{\sigma^2 + \lambda\sigma_Y^2}\right)\left[-\frac{1}{2r^3}e^{2r(T-t)} + \frac{2}{r^3}e^{r(T-t)}\right. \\ &\left. + \frac{1}{r^2}(t - T) + \frac{1}{2r^3} - \frac{2}{r^3}\right] - \frac{(\mu - r + \lambda\mu_Y)^2}{2\gamma_i\left(\sigma^2 + \lambda\sigma_Y^2\right)}(t - T), \end{aligned} \tag{26}$$

$$\overline{c}_{i0}(t) = e^{(\vartheta t/\zeta)}\int_t^T e^{-(\vartheta u/\zeta)}\left[\left(\alpha - \frac{(\mu - r + \lambda\mu_Y)\rho\beta\sigma}{\sigma^2 + \lambda\sigma_Y^2}\right)\overline{b}_{i0}(u) + \frac{(\mu - r + \lambda\mu_Y)^2}{\gamma_i\left(\sigma^2 + \lambda\sigma_Y^2\right)} + \frac{k^{\mathbb{P}}}{\gamma_i} - \frac{2\vartheta}{\gamma_i\zeta} + \frac{\vartheta^2}{\gamma_i\zeta^2 k^{\mathbb{P}}}\right]\mathrm{d}u, \tag{27}$$

$$\begin{aligned} \overline{C}_{i0}(t) = e^{k^{\mathbb{P}}t}\int_t^T e^{-k^{\mathbb{P}}u}&\left[\alpha\overline{B}_{i0}(u) - \frac{\gamma_i\beta^2}{2}\left(1 - \frac{\rho^2\sigma^2}{\sigma^2 + \lambda\sigma_Y^2}\right)\overline{b}_{i0}^2(u)\right. \\ &- \frac{(\mu - r + \lambda\mu_Y)\rho\beta\sigma}{\sigma^2 + \lambda\sigma_Y^2}\overline{b}_{i0}(u) + k^{\mathbb{P}}C_{i0}(u) - \left(k^{\mathbb{P}} - \frac{\vartheta}{\zeta}\right)\left(c_{i0}(u) - \overline{c}_{i0}(u)\right) \\ &\left. + \frac{(\mu - r + \lambda\mu_Y)^2}{2\gamma_i\left(\sigma^2 + \lambda\sigma_Y^2\right)} + \frac{k^{\mathbb{P}}}{2\gamma_i} - \frac{\vartheta}{\gamma_i\zeta} + \frac{\vartheta^2}{2\gamma_i\zeta^2 k^{\mathbb{P}}}\right]\mathrm{d}u. \end{aligned} \tag{28}$$

Table 1: Model parameters.

r	μ	σ	μ_Y	λ	κ_1	κ_2	γ_1	γ_2	ϑ	ζ	$k^{\mathbb{P}}$	α	β	ρ	T
0.03	0.12	0.2	0.2	0.5	0.2	0.4	0.5	0.9	0.01	0.5	0.005	0.1	0.6	−0.5	3

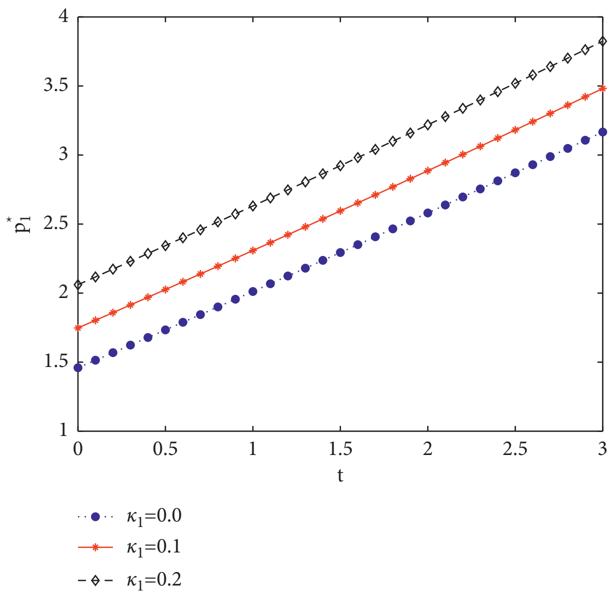

Figure 1: The effect of κ_1 on $p_1(t)$.

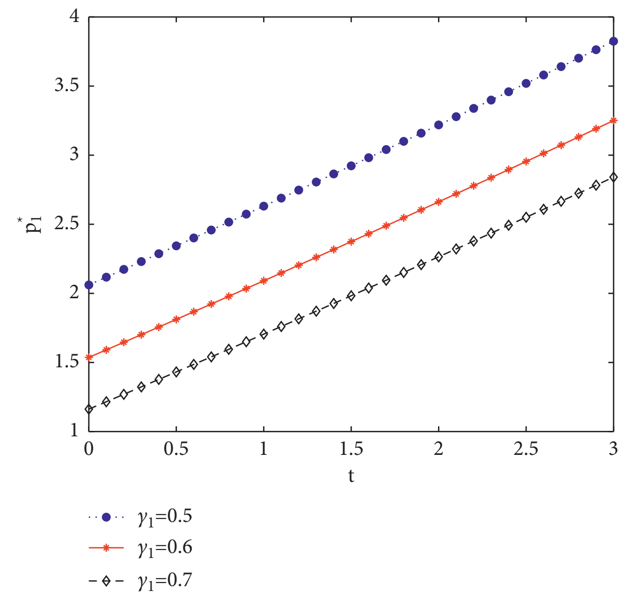

Figure 2: The effect of γ_1 on $p_1(t)$.

Remark 1

(i) From Theorem 2, we can find that the amounts invested in risky assets p_i^* and $\tilde{p}_i^*$ are influenced by the diffusion parameter β of random expenditures but are independent of the drift parameter α of random expenditures. This is the same as Yuan and Lai [9]. By equations (B.16) and (B.37), we have

$$\bar{c}_i'(t) - c_i'(t) - \frac{\vartheta}{\zeta}\left(\bar{c}_i(t) - c_i(t)\right) + \frac{k^{\mathbb{P}}}{\gamma_i} - \frac{2\vartheta}{\gamma_i \zeta} + \frac{\vartheta^2}{\gamma_i \zeta^2 k^{\mathbb{P}}} = 0, \quad \bar{c}_i(T) - c_i(T) = 0. \tag{29}$$

Solving the above equation and noting that $\vartheta = k^{\mathbb{Q}}\zeta$ and $(1/\Delta) = (k^{\mathbb{Q}}/k^{\mathbb{P}})$, we derive

$$\bar{c}_i(t) - c_i(t) = \frac{\left(\zeta k^{\mathbb{P}} - \vartheta\right)^2\left(1 - e^{-\vartheta(T-t)/\zeta}\right)}{\gamma_i \zeta \vartheta k^{\mathbb{P}}} = \frac{(\Delta - 1)^2\left(1 - e^{-\vartheta(T-t)/\zeta}\right)}{\gamma_i \Delta}. \tag{30}$$

Symmetrically, we have

$$\bar{c}_j(t) - c_j(t) = \frac{\left(\zeta k^{\mathbb{P}} - \vartheta\right)^2\left(1 - e^{-\vartheta(T-t)/\zeta}\right)}{\gamma_j \zeta \vartheta k^{\mathbb{P}}} = \frac{(\Delta - 1)^2\left(1 - e^{-\vartheta(T-t)/\zeta}\right)}{\gamma_j \Delta}. \tag{31}$$

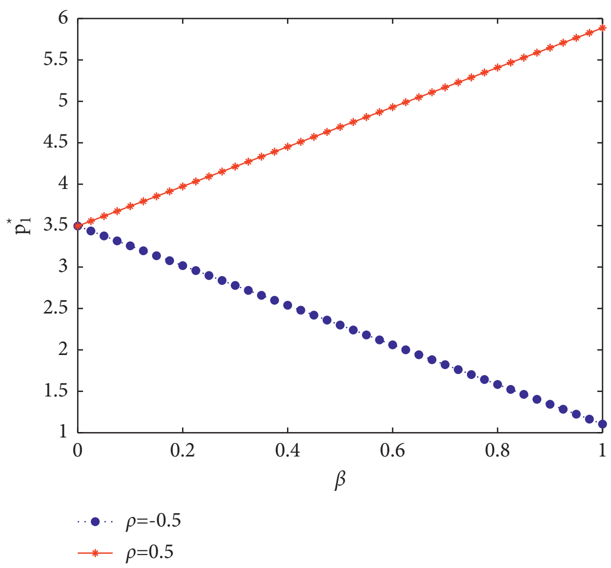

FIGURE 3: The effect of β on $p_1(0)$.

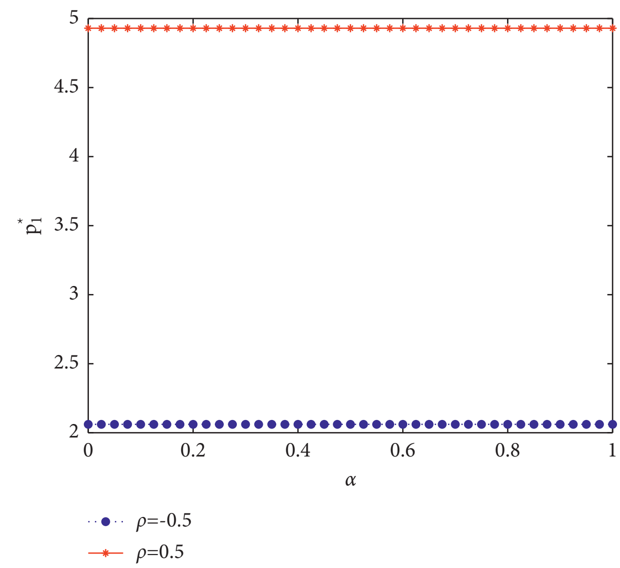

FIGURE 4: The effect of α on $p_1(0)$.

Noting equations (17) and (21), the amount invested in defaultable bonds is easily found to be independent of random expenditures.

(ii) From equations (18), (B.18), (B.40), (22), and (24), we have

$$\begin{aligned} \frac{\partial V_i(t,\hat{x}_i,w,z)}{\partial w} &= -\frac{1-\kappa_i}{r}\left(e^{r(T-t)}-1\right)<0, \\ \frac{\partial \widetilde{V}_i(t,x_i,w,z)}{\partial w} &= -\frac{1}{r}\left(e^{r(T-t)}-1\right)<0, \end{aligned} \quad (32)$$

that is, expenditure brings about loss of utility.

(iii) In fact, similar to the Cournot duopoly game in classical economics, there is utility loss in the psychology of mutual comparison between the two family homes we consider. Combining Theorem 2 and Corollary 1, we define the utility loss as follows:

$$\begin{aligned} \mathrm{UL}_i(t) &:= V_i(t,\hat{x}_i,w,z)-\widetilde{V}_i(t,x_i,w,z) \\ &= \begin{cases} e^{r(T-t)}\kappa_i x_j-\dfrac{\kappa_i}{r}\left(e^{r(T-t)}-1\right)w+\left(\alpha-\dfrac{(\mu-r+\lambda\mu_Y)\rho\beta\sigma}{\sigma^2+\lambda\sigma_y^2}\right)\Bigg[-\dfrac{\kappa_i}{r}e^{r(T-t)} \\ -\dfrac{\kappa_i}{r}(t-T)+\dfrac{\kappa_i}{r^2}\Bigg]+\dfrac{\gamma_i\beta}{2}\left(1-\dfrac{\rho^2\sigma^2}{\sigma^2+\lambda\sigma_Y^2}\right)\Bigg[\dfrac{\kappa_i^2-2\kappa_i}{2r^3}e^{2r(T-t)} \\ +\dfrac{4\kappa_i-2\kappa_i^2}{r^3}e^{r(T-t)}+\dfrac{2\kappa_i-\kappa_i^2}{r^2}(t-T)+\dfrac{2\kappa_i-\kappa_i^2}{2r^3}+\dfrac{2\kappa_i^2-4\kappa_i}{r^3}\Bigg], & z=1, \\ e^{r(T-t)}\kappa_i x_j-\dfrac{\kappa_i}{r}\left(e^{r(T-t)}-1\right)w+e^{k^{\mathbb{P}}t}\displaystyle\int_t^T e^{-k^{\mathbb{P}}u}\Big[\alpha\left(\overline{B}_{i0}(u)-\overline{B}_i(u)\right) \\ -\dfrac{\gamma_i\beta^2}{2}\left(1-\dfrac{\rho^2\sigma^2}{\sigma^2+\lambda\sigma_Y^2}\right)\left(\overline{b}_{i0}^2(u)-\overline{b}_i^2(u)\right)-\dfrac{(\mu-r+\lambda\mu_Y)\rho\beta\sigma}{\sigma^2+\lambda\sigma_Y^2}\left(\overline{b}_{i0}(u)-\overline{b}_i(u)\right) \\ +k^{\mathbb{P}}\left(C_{i0}(u)-C_i(u)\right)-\left(k^{\mathbb{P}}-\dfrac{\vartheta}{\zeta}\right)\left[\left(c_{i0}(u)-\overline{c}_{i0}(u)\right)-\left(c_i(u)-\overline{c}_i(u)\right)\right]\Big]\mathrm{d}u, & z=0. \end{cases} \end{aligned} \quad (33)$$

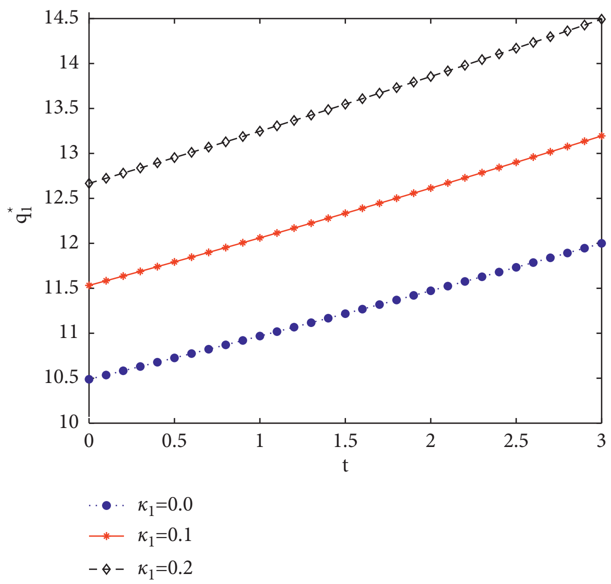

Figure 5: The effect of κ_1 on $q_1(t)$.

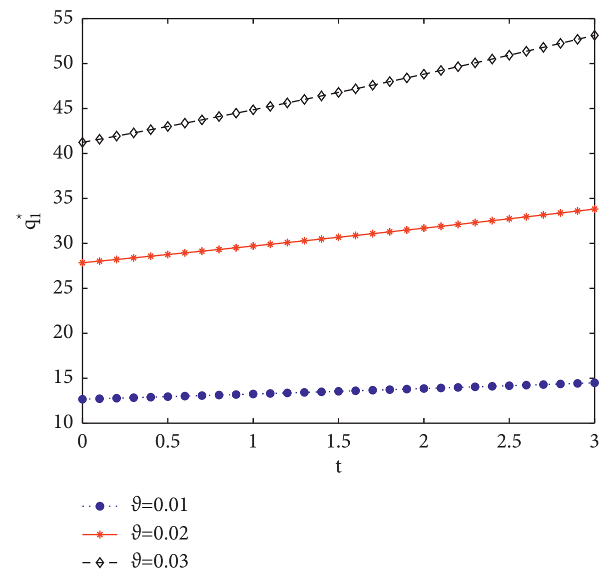

Figure 7: The effect of ϑ on $q_1(t)$.

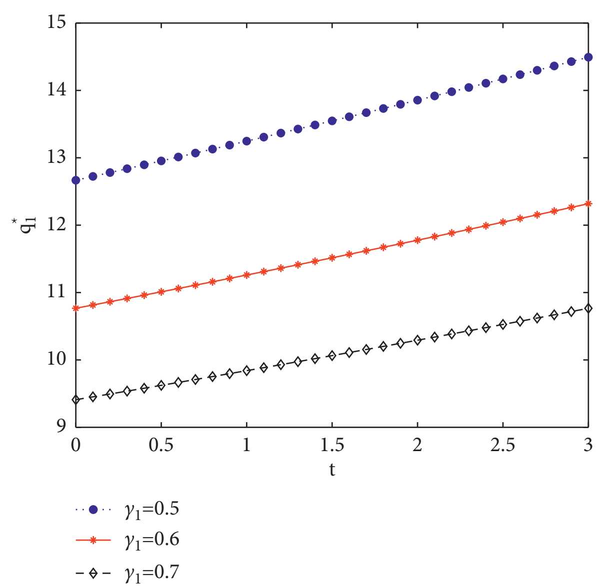

Figure 6: The effect of γ_1 on $q_1(t)$.

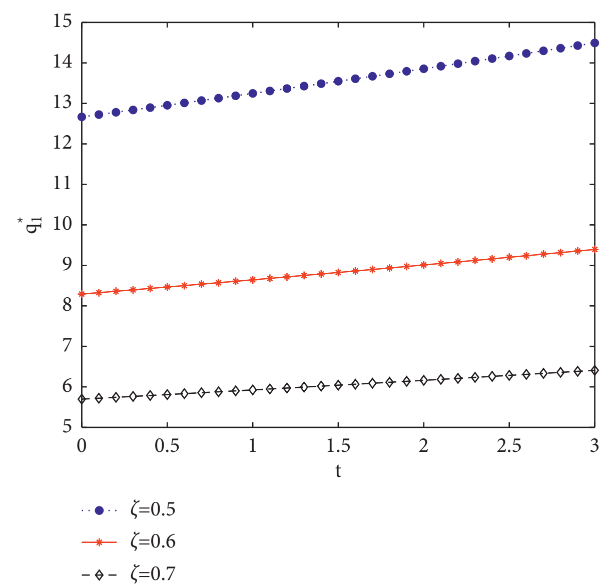

Figure 8: The effect of ζ on $q_1(t)$.

Notice that the utility loss $UL_i(t) \equiv 0$ when $\kappa_i = 0$.

4. Sensitivity Analysis

In this section, we provide a numerical example to illustrate the optimal time-consistent investment strategy with a random household expenditure under the relative performance, in which we analyze the effect of important parameters on results and give an economic explanation. According to the model settings in Section 2, unless otherwise stated, we select the parameters in Table 1 throughout this section. Next, we vary the value of one parameter by fixing other parameters to analyze the effect of the optimal time-consistent strategy. Due to symmetry, the effects of the parameters have the same trend for family 1 and family 2; thus, we only analyze the effects of the parameters on the optimal results for family 1.

Figures 1–4 depict the effects of parameters κ_1, γ_1, β, ρ, and α on family 1's optimal time-consistent investment strategy for risky assets, respectively. From Figure 1, it can be observed that the larger the parameter κ_1 that portrays the relative performance concern sensitivity, the larger the number of investments in risky assets by family 1. This is because the larger κ_1 is, the greater family 1 is concerned about the comparison of the wealth of its neighbors, and if family 1 increases its exposure to risky assets, then its

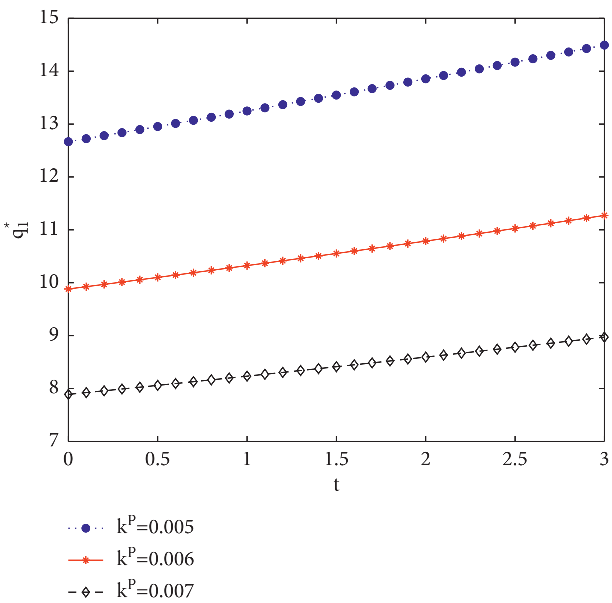

Figure 9: The effect of $k^{\mathbb{P}}$ on $q_1(t)$.

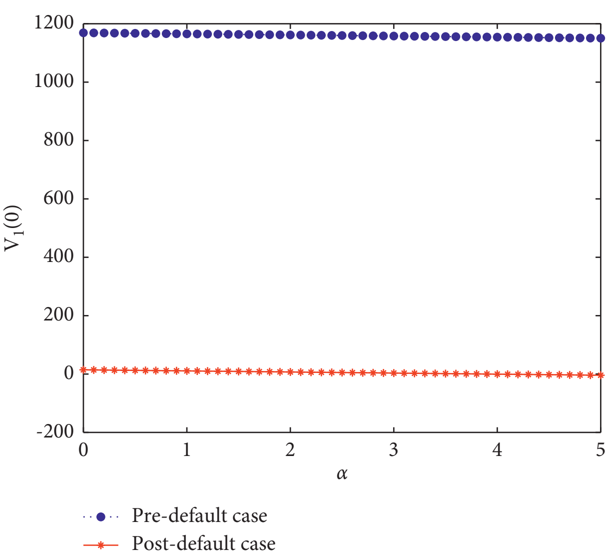

Figure 10: The effect of α on $V_1(0)$.

probability of creating more wealth than neighbors at the terminal moment increases. In Figure 2, the number of investments in risky assets decreases as the parameter γ_1 increases. γ_1 represents the degree of risk aversion, and a larger γ_1 indicates that family 1 is more risk-averse, and therefore, family 1 will reduce the number of investments in risky assets. Figure 3 shows that the amounts invested in risky assets decrease with the β for $\rho < 0$, and the amounts invested in risky assets increase with the β for $\rho > 0$. By equation (16), we have $(\partial p_1^*/\partial \beta) = (e^{-r(T-t)}(1-\kappa_1)\rho\sigma(e^{r(T-t)}-1)/(1-\kappa_1\kappa_2)r(\sigma^2+\lambda\sigma_Y^2))$. $(\partial p_1^*/\partial \beta) > 0$ when $\rho > 0$, which means that p_1^* increase with β, the family 1 is willing to invest more money in the risk asset to get more profits. In contrast, $(\partial p_1^*/\partial \beta) < 0$ when $\rho < 0$, that is to say, p_1^* decrease with β, and the family 1 will put less money in the risky asset. From Figure 4, we can see that the amount of investments in risky assets is not affected by the average expenditure α, which is consistent with equation (16).

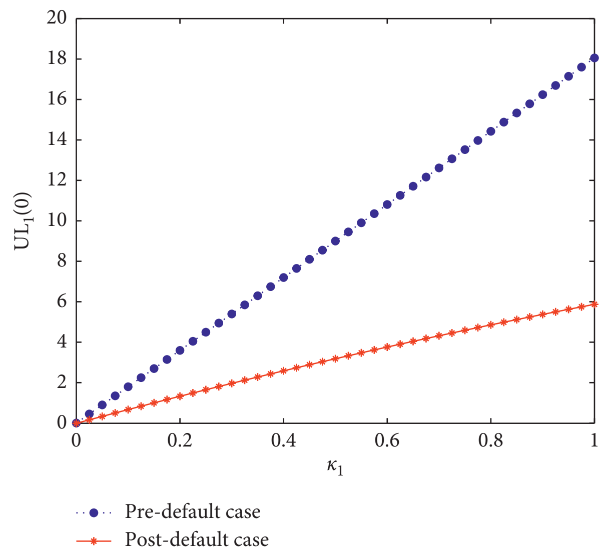

Figure 11: The effect of κ_1 on $UL_1(0)$.

Figures 5–9 illustrate the effect of parameters κ_1, γ_1, ϑ, ζ, and $k^{\mathbb{P}}$ on the amounts invested in the defaultable bonds. Figures 5 and 6 show that the amounts invested in the defaultable bonds increase with κ_1 and decrease with γ_1, in which the economic explanation is the same as Figures 1 and 2. Figures 7 and 8 show that the amounts invested in the defaultable bond $q_1(t)$ increase with the credit spread ϑ and decrease with the loss rate ζ because the lower credit spread ϑ or higher loss rate ζ can induce a larger potential loss. Figure 9 presents that the greater the default intensity $k^{\mathbb{P}}$, the less money will be invested in default bonds. This is because the greater the default intensity $k^{\mathbb{P}}$, the higher the default risk, and the insurer will naturally reduce the money of defaultable bonds.

Figure 10 depicts the effect of the average expenditure α on the equilibrium value function for family 1 and it can be found that the equilibrium value function decreases monotonically with α, which can be interpreted as a utility loss due to the expenditure. Also, we can find that the predefault equilibrium value function is higher than the postdefault equilibrium value function, which can be interpreted as a loss of utility due to the default event. In order to portray the effect of the intensity of family 1's relative concerns parameter κ_1 on utility loss in Figure 11, we set $x_2 = w = 1$. From Figure 11, it can be seen that the utility loss of family 1 increases with κ_1; i.e., the higher the degree of mind of rivalry, the greater the utility loss. And it can be noted that when $\kappa_1 = 0$, the utility loss is equal to 0, which is consistent with (iii) in Remark 1.

5. Conclusion

This paper investigates the stochastic differential game between two families for a random household expenditure with default risk under relative performance. There is a climbing mentality among families, especially neighbors, who will not only focus on their own wealth but also on that of their neighbors; thus, we assume that two families constitute a non-zero-sum game and that they face the same financial market consisting of a risk-free asset, a risky asset which is characterized by jump-diffusion model. And each family's random expenditure is described by Brownian motion with drift. In the mean-variance criteria and Nash equilibrium framework, by applying stochastic control theory within the framework of game theory, we obtain an explicit expression for each family's optimal time-consistent strategy and the corresponding equilibrium value function. We find that the heavier the climbing psychology, the higher the number of investments in risky assets and defaultable bonds. In addition, we define the utility loss from climbing and find that the utility loss increases with climbing psychology, similar to the static Cournot duopoly game in classical economics.

Appendix

A. Proof of Theorem 1

Suppose that the functions $V_i(t,\widehat{x}_i,w,z)$ and $g_i(t,\widehat{x}_i,w,z)$ satisfy the conditions of Theorem 1. In what follows, we complete the proof in (a) and (b).

(a) We aim to show that

$$\begin{aligned} g_i(t,\widehat{x}_i,w,z) &= E_{t,\widehat{x}_i,w,z}\left[\widehat{X}_i^{\pi_i^*,\pi_j^*}(T)\right], \\ J_i^{\left(\pi_i^*,\pi_j^*\right)}(t,\widehat{x}_i,w,z) &= V_i(t,\widehat{x}_i,w,z). \end{aligned} \tag{A.1}$$

By conditions $\mathscr{L}^{\pi_i^*,\pi_j^*} g_i(t,\widehat{x}_i,w,z)=0$ and $g_i(T,\widehat{x}_i,w,z)=\widehat{x}_i$ in Theorem 1, and by Dynkin's formula, we derive

$$\begin{aligned} &E_{t,\widehat{x}_i,w,z}\left[g_i\left(T,\widehat{X}_i^{\pi_i^*,\pi_j^*}(T),w(T),z\right)\right] \\ &= g_i(t,\widehat{x}_i,w,z)+E_{t,\widehat{x}_i,w,z}\left[\int_t^T \mathscr{L}^{\pi_i^*,\pi_j^*} g_i\left(u,\widehat{X}_i^{\pi_i^*,\pi_j^*}(u),w(u),z\right)\mathrm{d}u\right] \\ &= g_i(t,\widehat{x}_i,w,z), \end{aligned} \tag{A.2}$$

where the variational operator $\mathscr{L}^{\pi_i,\pi_j}$ is defined by (14). Moreover, we obtain

$$\begin{aligned} g_i(t,\widehat{x}_i,w,z) &= E_{t,\widehat{x}_i,w,z}\left[g_i\left(T,\widehat{X}_i^{\pi_i^*,\pi_j^*}(T),w(T),z\right)\right] \\ &= E_{t,\widehat{x}_i,w,z}\left[\widehat{X}_i^{\pi_i^*,\pi_j^*}(T)\right]. \end{aligned} \tag{A.3}$$

Since in extended HJB equation (15), the optimal strategy for family i is achieved at π_i^*, by conditions $\mathscr{L}^{\pi_i^*,\pi_j^*} g_i(t,\widehat{x}_i,w,z)=0$ and $g_i(T,\widehat{x}_i,w,z)=\widehat{x}_i$ in Theorem 1, we rewrite extended HJB equation as

$$\mathscr{L}^{\pi_i^*,\pi_j^*} V_i(t,\widehat{x}_i,w,z)-\frac{\gamma_i}{2}\mathscr{L}^{\pi_i^*,\pi_j^*} g_i^2(t,\widehat{x}_i,w,z)=0. \tag{A.4}$$

By condition $V_i(T,\widehat{x}_i,w,z)=\widehat{x}_i$ in Theorem 1 and Dynkin's formula, we derive

$$\begin{aligned} E_{t,\widehat{x}_i,w,z}\left[\widehat{X}_i^{\pi_i^*,\pi_j^*}(t)\right] &= E_{t,\widehat{x}_i,w,z}\left[V_i\left(T,\widehat{X}_i^{\pi_i^*,\pi_j^*}(T),w(T),z\right)\right] \\ &= V_i(t,\widehat{x}_i,w,z)+E_{t,\widehat{x}_i,w,z}\left[\int_t^T \mathscr{L}^{\pi_i^*,\pi_j^*} V_i\left(u,\widehat{X}_i^{\pi_i^*,\pi_j^*}(u),w(u),z\right)\mathrm{d}u\right]. \end{aligned} \tag{A.5}$$

Inserting (A.4) into the above equation, we derive

$$V_i(t,\widehat{x}_i,w,z)=E_{t,\widehat{x}_i,w,z}\left[\widehat{X}_i^{\pi_i^*,\pi_j^*}(t)\right]-\frac{\gamma_i}{2}\int_t^T \mathscr{L}^{\pi_i^*,\pi_j^*} g_i^2\left(u,\widehat{X}_i^{\pi_i^*,\pi_j^*}(u),w(u),z\right)\mathrm{d}u. \tag{A.6}$$

By terminal condition and Dynkin's formula, we have

$$\begin{aligned} E_{t,\widehat{x}_i,w,z}\left[\left(\widehat{X}_i^{\pi_i^*,\pi_j^*}(t)\right)^2\right] &= E_{t,\widehat{x}_i,w,z}\left[g_i^2\left(T,\widehat{X}_i^{\pi_i^*,\pi_j^*}(T),w(T),z\right)\right] \\ &= g_i^2(t,\widehat{x}_i,w,z) + \int_t^T \mathscr{L}^{\pi_i^*,\pi_j^*} g_i^2\left(u,\widehat{X}_i^{\pi_i^*,\pi_j^*}(u),w(u),z\right)\mathrm{d}u \\ &= \left(E_{t,\widehat{x}_i,w,z}\left[\widehat{X}_i^{\pi_i^*,\pi_j^*}(t)\right]\right)^2 + \int_t^T \mathscr{L}^{\pi_i^*,\pi_j^*} g_i^2\left(u,\widehat{X}_i^{\pi_i^*,\pi_j^*}(u),w(u),z\right)\mathrm{d}u. \end{aligned} \tag{A.7}$$

That is to say, we have

$$\mathrm{Var}_{t,\widehat{x}_i,w,z}\left[\widehat{X}_i^{\pi_i^*,\pi_j^*}(t)\right] = \int_t^T \mathscr{L}^{\pi_i^*,\pi_j^*} g_i^2\left(u,\widehat{X}_i^{\pi_i^*,\pi_j^*}(u),w(u),z\right)\mathrm{d}u. \tag{A.8}$$

Putting equation (A.8) into equation (A.6), we arrive at

$$\begin{aligned} V_i(t,\widehat{x}_i,w,z) &= E_{t,\widehat{x}_i,w,z}\left[\widehat{X}_i^{\pi_i^*,\pi_j^*}(t)\right] - \frac{\gamma_i}{2}\mathrm{Var}_{t,\widehat{x}_i,w,z}\left[\widehat{X}_i^{\pi_i^*,\pi_j^*}(t)\right] \\ &= J_i^{\pi_i^*,\pi_j^*}(t,\widehat{x}_i,w,z). \end{aligned} \tag{A.9}$$

(b) We aim to prove that π_i^* is an equilibrium strategy of family i. By $J_i^{\pi_i,\pi_j}(t,\widehat{x}_i,w,z) = E_{t,\widehat{x}_i,w,z}[\widehat{X}_i^{\pi_i,\pi_j}(T)] - (\gamma_i/2)\mathrm{Var}_{t,\widehat{x}_i,w,z}[\widehat{X}_i^{\pi_i,\pi_j}(T)]$ and the perturbed strategy π_i^ε in Definition 2, we can derive

$$\begin{aligned} J_i^{\pi_i^\varepsilon,\pi_j^*}(t,\widehat{x}_i,w,z) &= E_{t,\widehat{x}_i,w,z}\left[\widehat{X}_i^{\pi_i^\varepsilon,\pi_j^*}(T) - \frac{\gamma_i}{2}\left(\widehat{X}_i^{\pi_i^\varepsilon,\pi_j^*}(T)\right)^2\right] + \frac{\gamma_i}{2}\left(E_{t,\widehat{x}_i,w,z}\left[\widehat{X}_i^{\pi_i^\varepsilon,\pi_j^*}(T)\right]\right)^2 \\ &= E_{t,\widehat{x}_i,w,z}\left[E_{t+\varepsilon,\widehat{X}_i^{\widehat{\pi}_i,\pi_j^*}(t+\varepsilon),w(t+\varepsilon),z}\left[\widehat{X}_i^{\pi_i^*,\pi_j^*}(T) - \frac{\gamma_i}{2}\left(\widehat{X}_i^{\pi_i^*,\pi_j^*}(T)\right)^2\right]\right] \\ &\quad + \frac{\gamma_i}{2}\left(E_{t,\widehat{x}_i,w,z}\left[E_{t+\varepsilon,\widehat{X}_i^{\widehat{\pi}_i,\pi_j^*}(t+\varepsilon),w(t+\varepsilon),z}\left[\widehat{X}_i^{\pi_i^*,\pi_j^*}(T)\right]\right]\right)^2 \\ &= E_{t,\widehat{x}_i,w,z}\left[J_i^{\pi_i^*,\pi_j^*}\left(t+\varepsilon,\widehat{X}_i^{\widehat{\pi}_i,\pi_j^*}(t+\varepsilon),w(t+\varepsilon),z\right)\right] \\ &\quad - \frac{\gamma_i}{2}E_{t,\widehat{x}_i,w,z}\left[\left(E_{t+\varepsilon,\widehat{X}_i^{\widehat{\pi}_i,\pi_j^*}(t+\varepsilon),w(t+\varepsilon),z}\left[\widehat{X}_i^{\pi_i^*,\pi_j^*}(T)\right]\right)^2\right] \end{aligned}$$

$$
\begin{aligned}
&+\frac{\gamma_i}{2}\left(E_{t,\widehat{x}_i,w,z}\left[E_{t+\varepsilon,\widehat{X}_i^{\widehat{\pi}_i,\pi_j^*}(t+\varepsilon),w(t+\varepsilon),z}\left[\widehat{X}_i^{\pi_i^*,\pi_j^*}(T)\right]\right]\right)^2\\
&=E_{t,\widehat{x}_i,w,z}\left[J_i^{\pi_i^*,\pi_j^*}\left(t+\varepsilon,\widehat{X}_i^{\widehat{\pi}_i,\pi_j^*}(t+\varepsilon),w(t+\varepsilon),z\right)\right]\\
&-\frac{\gamma_i}{2}E_{t,\widehat{x}_i,w,z}\left[g_i^2\left(t+\varepsilon,\widehat{X}_i^{\widehat{\pi}_i,\pi_j^*}(t+\varepsilon),w(t+\varepsilon),z\right)\right]\\
&+\frac{\gamma_i}{2}\left(E_{t,\widehat{x}_i,w,z}\left[g_i\left(t+\varepsilon,\widehat{X}_i^{\widehat{\pi}_i,\pi_j^*}(t+\varepsilon),w(t+\varepsilon),z\right)\right]\right)^2,
\end{aligned}
\tag{A.10}
$$

and then we have

$$
J_i^{\pi_i^\varepsilon,\pi_j^*}(t,\widehat{x}_i,w,z)-J_i^{\pi_i^*,\pi_j^*}(t,\widehat{x}_i,w,z)=\Gamma_\varepsilon, \tag{A.11}
$$

where

$$
\begin{aligned}
\Gamma_\varepsilon=&E_{t,\widehat{x}_i,w,z}\left[J_i^{\pi_i^*,\pi_j^*}\left(t+\varepsilon,\widehat{X}_i^{\widehat{\pi}_i,\pi_j^*}(t+\varepsilon),w(t+\varepsilon),z\right)\right]-J_i^{\pi_i^*,\pi_j^*}(t,\widehat{x}_i,w,z)\\
&-\frac{\gamma_i}{2}\left\{E_{t,\widehat{x}_i,w,z}\left[g_i^2\left(t+\varepsilon,\widehat{X}_i^{\widehat{\pi}_i,\pi_j^*}(t+\varepsilon),w(t+\varepsilon),z\right)\right]-g_i^2(t,\widehat{x}_i,w,z)\right\}\\
&+\frac{\gamma_i}{2}\left\{\left(E_{t,\widehat{x}_i,w,z}\left[g_i\left(t+\varepsilon,\widehat{X}_i^{\widehat{\pi}_i,\pi_j^*}(t+\varepsilon),w(t+\varepsilon),z\right)\right]\right)^2-g_i^2(t,\widehat{x}_i,w,z)\right\}.
\end{aligned}
\tag{A.12}
$$

For any $\pi_i\in\Pi_i$, small enough $\varepsilon>0$ and $\Phi\in C^{1,2,2}([0,T]\times\mathbb{R}\times\mathbb{R}\times\{0,1\})$, we define the following operator:

$$
\mathscr{L}_\varepsilon^{\pi_i,\pi_j}\Phi(t,\widehat{x}_i,w,z)=E_{t,\widehat{x}_i,w,z}\left[\Phi\left(t+\varepsilon,\widehat{X}_i^{\widehat{\pi}_i,\pi_j^*}(t+\varepsilon),w(t+\varepsilon),z\right)\right]-\Phi(t,\widehat{x}_i,w,z), \tag{A.13}
$$

and then we have

$$
\lim_{\varepsilon\downarrow 0}=\frac{\mathscr{L}_\varepsilon^{\pi_i,\pi_j}\Phi(t,\widehat{x}_i,w,z)}{\varepsilon}=\mathscr{L}^{\pi_i,\pi_j}\Phi(t,\widehat{x}_i,w,z). \tag{A.14}
$$

By equations (A.12), (A.13) can be rewritten as

$$
\begin{aligned}
\Gamma_\varepsilon=&\mathscr{L}_\varepsilon^{\widehat{\pi}_i,\pi_j^*}J_i^{\pi_i^*,\pi_j^*}(t,\widehat{x}_i,w,z)-\frac{\gamma_i}{2}\mathscr{L}_\varepsilon^{\widehat{\pi}_i,\pi_j^*}g_i^2(t,\widehat{x}_i,w,z)\\
&+\frac{\gamma_i}{2}\left\{\left(E_{t,\widehat{x}_i,w,z}\left[g_i\left(t+\varepsilon,\widehat{X}_i^{\widehat{\pi}_i,\pi_j^*}(t+\varepsilon),w(t+\varepsilon),z\right)\right]\right)^2-g_i^2(t,\widehat{x}_i,w,z)\right\}.
\end{aligned}
\tag{A.15}
$$

By Dynkin's formula, we derive

$$E_{t,\widehat{x}_i,w,z}\left[g_i\left(t+\varepsilon,\widehat{X}_i^{\widehat{\pi}_i,\pi_j^*}(t+\varepsilon),w(t+\varepsilon),z\right)\right]=g_i(t,\widehat{x}_i,w,z)+E_{t,\widehat{x}_i,w,z}\left[\int_t^{t+\varepsilon}\mathscr{L}^{\widehat{\pi}_i,\pi_j^*}g_i\left(u,\widehat{X}_i^{\widehat{\pi}_i,\pi_j^*}(u),w(u),z\right)\mathrm{d}u\right],\tag{A.16}$$

which implies

$$\begin{aligned}&\left(E_{t,\widehat{x}_i,w,z}\left[g_i\left(t+\varepsilon,\widehat{X}_i^{\widehat{\pi}_i,\pi_j^*}(t+\varepsilon),w(t+\varepsilon),z\right)\right]\right)^2-g_i^2(t,\widehat{x}_i,w,z)\\&=2g_i(t,\widehat{x}_i,w,z)E_{t,\widehat{x}_i,w,z}\left[\int_t^{t+\varepsilon}\mathscr{L}^{\widehat{\pi}_i,\pi_j^*}g_i\left(u,\widehat{X}_i^{\widehat{\pi}_i,\pi_j^*}(u),w(u),z\right)\mathrm{d}u\right]\\&+\left(E_{t,\widehat{x}_i,w,z}\left[\int_t^{t+\varepsilon}\mathscr{L}^{\widehat{\pi}_i,\pi_j^*}g_i\left(u,\widehat{X}_i^{\widehat{\pi}_i,\pi_j^*}(u),w(u),z\right)\mathrm{d}u\right]\right)^2.\end{aligned}\tag{A.17}$$

Substituting equation (A.17) into equation (A.15), we have

$$\begin{aligned}\Gamma_\varepsilon&=\mathscr{L}_\varepsilon^{\widehat{\pi}_i,\pi_j^*}J_i^{\pi_i^*,\pi_j^*}(t,\widehat{x}_i,w,z)-\frac{\gamma_i}{2}\mathscr{L}_\varepsilon^{\widehat{\pi}_i,\pi_j^*}g_i^2(t,\widehat{x}_i,w,z)\\&+\gamma_i g_i(t,\widehat{x}_i,w,z)E_{t,\widehat{x}_i,w,z}\left[\int_t^{t+\varepsilon}\mathscr{L}^{\widehat{\pi}_i,\pi_j^*}g_i\left(u,\widehat{X}_i^{\widehat{\pi}_i,\pi_j^*}(u),w(u),z\right)\mathrm{d}u\right]\\&+\frac{\gamma_i}{2}\left(E_{t,\widehat{x}_i,w,z}\left[\int_t^{t+\varepsilon}\mathscr{L}^{\widehat{\pi}_i,\pi_j^*}g_i\left(u,\widehat{X}_i^{\widehat{\pi}_i,\pi_j^*}(u),w(u),z\right)\mathrm{d}u\right]\right)^2.\end{aligned}\tag{A.18}$$

From the extended HJB equation in (15), we can obtain

$$\begin{aligned}&\mathscr{L}^{\widehat{\pi}_i,\pi_j^*}V_i(t,\widehat{x}_i,w,z)-\frac{\gamma_i}{2}\mathscr{L}^{\widehat{\pi}_i,\pi_j^*}g_i^2(t,\widehat{x}_i,w,z)\\&+\gamma_i g_i(t,\widehat{x}_i,w,z)\mathscr{L}^{\widehat{\pi}_i,\pi_j^*}g_i(t,\widehat{x}_i,w,z)\le 0.\end{aligned}\tag{A.19}$$

Together with equation (A.14), we have

$$\begin{aligned}\Gamma_\varepsilon&=\mathscr{L}_\varepsilon^{\widehat{\pi}_i,\pi_j^*}J_i^{\pi_i^*,\pi_j^*}(t,\widehat{x}_i,w,z)-\frac{\gamma_i}{2}\mathscr{L}_\varepsilon^{\widehat{\pi}_i,\pi_j^*}g_i^2(t,\widehat{x}_i,w,z)\\&+\gamma_i g_i(t,\widehat{x}_i,w,z)E_{t,\widehat{x}_i,w,z}\left[\int_t^{t+\varepsilon}\mathscr{L}^{\widehat{\pi}_i,\pi_j^*}g_i\left(u,\widehat{X}_i^{\widehat{\pi}_i,\pi_j^*}(u),w(u),z\right)\mathrm{d}u\right]\\&+\frac{\gamma_i}{2}\left(E_{t,\widehat{x}_i,w,z}\left[\int_t^{t+\varepsilon}\mathscr{L}^{\widehat{\pi}_i,\pi_j^*}g_i\left(u,\widehat{X}_i^{\widehat{\pi}_i,\pi_j^*}(u),w(u),z\right)\mathrm{d}u\right]\right)^2\le o(\varepsilon),\end{aligned}\tag{A.20}$$

which means that

$$J_i^{\pi_i^\varepsilon,\pi_j^*}(t,\hat{x}_i,w,z) - J_i^{\pi_i^*,\pi_j^*}(t,\hat{x}_i,w,z) = \Gamma_\varepsilon \le o(\varepsilon), \tag{A.21}$$

i.e., π_i^* is an equilibrium strategy for family i.

B. Proof of Theorem 2

For the postdefault case $(z=1)$, by the operator $\mathscr{L}^{(\pi_i,\pi_j)}$ in equation (14), the first equation in equation (15) can be rewritten as

$$\begin{aligned}
&\sup_{\pi_i\in\Pi_i}\Bigg\{\frac{\partial V_i}{\partial t} + \left[r\hat{x}_i + (\mu-r)\left(p_i(t)-\kappa_i p_j^*(t)\right) - (1-\kappa_i)w\right]\frac{\partial V_i}{\partial \hat{x}_i} + \alpha\frac{\partial V_i}{\partial w} + \frac{1}{2}\left(p_i(t)\right.\\
&\left.-\kappa_i p_j^*(t)\right)^2\sigma^2\left[\frac{\partial^2 V_i}{\partial \hat{x}_i^2} - \gamma_i\left(\frac{\partial g_i}{\partial \hat{x}_i}\right)^2\right] + \frac{1}{2}\beta^2\left[\frac{\partial^2 V_i}{\partial w^2} - \gamma_i\left(\frac{\partial g_i}{\partial w}\right)^2\right] + \rho\beta\sigma\left(p_i(t)\right.\\
&\left.-\kappa_i p_j^*(t)\right)\left[\frac{\partial^2 V_i}{\partial \hat{x}_i\partial w} - \gamma_i\frac{\partial g_i}{\partial \hat{x}_i}\frac{\partial g_i}{\partial w}\right] + \lambda\Big[E\Big[V_i\left(t,\hat{x}_i + \left(p_i(t)-\kappa_i p_j^*(t)\right)y,w,1\right)\\
&-V_i(t,\hat{x}_i,w,1)\Big] - \frac{\gamma_i}{2}E\left[g_i^2\left(t,\hat{x}_i + \left(p_i(t)-\kappa_i p_j^*(t)\right)y,w,1\right) - g_i^2(t,\hat{x}_i,w,1)\right]\\
&+\gamma_i g_i(t,\hat{x}_i,w,z)E\left[g_i\left(t,\hat{x}_i + \left(p_i(t)-\kappa_i p_j^*(t)\right)y,w,1\right) - g_i(t,\hat{x}_i,w,1)\right]\Big]\Bigg\} = 0,
\end{aligned} \tag{B.1}$$

where $V_i(T,\hat{x}_i,w,1) = \hat{x}_i$ and $g_i(T,\hat{x}_i,w,1) = \hat{x}_i$. Noting that the terminal conditions, we conjecture that V_i and g_i are of the following form:

$$V_i(t,\hat{x}_i,w,1) = A_i(t)\hat{x}_i + B_i(t)w + C_i(t), \tag{B.2}$$

$$g_i(t,\hat{x}_i,w,1) = a_i(t)\hat{x}_i + b_i(t)w + c_i(t), \tag{B.3}$$

where $A_i(T) = a_i(T) = 1$ and $B_i(T) = b_i(T) = C_i(T) = c_i(T) = 0$. Differentiating V_i and g_i with respect to t, $\hat{x}_i$, and w, we derive

$$\begin{aligned}
&\frac{\partial V_i}{\partial t} = A_i'(t)\hat{x}_i + B_i'(t)w + C_i'(t), \frac{\partial V_i}{\partial \hat{x}_i} = A_i(t), \frac{\partial V_i}{\partial w} = B_i(t),\\
&\frac{\partial^2 V_i}{\partial \hat{x}_i^2} = \frac{\partial^2 V_i}{\partial w^2} = \frac{\partial^2 V_i}{\partial \hat{x}_i\partial w} = 0,\\
&\frac{\partial g_i}{\partial t} = a_i'(t)\hat{x}_i + b_i'(t)w + c_i'(t), \frac{\partial g_i}{\partial \hat{x}_i} = a_i(t), \frac{\partial g_i}{\partial w} = b_i(t),\\
&\frac{\partial^2 g_i}{\partial \hat{x}_i^2} = \frac{\partial^2 g_i}{\partial w^2} = \frac{\partial^2 g_i}{\partial \hat{x}_i\partial w} = 0.
\end{aligned} \tag{B.4}$$

After calculation, we also have

$$\begin{aligned}
&E\left[V_i\left(t,\hat{x}_i + \left(p_i(t)-\kappa_i p_j^*(t)\right)y,w,1\right) - V_i(t,\hat{x}_i,w,1)\right] = A_i(t)\left(p_i(t)-\kappa_i p_j^*(t)\right)\mu_Y,\\
&E\left[g_i^2\left(t,\hat{x}_i + \left(p_i(t)-\kappa_i p_j^*(t)\right)y,w,1\right) - g_i^2(t,\hat{x}_i,w,1)\right] = a_i^2(t)\left(p_i(t)-\kappa_i p_j^*(t)\right)^2\sigma_Y^2\\
&\qquad + 2a_i(t)\left(p_i(t)-\kappa_i p_j^*(t)\right)\mu_Y\left(a_i(t)\hat{x}_i + b_i(t)w + c_i(t)\right),\\
&E\left[g_i\left(t,\hat{x}_i + \left(p_i(t)-\kappa_i p_j^*(t)\right)y,w,1\right) - g_i(t,\hat{x}_i,w,1)\right] = a_i(t)\left(p_i(t)-\kappa_i p_j^*(t)\right)\mu_Y.
\end{aligned} \tag{B.5}$$

Substituting the above results into equation (B.1) and the second equation in equation (15), we derive

$$\begin{aligned}&\sup_{\pi_i\in\Pi_i}\Big\{A_i'(t)\widehat{x}_i + B_i'(t)w + C_i'(t) + \big[r\widehat{x}_i + (\mu - r + \lambda\mu_Y)\big(p_i(t) - \kappa_i p_j^*(t)\big)\\&\quad - (1-\kappa_i)w\big]A_i(t) + \alpha B_i(t) - \frac{\gamma_i}{2}\left(\sigma^2 + \lambda\sigma_Y^2\right)\big(p_i(t) - \kappa_i p_j^*(t)\big)^2 a_i^2(t) - \frac{\gamma_i}{2}\beta^2 b_i^2(t)\\&\quad - \gamma_i\rho\beta\sigma\big(p_i(t) - \kappa_i p_j^*(t)\big)a_i(t)b_i(t)\Big\} = 0,\end{aligned} \tag{B.6}$$

$$a_i'(t)\widehat{x}_i + b_i'(t)w + c_i'(t) + \big[r\widehat{x}_i + (\mu - r + \lambda\mu_Y)\big(p_i(t) - \kappa_i p_j^*(t)\big) - (1-\kappa_i w)\big]a_i(t) + \alpha b_i(t) = 0. \tag{B.7}$$

By the first-order condition, we obtain

$$p_i^*(t) = \frac{(\mu - r + \lambda\mu_Y)A_i(t)}{\gamma_i\left(\sigma^2 + \lambda\sigma_Y^2\right)a_i^2(t)} - \frac{\rho\beta\sigma b_i(t)}{\left(\sigma^2 + \lambda\sigma_Y^2\right)a_i(t)} + \kappa_i p_j^*(t), \tag{B.8}$$

and we can further obtain

$$p_i^*(t) = \frac{1}{1-\kappa_i\kappa_j}\left[\frac{(\mu - r + \lambda\mu_Y)A_i(t) - \gamma_i\rho\beta\sigma a_i(t)b_i(t)}{\gamma_i\left(\sigma^2 + \lambda\sigma_Y^2\right)a_i^2(t)} + \kappa_i\frac{(\mu - r + \lambda\mu_Y)A_j(t) - \gamma_j\rho\beta\sigma a_j(t)b_j(t)}{\gamma_j\left(\sigma^2 + \lambda\sigma_Y^2\right)a_j^2(t)}\right]. \tag{B.9}$$

Putting equation (B.8) into equations (B.6) and (B.7), we derive

$$\begin{aligned}&A_i'(t)\widehat{x}_i + B_i'(t)w + C_i'(t) + \left[r\widehat{x}_i - (1-\kappa_i)w\right]A_i(t) + \alpha B_i(t) - \frac{\gamma_i}{2}\beta^2 b_i^2(t)\\&\quad + \frac{(\mu - r + \lambda\mu_Y)^2 A_i^2(t)}{2\gamma_i\left(\sigma^2 + \lambda\sigma_Y^2\right)a_i^2(t)} - \frac{(\mu - r + \lambda\mu_Y)\rho\beta\sigma A_i(t)b_i(t)}{\left(\sigma^2 + \lambda\sigma_Y^2\right)a_i(t)}\\&\quad + \frac{\gamma_i\rho^2\beta^2\sigma^2 b_i^2(t)}{2\left(\sigma^2 + \lambda\sigma_Y^2\right)} = 0,\\&a_i'(t)\widehat{x}_i + b_i'(t)w + c_i'(t) + \left[r\widehat{x}_i - (1-\kappa_i)w\right]a_i(t) + \alpha b_i(t)\\&\quad + \frac{(\mu - r + \lambda\mu_Y)^2 A_i(t)}{\gamma_i\left(\sigma^2 + \lambda\sigma_Y^2\right)a_i(t)} - \frac{(\mu - r + \lambda\mu_Y)\rho\beta\sigma b_i(t)}{\sigma^2 + \lambda\sigma_Y^2} = 0.\end{aligned} \tag{B.10}$$

By separating variables, we obtain the following differential equations:

$$A_i'(t) + rA_i(t) = 0, \quad A_i(T) = 1, \tag{B.11}$$

$$B_i'(t) - (1-\kappa_i)A_i(t) = 0, \quad B_i(T) = 0, \tag{B.12}$$

$$C_i'(t) + \alpha B_i(t) - \frac{\gamma_i}{2}\beta^2 b_i^2(t) + \frac{(\mu - r + \lambda\mu_Y)^2 A_i^2(t)}{2\gamma_i\left(\sigma^2 + \lambda\sigma_Y^2\right)a_i^2(t)} - \frac{(\mu - r + \lambda\mu_Y)\rho\beta\sigma A_i(t) b_i(t)}{\left(\sigma^2 + \lambda\sigma_Y^2\right)a_i(t)} + \frac{\gamma_i\rho^2\beta^2\sigma^2 b_i^2(t)}{2\left(\sigma^2 + \lambda\sigma_Y^2\right)} = 0, \quad C_i(T) = 0, \tag{B.13}$$

$$a_i'(t) + r a_i(t) = 0, \quad a_i(T) = 1, \tag{B.14}$$

$$b_i'(t) - (1 - \kappa_i)a_i(t) = 0, \quad b_i(T) = 0, \tag{B.15}$$

$$c_i'(t) + \alpha b_i(t) + \frac{(\mu - r + \lambda\mu_Y)^2 A_i(t)}{\gamma_i\left(\sigma^2 + \lambda\sigma_Y^2\right)a_i(t)} - \frac{(\mu - r + \lambda\mu_Y)\rho\beta\sigma b_i(t)}{\sigma^2 + \lambda\sigma_Y^2} = 0, \quad c_i(T) = 0. \tag{B.16}$$

Solving the above equations, we derive

$$A_i(t) = a_i(t) = e^{r(T-t)}, \tag{B.17}$$

$$B_i(t) = b_i(t) = -\frac{1 - \kappa_i}{r}\left(e^{r(T-t)} - 1\right), \tag{B.18}$$

$$c_i(t) = -\left(\alpha - \frac{(\mu - r + \lambda\mu_Y)\rho\beta\sigma}{\sigma^2 + \lambda\sigma_Y^2}\right)\frac{1 - \kappa_i}{r^2}\left(e^{r(T-t)} - 1\right) - \left(\alpha - \frac{(\mu - r + \lambda\mu_Y)\rho\beta\sigma}{\sigma^2 + \lambda\sigma_Y^2}\right)\frac{1 - \kappa_i}{r}(t - T) - \frac{(\mu - r + \lambda\mu_Y)^2}{\gamma_i\left(\sigma^2 + \lambda\sigma_Y^2\right)}(t - T), \tag{B.19}$$

$$\begin{aligned} C_i(t) = {} & \left(\alpha - \frac{(\mu - r + \lambda\mu_Y)\rho\beta\sigma}{\sigma^2 + \lambda\sigma_Y^2}\right)\left[-\frac{1 - \kappa_i}{r^2}e^{r(T-t)} - \frac{1 - \kappa_i}{r}(t - T) + \frac{1 - \kappa_i}{r^2}\right] \\ & + \frac{\gamma_i\beta^2}{2}\left(1 - \frac{\rho^2\sigma^2}{\sigma^2 + \lambda\sigma_Y^2}\right)\left[-\frac{(1 - \kappa_i)^2}{2r^3}e^{2r(T-t)} + \frac{2(1 - \kappa_i)^2}{r^3}e^{r(T-t)} \right. \\ & \left. + \frac{(1 - \kappa_i)^2}{r^2}(t - T) + \frac{(1 - \kappa_i)^2}{2r^3} - \frac{2(1 - \kappa_i)^2}{r^3}\right] - \frac{(\mu - r + \lambda\mu_Y)^2}{2\gamma_i\left(\sigma^2 + \lambda\sigma_Y^2\right)}(t - T). \end{aligned} \tag{B.20}$$

Similarly, for the postdefault case ($z = 0$), the first equation in equation (15) can be rewritten as

$$\begin{aligned} \sup_{\pi_i \in \Pi_i} \Bigg\{ & \frac{\partial V_i}{\partial t} + \left[r\hat{x}_i + (\mu - r)\left(p_i(t) - \kappa_i p_j^*(t)\right) - (1 - \kappa_i)w + \vartheta\left(q_i(t) - \kappa_i q_j(t)\right)\right]\frac{\partial V_i}{\partial \hat{x}_i} \\ & + \alpha\frac{\partial V_i}{\partial w} + \frac{1}{2}\left(p_i(t) - \kappa_i p_j^*(t)\right)^2\sigma^2\left[\frac{\partial^2 V_i}{\partial \hat{x}_i^2} - \gamma_i\left(\frac{\partial g_i}{\partial \hat{x}_i}\right)^2\right] + \frac{1}{2}\beta^2\left[\frac{\partial^2 V_i}{\partial w^2} - \gamma_i\left(\frac{\partial g_i}{\partial w}\right)^2\right] \\ & + \rho\beta\sigma\left(p_i(t) - \kappa_i p_j^*(t)\right)\left[\frac{\partial^2 V_i}{\partial \hat{x}_i \partial w} - \gamma_i\frac{\partial g_i}{\partial \hat{x}_i}\frac{\partial g_i}{\partial w}\right] + \lambda\left[E\left[V_i\left(t, \hat{x}_i + \left(p_i(t) - \kappa_i p_j^*(t)\right)y, w, 0\right)\right.\right. \end{aligned}$$

$$\begin{aligned}
&- V_i(t,\widehat{x}_i,w,0)\big] - \frac{\gamma_i}{2} E\big[g_i^2\big(t,\widehat{x}_i + \big(p_i(t) - \kappa_i p_j^*(t)\big)y,w,0\big) - g_i^2(t,\widehat{x}_i,w,0)\big] \\
&+ \gamma_i g_i(t,\widehat{x}_i,w,z) E\big[g_i\big(t,\widehat{x}_i + \big(p_i(t) - \kappa_i p_j^*(t)\big)y,w,0\big) - g_i(t,\widehat{x}_i,w,0)\big]\big] \\
&+ \big[V_i\big(t,\widehat{x}_i - \zeta\big(q_i(t) - \kappa_i q_j(t)\big),w,1\big) - V_i(t,\widehat{x}_i,w,0)\big]k^{\mathbb{P}} \\
&- \frac{\gamma_i}{2}\big[g_i\big(t,\widehat{x}_i - \zeta\big(q_i(t) - \kappa_i q_j(t)\big),w,1\big) - g_i(t,\widehat{x}_i,w,0)\big]k^{\mathbb{P}}\Big\} = 0,
\end{aligned} \tag{B.21}$$

where $V_i(T,\widehat{x}_i,w,0) = \widehat{x}_i$ and $g_i(T,\widehat{x}_i,w,0) = \widehat{x}_i$. Noting the terminal conditions, we conjecture that V_i and g_i are of the following form:

$$V_i(t,\widehat{x}_i,w,0) = \overline{A}_i(t)\widehat{x}_i + \overline{B}_i(t)w + \overline{C}_i(t), \tag{B.22}$$

$$g_i(t,\widehat{x}_i,w,0) = \overline{a}_i(t)\widehat{x}_i + \overline{b}_i(t)w + \overline{c}_i(t), \tag{B.23}$$

where $\overline{A}_i(T) = \overline{a}_i(T) = 1$ and $\overline{B}_i(T) = \overline{b}_i(T) = \overline{C}_i(T) = \overline{c}_i(T) = 0$. Differentiating V_i and g_i with respect to t, $\widehat{x}_i$, and w, we derive

$$\begin{aligned}
&\frac{\partial V_i}{\partial t} = \overline{A}_i'(t)\widehat{x}_i + \overline{B}_i'(t)w + \overline{C}_i'(t), \frac{\partial V_i}{\partial \widehat{x}_i} = \overline{A}_i(t), \frac{\partial V_i}{\partial w} = \overline{B}_i(t), \\
&\frac{\partial^2 V_i}{\partial \widehat{x}_i^2} = \frac{\partial^2 V_i}{\partial w^2} = \frac{\partial^2 V_i}{\partial \widehat{x}_i \partial w} = 0, \\
&\frac{\partial g_i}{\partial t} = \overline{a}_i'(t)\widehat{x}_i + \overline{b}_i'(t)w + \overline{c}_i'(t), \frac{\partial g_i}{\partial \widehat{x}_i} = \overline{a}_i(t), \frac{\partial g_i}{\partial w} = \overline{b}_i(t), \\
&\frac{\partial^2 g_i}{\partial \widehat{x}_i^2} = \frac{\partial^2 g_i}{\partial w^2} = \frac{\partial^2 g_i}{\partial \widehat{x}_i \partial w} = 0.
\end{aligned} \tag{B.24}$$

After calculation, we also have

$$\begin{aligned}
E\big[V_i\big(t,\widehat{x}_i + \big(p_i(t) - \kappa_i p_j^*(t)\big)y,w,0\big) - V_i(t,\widehat{x}_i,w,0)\big] &= \overline{A}_i(t)\big(p_i(t) - \kappa_i p_j^*(t)\big)\mu_Y, \\
E\big[g_i^2\big(t,\widehat{x}_i + \big(p_i(t) - \kappa_i p_j^*(t)\big)y,w,0\big) - g_i^2(t,\widehat{x}_i,w,0)\big] &= \overline{a}_i^2(t)\big(p_i(t) - \kappa_i p_j^*(t)\big)^2\sigma_Y^2 \\
&\quad + 2\overline{a}_i(t)\big(p_i(t) - \kappa_i p_j^*(t)\big)\mu_Y\big(\overline{a}_i(t)\widehat{x}_i + \overline{b}_i(t)w + \overline{c}_i(t)\big), \\
E\big[g_i\big(t,\widehat{x}_i + \big(p_i(t) - \kappa_i p_j^*(t)\big)y,w,0\big) - g_i(t,\widehat{x}_i,w,0)\big] &= \overline{a}_i(t)\big(p_i(t) - \kappa_i p_j^*(t)\big)\mu_Y, \\
V_i\big(t,\widehat{x}_i - \zeta\big(q_i(t) - \kappa_i q_j(t)\big),w,1\big) - V_i(t,\widehat{x}_i,w,0) &= A_i(t)\big(\widehat{x}_i - \zeta\big(q_i(t) - \kappa_i q_j(t)\big)\big) \\
&\quad - \overline{A}_i\widehat{x}_i + (B_i(t) - \overline{B}_i(t))w + C_i(t) - \overline{C}_i(t), \\
g_i\big(t,\widehat{x}_i - \zeta\big(q_i(t) - \kappa_i q_j(t)\big),w,1\big) - g_i(t,\widehat{x}_i,w,0) &= a_i(t)\big(\widehat{x}_i - \zeta\big(q_i(t) - \kappa_i q_j(t)\big)\big) \\
&\quad - \overline{a}_i\widehat{x}_i + \big(b_i(t) - \overline{b}_i(t)\big)w + c_i(t) - \overline{c}_i(t).
\end{aligned} \tag{B.25}$$

Inserting the above results into equation (B.1) and the second equation in equation (15), we obtain

$$\begin{aligned}
&\sup_{\pi_i\in\Pi_i}\Big\{\overline{A}_i'(t)\widehat{x}_i+\overline{B}_i'(t)w+\overline{C}_i'(t)+\big[r\widehat{x}_i+(\mu-r+\lambda\mu_Y)\big(p_i(t)-\kappa_i p_j^*(t)\big)+\vartheta\big(q_i(t)\\
&-\kappa_i q_j^*(t)\big)-(1-\kappa_i)w\big]\overline{A}_i(t)+\alpha\overline{B}_i(t)-\frac{\gamma_i}{2}\big(\sigma^2+\lambda\sigma_Y^2\big)\big(p_i(t)-\kappa_i p_j^*(t)\big)^2\overline{a}_i^2(t)\\
&-\frac{\gamma_i}{2}\beta^2\overline{b}_i^2(t)-\gamma_i\rho\beta\sigma\big(p_i(t)-\kappa_i p_j^*(t)\big)\overline{a}_i(t)\overline{b}_i(t)+\big[A_i(t)\big(\big(\widehat{x}_i-\zeta\big(q_i(t)-\kappa_i q_j^*(t)\big)\big)\\
&-\overline{A}_i\widehat{x}_i+\big(B_i(t)-\overline{B}_i(t)\big)w+C_i(t)-\overline{C}_i(t)\big]k^{\mathbb{P}}-\frac{\gamma_i}{2}\big[a_i(t)\big(\widehat{x}_i-\zeta\big(q_i(t)-\kappa_i q_j^*(t)\big)\big)\\
&-\overline{a}_i\widehat{x}_i+\big(b_i(t)-\overline{b}_i(t)\big)w+c_i(t)-\overline{c}_i(t)\big]^2k^{\mathbb{P}}\Big\}=0,
\end{aligned}\tag{B.26}$$

$$\begin{aligned}
&\overline{a}_i'(t)\widehat{x}_i+\overline{b}_i'(t)w+\overline{c}_i'(t)+\big[r\widehat{x}_i+(\mu-r+\lambda\mu_Y)\big(p_i^*(t)-\kappa_i p_j^*(t)\big)-(1-\kappa_i w)\\
&+\vartheta\big(q_i^*(t)-\kappa_i q_j^*(t)\big)\big]\overline{a}_i(t)+\alpha\overline{b}_i(t)+\big[a_i(t)\big(\widehat{x}_i-\zeta\big(q_i^*(t)-\kappa_i q_j^*(t)\big)\big)-\overline{a}_i\widehat{x}_i\\
&+\big(b_i(t)-\overline{b}_i(t)\big)w+c_i(t)-\overline{c}_i(t)\big]k^{\mathbb{P}}=0.
\end{aligned}\tag{B.27}$$

Applying again the first-order condition, we derive

$$p_i^*(t)=\frac{(\mu-r+\lambda\mu_Y)\overline{A}_i(t)}{\gamma_i\big(\sigma^2+\lambda\sigma_Y^2\big)\overline{a}_i^2(t)}-\frac{\rho\beta\sigma\overline{b}_i(t)}{\big(\sigma^2+\lambda\sigma_Y^2\big)\overline{a}_i(t)}+\kappa_i p_j^*(t),\tag{B.28}$$

$$q_i^*(t)=\frac{\vartheta\overline{A}_i(t)}{\gamma_i\zeta^2k^{\mathbb{P}}a_i^2(t)}-\frac{A_i(t)}{\gamma_i\zeta a_i^2(t)}+\frac{\widehat{x}_i}{\zeta}-\frac{\overline{a}_i(t)\widehat{x}_i}{\zeta a_i(t)}+\frac{\big(b_i(t)-\overline{b}_i(t)\big)w}{\zeta a_i(t)}+\frac{c_i(t)-\overline{c}_i(t)}{\zeta a_i(t)}+\kappa_i q_j^*(t),\tag{B.29}$$

and we can also derive

$$p_i^*(t)=\frac{1}{1-\kappa_i\kappa_j}\left[\frac{(\mu-r+\lambda\mu_Y)\overline{A}_i(t)-\gamma_i\rho\beta\sigma\overline{a}_i(t)\overline{b}_i(t)}{\gamma_i\big(\sigma^2+\lambda\sigma_Y^2\big)\overline{a}_i^2(t)}+\kappa_i\frac{(\mu-r+\lambda\mu_Y)\overline{A}_j(t)-\gamma_j\rho\beta\sigma\overline{a}_j(t)\overline{b}_j(t)}{\gamma_j\big(\sigma^2+\lambda\sigma_Y^2\big)\overline{a}_j^2(t)}\right],\tag{B.30}$$

$$\begin{aligned}
q_i^*(t)=\frac{1}{1-\kappa_i\kappa_j}&\left[\frac{\vartheta\overline{A}_i(t)}{\gamma_i\zeta^2k^{\mathbb{P}}a_i^2(t)}-\frac{A_i(t)}{\gamma_i\zeta a_i^2(t)}+\frac{\widehat{x}_i}{\zeta}-\frac{\overline{a}_i(t)\widehat{x}_i}{\zeta a_i(t)}+\frac{\big(b_i(t)-\overline{b}_i(t)\big)w}{\zeta a_i(t)}\right.\\
&+\frac{c_i(t)-\overline{c}_i(t)}{\zeta a_i(t)}+\kappa_i\left(\frac{\vartheta\overline{A}_j(t)}{\gamma_j\zeta^2k^{\mathbb{P}}a_j^2(t)}-\frac{A_j(t)}{\gamma_j\zeta a_j^2(t)}+\frac{\widehat{x}_j}{\zeta}-\frac{\overline{a}_j(t)\widehat{x}_j}{\zeta a_j(t)}\right.\\
&\left.\left.+\frac{\big(b_j(t)-\overline{b}_j(t)\big)w}{\zeta a_j(t)}+\frac{c_j(t)-\overline{c}_j(t)}{\zeta a_j(t)}\right)\right].
\end{aligned}\tag{B.31}$$

Putting equations (B.28) and (B.29) into equations (B.26) and (B.27), we derive

$$\begin{aligned}
&\overline{A}_i'(t)\widehat{x}_i + \overline{B}_i'(t)w + \overline{C}_i'(t) + \left[r\widehat{x}_i - (1-\kappa_i)w\right]\overline{A}_i(t) + \alpha\overline{B}_i(t) - \frac{\gamma_i}{2}\beta^2\overline{b}_i^2(t) \\
&+ \frac{(\mu - r + \lambda\mu_Y)^2\overline{A}_i^2(t)}{2\gamma_i\left(\sigma^2 + \lambda\sigma_Y^2\right)\overline{a}_i^2(t)} - \frac{(\mu - r + \lambda\mu_Y)\rho\beta\sigma\overline{A}_i(t)\overline{b}_i(t)}{\left(\sigma^2 + \lambda\sigma_Y^2\right)\overline{a}_i(t)} \\
&+ \frac{\gamma_i\rho^2\beta^2\sigma^2\overline{b}_i^2(t)}{2\left(\sigma^2 + \lambda\sigma_Y^2\right)} + \left[\frac{\vartheta\overline{A}_i(t)}{\zeta} - \frac{\vartheta\overline{A}_i(t)\overline{a}_i(t)}{\zeta a_i(t)} - k^{\mathbb{P}}\overline{A}_i(t) + \frac{k^{\mathbb{P}}A_i(t)\overline{a}_i(t)}{a_i(t)}\right]\widehat{x}_i \\
&+ \left[\frac{\vartheta\overline{A}_i(t)\left(b_i(t) - \overline{b}_i(t)\right)}{\zeta a_i(t)} - \frac{k^{\mathbb{P}}A_i(t)\left(b_i(t) - \overline{b}_i(t)\right)}{a_i(t)} + k^{\mathbb{P}}\left(B_i(t) - \overline{B}_i(t)\right)\right]w \\
&+ k^{\mathbb{P}}\left(C_i(t) - \overline{C}_i(t)\right) - \frac{k^{\mathbb{P}}A_i(t)\left(c_i(t) - \overline{c}_i(t)\right)}{a_i(t)} + \frac{\vartheta\overline{A}_i(t)\left(c_i(t) - \overline{c}_i(t)\right)}{\zeta a_i(t)} \\
&+ \frac{k^{\mathbb{P}}A_i^2(t)}{2\gamma_i a_i^2(t)} - \frac{\vartheta A_i(t)\overline{A}_i(t)}{\gamma_i\zeta a_i^2(t)} + \frac{\vartheta^2\overline{A}_i^2(t)}{2\gamma_i\zeta^2 k^{\mathbb{P}}a_i^2(t)} = 0, \\
&\overline{a}_i'(t)\widehat{x}_i + \overline{b}_i'(t)w + \overline{c}_i'(t) + \left[r\widehat{x}_i - (1-\kappa_i)w\right]\overline{a}_i(t) + \alpha\overline{b}_i(t) + \frac{(\mu - r + \lambda\mu_Y)^2\overline{A}_i(t)}{\gamma_i\left(\sigma^2 + \lambda\sigma_Y^2\right)\overline{a}_i(t)} \\
&- \frac{(\mu - r + \lambda\mu_Y)\rho\beta\sigma\overline{b}_i(t)}{\sigma^2 + \lambda\sigma_Y^2} + \left[\frac{\vartheta\overline{a}_i(t)}{\zeta} - \frac{\vartheta\overline{a}_i^2(t)}{\zeta a_i(t)}\right]\widehat{x}_i + \frac{\vartheta\overline{a}_i(t)\left(b_i(t) - \overline{b}_i(t)\right)}{\zeta a_i(t)}w \\
&+ \frac{k^{\mathbb{P}}A_i(t)}{\gamma_i a_i(t)} - \frac{\vartheta\overline{A}_i(t)}{\gamma_i\zeta a_i(t)} - \frac{\vartheta A_i(t)\overline{a}_i(t)}{\gamma_i\zeta a_i^2(t)} + \frac{\vartheta^2\overline{A}_i(t)\overline{a}_i(t)}{\gamma_i\zeta^2 k^{\mathbb{P}}a_i^2(t)} \\
&+ \frac{\vartheta\overline{a}_i(t)\left(c_i(t) - \overline{c}_i(t)\right)}{\zeta a_i(t)} = 0.
\end{aligned} \tag{B.32}$$

By separating variables, we obtain the following differential equations:

$$\overline{A}_i'(t) + \left(r + \frac{\vartheta}{\zeta} - k^{\mathbb{P}}\right)\overline{A}_i(t) - \left(\frac{\vartheta\overline{A}_i(t)}{\zeta a_i(t)} - k^{\mathbb{P}}\right)\overline{a}_i(t) = 0, \quad \overline{A}_i(T) = 1, \tag{B.33}$$

$$\overline{a}_i'(t) + \left(r + \frac{\vartheta}{\zeta}\right)\overline{a}_i(t) - \frac{\vartheta\overline{a}_i^2(t)}{\zeta a_i(t)} = 0, \quad \overline{a}_i(T) = 1, \tag{B.34}$$

$$\overline{b}_i'(t) - \frac{\vartheta\overline{a}_i(t)}{\zeta a_i(t)}\overline{b}_i(t) - (1-\kappa_i)\overline{a}_i(t) + \frac{\vartheta\overline{a}_i(t)b_i(t)}{\zeta a_i(t)} = 0, \quad \overline{b}_i(T) = 0, \tag{B.35}$$

$$\begin{aligned}
&\overline{B}_i'(t) - k^{\mathbb{P}}\overline{B}_i(t) - (1-\kappa_i)\overline{A}_i(t) + k^{\mathbb{P}}B_i(t) + \frac{\vartheta\overline{A}_i(t)\left(b_i(t) - \overline{b}_i(t)\right)}{\zeta a_i(t)} \\
&\quad - \frac{k^{\mathbb{P}}A_i(t)\left(b_i(t) - \overline{b}_i(t)\right)}{a_i(t)} = 0, \quad \overline{B}_i(T) = 0,
\end{aligned} \tag{B.36}$$

$$\overline{c}_i'(t) - \frac{\vartheta \overline{a}_i(t)}{\zeta a_i(t)}\overline{c}_i(t) + \alpha \overline{b}_i(t) + \frac{(\mu - r + \lambda\mu_Y)^2 \overline{A}_i(t)}{\gamma_i(\sigma^2 + \lambda\sigma_Y^2)\overline{a}_i(t)} - \frac{(\mu - r + \lambda\mu_Y)\rho\beta\sigma\overline{b}_i(t)}{\sigma^2 + \lambda\sigma_Y^2} + \frac{k^{\mathbb{P}} A_i(t)}{\gamma_i a_i(t)} - \frac{\vartheta \overline{A}_i(t)}{\gamma_i \zeta a_i(t)} - \frac{\vartheta A_i(t)\overline{a}_i(t)}{\gamma_i \zeta a_i^2(t)} + \frac{\vartheta^2 \overline{A}_i(t)\overline{a}_i(t)}{\gamma_i \zeta^2 k^{\mathbb{P}} a_i^2(t)} + \frac{\vartheta \overline{a}_i(t) c_i(t)}{\zeta a_i(t)} = 0, \quad \overline{c}_i(T) = 0, \tag{B.37}$$

$$\overline{C}_i'(t) - k^{\mathbb{P}}\overline{C}_i(t) + \alpha \overline{B}_i(t) - \frac{\gamma_i}{2}\beta^2 \overline{b}_i^2(t) + \frac{(\mu - r + \lambda\mu_Y)^2 \overline{A}_i^2(t)}{2\gamma_i(\sigma^2 + \lambda\sigma_Y^2)\overline{a}_i^2(t)} - \frac{(\mu - r + \lambda\mu_Y)\rho\beta\sigma\overline{A}_i(t)\overline{b}_i(t)}{(\sigma^2 + \lambda\sigma_Y^2)\overline{a}_i(t)} + \frac{\gamma_i \rho^2 \beta^2 \sigma^2 \overline{b}_i^2(t)}{2(\sigma^2 + \lambda\sigma_Y^2)} + k^{\mathbb{P}} C_i(t) - \frac{k^{\mathbb{P}} A_i(t)(c_i(t) - \overline{c}_i(t))}{a_i(t)} + \frac{\vartheta \overline{A}_i(t)(c_i(t) - \overline{c}_i(t))}{\zeta a_i(t)} + \frac{k^{\mathbb{P}} A_i^2(t)}{2\gamma_i a_i^2(t)} - \frac{\vartheta A_i(t)\overline{A}_i(t)}{\gamma_i \zeta a_i^2(t)} + \frac{\vartheta^2 \overline{A}_i^2(t)}{2\gamma_i \zeta^2 k^{\mathbb{P}} a_i^2(t)} = 0, \quad \overline{C}_i(T) = 0. \tag{B.38}$$

Solving the above equations, we derive

$$\overline{A}_i(t) = \overline{a}_i(t) = e^{r(T-t)}, \tag{B.39}$$

$$\overline{B}_i(t) = \overline{b}_i(t) = -\frac{1 - \kappa_i}{r}\left(e^{r(T-t)} - 1\right), \tag{B.40}$$

$$\overline{c}_i(t) = e^{(\vartheta t/\zeta)} \int_t^T e^{-(\vartheta t/\zeta)} \left[\left(\alpha - \frac{(\mu - r + \lambda\mu_Y)\rho\beta\sigma}{\sigma^2 + \lambda\sigma_Y^2}\right)\overline{b}_i(u) + \frac{(\mu - r + \lambda\mu_Y)^2}{\gamma_i(\sigma^2 + \lambda\sigma_Y^2)} + \frac{k^{\mathbb{P}}}{\gamma_i} - \frac{2\vartheta}{\gamma_i \zeta} + \frac{\vartheta^2}{\gamma_i \zeta^2 k^{\mathbb{P}}}\right] \mathrm{d}u, \tag{B.41}$$

$$\overline{C}_i(t) = e^{k^{\mathbb{P}} t} \int_t^T e^{-k^{\mathbb{P}} u} \left[\alpha \overline{B}_i(u) - \frac{\gamma_i \beta^2}{2}\left(1 - \frac{\rho^2\sigma^2}{\sigma^2 + \lambda\sigma_Y^2}\right)\overline{b}_i^2(u) - \frac{(\mu - r + \lambda\mu_Y)\rho\beta\sigma}{\sigma^2 + \lambda\sigma_Y^2}\overline{b}_i(u) + k^{\mathbb{P}} C_i(u) - \left(k^{\mathbb{P}} - \frac{\vartheta}{\zeta}\right)(c_i(u) - \overline{c}_i(u)) + \frac{(\mu - r + \lambda\mu_Y)^2}{2\gamma_i(\sigma^2 + \lambda\sigma_Y^2)} + \frac{k^{\mathbb{P}}}{2\gamma_i} - \frac{\vartheta}{\gamma_i \zeta} + \frac{\vartheta^2}{2\gamma_i \zeta^2 k^{\mathbb{P}}}\right] \mathrm{d}u. \tag{B.42}$$

From symmetry, it follows that

$$A_i(t) = A_j(t) = \overline{A}_i(t) = \overline{A}_j(t) = a_i(t) = a_j(t) = \overline{a}_i(t) = \overline{a}_j(t), \tag{B.43}$$

$$B_j(t) = b_j(t) = \overline{B}_j(t) = \overline{b}_j(t) = -\frac{1 - \kappa_j}{r}\left(e^{r(T-t)} - 1\right), \tag{B.44}$$

$$c_j(t) = -\left(\alpha - \frac{(\mu - r + \lambda\mu_Y)\rho\beta\sigma}{\sigma^2 + \lambda\sigma_Y^2}\right)\frac{1 - \kappa_j}{r^2}\left(e^{r(T-t)} - 1\right) - \left(\alpha - \frac{(\mu - r + \lambda\mu_Y)\rho\beta\sigma}{\sigma^2 + \lambda\sigma_Y^2}\right)\frac{1 - \kappa_j}{r}(t - T) - \frac{(\mu - r + \lambda\mu_Y)^2}{\gamma_j(\sigma^2 + \lambda\sigma_Y^2)}(t - T), \tag{B.45}$$

$$C_j(t) = \left(\alpha - \frac{(\mu - r + \lambda\mu_Y)\rho\beta\sigma}{\sigma^2 + \lambda\sigma_Y^2}\right)\left[-\frac{1-\kappa_j}{r^2}e^{r(T-t)} - \frac{1-\kappa_j}{r}(t-T) + \frac{1-\kappa_j}{r^2}\right] + \frac{\gamma_j\beta^2}{2}\left(1 - \frac{\rho^2\sigma^2}{\sigma^2+\lambda\sigma_Y^2}\right)\left[-\frac{(1-\kappa_j)^2}{2r^3}e^{2r(T-t)} + \frac{2(1-\kappa_j)^2}{r^3}e^{r(T-t)} + \frac{(1-\kappa_j)^2}{r^2}(t-T) + \frac{(1-\kappa_j)^2}{2r^3} - \frac{2(1-\kappa_j)^2}{r^3}\right] - \frac{(\mu - r+\lambda\mu_Y)^2}{2\gamma_j(\sigma^2+\lambda\sigma_Y^2)}(t-T), \tag{B.46}$$

$$\bar{c}_j(t) = e^{(\vartheta t/\zeta)}\int_t^T e^{-(\vartheta t/\zeta)}\left[\left(\alpha - \frac{(\mu - r + \lambda\mu_Y)\rho\beta\sigma}{\sigma^2+\lambda\sigma_Y^2}\right)\bar{b}_j(u) + \frac{(\mu - r+\lambda\mu_Y)^2}{\gamma_j(\sigma^2+\lambda\sigma_Y^2)} + \frac{k^{\mathbb{P}}}{\gamma_j} - \frac{2\vartheta}{\gamma_j\zeta} + \frac{\vartheta^2}{\gamma_j\zeta^2k^{\mathbb{P}}}\right]\mathrm{d}u, \tag{B.47}$$

$$\overline{C}_j(t) = e^{k^{\mathbb{P}}t}\int_t^T e^{-k^{\mathbb{P}}u}\left[\alpha\overline{B}_j(u) - \frac{\gamma_j\beta^2}{2}\left(1 - \frac{\rho^2\sigma^2}{\sigma^2+\lambda\sigma_Y^2}\right)\bar{b}_j^2(u) - \frac{(\mu - r+\lambda\mu_Y)\rho\beta\sigma}{\sigma^2+\lambda\sigma_Y^2}\bar{b}_j(u) + k^{\mathbb{P}}C_j(u) - \left(k^{\mathbb{P}} - \frac{\vartheta}{\zeta}\right)\left(c_j(u) - \bar{c}_j(u)\right) + \frac{(\mu - r+\lambda\mu_Y)^2}{2\gamma_j(\sigma^2+\lambda\sigma_Y^2)} + \frac{k^{\mathbb{P}}}{2\gamma_j} - \frac{\vartheta}{\gamma_j\zeta} + \frac{\vartheta^2}{2\gamma_j\zeta^2k^{\mathbb{P}}}\right]\mathrm{d}u. \tag{B.48}$$

By equations (B.2), (B.3), (B.9), (B.17)–(B.20), (B.22), (B.23), (B.30), (B.31), and (B.39)–(B.48), we can obtain the results in Theorem 2.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Research on the Dependence Structure and Risk Spillover of Internet Money Funds Based on *C*-Vine Copula and Time-Varying *t*-Copula

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Internet money funds (IMFs) are the most widely involved products in the Internet financial products market. This research utilized the *C*-vine copula model to study the risk dependence structure of IMFs and then introduces the time-varying *t*-copula model to analyze the risk spillover of diverse IMFs. The results show the following: (1) The risks of Internet-based IMFs, bank-based IMFs, and fund-based IMFs have obvious dependence structure, and the degree of risk dependence among different categories of IMFs is significantly different. (2) There are risk spillover effects among diverse IMFs, and their risk dependence relationship is characterized by cyclical feature. (3) The risk spillover effect among diverse IMFs is pronounced, and dynamic risk dependence between IMFs is characterized by synchronization.

1. Introduction

In recent years, China has paid due attention to the digital transformation of finance and actively promoted the further improvement of the modern digital financial system, which has also stimulated the rapid rise of China's Internet financial products market. Internet financial products as "disintermediated" investment transactions are employing network information technology [1]. Among the Internet financial products, Internet money funds (IMFs) are the most widely participated products. IMFs, also known as Internet money market funds, usually gather idle funds of individual investors and then invest the idle funds by the fund management companies to obtain profit. The traditional money market funds usually implement the "$T+2$" mode, while the IMFs mostly use "$T+0$" or "$T+1$" subscription and redemption mode. Thus, users of IMFs proliferate. Taking Yu'E Bao as an example, its size was up to about 972.415 billion yuan as of the end of the first quarter of 2021.

However, some IMF platforms still have problems such as liquidity risk, maturity mismatch, and APP security loopholes, which further aggravate the uncertainty of IMFs market risk. At the beginning of 2020, the sudden outbreak of the COVID-19 pandemic caused a severe impact on both offline and online finance, making the Internet financial products market more vigorous and vulnerable. Due to the risk dependence relationship, the accumulation and superposition of risks in the Internet financial products market are accelerated, and it also quickly leads to the spread of individual risks to other financial products' markets and forms risk spillovers. In the post-COVID-19 era, it is essential for governments to pay full attention to the prevention and control of risks in the IMFs market.

In this context, does the market risk of IMFs have a dependence structure? Are there risk spillover effects between different categories of IMFs? How does the dependence of IMFs change dynamically? The above questions still need to be further explored and discussed. This research used the Canonical vine copula (*C*-vine copula) model to examine the risk spillover effect and dynamic dependence among IMFs based on the time-varying t-copula model to provide valuable references and suggestions for the risk prevention and control of the Internet financial products market.

2. Literature Review

Appropriate monetary liquidity is the primary concern for IMFs. Yang et al. [2] demonstrated that liquidity risk was considered as the main factor in Yu'E Bao's investment strategy. By employing the detailed portfolio holdings of US money market funds, Aftab and Varotto [3] found that these essential players in the shadow banking sector were vulnerable to liquidity shocks. Dong et al. [4] and Chen et al. [5] investigated the linkage effect between Internet finance and commercial banks. Dong et al. [4] found that the development of Internet finance has a negative impact on banks' liquidity. Meanwhile, Chen et al. [5] testified that Internet finance's innovation significantly increased commercial banks' risk-taking behavior.

Some research analyzed the impact of risks presented in the Internet financial products market. Tan et al. [6] conducted an in-depth revelatory case study on Yu'E Bao. Fernandes et al. [7] adopted the autoregressive distributed lag (ARDL) model and analyzed the contribution of digital financial services to financial inclusion in Mozambique. Wang and Ben [8] examined the relationship between online shopping and investment in e-commerce money market funds based on the data from the China Household Finance Survey dataset.

In terms of the relationship between risk and the Internet financial products market, Sung et al. [9] argued that the panic in the IMFs market might be triggered by distrust in the operation of fund managers. Qi et al. [10] found that credit risk and personal information risk were crucial elements that affected the development of Internet finance. From the perspective of the Internet financial products market risk, Xiong et al. [11] proposed a reasonable Internet financial products market portfolio plan for individual or family investment. From the perspective of complex systems, Xu et al. [12] explored the contagion relationship between different risk factors in Internet finance and concluded that risk was transmitted outward through the internal cycle of Internet finance. Fan et al. [13] considered credit risk as an essential issue in the development of Internet finance and conducted an in-depth study on online lending in China.

Copula can effectively measure nonlinear correlation and tail dependence. However, regular copula models cannot build multivariate models. Therefore, Bedford and Cooke [14, 15] proposed the vine copula model to solve this problem. The vine copula model can describe the pairwise correlation structure between variables and enhance the flexibility of modeling. Therefore, the vine copula has been widely used to research risk dependence structure and risk spillover in financial markets. Pourkhanali et al. [16] used C-vine copula and drawable vine copula (D-vine copula) to study the correlation between international financial institutions, and they analyzed the complex dependence among borrowers with an intuitive systematic risk model. Syuhada and Hakim [17] took cryptocurrency as the research object and carried out a risk portfolio on investment according to the risk dependence structure. Hadded et al. [18] and Xiao [19] both studied the risk dependence structure in the stock market using the vine copula, and Xiao [19] further looked at the risk spillovers of stock markets during periods of volatility and depression.

Considering the time-varying characteristics of variables, some researchers used time-varying copula models to study the dynamic dependence structure and spillover effects among financial markets. Yan et al. [20] studied the tail dependence of financial markets with the time-varying t-copula model and gave the optimal portfolio choice. Some researchers have also used the time-varying copula model to study a particular financial market. Duong and Huynh [21] and Wu et al. [22] studied the risk in the stock market. The latter focused on the impact of RMB exchange rate and equity spillover effects and found a positive relationship between them. Han et al. [23] used a time-varying copula to analyze the dynamic dependence between financial assets and constructed a value-at-risk (VaR) portfolio model. Rehman et al. [24, 25] studied the extreme dependence and risk spillover relationship between Bitcoin and precious metals using time-varying copula and later studied the dependence structure and found the existence of risk spillover effect between Bitcoin and Islamic stocks.

Existing research studies have mainly focused on analyzing single risk or portfolio risk in the financial market, and few quantitative analyses and empirical studies have been conducted on the risk dependence of different categories of IMFs and the dynamic risk spillover between them. In this context, it is of practical significance to study the risk dependence of IMFs and analyze the direction and intensity of risk spillover of IMFs for the stable, sustainable development of the Internet financial products market.

3. Data Sources and Preprocessing

3.1. Data Selection. The sample data were collected from the Wind database, which divided IMFs into three categories, including Internet-based IMFs (INTE), bank-based IMFs (BANK), and fund-based IMFs (FUND). INTE mainly refers to IMFs docked by the third-party payment institutions; BANK refers to IMFs docked by banks, while FUND refers to IMFs docked by the fund companies. Our research followed the categories in Wind. Five representative funds of each category were selected, respectively. The 15 sample IMFs were chosen according to their category, fund size, year of establishment, industry representativeness, and so on. The basic information of sample IMFs is shown in Table 1.

To ensure the continuity of the data, the seven-day annualized returns (%) of the 15 IMFs are recorded as $A_i\,(i = 1, \ldots, 15)$. The data covers January 31, 2016, to January 31, 2020. There are 1,462 observations of each fund return series after removing the invalid values, totaling 21,930 observations.

3.2. Descriptive Statistics. The first-order difference of the original data was used to obtain the logarithmic seven-day annualized return series of the sample IMFs, denoted as

Table 1: Sample information.

Category	Fund companies	IMFs	Fund size (billion)	Date of establishment	Experimental variables
INTE	Alipay	Tianhong Yu'E Bao	1093.60	2013-05-29	A1
	Baidu	Huaxia Xianjin Zengli A/E	29.13	2004-04-07	A2
	Tencent	Huitianfu Quan'E Bao	90.95	2013-12-13	A3
	Wangyilicai	Huitianfu Xianjin Bao	42.86	2013-09-12	A4
	JD	JiashiHuoqianbao A	26.86	2014-03-17	A5
BANK	China Construction Bank	Jianxin Xianjintianli A	156.35	2014-09-17	A6
	Industrial and Commercial Bank of China	Gongyin Xinjin A	6.81	2014-01-27	A7
	Bank of Communications	Nanfang Xianjintong E	9.48	2004-03-05	A8
	China Minsheng Banking	Minsheng Jiayinxianjin A	19.77	2013-10-18	A9
	Industrial Bank	Xingquan Tianli Bao	87.49	2014-02-27	A10
FUND	GF Fund Management	Guangfa Yindaizi A	16.37	2014-01-10	A11
	Bosera Funds	Boshi Xianjin A	163.72	2004-01-06	A12
	Galaxy Fund Management	Yinhe Yinfu A	18.28	2004-12-20	A13
	Rongtong Fund	Rongyitong Zhifu A	31.12	2006-01-19	A14
	Fullgoal Fund	Fuguo Fuqianbao	50.17	2014-05-07	A15

Note: fund size as of January 31, 2020.

$B_i\,(i = 1, \ldots, 15)$ to reflect the fluctuation of fund returns. We calculated B_i as follows:

$$B_i = \ln A_i - \ln A_{i-1}. \quad (1)$$

Table 2 presents the results of the descriptive analysis.

The average yield series of INTE, BANK, and FUND was used as the return series and subjected to first-order differencing. The descriptive statistics after first-order differencing are shown in Table 3.

According to Tables 2 and 3, the mean value of the log-return series $B_i\,(i = 1, \ldots, 15)$ and three categories of IMFs are close to 0 and have the characteristics such as "fat-tail" and "nonnormality," so the t-distribution can be considered to fit the log-return series of the three categories.

3.3. Stability Test. Heteroskedasticity and autocorrelation are common features of the time series of IMFs. Therefore, the stability test was performed for $B_i\,(i = 1, \ldots, 15)$. According to Table 4, it can be found that the ADF test statistics are statistically significant, indicating that $B_i\,(i = 1, \ldots, 15)$ and the log-return series of three categories of IMFs are stable.

3.4. ARCH Effect Test. Before the ARCH effect test, INTE, BANK, and FUND should be tested for autocorrelation. Taking the BANK as an example, firstly, the BANK series were tested for autocorrelation at lagged 36th order until the absolute value of Q-Stat at 36th order was greater than 0. The P value of Q-Stat results showed that it passed the significance test, indicating the existence of autocorrelation in the BANK series. According to the results of the BANK series autocorrelation test, AR (1) and AR (2) were established for comparison, and the orders were determined by AIC and SC minimum criteria. The results showed that AR (2) had the better results and the regression coefficients of AR (1) and AR (2) were significant. Finally, the ARCH-LM test was performed, and the length of the lag was set to 2. The results showed that the P value of the F-statistic was 0.002. Therefore, the BANK series had an ARCH effect, and the GARCH model could be applied later.

Similarly, the above tests were performed with the INTE and FUND series. The results showed autocorrelation and ARCH effects in INTE, BANK, and FUND, which provided the preconditions for constructing a model using the marginal distribution to describe the risk dependence among IMFs.

4. Model Design

The vine copula model was introduced to portray the risk dependence structure among multiple IMFs, forming a multilayer tree structure diagram and then realizing the measurement of multiple dependence structures. Subsequently, a time-varying t-copula model was introduced to calculate the risk spillover ΔCoVaR and analyze the changes of dynamic dependence among diverse IMFs.

4.1. Edge Distribution Model. The data tests reveal that the selected INTE, BANK, and FUND series are biased, nonnormal, peak fat-tail, autocorrelated, and volatility aggregated. Therefore, when modeling and analyzing the log-return, it is essential to eliminate the autocorrelation, volatility aggregation, and so on. Therefore, the AR model and GARCH model can be used. Katsiampa [26] and Ma et al. [27] pointed out that the GARCH model was more accurate for finance-related time series, and the t-distribution could better portray the nonnormal characteristics of finance-related time series data. Owing to that fact, the marginal

Table 2: Descriptive analysis of log-return series of sample IMFs.

Category	Series	Mean value	Std. deviation	Skewness	Kurtosis	Jarque–Bera	P value
INTE	B1	0.0002	0.109	−0.489	7.191	1127.204	≤0.001
	B2	0.0002	0.135	0.284	32.035	51339.78	≤0.001
	B3	0.0004	0.088	−0.469	25.434	30690.48	≤0.001
	B4	0.0003	0.055	0.256	72.188	291426.2	≤0.001
	B5	0.0013	0.111	0.580	48.356	125313.6	≤0.001
BANK	B6	0.0002	0.027	0.127	15.970	10244.57	≤0.001
	B7	0.0019	0.136	−0.499	42.192	93567.38	≤0.001
	B8	0.0004	0.070	0.099	38.983	78823.13	≤0.001
	B9	0.0007	0.069	0.274	17.301	12467.58	≤0.001
	B10	0.0002	0.061	0.052	12.858	5916.55	≤0.001
FUND	B11	0.0004	0.073	−0.354	56.419	173740.7	≤0.001
	B12	0.0007	0.072	−0.055	31.502	49454.89	≤0.001
	B13	0.0013	0.344	0.336	26.874	34723.43	≤0.001
	B14	0.0005	0.114	0.503	40.802	87051.22	≤0.001
	B15	0.0003	0.154	0.579	57.251	179249.7	≤0.001

Table 3: The descriptive statistics after first-order differencing.

Category	Mean value	Std. deviation	Skewness	Kurtosis	Jarque–Bera	P value
INTE	0.0005	0.041	0.034	13.020	6112.605	≤0.001
BANK	0.0007	0.038	0.082	16.510	11113.43	≤0.001
FUND	0.0006	0.083	0.393	18.909	15445.83	≤0.001

Table 4: Results of the log-return series test for INTE, BANK, and FUND.

Category	Experimental variables	ADF test	P value	ADF test	P value
INTE	B1	−5.397684	≤0.001	−8.670909	≤0.001
	B2	−10.85343	≤0.001		
	B3	−16.57159	≤0.001		
	B4	−15.58782	≤0.001		
	B5	−12.29044	≤0.001		
BANK	B6	−10.0594	≤0.001	−17.08869	≤0.001
	B7	−14.9402	≤0.001		
	B8	−15.2912	≤0.001		
	B9	−14.6561	≤0.001		
	B10	−10.0251	≤0.001		
FUND	B11	−11.47712	≤0.001	16.81036	≤0.001
	B12	−10.83287	≤0.001		
	B13	−13.06646	≤0.001		
	B14	−22.30595	≤0.001		
	B15	−11.83497	≤0.001		

distributions of INTE, BANK, and FUND were estimated using the AR (1)-GARCH (1, 1)-t model. The results are shown in Table 5.

According to the results in Table 5, the AIC and SC values of the log-return series model of the IMFs are relatively small, and the model can be considered as a better fit for the data. To estimate the residual series of $B_i\,(i = 1, \ldots, 15)$, the standardized residual series were derived, and the new series was obtained by MATLAB. According to the K–S test results, it can be considered that the marginal distribution sequence of IMFs $B_i\,(i = 1, \ldots, 15)$ is independent and identically distributed in the standard uniform distribution. Then, the new residual series was analyzed by the copula model.

Table 5: The estimation results of AR (1)-GARCH (1, 1)-t model.

Category	Parameter			
	AIC	SC	N	K–S value
INTE	−3.6822	−3.6713	2.0002	0.0268
BANK	−4.0265	−4.0156	2.9701	0.0176
FUND	−2.8131	−2.8022	2.0350	0.0204

4.2. C-Vine Structure and Modeling. The vine structure overcomes the limitation that traditional copula cannot accurately measure the different dependence structures among multiple variables. It divides the multivariable into binary structures and selects the appropriate copula function to establish the joint distribution according to the specific characteristics between variables. There are two common vine structures: C-vine copula and D-vine copula. The C-vine copula is suitable for the situation of primary variables leading to other variables, and the D-vine copula is ideal for the case that the relationship between variables is relatively independent [14, 28]. The parameters were estimated by the C-vine copula and D-vine copula, respectively (for results, see Table 6).

According to Table 6, the AIC and BIC values in C-vine are smaller than those in D-vine. Considering the likelihood and the model selection criterion of minimizing AIC and BIC, this research selected the C-vine copula to analyze the risk dependence structure of the three categories of IMFs.

Table 6: Parameters of C-vine copula and D-vine copula.

Copula	AIC	BIC	Log-likelihood
C-vine	−71.0679	−55.2073	38.534
D-vine	−69.8468	−53.9862	37.923

The decomposition of the C-vine copula is specified as

$$f(x_1, x_2, \ldots, x_n) = \prod_{k=1}^{n} f(x_k) \times \prod_{j=1}^{n-1} \prod_{i=1}^{n-j} c_{j,j+i|1,\ldots,j-1}\left(F\left(x_j|x_1, \ldots, x_{j-1}\right), F\left(x_{j+i}|x_1, \ldots, x_{j-1}\right)\right), \quad (2)$$

where F is the conditional distribution, f is the density function, and c is the conditional density.

4.3. Time-Varying t-Copula Model and ΔCoVaR. Considering the different dependence and time-varying characteristics of INTE, BANK, and FUND, we established a time-varying t-copula model to describe the dynamic dependence relationship between INTE, BANK, and FUND more accurately and evaluate their linkage correlation and contagion correlation. Considering the dynamic and complex nature of the risk linkage process, the idea of Tse and Tsui [29] was introduced here to portray the dynamic change of the dependence coefficient of the time-varying t-copula model:

$$\rho_t = (1 - m - n) \cdot R + m \cdot r_{t-1} + n \cdot \rho_{t-1}, \quad (3)$$

where ρ is the linear correlation coefficient of the two probabilistically integrated transformed random variables, r_{t-1} is the correlation coefficient of the samples within the rolling window period, R is the covariance of the sample series, and m and n are the unknown parameters to be estimated in the equation.

The GARCH model was used to calculate the VaR to predict the volatility of INTE, BANK, and FUND and to model their volatility patterns. The GARCH (1, 1) model is specified as

$$y_t = \mu_t + a_t, \quad (4)$$

$$a_t = \sigma_t \xi_t, \xi_t \sim \text{i.i.d}(0, 1), \quad (5)$$

$$\sigma_t^2 = \alpha_0 + \alpha_1 a_{t-1}^2 + \beta_1 \sigma_{t-1}^2, \quad (6)$$

where y_t is the time series of the rate of return, a_t is the disturbance of rate of return, ${\sigma_t}^2$ is the conditional variance, ξ_t is the independent identically distributed white noise sequence, and $\alpha_0, \alpha_1, \beta_1$ are model parameters, $\alpha_0 > 0, \alpha_1 > 0, \beta_1 > 0$.

CoVaR refers to the risk that other IMFs are affected during a certain confidence level when certain IMFs generate risk in a certain time period. The equation of CoVaR is as follows:

$$P\left(I^{a,b} \leq \text{CoVaR}_q^{a,b}\right) = q, \quad (7)$$

where q is the confidence level and $I^{a,b}$ is the VaR of fund a and fund b.

Adrian and Brunnermeier [30] captured the tail dependence between the financial system as a whole and specific institutions by using ΔCoVaR. Based on the research of Adrian and Brunnermeier, the risk-added value ΔCoVaR was used as an index to measure risk spillover. The calculation for ΔCoVaR can be summarized as

$$\Delta\text{CoVaR}_q^{a,b} = \text{CoVaR}_q^{a,b} - \text{VaR}_q^{a}, \quad (8)$$

where $\Delta\text{CoVaR}_q^{a,b}$ is the risk spillover from IMF a to IMF b and VaR_q^{a} is the unconditional VaR of IMF a.

5. Empirical Results and Analysis

5.1. Analysis of Risk Dependence Structure. The C-vine copula was used to model the dependence structure among IMFs. Kendall's rank correlation coefficient τ between two variables was calculated by the R language (see Table 7).

Each layer of the C-vine has a key node, which has a dominant influence on other nodes. According to the results in Table 7, FUND was selected as the pivotal variable in the C-vine copula structure. Figure 1 shows the dependence structure based on the C-vine copula.

As can be seen in Figure 1, there are two trees: T_j ($j = 1, 2$). The main pivot point in the first layer is FUND 1, which is connected to the BANK 2 and the INTE 3, with each edge corresponding to the pair-copula density.

In order to choose a suitable copula model to measure the dependence structure of the IMFs, it is necessary to observe the distribution sequence scatter plot and frequency diagram. Taking the first layer structure as an example, the plots and diagrams are shown in Figures 2–5.

According to Figures 2 and 4, although the scatter distribution area is wide, the distribution is more obvious on the main diagonal. Figures 3 and 5 can visually show the tail correlation between the two sequences, showing an upper and lower tail correlation between BANK and FUND.

Table 7: Kendall rank correlation coefficients among the IMFs.

	INTE	BANK	FUND	Summation
INTE	1	0.0586	0.0628	0.1214
BANK	0.0586	1	0.0781	0.1367
FUND	0.0628	0.0781	1	0.1409

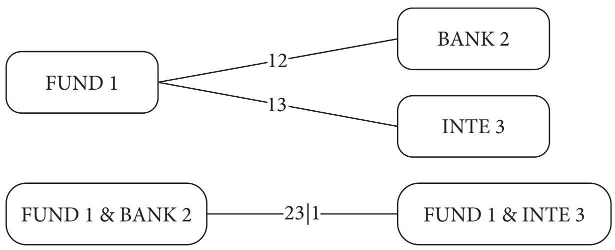

Figure 1: Dependence structure diagram based on *C*-vine copula.

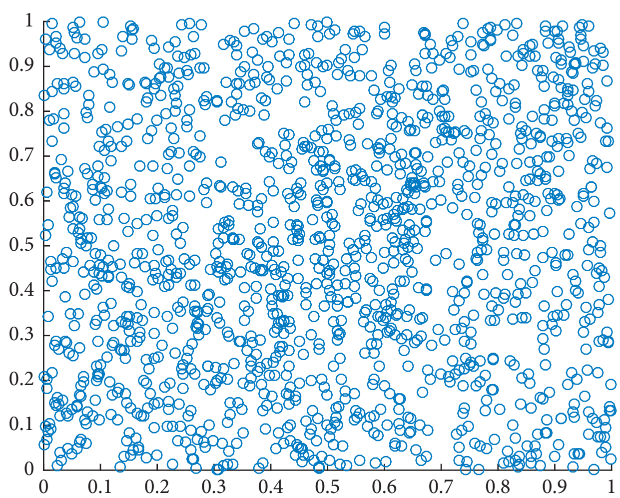

Figure 2: INTE-FUND scatter plot.

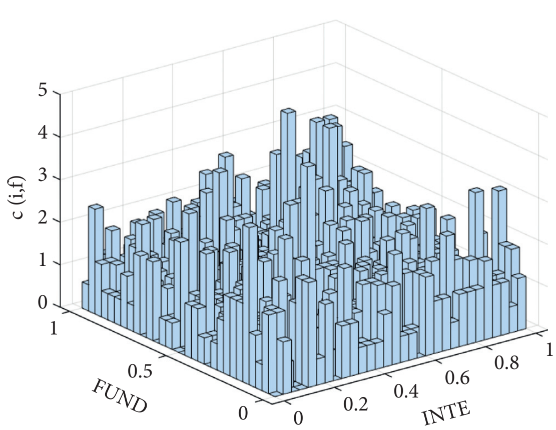

Figure 3: INTE-FUND frequency diagram.

The *t*-copula, Gaussian copula, and Clayton copula were modeled, respectively. The parameter estimation results (see Table 8) show that *t*-copula was the most appropriate model in this study by the AIC criterion.

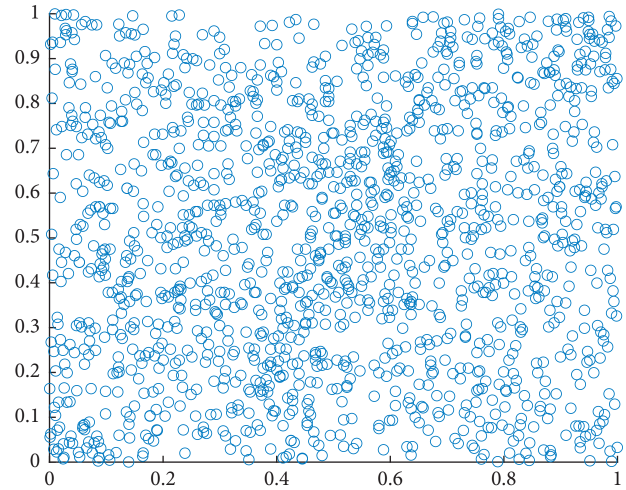

Figure 4: BANK-FUND scatter plot.

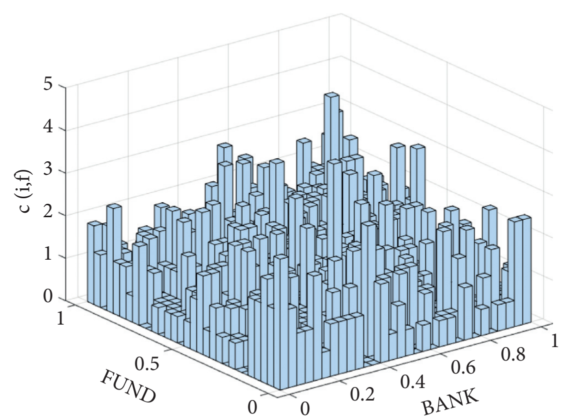

Figure 5: BANK-FUND frequency diagram.

FUND is the critical node in the relationship among IMFs. As seen from the first layer in Table 8, each category of IMFs shows high unconditional dependence. In the second layer, the INTE-BANK|FUND indicates a conditional correlation, which means that the FUND must be used as known information for the *C*-vine copula when INTE is fitted with the BANK.

Among them, the correlation coefficients of INTE-FUND and BANK-FUND in the first layer are positive, and the correlation coefficient of BANK-FUND is the highest, which indicates that the return rate of BANK-FUND is more likely to move in the same direction. In the second layer, the correlation coefficient of INTE-BANK is positive when FUND is taken as a known condition, and the return of BANK and INTE will also move in the same direction.

5.2. Measure of Risk Spillover Effects. Based on the above results, the time-varying *t*-copula model was introduced as a way to calculate the CoVaR values and the VaR values between IMFs. Then, the ΔCoVaR values of spillover effects were calculated to analyze the direction and intensity of risk spillover among INTE, BANK, and FUND.

Table 8: Parameter estimation results of IMFs.

Number of layers	Related funds	Rho correlation coefficient	Degree of freedom	AIC
First layer	INTE-FUND	0.0757	13.640	−8.6175
	BANK-FUND	0.1093	5.776	−48.6754
Second layer	INTE-BANK|FUND	0.0834	13.768	−13.5544

Note: the results are calculated by MATLAB.

The VaR values of the INTE, BANK, and FUND series and their mean values are shown in Table 9.

The mean VaR value of the FUND is 0.2034, which is much larger than the INTE (0.1169) and the BANK (0.0830), indicating that the FUND products are exposed to the most significant risk. The possible reason is that the FUND's asset allocation is much more prominent in bonds and securities, and its cash holdings are smaller than the INTE and BANK. From a temporal perspective, the VaR values of the BANK and FUND both show an overall upward trend from 2016 to 2019. Meanwhile, the INTE shows a fluctuating decline, indicating that the risk regulation measures for INTE have played a specific role in recent years.

The parameters were estimated by the time-varying t-copula model. Results are shown in Table 10.

Monte Carlo simulation was carried out based on the results in Table 10. The results of ΔCoVaR are shown in Table 11.

The sequence diagrams of the pair-to-pair risk spillover relationship among IMFs based on the ΔCoVaR results are shown in Figures 6–8.

Figures 6–8 reveal that the IMFs' risk spillover effects show periodic characteristics. IMFs have more obvious risk spillovers around September 2017, around April 2019, and after October 2019, respectively. The occurrence probability of risk spillover among IMFs is strongly related to the central bank's policy; for most investments of IMFs are cash, bank deposits, central bank bills, and so on. On September 30, 2017, the People's Bank of China cut the reserve requirement ratio by 0.5%, and in March 2019, ten-year government bond yields in China touched the lowest point of the year. Those policies might explain the risk spillover effects in IMFs. Thus, changes in macroeconomic policy play an influential role in the risk spillover of the IMFs market.

The risk spillover among diverse IMFs is directional. From the perspective of the year-by-year risk spillover effect, the ΔCoVaR from BANK to FUND is enormous and increasing year by year from 2016 to 2018. While the ΔCoVaR from FUND to BANK is relatively small, indicating that when the BANK produces risks, they are more likely to infect the FUND products. Nevertheless, when FUND's risk spillover occurs, it will not have a significant impact on BANK.

The empirical study of Dong et al. [4] and Chen et al. [31] demonstrated that there was mutual causality between Internet finance and the banking industry. On the whole, our empirical results on the risk spillover effect between INTE and BANK are similar to their research, but still, there are differences.

Table 9: VaR value for INTE, BANK, and FUND (2016–2019).

	INTE	BANK	FUND
2016	0.1169	0.0645	0.1073
2017	0.1239	0.0706	0.1410
2018	0.1141	0.0726	0.1626
2019	0.1225	0.1222	0.3805
Mean value	0.1169	0.0830	0.2034

In terms of spillover intensity, the absolute value of ΔCoVaR from INTE to BANK is greater than that from BANK to INTE, which indicates that the volatility spillover effect from INTE to BANK is more substantial. The ΔCoVaR from INTE to FUND is relatively small, while the risk spillover from FUND to INTE is relatively large. That result demonstrates that INTE would be affected by FUND when FUND is at risk. But on the contrary, FUND is not obviously affected by INTE. In 2019, although the two-way risk spillover value between BANK and INTE was similar, the spillover direction between BANK and FUND changed. When the risk of FUND occurs, it is likely to be transmitted to BANK.

In general, there is indeed a risk spillover phenomenon between diverse IMFs in recent years. (1) FUND has a significant influence on both BANK and INTE. There is a clear trend risk spillover from the FUND to other IMFs, indicating that once a certain risk was generated by the FUND products, it would easily affect the whole IMFs market. Figure 8 also shows that the spillover peaked around October 2019, indicating that both INTE and BANK are vulnerable to FUND. FUND products share part of the risk generated by INTE and BANK products and simultaneously increase the probability of risk occurrence for INTE and BANK products. (2) The mean value of risk spillover from BANK to FUND is the largest, while the risk spillover effect of INTE to BANK shows a fluctuating downward trend.

5.3. Dynamic Dependence Analysis of Risk Spillover. In order to show the changes of dependence among INTE, BANK, and FUND, time-varying t-copula was used for the dynamic dependence coefficient sequences (see Figures 9–11).

Figures 9–11 show that the dynamic correlation coefficients between INTE, BANK, and FUND fluctuate up and down in the range of [−0.3, 0.3], which is quite different from the Kendall rank correlation coefficient results obtained by the C-vine copula model. It indicates that the Kendall rank correlation coefficients are not accurate to show the risk dependence between IMFs. The dynamic correlation coefficient between the BANK and the FUND remains at 0.09 and basically does not fluctuate, which is related to the value

Table 10: Results of time-varying *t*-copula parameter estimation for IMFs.

	Parameter 1	Parameter 2	Parameter 3	AIC	LogL
INTE-BANK	18.5768	0.0344	0.8705	−15.9343	10.967
INTE-FUND	13.6868	0.0439	0.7623	−11.5089	8.754
BANK-FUND	5.3921	0.0000	0.9301	−43.9061	24.953

Table 11: ΔCoVaR value for INTE, BANK, and FUND (2016–2019).

	INTE⟶BANK	BANK⟶INTE	BANK⟶FUND	FUND⟶BANK	FUND⟶INTE	INTE⟶FUND
2016	−0.0348	0.0176	0.0639	0.0109	0.0117	0.0020
2017	−0.0367	0.0166	0.0789	−0.0154	−0.0173	−0.0003
2018	−0.0254	0.0161	0.0790	−0.0368	−0.0371	0.0114
2019	−0.0301	−0.0298	0.1307	−0.2434	−0.2515	0.0066
Mean value	−0.0289	0.0050	0.0882	−0.0767	−0.0786	0.0078

Note: ⟶ denotes the direction of risk spillover.

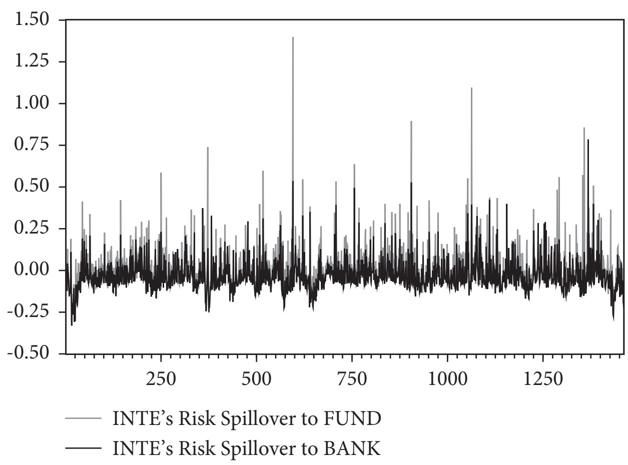

Figure 6: INTE's risk spillover to BANK and FUND.

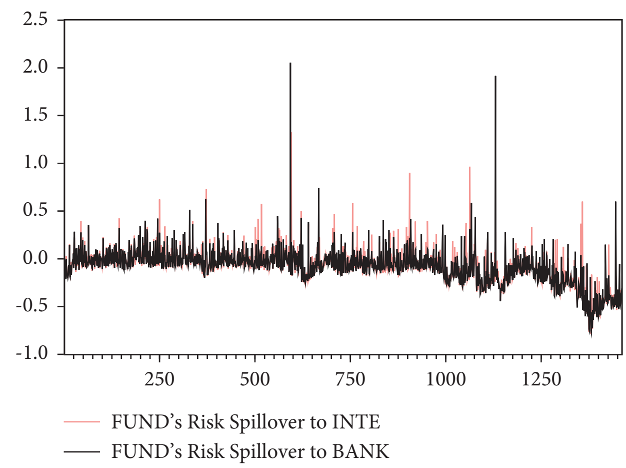

Figure 8: FUND's risk spillover to INTE and BANK.

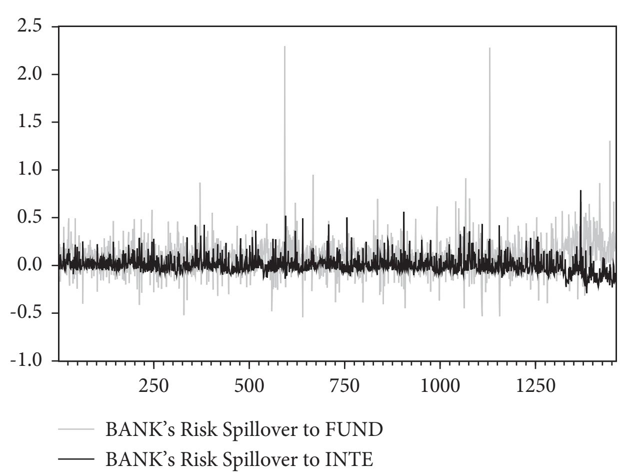

Figure 7: BANK's risk spillover to INTE and FUND.

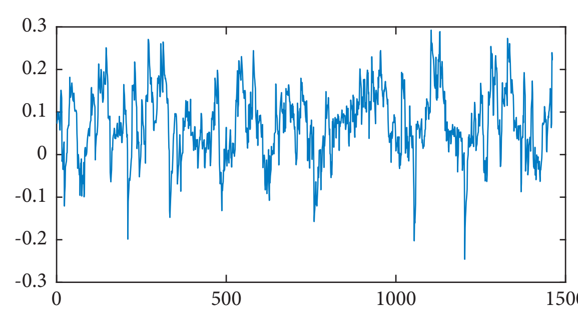

Figure 9: INTE and BANK sequence diagram.

of parameter 3 in Table 10, and the trend of the dynamic correlation coefficient changes more smoothly when the value of parameter 3 is closer to 1.

The estimated values of parameter 3 in the time-varying *t*-copula model are 0.8705, 0.7623, and 0.9301, indicating that the trend of the dependence change between the BANK and the FUND is stable. The obtained dynamic correlation coefficients were subjected to descriptive statistics. The results are shown in Table 12.

The mean value of INTE-BANK is 0.0721, with a positive correlation ratio of 73.5%, while INTE-FUND is 0.0513 and 70.7%, and BANK-FUND is 0.0940 and 100%. These results indicate that there is a positive correlation between INTE and BANK, INTE and FUND, and BANK and FUND during most of the trading time. Relatively, BANK-FUND always

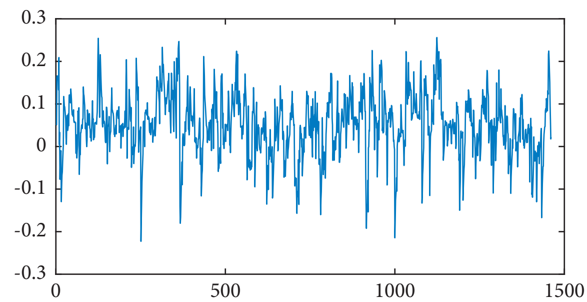

Figure 10: INTE and FUND sequence diagram.

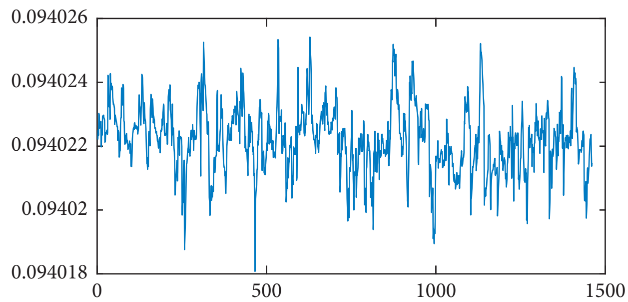

Figure 11: BANK and FUND sequence diagram.

Table 12: Statistical characteristics of dynamic correlation coefficients of IMFs.

Correlation coefficient	Mean value	Standard deviation	Maximum value	Minimum value	Percentage of positive correlation	Percentage of negative correlation
INTE-BANK	0.0721	0.08	0.29	−0.25	73.5	26.5
INTE-FUND	0.0513	0.05	0.26	−0.22	70.7	29.3
BANK-FUND	0.0940	0.00	0.09	0.09	100	0.00

maintains a strong positive correlation during the trading process. Considering that the rise and fall of the price of BANK products are likely to coincide with FUND products, some banks also have business relations with fund companies, leading to a cross-influence between BANK and FUND.

In terms of the valley and the peak value, INTE-BANK and INTE-FUND do not differ much, and they both show similar periodic changes. The maximum and minimum values of BANK-FUND differ in a tiny order of magnitude. Due to the massive scale of INTE and the wide range of products covered, it will have a greater correlation with BANK and FUND in certain time periods, and the probability of having the same or opposite change in returns is high. In terms of volatility (standard deviation), BANK-FUND fluctuates very smoothly, while the difference of standard deviation between INTE-BANK and INTE-FUND is 0.03, indicating that the fluctuation degree of INTE-BANK is the largest, followed by INTE-FUND. The sequence diagrams (Figures 9–11) also show that INTE-BANK and INTE-FUND have been in a state of greater volatility, indicating that the FUND and BANK yields maintain a weak positive correlation, and the positive or negative relationship between the INTE and other IMFs yields change over time.

In summary, from January 31, 2016, to January 31, 2020, the INTE-BANK and the INTE-FUND show a significant positive correlation in most of the trading time. As a whole, the dependence relationship fluctuates a lot, and those IMFs' profits and losses are synchronous. Among them, the BANK-FUND maintains a positive correlation during the trading process, and its degree of fluctuation is almost zero, which means that the trend of dependence and association between them is the most stable.

6. Conclusions

Our research selected 15 IMFs for empirical analysis. The *C*-vine copula model was chosen to analyze the dependence structure of INTE, BANK, and FUND. Then the time-varying *t*-copula model was introduced to calculate the risk spillover between them. The conclusions obtained are as follows.

Firstly, there is a well-defined risk dependence structure among INTE, BANK, and FUND. Secondly, risk spillovers do exist among the IMFs, their risk spillovers are similar in periodicity, and the risk spillover among different categories has directionality. Thirdly, both INTE-BANK and INTE-FUND show positive correlation in most trading time and both fluctuate a lot, while BANK-FUND has maintained a significant positive correlation during the trading process and has a more stable dependence relationship.

This research sheds some light on the research on the dependence structure and risk spillover of IMFs, and the findings imply that investors should clearly understand that no IMFs can guarantee an absolute return. They should pay attention to the return scale and various risk indicators of IMFs. And investors can further optimize their investment portfolios based on the risk dependence relationship between different IMFs.

Still, there are some limitations to this research. For instance, as we used 15 IMFs for the sample, further expansion of the sample size would be considered to obtain more accurate research results. In addition, we used the *C*-vine copula and *D*-vine copula in the empirical test, and we would take more copula functions into account in future research and select the best fitting copula model.

Data Availability

All data used to support the findings of this study are downloaded from the Wind database, and the data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this research.

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Research Article

Manufacturer's Collaborative Business Strategy with Two Different Reverse Channels in a Closed-Loop Supply Chain

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Reuse of products has become increasingly critical to reduce manufacturing costs and revitalize the new product market. With two different investment perspectives, manufacturers cooperate with retailers and recyclers to collect products from customers. By investing in the retailer, manufacturers gain an opportunity to sell new products, whereas by investing in the recycler, manufacturers can reduce production costs through remanufacturing. Therefore, manufacturers must determine the appropriate investment strategies to be applied to the two channels by analyzing the trade-offs between these opportunities. For this purpose, we discuss three investment strategies: Revenue-Sharing Investment, Direct Subsidy per Unit Returned Cartridge, and Hybrid Investment. The system dynamics model is used to construct scenarios of various investment strategies used by the manufacturer with the collection partners and analyze the corresponding changes in the revenues of the manufacturer. The results indicate that the application of the revenue-sharing strategy and the hybrid strategy to support retailers and recyclers is effective in increasing manufacturer profit. More specifically, by considering the hybrid investment strategy of revenue-sharing investment and the direct subsidy per unit returned cartridge for the recycler, the manufacturer can simultaneously avoid excess investment by the recycler and promote return activities through the recycler.

1. Introduction

Closed-loop supply chains (CLSCs) focus on collecting used products from customers and reusing them to generate value. This loop consists of a traditional forward supply chain (FSC), in which products are sold via retailers, and a reverse supply chain (RSC), in which used products are returned via reverse channels [1].

The value of the RSC is threefold. First, the process of remanufacturing used products reduces the requirement for raw materials inherent to traditional production processes and could ultimately lower manufacturing costs. Second, partners in the supply chain, such as retailers and manufacturers, can acquire an opportunity to sell new products to the customers who participate in the return activity. Third, for auxiliary and consumable products that depend on another device, such as ink cartridges for a printer, the manufacturer can encourage customers to buy new products rather than refurbish or refill the used ones when the RSC is employed.

A variety of reverse channel formats are currently deployed by manufacturers [2]. In some cases, manufacturers collect their used products directly from customers. For instance, Xerox Corporation provides prepaid boxes for customers to use to return cartridges. Manufacturers utilize retailers as another reverse channel to collect used products. For instance, Eastman Kodak Company retrieves single-use cameras from large retailers. Manufacturers also often enter into contracts with recycling companies, such as GENCO Distribution System, to collect used products.

Although the manufacturer takes advantage of both partners to increase the collection of used products, the expectations of the manufacturer regarding the collection activities of the two partners differ. The manufacturer expects retailers to not only reclaim more used products from customers who visit the retail market with used products but also create opportunities to sell new products when used products are returned. By contrast, the manufacturer expects the recycler to collect used products from customers who did not visit the retail market and prefer discarding to returning. Then, the manufacturer uses the returned products in a remanufacturing process, and the finished products are distributed through forward supply chain channels. Such activities reduce the requirements for raw materials associated with traditional production processes and ultimately lower manufacturing costs. The manufacturer also recognizes that the return activity of the retailer does not entirely depend on the manufacturer's subsidy, because the retailer invests in customers to increase sales opportunities for new products. However, the volume of cartridges collected by the recycler is proportional to its ability to visit customers within a given period, which in turn is determined by the reward provided by the manufacturer.

Manufacturers would like to increase the return rate of used products by sharing with their partners (recycler and retailer) the benefits generated from the CLSC channel. Recycler would expect high compensation for active recycling activities and the retailer would expect compensation from manufacturers for discounted prices when selling new products. The results of this study will contribute to finding the best way for manufacturers to share benefits with both partners on CLSC revenue and ways to share benefits.

For effective analysis, we developed a CLSC model comprising a manufacturer, a retailer, and a recycler using the system dynamics model. The developed model configures various scenarios based on the manufacturer's investment strategies to promote the collection activity of collection partners and encourage customers to return used products more often. We also discuss which investment strategy the manufacturer should consider for the two channels based on the trade-offs between the opportunity to sell new products by investing in the retailer and the reduction in production costs created by investing in the recycler.

The rest of this paper is organized as follows. We review the related literature in the next section. The developed simulation model of the CLSC, including the customer, manufacturer, retailer, and recycler, is described in Section 3. We provide the experimental results and the analysis of the manufacturer's investment strategies based on the model in Section 4. Finally, concluding remarks and suggested directions for further research are discussed in Section 5.

2. Literature Review

The CLSC is a model that integrates the FSC with its cycle of production, distribution, and delivery to customers, and the RSC with its cycle of collection, delivery, remanufacturing, and resale of used products [3]. Thus, the CLSC not only creates profit for corporations but also supports efforts to protect the natural environment. This mechanism, however, involves many factors, including the relationships among supply chain participants, price decisions, product retrieval strategy, regulations, and environmental restrictions, which in turn complicate decision-making by the participants [4]. This complexity has attracted researchers and field workers to study the subject for the past twenty years [1].

Savaskan and Van Wassenhove [5] studied an RSC with a single manufacturer and two retailers in a relationship of retail price competition. The study formulated and analyzed two decentralized CLSC models: (1) Model DD (decentralized direct collection), in which the manufacturer collects used products directly from the customers; and (2) Model DI (decentralized indirect collection), in which the manufacturer contracts with the retailers to collect used products indirectly.

The most fundamental issues in a CLSC are the decision-making factors that influence customer willingness. Prior to 2004, studies focused on decision-making by a central decision-maker or on optimizing the total system profit [6–9]; the trend evolved under Savaskan and Van Wassenhove [5]; who used game theory to solve problems among independent agents such as manufacturers and retailers. Mafakheri and Nasiri [10] introduced a typical leader-follower (Stackelberg) strategic decision-making game problem observed between manufacturers and retailers. In this problem, retailers determine the appropriate level of return incentives for customers based on the expected revenue shared by the manufacturer. Simultaneously, the manufacturer assumes that it can predict the behavior of the retailers and adjusts its revenue-sharing strategy to maximize its own profits.

Saha et al. [11] conducted a study at CLSC on the Reward driven policy to return used products from customers. They considered a single forward supply channel and three reverse supply channels. In the presented models, they analyzed how the maximum amount of recovery compensation that the retailer and recycler could pay to the customer and how it would affect the selling price of the product on the models if used products are recovered from the customer through both.

Studies have also analyzed how the main drivers that facilitate the return of used products influence the performance of the supply chain partners. Savaskan et al. [2] studied the impact of the choice of RSC on the forward channel decision and rate of the product return. Savaskan and Van Wassenhove [5] studied an RSC structure in which retailers compete; in this model, manufacturers directly collecting used products and indirectly collecting them through retailers were observed, and the impact of each method on wholesale and retail prices as well as the used products' return rate was analyzed. Yoon and Jeong [12] proposed three procedures for implementing contracts between the manufacturer and retailer to maximize both individual and total profits in an RSC environment.

Nielsen et al., [13] has tracked CLSC performance according to the three types of government subsidy to increase return rates of used products from customers on the CLSC channel. They pointed out that government support can contribute significantly to environmental effects as well as economic effects.

Chen and Chang [14] deal with the strategic issue of closed-loop supply chains with remanufacturing by developing analytical models under cooperative and competitive settings. The primary goal behind the analytic formulation is to investigate under what conditions an original equipment manufacturer (OEM) may take a cooperative approach by participating in remanufacturing. In contrast, the OEM may take a competitive approach by letting the third-party firm remanufacture the returned cores and remarket in the secondary market that competes with the new product.

The above studies considered only general contract design, such as the revenue sharing of the manufacturer, in the coordination among the collection partners [5, 10, 15]. Numerous formats of the contract between the manufacturer and retailer have been studied, such as buy-back, quantity-flexibility, revenue-sharing, price-discount, sales-rebate, and quantity discount [16–21]. However, when a manufacturer contracts with collector partners, for example, a retailer or a recycler, it has no information about collection intensity and collection cost. Therefore, it is a challenging problem for the manufacturer to design a proper contract mechanism under asymmetric partner information to maximize profits and ensure a sufficient collection rate. Li et al. [22] studied an incentive contract model in which a manufacturer assigns the used product collection to a company using only imperfect information on the company's collection costs under the extended producer responsibility (EPR) law. The contract design of the manufacturer incorporates the level of investment by its partner and the collection rate of that partner. Changes in contract design parameters in accordance with changes in the level of EPR law and remanufacturing cost were analyzed.

We propose three investment strategies of the manufacturer regarding two collection partners for an example of an ink cartridge: (1) the manufacturer shares some portion of its revenue with both partners, (2) the manufacturer shares some revenue with the retailer while paying a direct subsidy per unit returned cartridge to the recycler based on the number of used cartridges collected, and (3) a combination of (1) and (2).

The decisions about such strategic alternatives influence the volume of used products collected from customers, which in turn influences the profits of the partners and the revenue of the entire supply chain. Ultimately, the quantity of used products collected is an important factor linking cause and result variables in CLSC research. A critical assumption of most studies, however, is that the rate at which customers return used products is proportional to the size of the revenue shared by the manufacturer with collectors in collecting used products, regardless of customer willingness to respond to recycling rewards (cashback) offered by collectors. For example, where the retailer collects used products from its customers who directly visit the retailer, the rewards for the collection offered by the retailer to its customers, as well as the distance between the customers and the retailer, can be critical factors determining whether the customers will return the used products. The customers' tendency to favor cost savings by reuse can also affect collection activities. This study reflects not only the rewards for returning products provided to customers by the collection partner but also customer willingness, including their tendencies and their distance to the collector.

3. System Dynamics Model

3.1. Causal Relationships. A causal loop diagram (CLD) depicts the major variables linked together in a feedback cycle. In a CLD system, variables are linked by arrows that show interdependencies and feedback processes between variables, and the polarity markers near the arrows depict the effect of influence: positive for a direct effect and negative for an inverse influence [23].

Figure 1 depicts the causal loop diagram (CLD) of the CLSC model with a single recycler company and a retailer considered here. The goal of the model is to construct scenarios of various investment strategies used by the manufacturer with the collection partners, i.e., the retailer and the recycling company, and analyze the corresponding changes in the revenues of the manufacturer. Figure 1 also indicates the causal relationships in the manufacturer's strategy of sharing revenue with the retailer and the recycler. First, the manufacturer shares a part of its profit to encourage the retailer to collect used cartridges from customers. The retailer, in turn, uses the amount shared by the manufacturer to provide return rewards to customers. Consequently, the retailer's activity benefits the manufacturer by bringing in profits from selling more new products and providing used cartridges for the remanufacturing process, thereby reducing manufacturing costs.

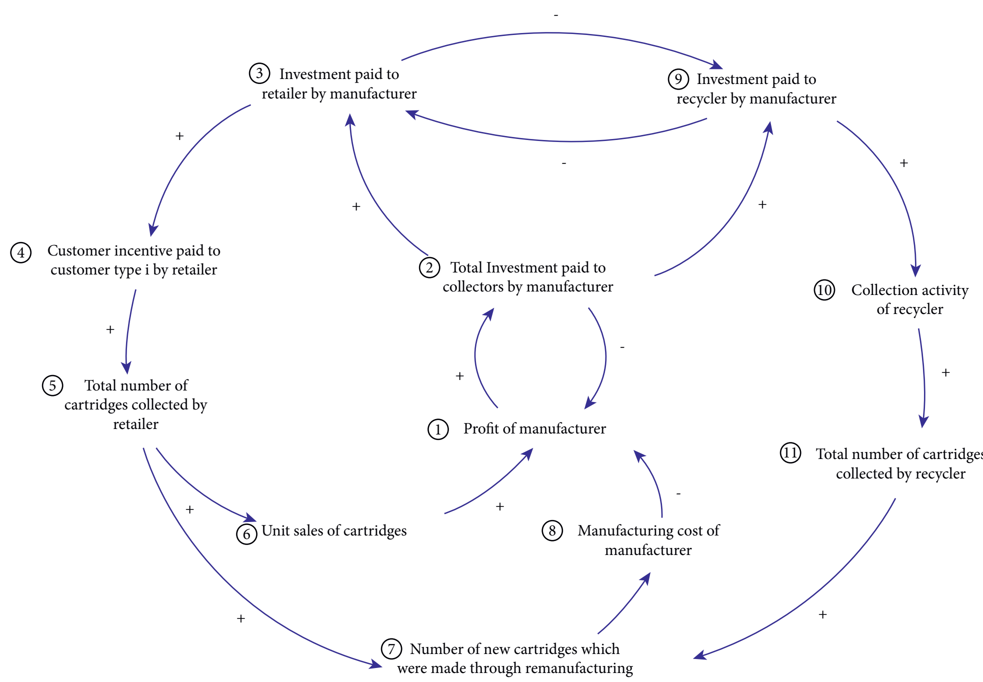
By contrast, the recycler uses the shared revenue to visit customers who find it bothersome to return cartridges. Consequently, the activities of the recycler only impact the manufacturing cost since its collection activity does not generate sales.

The revenue shared by the manufacturer with each partner is limited; if the manufacturer shares a greater portion with the retailer, the recycler will receive less, and vice versa.

Under these scenarios, if the manufacturer pays more to the recycler, the manufacturing costs are reduced more because the recycler can visit more customers, which in turn brings in more used cartridges. This, however, will reduce the amount shared with the retailer, which reduces the number of rewards that the retailer can provide to customers. Thus, the number of cartridges returned to the retailer will decline, along with the volume of new purchases, which will ultimately reduce new cartridge sales and the collection of used cartridges. There is a danger that the manufacturer's profit will decline if the sharing amount disproportionately favors one partner over the other. It is, therefore, important for the manufacturer to determine the appropriate ratio of amounts to be shared with the retailer and recycler.

3.2. Simulation Model Description. The simulation method is used to capture the decision-making process of the manufacturer, retailer, and recycler in the CLSC model for used ink cartridges. Table 1 lists the Nomenclature used in the simulation model.

A system dynamics (SD) model using Vensim Pro 5.9e software was built to perform the simulation. Figure 2



Reinforcing Loop		Balance Loop	
R1	① → ② → ③ → ④ → ⑤ → ⑥ → ①	B1	① → ② → ⑨ → ③ → ④ → ⑤ → ⑦ → ⑧ → ①
R2	① → ② → ③ → ④ → ⑤ → ⑦ → ⑧ → ①	B2	① → ② → ⑨ → ③ → ④ → ⑤ → ⑥ → ①
R3	① → ② → ⑨ → ⑩ → ⑪ → ⑦ → ⑧ → ①	B3	① → ② → ③ → ⑨ → ⑩ → ⑪ → ⑦ → ⑧ → ①
		B4	① → ② → ①

Figure 1: Causal loop diagram of the CLSC in this study.

presents the elements of the system dynamics model. To capture the value of the manufacturer and the two partners, we describe the decision-making processes of all participants in the SD.

3.2.1. Customer Types. For the ink cartridge example, we consider two types of customers with used ink cartridges. The first type includes those customers who prefer to refill the used cartridges because refilling is less expensive than buying new cartridges; these customers do not discard or return the used cartridges. Cooperation between the manufacturer and retailer is crucial in inducing these customers to return their used products; it is assumed that these customers would participate in the return cycle if the cost associated with returning the used cartridges and purchasing new ones was no different from that of refilling the used cartridges. Thus, the retailer would be able to change the customer's decision by providing sufficient rewards to return the used cartridges and purchase new ones.

The second type includes those customers who prefer to discard used cartridges as they find it bothersome to visit retailers to return used products. This group does not consider the return activity important. As they dislike visiting the retailer for this purpose, they will discard the cartridges when the ink runs out and purchase new ones via other channels, such as online markets.

Such customer behavior is observed more often among customers at a greater distance from the retailer, potentially implying that customers located nearer to the retailer would find the offered rewards more attractive and respond by returning the cartridges. The manufacturer would provide sufficient financial support to the retailer to offer collection rewards to customers by sharing more of its own revenue. In addition to addressing this customer segment, the manufacturer may consider employing a recycler to visit customers directly to collect used products.

Figure 3 shows the changes in customer types prior to and after the manufacturer, retailer, and recycler implement strategies to collect used cartridges. The left side shows the initial state of the customer grouping before the retailer and recycler collect the empty cartridges. At this point, the customers are grouped into those who prefer to refill and those who prefer to discard the used cartridges.

The right side shows the shift to four customer types after the retailer and the recycler introduce activities that encourage used ink cartridge returns. The customers who initially preferred refilling the used cartridges are split

Table 1: Nomenclature.

Index		
t	Index of time period $\{1,\ldots,T\}$	
M	Manufacturer	
R	Retailer	
3PL	Recycler = Third-party logistics company	
i	Customer type (1 = Customer who wants to discard the used cartridge, 2 = Customer who wants to refill the used cartridge)	
j	Collector type (1 = Retailer, 2 = Recycler)	
k	Customer group based on distance from the retailer (1 = first closest customer group, . . ., 5 = fifth closest customer group ∈ (1, 2, 3, 4, 5)	
τ	Scaling parameter	
Terms	**Description**	**Measure**
RP	Retail price	\$/unit
RFP	ReFilling price	\$/unit
WP	Wholesale price	\$/unit
RCF	ReCycling	Fee \$/unit
MC	Manufacturing cost	\$/unit
PMC	ReManufacturing cost	\$/unit
$\mathrm{PR}_{i\in\{1\},k,t}$	Perceived rewards of customer in period t	\$/unit
D_t	Demand of new customers purchasing cartridge in period t	Person/month
NC_{it}	Number of Customer type i in period t	Person/month
$\mathrm{WC}_{i\in\{1\},k,t}$	Willingness of Customer group k of customer type 1 in period t	%/month
$\mathrm{WC}_{i\in\{2\},t}$	Willingness of Customer type 2 in period t	%/month
QREM	Quantity of new cartridges REManufactured in period t	units/month
SP^j	Sharing Portion paid to collector j by manufacturer	%/month
TCR_t^R	Total number of Cartridges collected by Retailer in period t	units/month
RE_t^R	Return Rewards paid to the customer by the retailer in period t	\$/month
REmax_t^R	MAXimum return REwards paid to customer type i by retailer	\$/month
BRR^i	Basic Rewards Rate set by retailer	%
BRF^{3PL}	Basic Recycling fee set by Recycler	\$
CRP_t^R	Change rate of Retailer's Profit in period t	%/month
WF_k	Weight factor based on the distance between the retailer and customer group k	
REV_t	Total REVenue in period t	\$/month
COST_t	Total COST in period t	\$/month
TS_t^M	Total amount shared by the manufacturer with the retailer and recycler in period t	\$/month
PROFIT_t	Total PROFIT in period t	\$/month

between those who maintain their decision to refill and those who do not. Thus, some customers who prefer to refill decide to return their used cartridges to the retailer and buy new ones; their decision to refill or return will be dependent on the difference between the refill cost and the size of the rewards offered by the retailer.

Simultaneously, the customers who previously preferred to discard used products are newly segmented into two groups: those who return the used products via the recycler and those who still discard their used cartridges.

Customers who are physically closer to the retailer will respond more readily to the strategy by encouraging ink cartridge returns; that is, proximity to the retailer influences customers' perceptions of the rewards scale. To apply this concept to the relative perception of customers, we classified customers into five groups depending on their proximity to the retailer, from the first closest to the fifth closest. The perceived rewards scale is considered lower for customers with a greater physical distance from their retailer. Thus, the perceived rewards scale is calculated by multiplying the actual amount of rewards provided by the retailer by the weight factor of the distance between the retailer and customers. Among those who previously preferred disposal, some who are not responsive to the return rewards offered by the retailer because it is bothersome to visit the retailer directly will choose to return their cartridges if the recycler visits their location. We assume the recycler only pays them a basic return fee that is lower than the retailer reward. Finally, the remaining customers who are not attracted by the basic return fee offered by the recycler will maintain their initial choice to discard the used cartridges.

3.2.2. Manufacturer Profit. Manufacturer profit occurs when new products are sold via FSCs. Customers who purchase new products through the FSC are classified into new customers and previous customers who return their used products to the retailer. The total revenue of the manufacturer in the previous period can be defined as

$$\mathrm{REV}_t^M = \left[\left(D_t + \mathrm{TCR}_t^R\right) \times \mathrm{WP}\right], \quad t = 1, 2, \ldots, T. \qquad (1)$$

In general, the manufacturing cost of new products is considered greater than the cost of remanufacturing used products. Savaskan et al. [2] indicated that the savings of

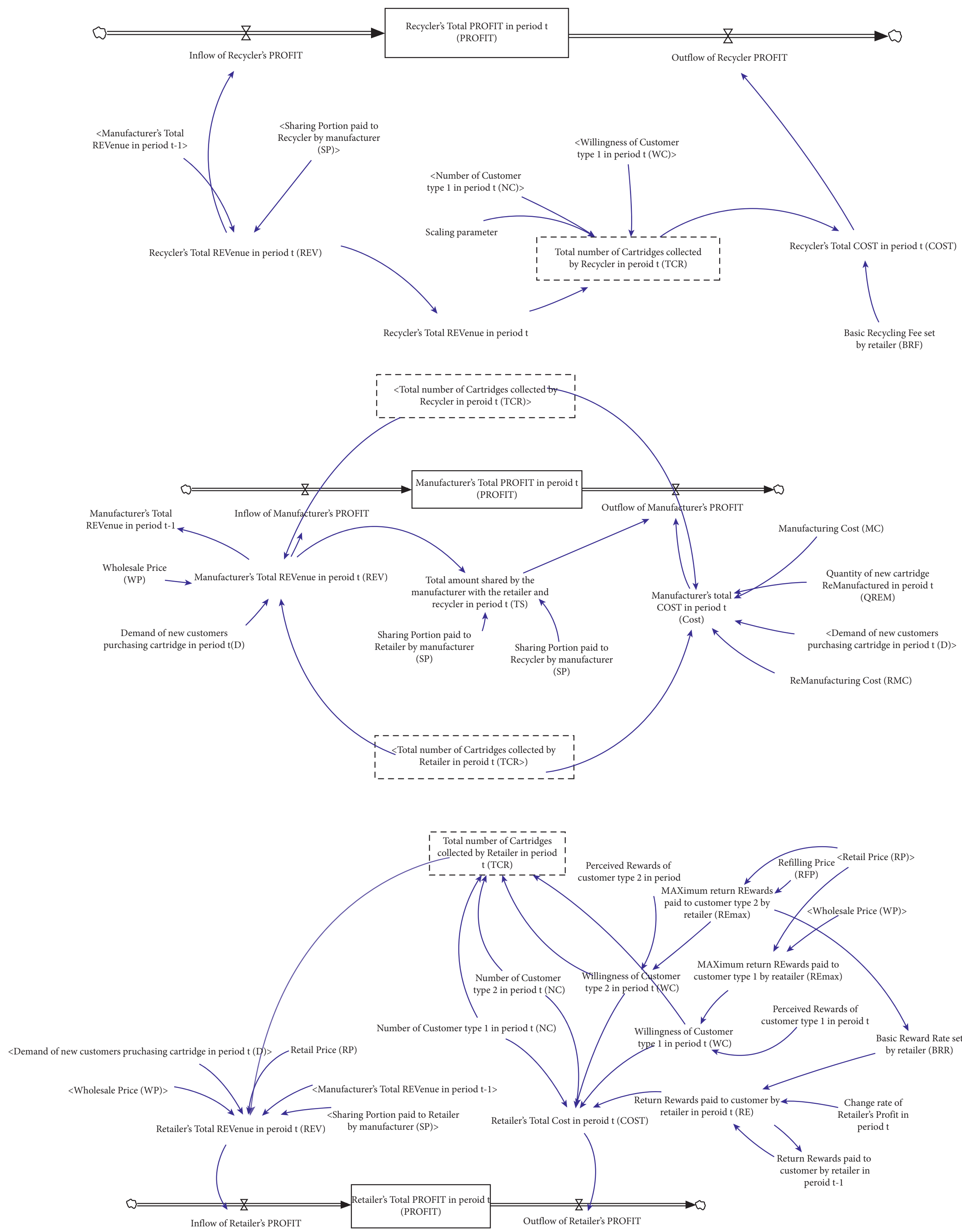


Figure 2: CLSC with a single manufacturer, single retailer, and single recycler.

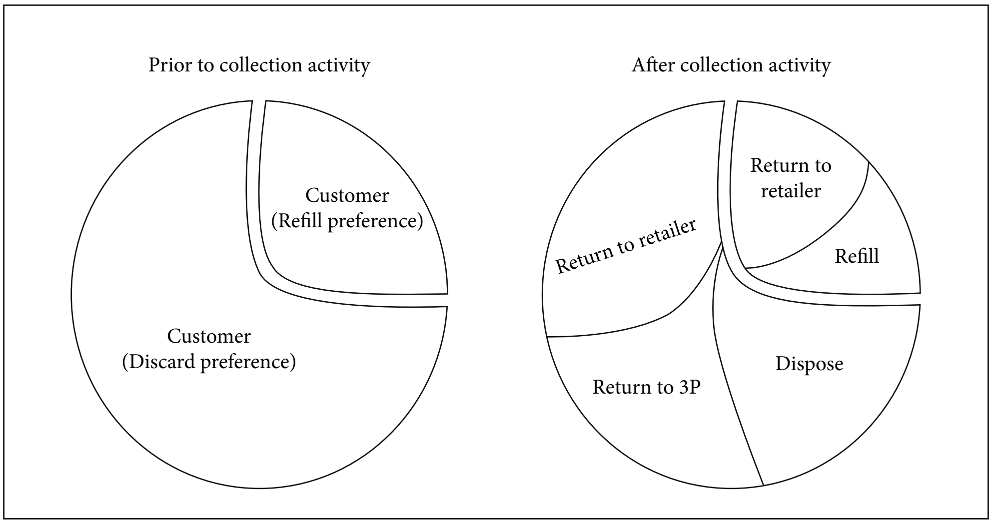


Figure 3: Changes in customer types prior to and after the collection activity.

materials and the assembly of subsystems for a new product are greater than the additional costs of disassembly, inspection for reusability, and the cost of remanufacturing. Consequently, the manufacturing cost of new ink cartridges will decrease as the number of cartridges produced by the remanufacturing process increases. The equation is designed to apply the remanufacturing cost if the proportion of remanufactured cartridges is small and use the manufacturing cost for the remaining product volume. Therefore, the total manufacturing cost of the manufacturer in each period can be defined according to

$$\mathrm{COST}_t^M = \left\{ \begin{array}{c} \left(D_t + \mathrm{TCR}_t^R\right) \geq \mathrm{QREM}_t^M, \left[\left(D_t + \mathrm{TCR}_t^R\right) - \mathrm{QREM}_t^M\right] \times \mathrm{MC} + \left(\mathrm{QREM}_t^M \times \mathrm{RMC}\right) \\ \left(D_t + \mathrm{TCR}_t^R\right) < \mathrm{QREM}_t^M, \left[\left(D_t + \mathrm{TCR}_t^R\right) \times \mathrm{RMC}\right] \end{array} \right\}, \quad t = 1, 2, \ldots, T. \tag{2}$$

In addition, the manufacturer shares some revenue to allow the retailer and recycler to collect the used cartridges more proactively. This study seeks to analyze the changes to the manufacturer's profit depending on the amount of revenue shared with each partner by each sharing method. Equation (3) indicates the total amount of revenue sharing by the manufacturer with the retailer and recycler in each period. Thus, the manufacturer's profit during the total simulation time is calculated from the difference between the total revenue and the sum of the cost of manufacturing new cartridges and the amount of revenue shared with each of the retailer and the recycler, as shown in

$$\mathrm{TS}_t^M = \sum_j \mathrm{REV}_t^M \times \mathrm{SP}^j, \quad t = 1, 2, \ldots, T, \ j = 1, 2, \tag{3}$$

$$\mathrm{PROFIT}^M = \int_{t=0}^{T} \mathrm{REV}_t^M - \mathrm{COST}_t^M - \mathrm{TS}_t^M \mathrm{d}t. \tag{4}$$

3.2.3. Retailer Profit. Because customers who return their used cartridges to the retailer will buy new ones from the retailer, a larger volume of used ink cartridges returned to the retailer will increase new cartridge sales. Although the retailer seeks to collect used ink cartridges to gain increase sharing by the manufacturer, more significantly, the retailer has more opportunities to sell new products when customers return used cartridges. The rewards offered by the retailer to the customers originate from the sales profit in the previous period and the revenue shared by the manufacturer.

The retailer provides distinct rewards to customers who prefer disposal and those who prefer to refill their used cartridges. Because the former group will return more cartridges when the rewards scale is larger, it is assumed that

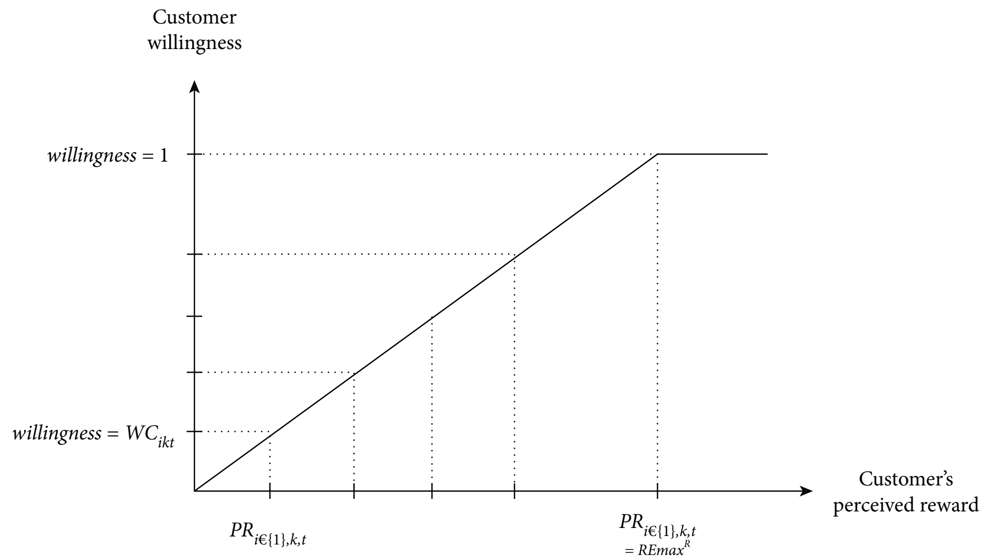


Figure 4: Linear function of the willingness to return according to the change in the customer's perceived rewards.

the retailer will set a minimum reward for these customers and adjust the magnitude of the reward in the following periods depending on the profit changes in the previous period. Equations (5) through (7) address the rewards offered to customers preferring disposal.

$$\mathrm{REmax}_i^R = \begin{cases} \mathrm{RP} - \mathrm{WP}, & i = 1, \\ \mathrm{RP} - \mathrm{RFP}, & i = 2, \end{cases} \quad (5)$$

$$\mathrm{RE}_{it}^R = \left\{ \max\left[\mathrm{BRR}^R \times \mathrm{REmax}_i^R, \mathrm{RE}_{it-1}^R + \left[\left(1 - \mathrm{BRR}^R\right) \times \mathrm{REmax}_i^R \times \mathrm{CRP}_t^R\right]\right]\right\}, \quad i = 1, 2;\ t = 1, 2, \ldots, T, \quad (6)$$

$$\mathrm{RE}_{i,t=0}^R = \mathrm{BRR}^R \times \mathrm{REmax}_i^R, \quad i = 1, 2. \quad (7)$$

Whether disposal-leaning customers will alter their decision is determined by the customer's perception of the rewards provided by the retailer, which is dependent on the customer's geographic distance from the retailer. We defined this concept as perceived perception and assumed that the customer's willingness to return rather than discard is linearly proportional to the size of the perceived rewards (see equation (8)), as shown in Figure 4 [15].

$$\mathrm{WC}_{i\in\{1\},k,t} = \begin{cases} \dfrac{\mathrm{PR}_{i\in\{1\},k,t}}{\mathrm{REmax}_{i\in\{1\}}^R}, & 0 < \mathrm{PR}_{i\in\{1\},k,t} < \mathrm{REmax}_{i\in\{1\}}^R, \\ 1, & \mathrm{PR}_{i\in\{1\},k,t} > RE\max_{i\in\{1\}}^R, \end{cases} \quad k = 1, 2, \ldots, 5;\ t = 1, 2, \ldots, T. \quad (8)$$

Furthermore, we define the probability of collecting cartridges from customers who prefer to refill them as customer willingness to return rather than refill. As shown in equation (9), the probability to collect used cartridges is determined by the difference between the cost to refill and the cost to purchase new products at the discount price offered for returning cartridges. The customer's willingness to return rather than refill increases when the discount price of the new product is closer to the cost of the refill; if there is no difference between the former and the latter costs, we assume that all refill-preferring customers will choose to return their used ink cartridges [10].

$$\mathrm{WC}_{i\in\{2\},t} = \frac{\mathrm{RE}_{i\in\{2\},t}^R}{\mathrm{REmax}_{i\in\{2\}}^R}, \quad t = 1, 2, \ldots, T. \quad (9)$$

Finally, equation (10) indicates the number of customers who prefer to discard rather than return the used ink cartridges and the volume of collected cartridges from refill-preferring customers.

$$\mathrm{TCR}_t^R = \sum_k \mathrm{NC}_{i\in\{1\},t} \times \mathrm{WC}_{i\in\{1\},k,t} + \mathrm{NC}_{i\in\{2\},t} \times \mathrm{WC}_{i\in\{2\},t}, \quad t = 1, 2, \ldots, T. \tag{10}$$

New product sales are generated from new customers and from customers who return used cartridges and buy new ones. Equation (11) shows that the retailer's revenue comprises sales profits from new cartridges and the amount shared by the manufacturer to encourage customers to return used products. The costs paid to the customer by the retailer, as shown in equation (12), are determined by the size of the rewards for each customer. Consequently, the profit of the retailer can be defined according to equation (13):

$$\mathrm{REV}_t^R = \left(D_t + \mathrm{TCR}_t^R\right) \times (\mathrm{RP} - \mathrm{WP}) + \mathrm{REV}_{t-1}^M \times \mathrm{SP}^R, \quad t = 1, 2, \ldots, T, \tag{11}$$

$$\mathrm{COST}_t^R = \left(\sum_k \mathrm{NC}_{i\in\{1\},t} \times \mathrm{WC}_{i\in\{1\},k,t}\right) \times RE_{i\,\in\,\{1\},t}^R + \left(\mathrm{NC}_{i\in\{2\},t} \times \mathrm{WC}_{i\in\{2\},t}\right) \times \mathrm{RE}_{i\in\{2\},t}^R, \quad t = 1, 2, \ldots, T, \tag{12}$$

$$\mathrm{PROFIT}^R = \int \mathrm{REV}_t^R - \mathrm{COST}_t^R \mathrm{d}t. \tag{13}$$

3.2.4. Recycler Profit. The recycler collects used products by visiting customers who prefer disposal. The current study assumes that the volume of cartridges collected by the recycler is proportional to its ability to visit customers within a given period, which in turn is determined by the portion of the profit shared by the manufacturer [2] (see equation (15)).

The recycler's profits are determined by the profits shared by the manufacturer minus the basic return fee required to visit customers and collect used cartridges, as indicated by

$$\mathrm{REV}_t^{3\mathrm{PL}} = \mathrm{REV}_{t-1}^M \times \mathrm{SP}^{3\mathrm{PL}}, \quad t = 1, 2, \ldots, T, \tag{14}$$

$$\mathrm{TCR}_t^{3\mathrm{PL}} = \left[\mathrm{NC}_{i\in\{1\},t} - \left(\sum_k \mathrm{NC}_{i\in\{1\},t} \times \mathrm{WC}_{i\in\{1\},k,t}\right)\right] \times \sqrt{\frac{\mathrm{REV}_t^{3\mathrm{PL}}}{\tau}}, \quad t = 1, 2, \ldots, T, \tag{15}$$

$$\mathrm{COST}_t^{3\mathrm{PL}} = \mathrm{BRF}_{i=1}^{3\mathrm{PL}} \times \mathrm{TCR}_t^{3\mathrm{PL}}, \quad t = 1, 2, \ldots, T, \tag{16}$$

$$\mathrm{PROFIT}^{3\mathrm{PL}} = \int_{t=0}^{T} \mathrm{REV}_t^{3\mathrm{PL}} - \mathrm{COST}_t^{3\mathrm{PL}} \mathrm{d}t. \tag{17}$$

4. Simulation Experiment Results

We analyzed how much an investment would maximize profits when the manufacturer invests a percentage in two channels with different return objectives. When making decisions about the size of the investment, the manufacturer considers the following relationship. If the manufacturer allocates a large share of the profits to the retailer, the return volume from customers who prefer refilling will be large, and chances for the manufacturer to sell new cartridges will increase. However, sharing more profits with the retailer reduces the rate of investment in the recycler and makes it difficult to collect more cartridges from customers who prefer disposal. The reduced recovery by the recycler also reduces the manufacturer's opportunity to reduce production costs by remanufacturing the returned cartridges during a new cartridge production process. Therefore, manufacturers should determine the appropriate ratio of investment to be paid to the two channels by analyzing the trade-offs between the opportunity to sell new products by investing in the retailer and the reduction in production costs created by investing in the recycler.

Equation (18) shows the manufacturer's profitable relationship for the simulation experiment. Here, s represents the difference between the wholesale price and the manufacturing cost of a new cartridge, and k is the difference between the cost of manufacturing and remanufacturing. That is, the value of s reflects the size of the manufacturer's profit margin when the retailer sells a new cartridge to a customer who prefers to refill. The value of k reflects the size of the cost-saving effect of using a cartridge collected by the recycler to produce a new cartridge. As both benefits can vary with changes in s and k, we set the ranges of s and k and performed a sensitivity analysis to track the differences in the ratio of investments in both channels according to these changes. The interim values of s and k ($s = 0.65$; $k = 0.6$) were used as the initial values for the experiment.

$$\begin{cases} \text{MC} = s.\text{WP}, & 0.5 \leq s \leq 0.8, \\ \text{RMC} = k.\text{MC}, & 0.4 \leq s \leq 0.8. \end{cases} \tag{18}$$

4.1. Manufacturer's Revenue-Sharing Investment Strategy. Figure 5 describes the procedure in which the manufacturer applies the revenue-sharing investment (RSI) strategy at time t. Based on the sales and recovery activities of the retailer and recycler, respectively, over the period $t-1$ (previous period), the manufacturer calculates its net profit at the beginning of period t. Some portion of the net profit is then set as an investment budget to support the return of used cartridges by retailers and recyclers over the period t. The manufacturer determines the percentage of the investment budget to invest in each retailer and recycler.

Figure 6 and Table 1 show the manufacturer's profit margin, cost savings, and net profits by increasing and decreasing the investment shares of the retailer and recycler by 5% with $s = 0.65$ and $k = 0.6$. The results of the experiment show that there is a greater effect on profit sharing at the proper level than investing in either channel. This result proves that new cartridge sales due to investments in retailers and the savings in production costs from investments in recyclers have a trade-off relationship.

As shown in Table 2, when $s = 0.65$ and $k = 0.6$, the manufacturer generates the highest profits when investing equal portions of its profits in the retailer and recycler. We further analyzed the investment amount paid per unit returned based on the investment amounts paid to the retailer and the recycler using the optimal rate. This analysis was performed to investigate whether the size of the investment in both channels is excessive to the volume actually returned when the manufacturer applies the RSI strategy.

As stated above, the effect expected by the manufacturer in supporting the return channel with the retailer is that customers who preferred refilling visit the retailer to return used cartridges and buy new ones. Thus, the manufacturer's per unit profit from the recovery of a unit used cartridge by the retailer is the difference between the wholesale price and the manufacturing cost. When $s = 0.65$, since the marginal investment per unit (WP-MC) is 0.35, it is appropriate for the manufacturer to invest 0.31 per unit of recovery volume in the retailer. By contrast, the effect expected by the manufacturer from investing in the recycler's return activity is to increase the return rate of the recycler by providing customers who preferred to dispose of their used cartridges with the proper incentive.

Thus, the expected effect of the manufacturer is to reduce manufacturing costs by remanufacturing returned cartridges, which is expressed as WC-RMC. When $k = 0.6$, the marginal manufacturing cost per unit cartridge is 0.29 (0.65–0.39). Since the manufacturer invests 0.34 in the recycler to return per unit in the RSI strategy, an overinvestment of 0.08 occurs. This excess investment occurs because the manufacturer paid part of its profits without understanding the level of the return rate against the investment in the recycler.

4.2. Direct Subsidy Payment per Unit Returned Cartridge. To prevent excess investment in the recycler when the RSI strategy is applied, a direct subsidy per unit returned cartridge (DSURC) strategy is proposed. This strategy consists of paying the recovery activity subsidy at the beginning of period t in proportion to the return rate of the recycler during period $t-1$ before applying the RSI strategy.

Figure 7 shows the detailed procedure for implementing the DSURC strategy. Similar to the RSI strategy, the manufacturer allocates a portion of its net profit to both channels at a predetermined rate. However, in the total investment, the manufacturer first allocates the basic subsidy per unit for the amount collected by the recycler during period $t-1$. The manufacturer then determines the size of the investment to be paid to each retailer and recycler for the remaining investment. A major decision in this strategy is to determine how much the manufacturer allocates for the additional subsidy per unit to promote the activity during period t in addition to the basic subsidy to the recycler. The total amount of additional grants per unit is also paid in proportion to the number of used cartridges collected by the recycler over period t, and the remaining amount is paid to the retailer as the investment during period t.

The results of the experiment using this strategy to maximize the manufacturer's profit are shown in Table 3. The net profit of the manufacturer is 12.9, indicating better results than with the RSI strategy. In the analysis of the unit investment, the unit investment paid to the recycler is 0.22, which is lower than the marginal cost of 0.26. Thus, the DSURC strategy is effective in preventing excess investment. However, the DSURC strategy can negatively affect the return rate of the recycler because the reduction in unit investment will lower the incentive levels offered to customers who preferred disposal.

To monitor these phenomena, we examined the differences in the return rate of the recycler between the RSI strategy and the DSURC strategy. The recycler's return rate is approximately 7% lower under the DSURC strategy than under the RSI strategy. Of course, this reduced share of the investment in the recycler compared with the RSI strategy increases the share of the investment in the retailer and the return rate of the retailer. However, as shown in Figure 1, because the number of customers that the recycler visits is larger than the number of customers who visit the retailer, the increase in the return rate from the retailer has a limited effect on maximizing the manufacturer's net profit.

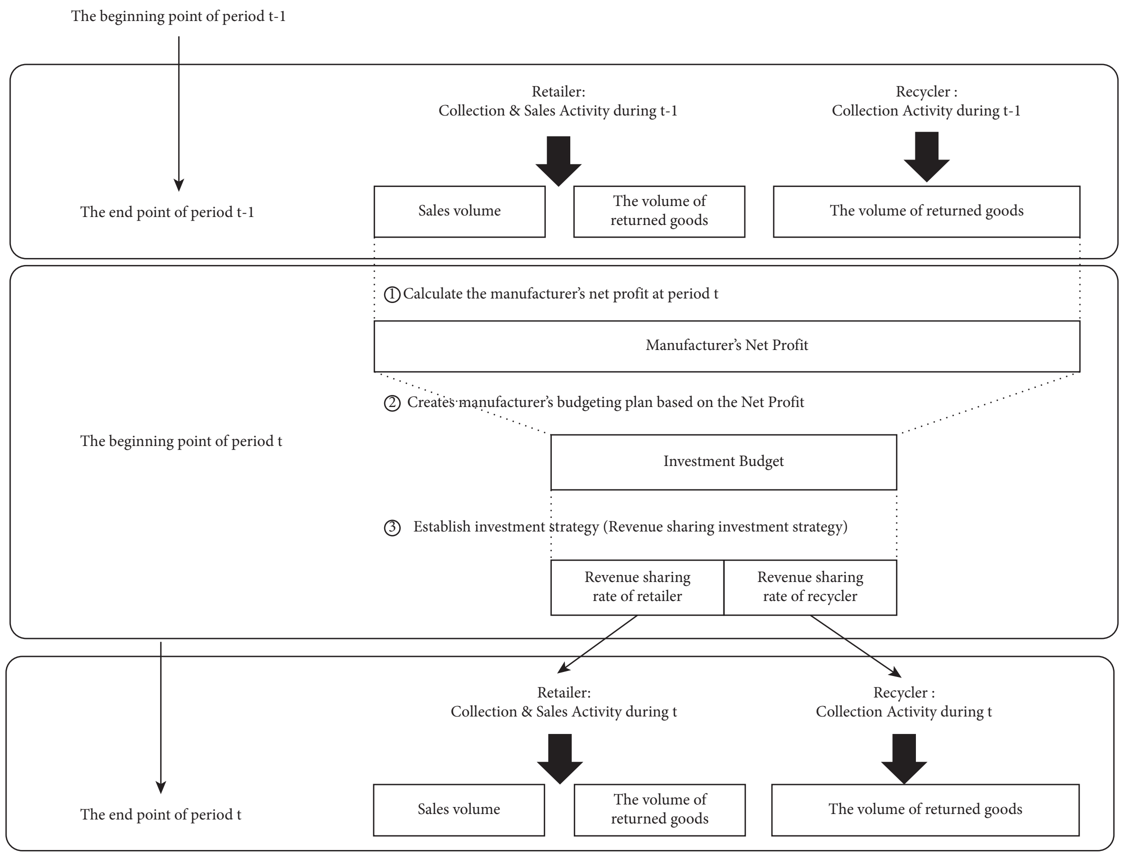


Figure 5: Linear function of the willingness to return according to the change in the customer's perceived rewards.

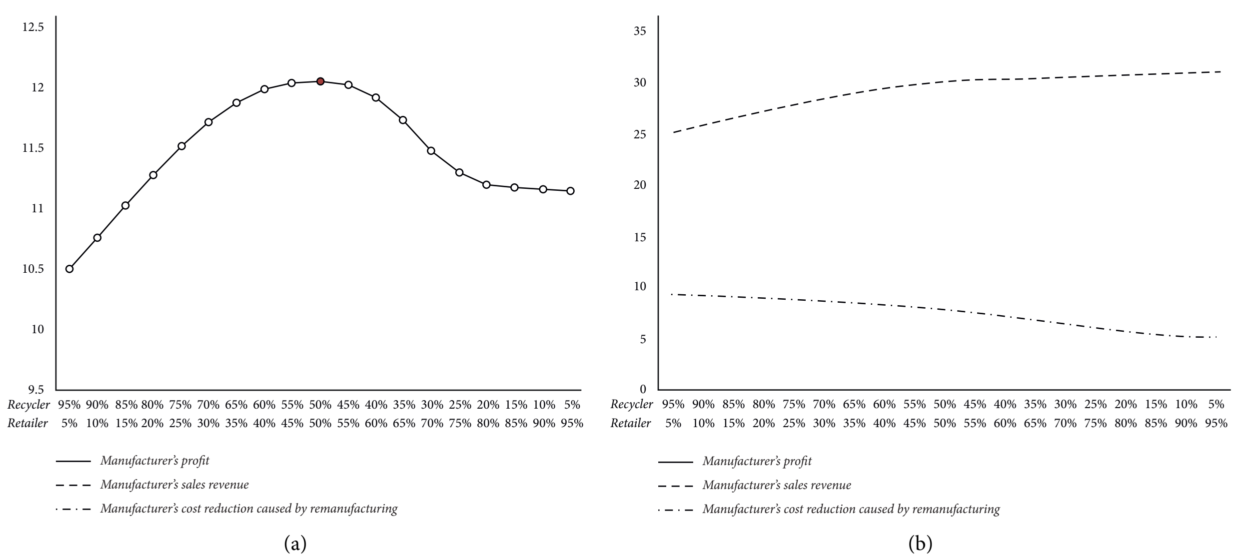


Figure 6: A graphical presentation of the results for the revenue-sharing strategy ($s = 0.65$, $k = 0.6$).

4.3. Manufacturer's Hybrid Investment Strategy. Figure 8 shows the implementation procedures for the hybrid strategy to complement the weaknesses of the RSI and DSURC strategies. Similar to the DSURC strategy, the manufacturer pays the basic subsidy to the recycler based on the number of used cartridges collected during period $t-1$. For the remaining investments, as with the RSI strategy, the optimal sharing ratio for the two channels is determined to maximize the manufacturer's profits. This strategy avoids excessive investment by providing basic grants for the performance of the return activities the recycler has performed over the previous period.

Table 2: Results for the revenue-sharing strategy ($s = 0.65$, $k = 0.6$).

Manufacturer's investment		Manufacturer's profit	Manufacturer's sales revenue	The effect of manufacturing cost reduction
Retailer (%)	Recycler (%)			
5	95	10.51	25.08	9.34
10	90	10.76	25.73	9.22
15	85	11.04	26.48	9.12
20	80	11.28	27.18	9.01
25	75	11.52	27.88	8.88
30	70	11.72	28.51	8.73
35	65	11.88	29.04	8.54
40	60	11.99	29.49	8.34
45	55	12.04	29.83	8.12
50	50	12.06	30.10	7.88
55	45	12.03	30.28	7.63
60	40	11.92	30.30	7.35
65	35	11.73	30.43	6.99
70	30	11.48	30.58	6.55
75	25	11.30	30.67	6.11
80	20	11.20	30.76	5.76
85	15	11.18	30.89	5.50
90	10	11.17	30.99	5.30
95	5	11.15	31.10	5.16

Detailed analysis of optimal investment in the revenue-sharing strategy

Total investment of manufacturer		Manufacturer's profit	Proportion of customers who return cartridges		Manufacturer's investment/ returned cartridge unit	
Recycler	Retailer		Recycler	Retailer	Recycler	Retailer
4.36 (50%)	4.36 (50%)	12.06	67.8%	32.2%	0.34	0.31

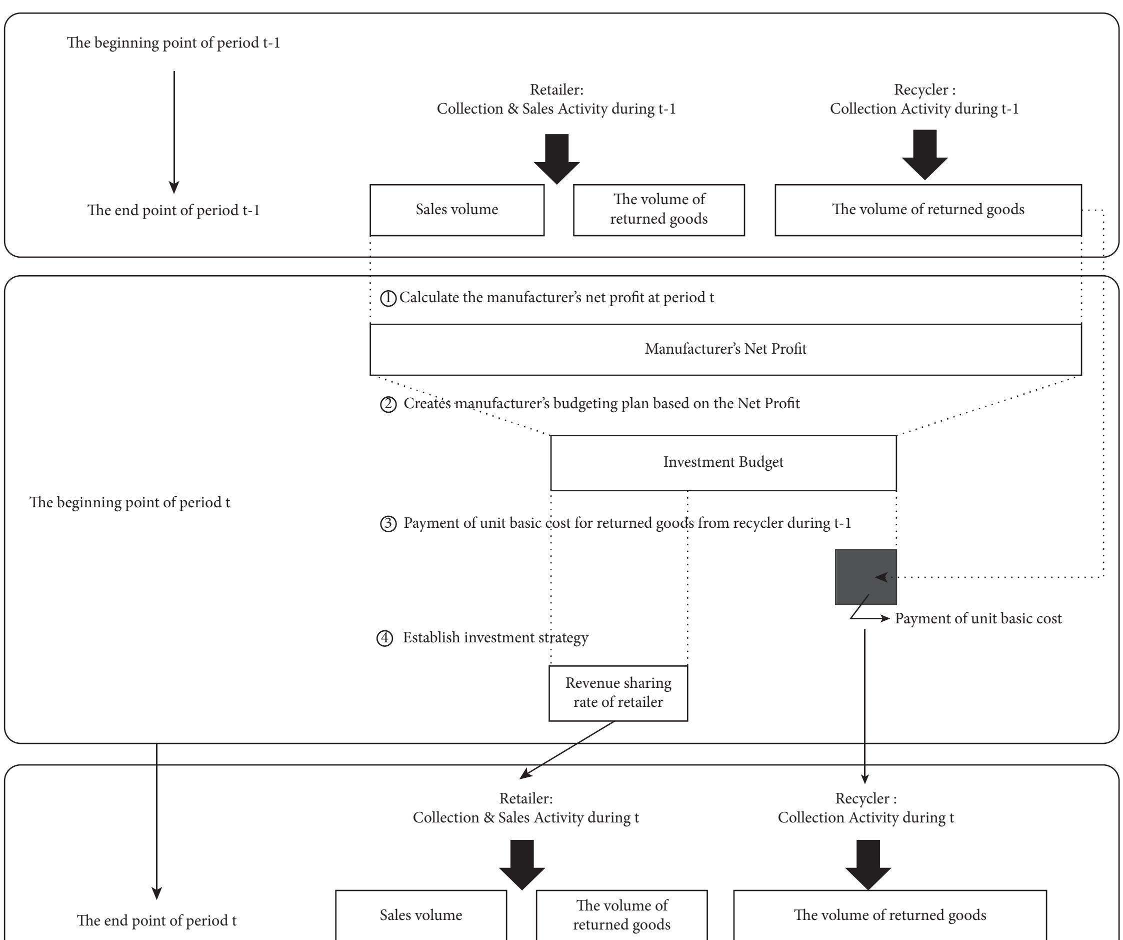


Figure 7: The procedure for direct payment per unit returned cartridge.

Table 3: Results of the payment strategy per unit returned cartridge ($s = 0.65$, $k = 0.6$).

Manufacturer's investment: Retailer	Manufacturer's investment: Recycler	Manufacturer's profit	Manufacturer's sales revenue	Total investment	The effect of manufacturing cost reduction
Share of revenue from manufacturing cost reduction + Share of revenue from new cartridge sales = (74%)	0.139/return cartridge	11.4	29.1	2.1	3.8
	0.167/unit returned cartridge	12.4	30.3	3.8	6.4
	0.222/unit cartridge	12.9	32.2	5.6	8.5
	0.278/return cartridge	12.4	33.4	7.1	9.9

Detailed analysis of optimal investment in the payment strategy per unit returned cartridge

Total investment of manufacturer		Manufacturer's profit	Proportion of customers who return cartridges		Manufacturer's investment/returned cartridge unit	
Recycler	Retailer		Recycler	Retailer	Recycler	Retailer
2.01 (26%)	5.81 (74%)	12.9	57.4%	42.6%	0.22	0.356

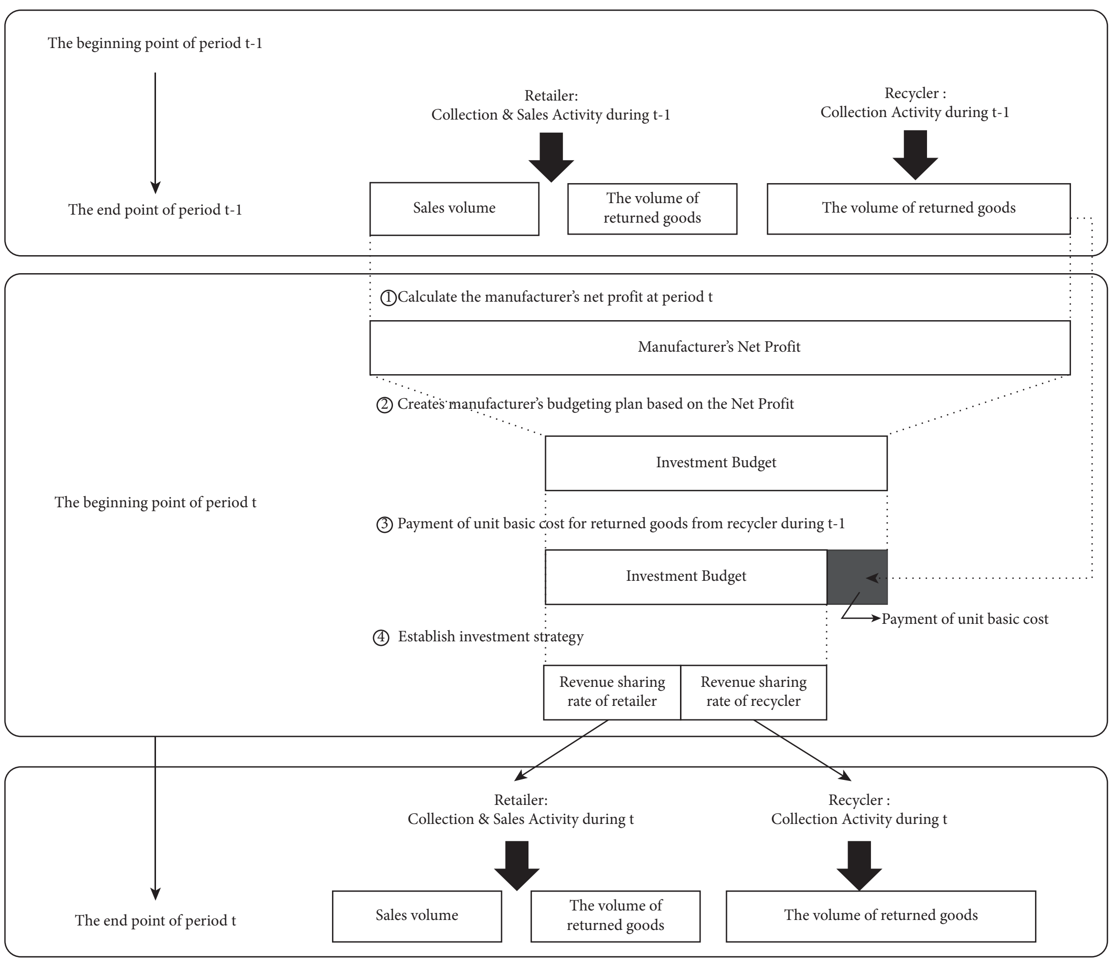


Figure 8: The procedure for the hybrid investment strategy.

The remainder of the amount is used to facilitate the return activity of the recycler during period t by providing the investment in advance at the beginning of period t.

Table 4 shows the results of the hybrid strategy. Based on the implementation of this strategy, we determined the sharing ratio of both channels that maximizes the manufacturer's profit. The manufacturer's net profit is 13.34, revealing a positive effect on increasing the profits of the manufacturer compared with applying the two strategies separately. Based on the investigation of the unit investment amount for each return channel, the manufacturer paid 0.26 and 0.31 per unit return to the recycler and retailer, respectively. Although the

Table 4: The results of the hybrid investment strategy ($s = 0.65$, $k = 0.6$).

Manufacturer's investment		Manufacturer's profit	Manufacturer's sales revenue	Total investment	The effect of manufacturing cost reduction
Retailer	Recycler				
Share of revenue from manufacturing cost reduction + Share of revenue from new cartridge sales = (66%)	Share of revenue from manufacturing cost reduction (5%) + 0.111/ return cartridge	11.9	29.1	2.5	5.5
	Share of revenue from manufacturing cost reduction (10%) + 0.111/ return cartridge	12.6	30.6	3.3	7.3
	Share of revenue from manufacturing cost reduction (15%) + 0.111/ return cartridge	13.1	31.5	3.9	8.1
	Share of revenue from manufacturing cost reduction (20%) + 0.111/ return cartridge	13.3	32.5	4.6	8.8

Detailed analysis of optimal investment in the hybrid investment strategy

Total investment of the manufacturer		Manufacturer's profit	Proportion of customers who return cartridges		Manufacturer's investment/ returned cartridge unit	
Recycler	Retailer		Recycler	Retailer	Recycler	Retailer
2.77 (35%)	5.15 (66%)	13.34	61.3%	38.7%	0.26	0.310

investment per unit return paid to the recycler was 0.04, higher than under the DSURC strategy, the return rate from the recycler was higher than under the DSURC strategy. Thus, it is more effective for manufacturers to use a hybrid of the two strategies to prevent excessive investment in the recycler and to increase the return rates from both channels.

4.4. Sensitivity Analysis. Based on the previous experiments in Sections 4.1 to 4.3, the hybrid strategy is effective in terms of increasing manufacturer profits, avoiding excess investment by the recycler, and promoting return activity through the recycler. However, since the results are only valid for the median ($s = 0.65$, $k = 0.6$) of the two parameters, a sensitivity analysis is performed to verify that the results of the experiment are robust, even with the changes in the two parameters.

The four additional scenarios were further tested through a combination of two parameters with a minimum and maximum value in Figure 9. Case 1 has a noticeable reduction in manufacturing costs over the new sales profit effects. In Case 1, the reduced manufacturing cost effect due to remanufacturing is greater than the new sale effect (s: high, k: low), and in Case 2, the manufacturing cost savings and new sales effect are significant for increasing the manufacturer's profits (s and k: low). In Case 3, the return activities of both channels have a low impact on the change in the manufacturer's profits (s and k: high). Case 4 is the opposite of Case 1; i.e., the new sales effect generated by the retailer's return activity is great.

The results for Cases 1 and 2 show that it is more effective for the manufacturer to directly pay the appropriate subsidy to compensate the recycler for performing the return activity during the previous period and then determine the optimal sharing ratio between the two channels to allocate the remaining investment. The different investment methods in the recycler before and after the return activity could simultaneously promote the return activity and avoid excess investment in the recycler, eventually increasing the manufacturer's profits during period t.

Although the hybrid strategy mixing the RSI and DSURC strategies is clearly valid for increasing the return rate of the recycler during period t by allocating high investment in the recycler, there is still a risk of excess investment in the recycler. Therefore, in cases where the manufacturing cost reduction effects due to the recycler's activity are greater than the cost of overinvestment in the recycler, the hybrid strategy can be applied effectively.

By contrast, in Cases 3 and 4, when the manufacturing cost saving is limited due to the small difference between the manufacturing costs and remanufacturing costs, the manufacturer should prevent excessive investment in the recycler through the return on investment per unit. That is, the manufacturer should determine the optimal amount of investment in the recycler based on the amount recovered over the previous period and adjust the sizes of investment in both channels within the confines of no excess investment.

4.5. Managerial Implication. As the importance of the recovery supply chain increases, the manufacturer leading the supply chain should make efforts to promote recovery activities through strategic partnerships with

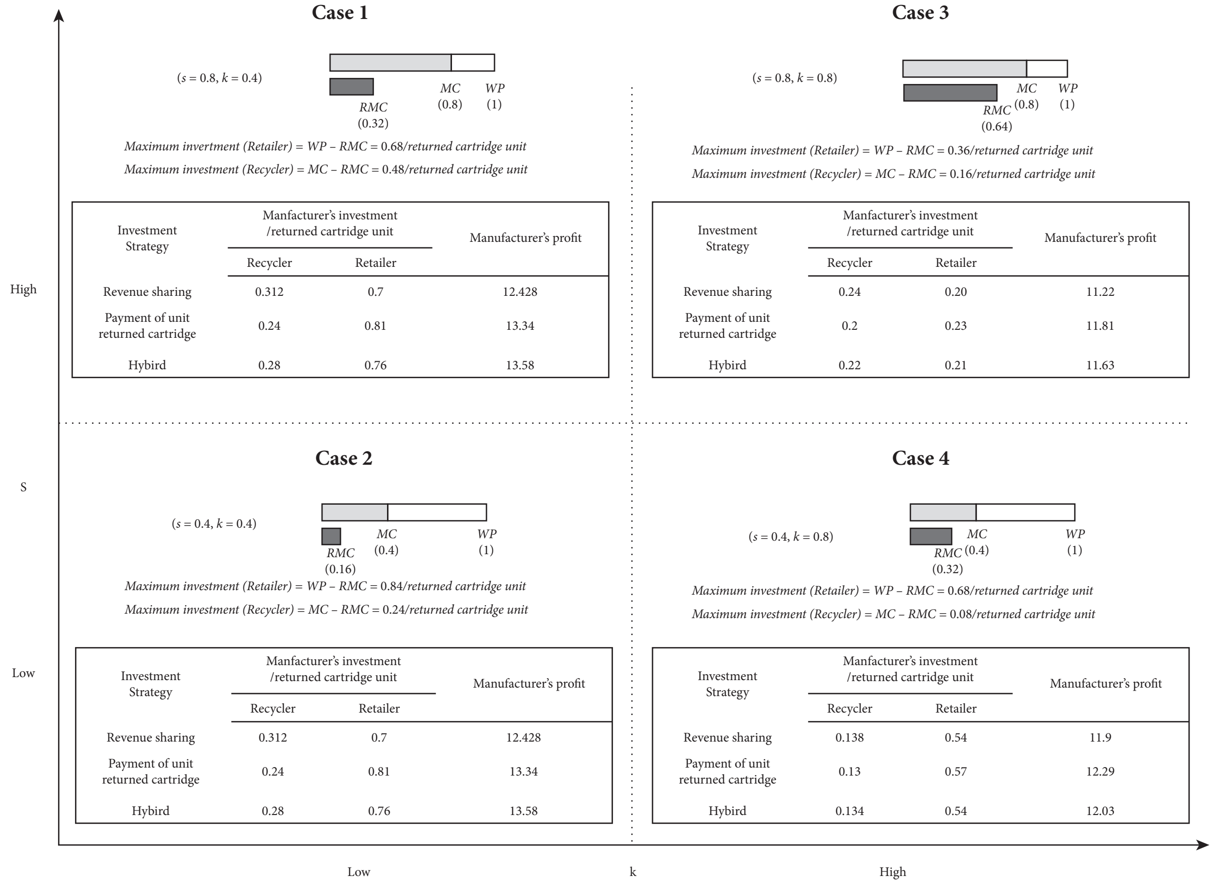


Figure 9: Sensitivity analysis with two parameters.

supply chain partners such as retailers or recyclers to increase its own profit. It is self-evident that the manufacturer should provide adequate compensation to recyclers and retailers participating in recovery activities to make recovery channels more active. Partners will expect the promise of appropriate compensation to precede the active implementation of recovery activities at the request of the manufacturer. Consequently, the manufacturer should establish appropriate investment strategies for profit sharing or compensation amounts through pre-simulation to pay compensation based on profit sharing and recovery rates. The analytical procedures and experimental analysis results presented in this study are believed to contribute to helping the manufacturer make decisions on the level of investment it can provide to prevent excessive investment in advance and enhance their partners' recovery activities.

5. Conclusion

This paper explores the investment strategies of the manufacturer in a CLSC comprising a single manufacturer, retailer, and recycler. We discuss how and to what extent a manufacturer should share its profits with the retailer and recycler, which have different goals and methods of collection activities. The experimental results reveal that the best investment strategy is for the manufacturer to offer differentiated payments to the retailer and recycler considering the degree of the trade-off relationship between sales profit and the manufacturing cost reduction effect. Our results have practical value by simulating a scenario-based analysis of the trade-offs a manufacturer faces in generating its own maximum revenue from sharing amounts with a retailer and a recycler collecting used products.

While this study creates a better understanding of the effects of a manufacturer's sharing strategy in a CLSC, additional analyses are needed. Extensions can add multiple partners and establish a competitive relation in attracting more used products. Additionally, to observe the real application of the proposed strategies, a sensitivity analysis that changes the unit prices (e.g., the wholesale price and retail price) and relevant unit costs in our model should be included.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this article.

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Research Article

A Tripartite Game Analysis of Environmental Pollution Control Based on Complicated Intergovernmental Relations

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An excellent ecological environment is conducive for improving economic benefits and social benefits. The environmental pollution control requires the cooperation of governments at all levels and a large amount of capital investment. However, under the system with Chinese characteristics, the intergovernmental relations present complex and dynamic characteristics: the central government is authoritative, the local governments are obedient and self-interested, and the environmental pollution control usually involves multiple government departments, while it has strong externality, which makes it easy to breed "free rider" behavior in the process of environmental pollution control. Therefore, the cross-regional environmental pollution control cooperation model of governments at all levels is a complex and worthwhile research problem. Based on this, the paper studies a tripartite game problem of environmental pollution control from both horizontal and vertical intergovernmental relations. The Hamilton–Jacobi–Bellman equation was used to obtain the optimal effort strategy, environmental pollution control level, and environmental pollution losses under the Nash game model, the Stackelberg game model, and the Cooperative game model. The results show the following: firstly, the governments' environmental pollution control efforts are positively related to their own execution ability and influence ability and negatively related to the cost coefficient; secondly, from the perspectives of environmental pollution control level and environmental pollution losses, the Cooperative game model is superior to the Nash game model and the Stackelberg game; thirdly, this paper analyzes the relationship between the loss-bearing ratio, the special financial funds, the effort level of government, and the environmental pollution control level; finally, the conclusions are verified by numerical analysis, which proves the validity of the models.

1. Introduction

With the acceleration of globalization and regional economic integration, China's regional environmental pollution problems have become increasingly prominent, showing obvious regional characteristics [1–3]. The deterioration of the overall regional environmental quality is a severe threat to public health and economic development. It is tough to control the spread of pollutants, as the ecological environment is increasingly showing obvious integration characteristics, and a single local government is often unable to solve complex regional environmental problems. Therefore, as an effective form of environmental protection, cross-regional cooperation in environmental governance has received widespread attention [4]. However, due to the externality of environmental pollution control and the division of administrative regions, cross-border environmental disputes between various administrative jurisdictions in China have gradually increased. Therefore, how to effectively regulate trans-boundary environmental pollution has always been an important issue in environmental protection.

Under China's traditional performance evaluation system and fiscal decentralization system, the competition goal of local governments is mainly the growth of regional GDP, which has an adverse effect on environmental pollution and environmental governance, and an impact on the regional ecological environment through the negative externality of environmental pollution and the positive externality of environmental governance. In terms of environmental pollution, local governments are overly pursuing economic growth while neglecting the ecological environment, and even sacrificing the environment in exchange for short-term economic growth, leading to environmental pollution. For example, local governments have adopted fiscal and tax preferential measures to attract certain companies that pollute, causing environmental pollution in the region to increase. The environmental pollution has negative externality, which can affect the environmental conditions of neighboring areas through transfer and diffusion, resulting in the worsening of pollution in neighboring areas. In terms of environmental governance, local governments often squeeze environmental protection expenditure due to excessive emphasis on local economic construction, resulting in insufficient investment in ecological environmental governance. Environmental governance has positive externality. When local governments increase local environmental protection and pollution control efforts, neighboring areas can freely enjoy the results of environmental governance through free-riding. In addition, the financial competition of local governments can easily derive local protectionist behaviors, hinder the realization of cross-regional environmental governance cooperation, and cause the negative externality of environmental pollution to become more obvious. At the same time, it also reduces the positive externality of environmental governance.

In order to achieve better governance results, coordination and cooperation between all levels of government must be strengthened. This is the realistic basis for this paper. There is no shortage of such examples in China. In the revision, we have added two typical examples of government cooperation in the treatment of environmental pollution. The details are as follows:

(1) As a highly systematic natural geographic unit of surface water, the watershed is inevitably divided by different administrative regions, which has spawned a contradiction between the integrity of the watershed and the division of administrative divisions. As a result, a series of disputes over the trans-boundary treatment of water pollution have emerged. The Yellow River flows through nine provinces (autonomous regions) of China, including Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong. It flows into the Bohai Sea in Shandong Province and flows through a vast area. Most of the key industrial enterprises in the upper and middle reaches of the Yellow River Basin rely on energy advantages to build, including petrochemical and metallurgical enterprises. Although these companies have vigorously promoted the rapid economic and social development, they have also caused an imbalance in the industrial layout and frequent safety accidents of some companies, leading to the occurrence of major water pollution incidents. The coordinated management of water pollution in the Yellow River Basin has received great attention from the state. In September 2019, Xi Jinping personally deployed at the Symposium on Ecological Protection and High-Quality Development of the Yellow River Basin, elevated the ecological protection and high-quality development of the Yellow River Basin to a major national strategy, and pointed out that "the Yellow River Basin is governed by protection and governance." At the same time, it requires "coordinated promotion of large-scale governance"; in December of the same year, Xi Jinping delivered an important speech in the "Seeking Truth" magazine, in which he stated that ecological protection and high-quality development of the Yellow River Basin should be an important part of regional coordinated development.

(2) The Beijing–Tianjin–Hebei region is the most affected area in my country where air pollution is discharged continuously and superimposed across administrative regions. According to the "2020 China Ecological and Environmental Status Bulletin" issued by the Ministry of Ecology and Environment, the air quality in Shijiazhuang, Tangshan, and Handan in the Beijing–Tianjin–Hebei region is poor. The percentage of days with good air quality in Beijing–Tianjin–Hebei and in the "2 + 26" surrounding cities is 63.5%. As a typical developed urban agglomeration in my country, the Beijing–Tianjin–Hebei region began to explore cross-administrative cooperative air pollution control methods relatively early and gained certain experience. At present, the Beijing–Tianjin–Hebei Air Pollution Prevention and Control Team has been established, and its members include "seven provinces and regions, eight ministries and commissions" (The seven provinces and regions include: Beijing, Tianjin, Hebei, Shanxi, Shandong, Henan, and Inner Mongolia; the ministries and commissions include: the Environmental Protection Agency, the Development and Reform Commission, the Ministry of Industry and Information Technology, the Ministry of Finance, the Ministry of Housing and Urban-rural Development, the Bureau of Meteorology, the Bureau of Energy, and the Ministry of Transport). The air pollution prevention and control coordination mechanism of Beijing–Tianjin–Hebei and surrounding areas has been successfully established, which provides a mode for the cooperation of governments at all levels in environmental governance across administrative regions.

Under the system with Chinese characteristics, the central government is authoritative in vertical intergovernmental relations, ensuring that the central government effectively controls and leads local governments. China's traditional fiscal decentralization system and the promotion mechanism of local government officials also determine the versatility of government functions. Local governments obey the leadership of the central government and accept supervision.

Therefore, based on the externality of the environmental pollution control, the authority of the central government, and the obedience and self-interest of local governments, this paper constructs a tripartite game between the central government and dual local governments to discuss the optimizing strategy of capital investment in the environmental pollution control under intergovernmental relations. This is of great significance for clarifying as to how to coordinate and promote environmental protection among governments at all levels in the future.

The theoretical significance, practical contribution, and innovation of the paper are as follows:

(1) The theoretical significance: taking the cross-administrative environmental issues as the research category, the benefit analysis as the research perspective, and the differential game as the research method, this paper is based on the intergovernmental relationship in environmental pollution control, and builds the benefit game and coordination analysis framework of the cross-administrative environmental governance. In addition, this paper conducts an in-depth analysis of the benefit games and conflicts behind noncooperative behaviors among governments at all levels, and proposes a path for constructing benefit coordination mechanisms in cross-administrative environmental governance, which can deeply reveal the general laws of regional public governance. This has certain theoretical significance for enriching and perfecting the theory of regional public governance.

(2) The practical contribution: facing the inefficiency of cross-administrative ecological environment governance, this paper takes the cross-administrative environmental governance as the starting point, and analyzes how the central government and local governments cooperate and the benefit games that appear in the cooperation. The research conclusions of this paper are of great significance to effectively solve the environmental problems of cross-administrative regions and realize the coordinated development of regions. At the same time, they also provide a reference for the mode of government cooperation in various fields such as politics, economy, culture, and society. It is conducive for promoting the sustained and healthy development of the entire national economy.

(3) The innovation: there are two main limitations in the existing research on the coordinated governance of environmental pollution between governments: (1) Most scholars adopt static game and staged game models, and do not consider the continuous changes of state variables and the amount of change in the strategies of the participants as the state changes; (2) existing studies are mostly two-party games. However, the actual participants in cross-regional environmental governance are generally three parties or even multiple parties. Relying on the differential game theory, in order to find the internal factors that affect the cooperation of all parties, this paper constructs a tripartite game model between the central government and the two local governments, discusses resource allocation and financial special funding strategies in environmental pollution control, and analyzes the endogenous reasons and paths of cooperation between the parties.

2. Literature Review

2.1. The Government Competition. Chirinko and Wilson [5] used the strategic tax competition theory to analyze how changes in capital tax policies in neighboring jurisdictions affect capital tax policies in a given jurisdiction for the USA. Perdiguero and Jiménez's research showed that the local competition, technical difficulties, and government competition were the main factors affecting the introduction of bio-diesel into the Spanish gasoline market [6]. Xu's research found that regional government competition was conducive for stimulating local governments to initiate and implement market-oriented reform activities, which reduced the occurrence of corruption to a certain extent [7]. Lin et al.'s research found that corporate political capital played an important but negative role in the cooperation of green product and the process of innovation performance [8]. Kubick and Masli's study found that government competition affected the provision and consumption of public goods. The positive impact of government competition on economic growth can make local governments take risky behavior [9]. Yu et al. [10] studied the spatial effects of prefecture-level cities in China and found that after excluding other factors such as economic spillovers and tax competition, competition among government leaders at the same level is the most important factor affecting the spatial effects. Hong and Lee [11] analyzed the policy differences of 47 cities in the USA and found that political competition will affect the government's supervision of the sharing economy. The government cared more about the benefit of market players than that of the public. Shi and Xi [12] found that competition between local governments may have a positive effect under certain conditions. The performance appraisal under the leadership of the central government had promoted spatial competition in safety governance and enlarged the intensity of safety supervision. This may be an important factor leading to a significant improvement in coal mine production safety in recent years. Gang et al. [13] used the random boundary model to calculate the green total factor productivity of 278 provinces and cities in China from 2004 to 2013. The study found an inverted U-shaped relationship between county-level government competition and green total factor productivity, and excessive cross-jurisdictional competition has an adverse effect on green total factor productivity (GTFP), while moderate government competition does not. Deng et al. [14] studied the impact of political competition through a game theory model and found that political competition will affect the best green technology innovation strategic model and the optimal investment ratio of environmental governance of local governments and enterprises. Wu [15] found that although the competition among local governments is not the main driving force for the formation of the industrial structure and division in the Yangtze River Delta, its role cannot be underestimated. Deng et al. [16] used super-efficiency data envelopment analysis to test the impact of local government competition and environmental regulation intensity on regional innovation performance and regional heterogeneity. At the same time, local governments compete for foreign direct investment (FDI) to participate in regional innovative production.

2.2. The Government's Role in the Environment. The positive effects: Fairchild [17] believed that increasing government subsidies to green production enterprises can effectively improve the clean production behavior of enterprises and indirectly reduce environmental pollution. Qiu and Yang [18] believed that the government plays an important coordinating role in environmental protection, and the implementation of the emission permit trading system is conducive for compensating the environmental protection costs of upstream companies and can promote the realization of Pareto optimal. Mir et al. [19] studied the relationship between government competition and environmental information disclosure in New Zealand, and the results showed that intensified political competition is conducive for increasing environmental information disclosure. Through the analysis of data from 29 provinces and cities in China, Li and He [20] studied the interaction between regional competition, environmental taxes, and green technology innovation. The results show that the influence of regional competition on green technology innovation also presents an "inverted U" shape, that is, benign regional competition is conducive for green technology innovation, but excessive regional competition produces the opposite result. Eichner and Pethig [21] analyzed countries with liquidity and local cross-border environmental pollution and found that competition between government emission taxes and capital taxes will have a significant impact on environmental pollution. Through the research on environmental issues in the Guangdong-Hong Kong-Macao Greater Bay Area, Ren [22] found that coordinated governance and administrative supervision between governments at all levels is an important driving force for promoting the construction of an environmental protection system. Tang and Qin [23] analyzed the impact of local government competition on green total factor productivity (GTFP) and its internal mechanism by using the SDM model and the mediating effect model.

The negative effects: Cremer's research on US emissions taxes found that the greater the pressure of political competition, the lower the willingness of local governments to implement high environmental taxes [24]. Qi and Zhang [25] have studied the relationship between the central government and local governments in China. The research shows that in order to attract more external investment and promote the development of the local economy, local governments tend to sacrifice the environment and protect environmentally polluting enterprises. Fedyukin and Igor's research showed that the existence of political competition will make local governments pay more attention to economic development to a certain extent, reduce their attention to environmental protection, and lead to aggravation of local environmental pollution [26].

2.3. The Game of Cross-Regional Government. Yu [27] drew on the experience of the European Union and the Netherlands in the treatment of water pollution, and on this basis, he studied the problem of trans-boundary water pollution in China. Kim et al. [28] designed a set of games with externality and connections to solve cross-regional water resources management problems. Fernandez [29] analyzed the problem of cross-border water pollution control in North America through the establishment of a game theory model. The research results show that cooperative games with water monitoring and information sharing decision-making are beneficial to reduce pollution costs and pollution damage. Li et al. [30] established a model to determine the comprehensive control strategy of cross-regional lake pollution in China based on environmental green costs, and the research results provided a theoretical basis for the formulation of emission permit prices.

2.4. The Fiscal Expenditure and Decentralization Theory. Brueckner and Jan [31] believed that when a fiscal policy has positive externality, it often leads to fiscal competition among local governments to reduce expenditures. This is the "free rider" psychology of local governments. The research of Wilson and Gordon [32] found that fiscal expenditure competition can benefit regional economic growth by improving the efficiency of fiscal fund use. Xu et al. [33] studied China's provincial panel data from 1995 to 2008 and found that there is a long-term equilibrium relationship between fiscal decentralization, local government competition, and cultivated land transfer. The research of Becker and Rauscher [34] believed that tax competition is conducive to economic growth by enhancing the mobility of factors. Prud'homme [35] pointed out that China's economic decentralization system has stimulated the effectiveness of local government's industrial decision-making to a certain extent, thereby promoting the development of strategic emerging industries, but these are inseparable from the central government's supervisory role. Skovgaard [36] found that environmental decision-making increasingly involves departments other than the environmental sector; especially, the Ministry of Finance has an increasingly important influence on environmental decision-making because they solve environmental problems by controlling the budget from a different perspective. Ercolano and Romano [37] studied the local fiscal environmental protection expenditures of European governments and found that the national local fiscal environmental protection expenditures are related to the country's development status. Bazavan. [38] found that China's decentralization system also allows local governments to play different roles in the process of economic development. They play the role of manager in some industries and the role of partner or investor in others.

3. Model and Assumption

This paper constructs a game model of environmental pollution control based on intergovernmental relationship. The model assumes that the environmental pollution control system consists of a central government (the abbreviation of a central government is Cent-gov), a local government A (the abbreviation of a local government A is Local-gov A), which is mainly affected by environmental pollution, and a local government B (the abbreviation of a local government B is Local-gov B), which is secondarily affected by environmental pollution. When a sudden environmental pollution incident occurs, the city with the higher level of environmental pollution control can timely mobilize human, material, and financial resources; promptly organize emergency evacuation and resettlement of residents; and narrow the scope of environmental pollution. After the occurrence of environmental pollution, the central government and local governments will work together to verify the targets of assistance, transfer and resettle the victims, calculate the economic losses, improve the level of environmental pollution control, and carry out restoration and reconstruction work, in order to minimize environmental pollution losses.

In order to study the intergovernmental relationship, this paper makes the following variable hypotheses. $E_a(t)$ is the effort level of Local-gov A in the process of environmental pollution control. $E_b(t)$ is the effort level of Local-gov B in the process of environmental pollution control. The effort level of the Cent-gov to improve the environmental pollution control level of Local-gov A and Local-gov B is $E_{as}(t)$ and $E_{bs}(t)$, the environmental pollution control costs paid by the Cent-gov, Local-gov A, and Local-gov B are $C_s(t)$, $C_a(t)$, and $C_b(t)$:

$$
\begin{aligned}
C_s(t) &= \frac{\mu_s}{2}\left[E_{as}^2(t) + E_{bs}^2(t)\right],\\
C_a(t) &= \frac{\mu_a}{2}E_a^2(t),\\
C_b(t) &= \frac{\mu_b}{2}E_b^2(t).
\end{aligned}
\tag{1}
$$

The environmental pollution control effort is directly proportional to the environmental pollution control costs, that is, as the environmental pollution control effort increases, the costs will also increase. μ_s, μ_a, and μ_b, respectively, represent the cost coefficient of environmental pollution control by the Cent-gov, the Local-gov A, and the Local-gov B. $R_a(t)$, $R_b(t)$, respectively, indicate the environmental pollution control level of the Local-gov A and the Local-gov B at time t. The improvement of local government's environmental pollution control level stems from the joint efforts of the central government and the local governments. The improvement of environmental pollution control level has a natural decay law with time, and has the characteristics of cross-border and positive externality. Therefore, there is a certain spillover effect in the improvement of environmental pollution control level. The environmental pollution control level of Local-gov B is affected by Local-gov A. The changes of environmental pollution control level of the Local-gov A and the Local-gov B over time can be described by the following stochastic differential equations:

$$
\begin{aligned}
\frac{\mathrm{d}R_a(t)}{\mathrm{d}t} &= \alpha_a E_{as}(t) + \beta_a E_a(t) - \gamma_a R_a(t),\\
\frac{\mathrm{d}R_b(t)}{\mathrm{d}t} &= \alpha_b E_{bs}(t) + \beta_b E_b(t) - \gamma_b R_b(t) + \eta\frac{\mathrm{d}R_a(t)}{\mathrm{d}t}\\
&= \eta\left[\alpha_a E_{as}(t) + \beta_a E_a(t) - \gamma_a R_a(t)\right] + \alpha_b E_{bs}(t)\\
&\quad + \beta_b E_b(t) - \gamma_b R_b(t).
\end{aligned}
\tag{2}
$$

The initial values of environmental pollution control level in the two regions: $R_a(0) = R_a \geq 0, R_b(0) = R_b \geq 0$, α represents the impact of the effort level of the Cent-gov on the local environmental pollution control level; β represents the impact of the effort level of the local government on the local environmental pollution control level; $\gamma > 0$ represents the degree of attenuation of environmental pollution control level; and $\eta \geq 0$ indicates the impact coefficient of Local-gov A's environmental pollution control level on Local-gov B's.

$L_s(t)$, $L_a(t)$, and $L_b(t)$, respectively, represent the environmental pollution losses of the Cent-gov, Local-gov A, and Local-gov B at time t. $T_s(t)$, $T_a(t)$, and $T_b(t)$, respectively, represent the total environmental pollution losses of the Cent-gov, Local-gov A, and Local-gov B at time $0 - t$. At time t, the environmental pollution losses of the Local-gov A and the Local-gov B are $L_a(t)$ and $L_b(t)$, respectively, which can be expressed as

$$
\begin{aligned}
L_a(t) &= M(t) - \varepsilon_a E_{as}(t) - \delta_a E_a(t) - \theta_a R_a(t),\\
L_a(t) &= N(t) - \varepsilon_b E_{bs}(t) - \delta_b E_b(t) - \theta_b R_b(t),
\end{aligned}
\tag{3}
$$

where M, N are real numbers, indicating the maximum losses degree of the Local-gov A and the Local-gov B, $M > N$. ε, δ are constants greater than 0, indicating the influence level of the Cent-gov's efforts and local government's efforts on environmental pollution losses, that is, the executive capacity of the Cent-gov and the local government. θ is the impact level of environmental pollution control level on environmental pollution losses.

4. Game Strategy in Different Models

According to different types of intergovernmental relations, environmental pollution control models can be divided into three types: the Nash game model, the Stackelberg game model, and the Cooperative game model.

4.1. The Nash Game Model. The Nash game model is based on the natural division of labor, and the scope of interaction is small. The local government is decentralized, closed, and self-sufficient. Strictly speaking, this phenomenon does not exist, as local governments in this model, especially local governments with similar geographical areas, have no connection and communication. But, as power moves down, the central government has reduced the supervision of local governments. It is rare to actively engage in competition and cooperation strategies between local governments. The Local-gov A and the Local-gov B spontaneously carry out environmental pollution control, the Cent-gov does not subsidize local governments, and the three parties conduct noncooperative games. In the infinite time zone, all parties aim at minimizing their own environmental pollution losses, and they accordingly select the optimal effort level and make rational decisions. The environmental pollution losses are shared by the Cent-gov and local governments, the share ratio of the Cent-gov is ω_i $(0 \leq \omega_i \leq 1, i = a, b)$, and the share ratio of local government is $1 - \omega_i$. The Cent-gov and local government have the same positive discount rate r.

The objective function of Local-gov A can be expressed as

$$T_a = \int_0^{\infty} e^{-rt}\left\{(1-\omega_a)\left[M(t) - \varepsilon_a E_{as}(t) - \delta_a E_a(t) - \theta_a R_a(t)\right] + \frac{\mu_a}{2} E_a^2(t)\right\} \mathrm{d}t. \tag{4}$$

The objective function of Local-gov B can be expressed as

$$T_b = \int_0^{\infty} e^{-rt}\left\{(1-\omega_b)\left[N(t) - \varepsilon_b E_{bs}(t) - \delta_b E_b(t) - \theta_b R_b(t)\right] + \frac{\mu_b}{2} E_b^2\right\} \mathrm{d}t. \tag{5}$$

The objective function of Cent-gov can be expressed as

$$T_s = \int_0^{\infty} e^{-rt}\left\{\begin{array}{l} \omega_a\left[M(t) - \varepsilon_a E_{as}(t) - \delta_a E_a(t) - \theta_a R_a(t)\right] + \frac{\mu_a}{2} E_{as}^2 \\ \\ +\omega_b\left[N(t) - \varepsilon_b E_{bs}(t) - \delta_b E_b(t) - \theta_b R_b(t)\right] + \frac{\mu_b}{2} E_b^2 \end{array}\right\} \mathrm{d}t. \tag{6}$$

$E_{as}(t), E_{bs}(t), E_a(t), E_b(t)$ are control variables, $R_a(t)$ and $R_b(t)$ are state variables. In addition to this, all other parameters are constants greater than 0 and not related to time. The optimal decision of each party is determined by the feedback control strategy. Since the parameters in the model are not related to time, the game subjects face the same game in the infinite time zone, and their strategies are static feedback equilibrium.

Proposition 1. *In the Nash game model, the static feedback Nash equilibrium strategies of the Local-gov A, the Local-gov B, and the Cent-gov are*

$$E_a^* = \frac{1-\omega_a}{\mu_a}\left(\delta_a + \frac{\beta_a \theta_a}{r + \gamma_a}\right), \tag{7}$$

$$E_b^* = \frac{1-\omega_b}{\mu_b}\left(\delta_b + \frac{\beta_b \theta_b}{r + \gamma_b}\right), \tag{8}$$

$$E_{as}^* = \frac{\omega_a}{\mu_s}\left(\varepsilon_a + \frac{\alpha_a \theta_a}{r + \gamma_a}\right) + \frac{\eta r \alpha_a \omega_b \theta_b}{\mu_s (r + \gamma_a)(r + \gamma_b)}, \tag{9}$$

$$E_{bs}^* = \frac{\omega_b}{\mu_s}\left(\varepsilon_b + \frac{\alpha_b \theta_b}{r + \gamma_b}\right). \tag{10}$$

Proof. In order to obtain the Markov refined Nash equilibrium, it is assumed that there is a continuous bounded differential function $V_i(R_a, R_b)\ i \in (a, b, s)$ of environmental pollution losses, which satisfies the HJB (Hamilton–Jacobi–Bellman) equation for all $R_a \geq 0$, $R_b \geq 0$:

$$r \cdot V_a(R_a, R_b) = \min_{E_a \geq 0} \left\{ \begin{array}{c} (1-\omega_a)(M - \varepsilon_a E_{as} - \delta_a E_a - \theta_a R_a) + \dfrac{\mu_a}{2} E_a^2 \\ -\left(\dfrac{\partial V_a}{\partial R_a} + \eta \dfrac{\partial V_a}{\partial R_b}\right)(\alpha_a E_{as} + \beta_a E_a - \gamma_a R_a) - \dfrac{\partial V_a}{\partial R_b}(\alpha_b E_{bs} + \beta_b E_b - \gamma_b R_b) \end{array} \right\}, \tag{11}$$

$$r \cdot V_b(R_a, R_b) = \min_{E_b \geq 0} \left\{ \begin{array}{c} (1-\omega_b)(N - \varepsilon_b E_{as} - \delta_b E_a - \theta_b R_b) + \dfrac{\mu_b}{2} E_b^2 \\ -\left(\dfrac{\partial V_b}{\partial R_a} + \eta \dfrac{\partial V_b}{\partial R_b}\right)(\alpha_a E_{as} + \beta_a E_a - \gamma_a R_a) - \dfrac{\partial V_b}{\partial R_b}(\alpha_b E_{bs} + \beta_b E_b - \gamma_b R_b) \end{array} \right\}, \tag{12}$$

$$r \cdot V_s(R_a, R_b) = \min_{E_{as} \geq 0, E_{bs} \geq 0} \left\{ \begin{array}{c} \omega_a(M - \varepsilon_a E_{as} - \delta_a E_a - \theta_a R_a) + \omega_b(N - \varepsilon_b E_{bs} - \delta_b E_b - \theta_b R_b) + \dfrac{\mu_s}{2}(E_{as}^2 + E_{bs}^2) \\ -\left(\dfrac{\partial V_s}{\partial R_a} + \eta \dfrac{\partial V_s}{\partial R_b}\right)(\alpha_a E_{as} + \beta_a E_a - \gamma_a R_a) - \dfrac{\partial V_s}{\partial R_b}(\alpha_b E_{bs} + \beta_b E_b - \gamma_b R_b) \end{array} \right\}. \tag{13}$$

By calculating the first-order partial derivatives of E_a and E_b for the right end of equations (11) and (12), and calculating the first-order partial derivatives of E_{as} and E_{bs} by formula (13), and making them equal to zero, we can get

$$E_a = \frac{(1-\omega_a)\delta_a + \beta_a((\partial V_a/\partial R_a) + \eta(\partial V_a/\partial R_b))}{\mu_a}, \tag{14}$$

$$E_b = \frac{(1-\omega_b)\delta_b + \beta_b(\partial V_b/\partial R_b)}{\mu_b}, \tag{15}$$

$$E_{as} = \frac{\omega_a\varepsilon_a + \alpha_a((\partial V_s/\partial R_a) + \eta(\partial V_s/\partial R_b))}{\mu_s}, \tag{16}$$

$$E_{bs} = \frac{\omega_b\varepsilon_b + \alpha_b(\partial V_s/\partial R_b)}{\mu_b}. \tag{17}$$

Substituting equations (14)–(17) into equations (11)–(13), we can get

$$\begin{aligned} r \cdot V_a = {} & \left[\gamma_a\left(\frac{\partial V_a}{\partial R_a} + \eta\frac{\partial V_a}{\partial R_b}\right) - (1-\omega_a)\theta_a\right]R_a + \gamma_b\frac{\partial V_a}{\partial R_b}R_b \\ & - \frac{[\omega_a\varepsilon_a + \alpha_a((\partial V_s/\partial R_a) + \eta(\partial V_s/\partial R_b))][(1-\omega_a)\varepsilon_a + \alpha_a((\partial V_a/\partial R_a) + \eta(\partial V_a/\partial R_b))]}{\mu_s} - \frac{\alpha_b(\partial V_a/\partial R_b)(\omega_b\varepsilon_b + \alpha_b(\partial V_s/\partial R_b))}{\mu_s} \\ & - \frac{[(1-\omega_a)\delta_a + \beta_a((\partial V_a/\partial R_a) + \eta(\partial V_a/\partial R_b))]^2}{2\mu_a} - \frac{\beta_b(\partial V_a/\partial R_b)[(1-\omega_b)\delta_b + \beta_b(\partial V_b/\partial R_b)]}{2\mu_b} + (1-\omega_a)M, \end{aligned} \tag{18}$$

$$\begin{aligned} r \cdot V_b = {} & \gamma_a\left(\frac{\partial V_b}{\partial R_a} + \eta\frac{\partial V_b}{\partial R_b}\right)R_a + \left[\gamma_b\frac{\partial V_b}{\partial R_b} - (1-\omega_b)\theta_b\right]R_b \\ & - \frac{(\omega_b\varepsilon_b + \alpha_b(\partial V_s/\partial R_b))[(1-\omega_b)\varepsilon_b + \alpha_b(\partial V_s/\partial R_b)]}{\mu_s} \\ & - \frac{\alpha_a((\partial V_b/\partial R_a) + \eta(\partial V_b/\partial R_b))[\omega_a\varepsilon_a + \alpha_a(\partial V_s/\partial R_a + \eta(\partial V_s/\partial R_b))]}{\mu_s} \\ & - \frac{\beta_a((\partial V_b/\partial R_a) + \eta(\partial V_b/\partial R_b))[(1-\omega_a)\delta_a + \beta_a((\partial V_a/\partial R_a) + \eta(\partial V_a/\partial R_b))]}{2\mu_a} \\ & - \frac{[(1-\omega_b)\delta_b + \beta_b(\partial V_b/\partial R_b)]^2}{2\mu_b} + (1-\omega_b)N, \end{aligned} \tag{19}$$

$$r \cdot V_s = \left[\gamma_a\left(\frac{\partial V_s}{\partial R_a} + \eta\frac{\partial V_s}{\partial R_b}\right) - \omega_a\theta_a\right]R_a + \left(\gamma_b\frac{\partial V_s}{\partial R_b} - \omega_b\theta_b\right)R_b - \frac{[\omega_a\varepsilon_a + \alpha_a((\partial V_s/\partial R_a) + \eta(\partial V_s/\partial R_b))]^2}{2\mu_s} - \frac{(\omega_b\varepsilon_b + \alpha_b(\partial V_s/\partial R_b))^2}{2\mu_s} - \frac{[(1-\omega_a)\delta_a + \beta_a((\partial V_a/\partial R_a) + \eta(\partial V_a/\partial R_b))][\omega_a\delta_a + \beta_a((\partial V_s/\partial R_a) + \eta(\partial V_s/\partial R_b))]}{\mu_a} - \frac{[(1-\omega_b)\delta_b + \beta_b(\partial V_b/\partial R_b)](\omega_b\delta_b + \beta_b(\partial V_s/\partial R_b))}{\mu_b} + \omega_a M + \omega_b N. \quad (20)$$

From equations (18)–(20), it can be known that the linear optimal functions about R_a, R_b are the solutions of the HJB equation. Let

$$V_a(R_a, R_b) = p_a R_a + q_a R_b + u_a, \quad (21)$$

$$V_b(R_a, R_b) = p_b R_a + q_b R_b + u_b, \quad (22)$$

$$V_s(R_a, R_b) = p_s R_a + q_s R_b + u_s. \quad (23)$$

$p_a, q_a, p_b, q_b, p_s, q_s$ are constants, and the derivatives of equations (21)–(23) are calculated and substituted into the results of equations (18)–(20). We can get

$$r(p_a R_a + q_a R_b + u_a) = [\gamma_a(p_a + \eta q_a) - (1-\omega_a)\theta_a]R_a + \gamma_b q_a R_b - \frac{[\omega_a\varepsilon_a + \alpha_a(p_s + \eta q_s)][(1-\omega_a)\varepsilon_a + \alpha_a(p_a + \eta q_a)]}{\mu_s} - \frac{\alpha_b q_a(\omega_b\varepsilon_b + \alpha_b q_s)}{\mu_s} - \frac{[(1-\omega_a)\delta_a + \beta_a(p_a + \eta q_a)]^2}{2\mu_a} - \frac{\beta_b q_a[(1-\omega_b)\delta_b + \beta_b q_b]}{2\mu_b} + (1-\omega_a)M, \quad (24)$$

$$r(p_b R_a + q_b R_b + u_b) = \gamma_a(p_b + \eta q_b)R_a + [\gamma_b q_b - (1-\omega_b)\theta_b]R_b - \frac{(\omega_b\varepsilon_b + \alpha_b g_2)[(1-\omega_b)\varepsilon_b + \alpha_b q_b]}{\mu_s} - \frac{\alpha_a(p_b + \eta q_b)[\omega_a\varepsilon_a + \alpha_a(p_s + \eta q_s)]}{\mu_s} - \frac{\beta_a(p_b + \eta q_b)[(1-\omega_a)\delta_a + \beta_a(p_a + \eta q_a)]}{2\mu_a} - \frac{[(1-\omega_b)\delta_b + \beta_b q_b]^2}{2\mu_b} + (1-\omega_b)N, \quad (25)$$

$$r(p_s R_a + q_s R_b + u_s) = [\gamma_a(p_s + \eta q_s) - \omega_a\theta_a]R_a + (\gamma_b q_s - \omega_b\theta_b)R_b - \frac{[\omega_a\varepsilon_a + \alpha_a(p_s + \eta q_s)]^2}{2\mu_s} - \frac{(\omega_b\varepsilon_b + \alpha_b q_s)^2}{2\mu_s} - \frac{[(1-\omega_a)\delta_a + \beta_a(p_a + \eta q_a)][\omega_a\delta_a + \beta_a(p_s + \eta q_s)]}{\mu_a} - \frac{[(1-\omega_b)\delta_b + \beta_b q_b](\omega_b\delta_b + \beta_b q_s)}{\mu_b} + \omega_a M + \omega_b N. \quad (26)$$

If equations (24)–(26) satisfy all $R_a \geq 0, R_b \geq 0$, it is easy to get

$$p_a = -\frac{(1-\omega_a)\theta_a}{r + \gamma_a},$$

$$p_b = 0,$$

$$u_a = -\frac{(1-\omega_a)[\varepsilon_a(r+\gamma_a) + \alpha_a\theta_a]\{\omega_a[\varepsilon_a(r+\gamma_a) + \alpha_a\theta_a] + (\eta r\alpha_a\omega_b\theta_b/(r+\gamma_b))\}}{\mu_s r(r+\gamma_a)^2} - \frac{(1-\omega_a)^2[\delta_a(r+\gamma_a) + \beta_a\theta_a]^2}{2\mu_a r(r+\gamma_a)^2} + \frac{(1-\omega_a)M}{r}, \quad (27)$$

$$\begin{aligned}
p_b &= \frac{\lambda\gamma_a(1-\omega_b)\theta_b}{(r+\gamma_a)(r+\gamma_b)},\\
q_b &= -\frac{(1-\omega_b)\theta_b}{r+\gamma_b},\\
u_b &= -\frac{\eta\alpha_a(1-\omega_b)\theta_b\{\omega_a[\varepsilon_a(r+\gamma_a)+\alpha_a\theta_a]+(\eta r\alpha_a\omega_b\theta_b/(r+\gamma_b))\}}{\mu_s(r+\gamma_a)^2(r+\gamma_b)}\\
&\quad-\frac{\omega_b(1-\omega_b)[\varepsilon_b(r+\gamma_b)+\alpha_b\theta_b]^2}{\mu_s r(r+\gamma_b)^2}-\frac{\eta\beta_a(1-\omega_b)\theta_b(1-\omega_a)[\delta_a(r+\gamma_a)+\beta_a\theta_a]}{\mu_a(r+\gamma_a)^2(r+\gamma_b)}\\
&\quad-\frac{(1-\omega_b)^2[\delta_b(r+\gamma_b)+\beta_b\theta_b]^2}{2\mu_b r(r+\gamma_b)^2}+\frac{(1-\omega_b)N}{r},
\end{aligned} \tag{28}$$

$$\begin{aligned}
p_s &= \frac{\lambda\gamma_a(1-\omega_b)\theta_b}{(r+\gamma_a)(r+\gamma_b)}-\frac{\omega_a\theta_a}{r+\gamma_a},\\
q_s &= -\frac{\omega_2\theta_b}{r+\gamma_b},\\
u_s &= -\frac{\{\omega_a[\varepsilon_a(r+\gamma_a)+\alpha_a\theta_a]+(\eta r\alpha_a\omega_b\theta_b/(r+\gamma_b))\}^2}{2\mu_s r(r+\gamma_a)^2}-\frac{\omega_b^2[\varepsilon_b(r+\gamma_b)+\alpha_b\theta_b]^2}{2\mu_s r(r+\gamma_b)^2}+\frac{\omega_a M+\omega_b N}{r}\\
&\quad-\frac{(1-\omega_a)[\delta_a(r+\gamma_a)+\beta_a\theta_a]\{\omega_a[\delta_a(r+\gamma_a)+\beta_a\theta_a]+(\eta r\beta_a\omega_b\theta_b/(r+\gamma_b))\}}{\mu_a r(r+\gamma_a)^2}-\frac{\omega_b(1-\omega_b)[\delta_b(r+\gamma_b)+\beta_b\theta_b]^2}{\mu_b r(r+\gamma_b)^2}.
\end{aligned} \tag{29}$$

Substituting equations (27)–(29) into equations (21)–(23), we can obtain the minimum environmental pollution losses functions of Local-gov A, Local-gov A, and Cent-gov, as follows:

$$\begin{aligned}
V_a^* &= \frac{(1-\omega_a)M}{r}-\frac{(1-\omega_a)\theta_a}{r+\gamma_a}R_a-\frac{(1-\omega_a)^2[\delta_a(r+\gamma_a)+\beta_a\theta_a]^2}{2\mu_a r(r+\gamma_a)^2}\\
&\quad-\frac{(1-\omega_a)[\varepsilon_a(r+\gamma_a)+\alpha_a\theta_a]\{\omega_a[\varepsilon_a(r+\gamma_a)+\alpha_a\theta_a]+(\eta r\alpha_a\omega_b\theta_b/(r+\gamma_b))\}}{\mu_s r(r+\gamma_a)^2},
\end{aligned} \tag{30}$$

$$\begin{aligned}
V_b^* &= \frac{(1-\omega_b)N}{r}+\frac{\eta\gamma_a(1-\omega_b)\theta_b}{(r+\gamma_a)(r+\gamma_b)}R_a-\frac{(1-\omega_b)\theta_b}{r+\gamma_b}R_b\\
&\quad-\frac{\eta\alpha_a(1-\omega_b)\theta_b\{\omega_a[\varepsilon_a(r+\gamma_a)+\alpha_a\theta_a]+(\eta r\alpha_a\omega_b\theta_b/(r+\gamma_b))\}}{\mu_s(r+\gamma_a)^2(r+\gamma_b)}-\frac{\omega_b(1-\omega_b)[\varepsilon_b(r+\gamma_b)+\alpha_b\theta_b]^2}{\mu_s r(r+\gamma_b)^2}\\
&\quad-\frac{\eta\beta_a(1-\omega_b)\theta_b(1-\omega_a)[\delta_a(r+\gamma_a)+\beta_a\theta_a]}{\mu_a(r+\gamma_a)^2(r+\gamma_b)}-\frac{(1-\omega_b)^2[\delta_b(r+\gamma_b)+\beta_b\theta_b]^2}{2\mu_b r(r+\gamma_b)^2},
\end{aligned} \tag{31}$$

$$\begin{aligned}
V_s^* &= \frac{\omega_a M+\omega_b N}{r}+\left[\frac{\lambda\gamma_a(1-\omega_b)\theta_b}{(r+\gamma_a)(r+\gamma_b)}-\frac{\omega_a\theta_a}{r+\gamma_a}\right]R_a-\frac{\omega_b\theta_b}{r+\gamma_b}R_b\\
&\quad-\frac{\{\omega_a[\varepsilon_a(r+\gamma_a)+\alpha_a\theta_a]+(\eta r\alpha_a\omega_b\theta_b/(r+\gamma_b))\}^2}{2\mu_s r(r+\gamma_a)^2}-\frac{\omega_2^2[\varepsilon_b(r+\gamma_b)+\alpha_b\theta_b]^2}{2\mu_s r(r+\gamma_b)^2}\\
&\quad-\frac{(1-\omega_a)[\delta_a(r+\gamma_a)+\beta_a\theta_a]\{\omega_a[\delta_a(r+\gamma_a)+\beta_a\theta_a]+(\eta r\beta_a\omega_b\theta_b/(r+\gamma_b))\}}{\mu_a r(r+\gamma_a)^2}-\frac{\omega_b(1-\omega_b)[\delta_b(r+\gamma_b)+\beta_b\theta_b]^2}{\mu_b r(r+\gamma_b)^2}.
\end{aligned} \tag{32}$$

At this time, the total environmental pollution losses in the region are

$$\begin{aligned} V^*(R_a, R_b) &= V_a^* + V_b^* + V_s^* \\ &= \frac{M+N}{r} + \left[\frac{\lambda\gamma_a(1-\omega_b)\theta_b}{(r+\gamma_a)(r+\gamma_b)} - \frac{\omega_a\theta_a}{r+\gamma_a}\right]R_a - \frac{\theta_b}{r+\gamma_b}R_b \\ &\quad - \frac{\{\omega_a[\varepsilon_a(r+\gamma_a)+\alpha_a\theta_a] + (\eta r\alpha_a\omega_b\theta_b/(r+\gamma_b))\}\{(2-\omega_a)[\varepsilon_a(r+\gamma_a)+\alpha_a\theta_a] + (\eta r\alpha_a\omega_b\theta_b/(r+\gamma_b))\}}{2\mu_s r(r+\gamma_a)^2} \\ &\quad - \frac{\omega_b(2-\omega_b)[\varepsilon_b(r+\gamma_b)+\alpha_b\theta_b]^2}{2\mu_s r(r+\gamma_b)^2} \\ &\quad - \frac{(1-\omega_a)[\delta_a(r+\gamma_a)+\beta_a\theta_a]\{(1+\omega_a)[\delta_a(r+\gamma_a)+\beta_a\theta_a] + (2\eta r\beta_a\omega_b\theta_b/(r+\gamma_b))\}}{2\mu_a r(r+\gamma_a)^2} \\ &\quad - \frac{(1-\omega_b)^2[\delta_b(r+\gamma_b)+\beta_b\theta_b]^2}{2\mu_b r(r+\gamma_b)^2}. \end{aligned} \tag{33}$$

Find the partial derivatives for equations (30)–(32) and bring the results into equations (14)–(17). It is easy to get equations (7)–(10).

Under the equilibrium of the Nash game model, the environmental pollution control level of Local-gov A is

$$\begin{cases} R_a^*(t) = \dfrac{1}{\gamma_a}\left[\dfrac{\omega_a\alpha_a}{\mu_s}\left(\varepsilon_a + \dfrac{\alpha_a\theta_a}{r+\gamma_a}\right) + \dfrac{(1-\omega_a)\beta_a}{\mu_s}\left(\delta_a + \dfrac{\beta_a\theta_a}{r+\gamma_b}\right) - e^{-\gamma_a t + D_a}\right], \\ R_a^*(0) = R_a. \end{cases} \tag{34}$$

The environmental pollution control level of Local-gov B is

$$\begin{cases} R_b^*(t) = \dfrac{\eta}{\gamma_b}\left[\dfrac{\omega_a\alpha_a}{\mu_s}\left(\varepsilon_a + \dfrac{\alpha_a\theta_a}{r+\gamma_a}\right) + \dfrac{(1-\omega_a)\beta_a}{\mu_a}\left(\delta_a + \dfrac{\beta_a\theta_a}{r+\gamma_a}\right) - e^{-\gamma_a t + D_a}\right] \\ \quad + \dfrac{1}{\gamma_b}\left[\dfrac{\omega_b\alpha_b}{\mu_s}\left(\varepsilon_b + \dfrac{\alpha_b\theta_b}{r+\gamma_b}\right) + \dfrac{(1-\omega_b)\beta_b}{\mu_b}\left(\delta_b + \dfrac{\beta_b\theta_b}{r+\gamma_b}\right) - e^{-\gamma_b t + D_b}\right], \\ R_b^*(0) = R_b, \\ e^{D_a} = \dfrac{\omega_a\alpha_a}{\mu_s}\left(\varepsilon_a + \dfrac{\alpha_a\theta_a}{r+\gamma_a}\right) + \dfrac{(1-\omega_a)\beta_a}{\mu_a}\left(\delta_a + \dfrac{\beta_a\theta_a}{r+\gamma_a}\right) - \gamma_a R_a, \end{cases} \tag{35}$$

where D_a, D_b are arbitrary constants.

Equations (7) and (8) indicate that under the Nash game model, the effort level of the local government E_a, E_b are negatively correlated with the cost coefficient μ, the attenuation coefficient of environmental pollution control level γ, the discount rate r, and the share ratio of environmental pollution losses ω; the effort level of the local government is positively related to the impact coefficient of local government effort on pollution losses δ, the impact coefficient on environmental pollution control level β, and the impact coefficient of environmental pollution control level on pollution losses θ. In other words, local governments should raise the environmental pollution control level from the aspects of environmental pollution control level, impact capacity, executive ability, and so on.

Equations (9) and (10) indicate that under the Nash game model, the Cent-gov's optimal effort levels E_{as}, E_{bs} are negatively correlated with the cost coefficient μ_s, the attenuation coefficient of the environmental pollution control γ, and the discount rate r; the Cent-gov's optimal effort levels E_{as}, E_{bs} are positively correlated with the distribution ratio of environmental pollution losses ω, the influence coefficient of the Cent-gov's efforts on environmental pollution losses ε, the impact coefficient of environmental pollution control level on pollution losses θ, and the influence coefficient of the Cent-gov's effort on the environmental pollution control level α. The Cent-gov should comprehensively consider the local government's environmental pollution control issues in terms of environmental pollution control level, impact capability, and executive ability to make decisions. □

4.2. The Stackelberg Game Model. In order to improve the efficiency of resource allocation, the Cent-gov has made policy guidance through special fiscal expenditure, that is, the Cent-gov has undertaken a certain proportion of environmental pollution control costs for the local government, the funding ratios are $\lambda_a(t)$ and $\lambda_b(t)$, the Cent-gov first determines the funding ratios for Local-gov A and Local-gov B, then the local governments select the appropriate effort level after observing the actions of the Cent-gov. The Cent-gov is the leader, the local governments are the followers, and the three parties launch the Stackelberg game.

The objective function of Local-gov A can be expressed as

$$T_a = \int_0^\infty e^{-rt}\left\{(1-\omega_a)(M-\varepsilon_a E_{as}-\delta_a E_a-\theta_a R_a)+\frac{\mu_a}{2}(1-\lambda_a)E_a^2\right\}dt. \tag{36}$$

The objective function of Local-gov B can be expressed as

$$T_b = \int_0^\infty e^{-rt}\left\{(1-\omega_b)(N-\varepsilon_b E_{bs}-\delta_b E_b-\theta_b R_b)+\frac{\mu_b}{2}(1-\lambda_b)E_b^2\right\}dt. \tag{37}$$

The objective function of Cent-gov can be expressed as

$$T_s = \int_0^\infty e^{-rt}\left\{\begin{array}{c}\omega_a(M-\varepsilon_a E_{as}-\delta_a E_a-\theta_a R_a)+\omega_b(N-\varepsilon_b E_{bs}-\delta_b E_b-\theta_b R_b)\\ +\frac{\mu_s}{2}\left(E_{as}^2+E_{bs}^2\right)+\frac{1}{2}\left(\mu_a\lambda_a E_a^2+\mu_b\lambda_b E_b^2\right)\end{array}\right\}dt. \tag{38}$$

Proposition 2. *Under the Stackelberg game model, the static feedback equilibrium strategies of Local-gov A, Local-gov B, and Cent-gov are*

$$E_a^{**} = \frac{1+\omega_a}{2\mu_a}\left(\delta_a+\frac{\beta_a\theta_a}{r+\gamma_a}\right)+\frac{\eta r\beta_a\omega_b\theta_b}{\mu_a(r+\gamma_a)(r+\gamma_b)}, \tag{39}$$

$$E_b^{**} = \frac{1+\omega_b}{2\mu_b}\left(\delta_b+\frac{\beta_b\theta_b}{r+\gamma_b}\right), \tag{40}$$

$$E_{as}^{**} = \frac{\omega_a}{\mu_s}\left(\varepsilon_a+\frac{\alpha_a\theta_a}{r+\gamma_a}\right)+\frac{\eta r\alpha_a\omega_b\theta_b}{\mu_s(r+\gamma_a)(r+\gamma_b)}, \tag{41}$$

$$E_{bs}^{**} = \frac{\omega_b}{\mu_s}\left(\varepsilon_b+\frac{\alpha_b\theta_b}{r+\gamma_b}\right), \tag{42}$$

$$\lambda_a^{**} = \begin{cases} 0, & \left(0 \le \omega_a \le \dfrac{1}{3}\right), \\ \dfrac{(3\omega_a - 1)[\delta_a (r + \gamma_a) + \beta_a \theta_a] + (2\eta r \beta_a \omega_b \theta_b / (r + \gamma_b))}{(\omega_a + 1)[\delta_a (r + \gamma_a) + \beta_a \theta_a] + (2\eta r \beta_a \omega_b \theta_b / (r + \gamma_b))}, & \left(\dfrac{1}{3} < \omega_a \le 1\right), \end{cases} \quad (43)$$

$$\lambda_b^{**} = \begin{cases} 0, & \left(0 \le \omega_b \le \dfrac{1}{3}\right), \\ \dfrac{3\omega_b - 1}{\omega_b + 1}, & \left(\dfrac{1}{3} < \omega_b \le 1\right). \end{cases} \quad (44)$$

Proof. In order to obtain the Stackelberg equilibrium, the inverse induction method is used. Firstly, this paper assumes that there is a continuous bounded differential income function $V_i(R_a, R_b)\, i \in (a, b, s)$. The following HJB equations are satisfied for all $R_a \ge 0$, $R_b \ge 0$:

$$r \cdot V_a(R_a, R_b) = \min_{E_a \ge 0} \left\{ \begin{array}{c} (1 - \omega_a)(M - \varepsilon_a E_{as} - \delta_a E_a - \theta_a R_a) + \dfrac{\mu_a}{2}(1 - \lambda_a) E_a^2 \\ -\left(\dfrac{\partial V_a}{\partial R_a} + \eta \dfrac{\partial V_a}{\partial R_b}\right)(\alpha_a E_{as} + \beta_a E_a - \gamma_a R_a) - \dfrac{\partial V_a}{\partial R_b}(\alpha_b E_{bs} + \beta_b E_b - \gamma_b R_b) \end{array} \right\}, \quad (45)$$

$$r \cdot V_b(R_a, R_b) = \min_{E_b \ge 0} \left\{ \begin{array}{c} (1 - \omega_b)(N - \varepsilon_b E_{as} - \delta_b E_a - \theta_b R_b) + \dfrac{\mu_b}{2}(1 - \lambda_b) E_b^2 \\ -\left(\dfrac{\partial V_b}{\partial R_a} + \eta \dfrac{\partial V_b}{\partial R_b}\right)(\alpha_a E_{as} + \beta_a E_a - \gamma_a R_a) - \dfrac{\partial V_b}{\partial R_b}(\alpha_b E_{bs} + \beta_b E_b - \gamma_b R_b) \end{array} \right\}. \quad (46)$$

Find the first-order partial derivatives of the effort level E_a, E_b from the expressions in the right-hand brace of equations (45) and (46), making them equal to zero, we can get

$$E_a = \frac{(1 - \omega_a)\delta_a + \beta_a ((\partial V_a / \partial R_a) + \eta (\partial V_a / \partial R_b))}{\mu_a (1 - \lambda_a)}, \quad (47)$$

$$E_b = \frac{(1 - \omega_b)\delta_b + \beta_b (\partial V_b / \partial R_b)}{\mu_b (1 - \lambda_b)}. \quad (48)$$

The Cent-gov rationally predicts that Local-gov A and Local-gov B will choose their efforts functions E_a, E_b according to the above formulas. Therefore, the Cent-gov should determine its own efforts strategy and funding ratio according to the rational response of local governments. The Cent-gov's HJB equation is

$$r \cdot V_s(R_a, R_b) = \min_{E_{as} \ge 0, E_{bs} \ge 0} \left\{ \begin{array}{c} \omega_a (M - \varepsilon_a E_{as} - \delta_a E_a - \theta_a R_a) + \omega_b (N - \varepsilon_b E_{bs} - \delta_b E_b - \theta_b R_b) \\ + \dfrac{\lambda_a \mu_a}{2} E_a^2 + \dfrac{\lambda_b \mu_b}{2} E_b^2 + \dfrac{\mu_s}{2}(E_{as}^2 + E_{bs}^2) \\ -\left(\dfrac{\partial V_s}{\partial R_a} + \eta \dfrac{\partial V_s}{\partial R_b}\right)(\alpha_a E_{as} + \beta_a E_a - \gamma_a R_a) - \dfrac{\partial V_s}{\partial R_b}(\alpha_b E_{bs} + \beta_b E_b - \gamma_b R_b) \end{array} \right\}. \quad (49)$$

Substitute formulas (47) and (48) into formula (49) , and solve the right part of formula (49). Solving method is as follows: find the first-order partial derivative of the formula in parentheses on the right end of the formula (49) with respect to $E_{as}, E_{bs}, \eta_a, \eta_b$ and then make the first-order partial derivative equal to zero, and it is easy to obtain:

$$E_{as} = \frac{\omega_s \varepsilon_a + \alpha_a \left((\partial V_s / \partial R_a) + \eta (\partial V_s / \partial R_b) \right)}{\mu_s}, \tag{50}$$

$$E_{bs} = \frac{\omega_b \varepsilon_b + \alpha_b (\partial V_s / \partial R_b)}{\mu_b}, \tag{51}$$

$$\lambda_a = \frac{(3\omega_a - 1)\delta_a + \beta_a \left[2\left((\partial V_s/\partial R_a) + \eta (\partial V_s/\partial R_b) \right) - \left((\partial V_a/\partial R_a) + \eta (\partial V_a/\partial R_b) \right) \right]}{(\omega_a + 1)\delta_a + \beta_a \left[2\left((\partial V_s/\partial R_a) + \eta (\partial V_s/\partial R_b) \right) + \left((\partial V_a/\partial R_a) + \eta (\partial V_a/\partial R_b) \right) \right]}, \tag{52}$$

$$\lambda_b = \frac{(3\omega_b - 1)\delta_b + \beta_b \left(2 (\partial V_s/\partial R_b) - (\partial V_b/\partial R_b) \right)}{(\omega_b + 1)\delta_b + \beta_b \left(2 (\partial V_s/\partial R_b) + (\partial V_b/\partial R_b) \right)}. \tag{53}$$

Substituting equations (47), (48), and (50)–(53) into equations (45), (46), and (49), by simplifying, we can get

$$\begin{aligned} r \cdot V_a = {} & \left[\gamma_a \left(\frac{\partial V_a}{\partial R_a} + \eta \frac{\partial V_a}{\partial R_b} \right) - (1 - \omega_a)\theta_a \right] R_a + \gamma_b \frac{\partial V_a}{\partial R_b} R_b \\ & - \frac{\left[\omega_a \varepsilon_a + \alpha_a \left((\partial V_s/\partial R_a) + \eta (\partial V_s/\partial R_b) \right) \right] \left[(1 - \omega_a)\varepsilon_a + \alpha_a \left((\partial V_a/\partial R_a) + \eta (\partial V_a/\partial R_b) \right) \right]}{\mu_s} - \frac{\alpha_b (\partial V_a/\partial R_b) \left(\omega_b \varepsilon_b + \alpha_b (\partial V_s/\partial R_b) \right)}{\mu_s} \\ & - \frac{\left[(1 - \omega_a)\delta_a + \beta_a \left((\partial V_a/\partial R_a) + \eta (\partial V_a/\partial R_b) \right) \right] \left\{ (1 + \omega_a)\delta_a + \beta_a \left[2\left((\partial V_s/\partial R_a) + \eta (\partial V_s/\partial R_b) \right) + \left((\partial V_a/\partial R_a) + \eta (\partial V_a/\partial R_b) \right) \right] \right\}}{4\mu_a} \\ & - \frac{\beta_b (\partial V_a/\partial R_b) \left[(1 - \omega_b)\delta_b + \beta_b (\partial V_s/\partial R_b) \right]}{2\mu_b} + (1 - \omega_a) M, \end{aligned} \tag{54}$$

$$\begin{aligned} r \cdot V_b = {} & \gamma_a \left(\frac{\partial V_b}{\partial R_a} + \eta \frac{\partial V_b}{\partial R_b} \right) R_a + \left[\gamma_b \frac{\partial V_b}{\partial R_b} - (1 - \omega_b)\theta_b \right] R_b \\ & - \frac{\left(\omega_b \varepsilon_b + \alpha_b (\partial V_s/\partial R_b) \right) \left[(1 - \omega_b)\varepsilon_b + \alpha_b (\partial V_b/\partial R_b) \right]}{\mu_s} \\ & - \frac{\alpha_a \left((\partial V_b/\partial R_a) + \eta (\partial V_b/\partial R_b) \right) \left[\omega_a \varepsilon_a + \alpha_a \left((\partial V_s/\partial R_a) + \eta (\partial V_s/\partial R_b) \right) \right]}{\mu_s} \\ & - \frac{\beta_a \left((\partial V_b/\partial R_a) + \eta (\partial V_b/\partial R_b) \right) \left\{ (1 + \omega_a)\delta_a + \beta_a \left[2\left((\partial V_s/\partial R_a) + \eta (\partial V_s/\partial R_b) \right) + \left((\partial V_a/\partial R_a) + \eta (\partial V_a/\partial R_b) \right) \right] \right\}}{2\mu_a} \\ & - \frac{\left[(1 - \omega_b)\delta_b + \beta_b (\partial V_b/\partial R_b) \right] \left[(1 + \omega_b)\delta_b + \beta_b \left(2 (\partial V_s/\partial R_b) + (\partial V_b/\partial R_b) \right) \right]}{4\mu_b} + (1 - \omega_b) N, \end{aligned} \tag{55}$$

$$\begin{aligned} r \cdot V_s = {} & \left[\gamma_a \left(\frac{\partial V_s}{\partial R_a} + \eta \frac{\partial V_s}{\partial R_b} \right) - \omega_a \theta_a \right] R_a + \left(\gamma_b \frac{\partial V_s}{\partial R_b} - \omega_b \theta_b \right) R_b \\ & - \frac{\left[\omega_a \varepsilon_a + \alpha_a \left((\partial V_s/\partial R_a) + \eta (\partial V_s/\partial R_b) \right) \right]^2}{2\mu_s} - \frac{\left(\omega_b \varepsilon_b + \alpha_b (\partial V_s/\partial R_b) \right)^2}{2\mu_s} \\ & - \frac{\left[\omega_a \delta_a + \beta_a \left((\partial V_s/\partial R_a) + \eta (\partial V_s/\partial R_b) \right) \right] \left[\omega_a \delta_a + \beta_a \left((\partial V_s/\partial R_a) + \eta (\partial V_s/\partial R_b) + (\partial V_a/\partial R_a) + \eta (\partial V_a/\partial R_b) \right) \right]}{2\mu_a} \\ & - \frac{\left[(1 - \omega_a)\delta_a + \beta_a \left((\partial V_a/\partial R_a) + \eta (\partial V_a/\partial R_b) \right) \right]^2}{8\mu_a} - \frac{\left[\omega_b \delta_b + \beta_b \left((\partial V_s/\partial R_a) + (\partial V_s/\partial R_b) \right) \right] \left(\delta_b + \beta_b (\partial V_b/\partial R_b) \right)}{\mu_b} \\ & - \frac{\left[(1 - \omega_b)\delta_b + \beta_b (\partial V_b/\partial R_b) \right]^2}{8\mu_b} + \omega_a M + \omega_b N. \end{aligned} \tag{56}$$

From equations (54)–(56), it is known that the linear optimal functions about R_a, R_b are the solutions of the HJB equation. Let

$$V_a(R_a, R_b) = p_a R_a + q_a R_b + u_a, \tag{57}$$

$$V_b(R_a, R_b) = p_b R_a + q_b R_b + u_b, \tag{58}$$

$$V_s(R_a, R_b) = p_s R_a + q_s R_b + u_s, \tag{59}$$

where $p_a, q_a, p_b, q_b, p_s, q_s$ are constants, and the equations (57)–(59) are derived and substituted into the results of equations (54)–(56), we can get

$$\begin{aligned} r(p_a R_a + q_a R_b + u_a) = {} & [\gamma_a(p_a + \eta q_a) - (1-\omega_a)\theta_a]R_a + \gamma_b q_a R_b \\ & - \frac{[\omega_a \varepsilon_a + \alpha_a(p_s + \eta q_s)][(1-\omega_a)\varepsilon_a + \alpha_a(p_a + \eta q_a)]}{\mu_s} - \frac{\alpha_b q_a(\omega_b \varepsilon_b + \alpha_b q_s)}{\mu_s} \\ & - \frac{[(1-\omega_a)\delta_a + \beta_a(p_a + \eta q_a)]\{(1+\omega_a)\delta_a + \beta_a[2(p_s + \eta q_s) + (p_a + \eta q_a)]\}}{4\mu_a} \\ & - \frac{\beta_b q_a[(1-\omega_b)\delta_b + \beta_b q_b]}{2\mu_b} + (1-\omega_a)M, \end{aligned} \tag{60}$$

$$\begin{aligned} r(p_b R_a + q_b R_b + u_b) = {} & \gamma_a(p_b + \eta q_b)R_a + [\gamma_b q_b - (1-\omega_b)\theta_b]R_b \\ & - \frac{(\omega_b \varepsilon_b + \alpha_b q_s)[(1-\omega_b)\varepsilon_b + \alpha_b q_b]}{\mu_s} - \frac{\alpha_a(p_b + \eta q_b)[\omega_a \varepsilon_a + \alpha_a(p_s + \eta q_s)]}{\mu_s} \\ & - \frac{\beta_a(p_b + \eta q_b)\{(1+\omega_a)\delta_a + \beta_a[2(p_s + \eta q_s) + (p_a + \eta q_a)]\}}{2\mu_a} \\ & - \frac{[(1-\omega_b)\delta_b + \beta_b q_b][(1+\omega_b)\delta_b + \beta_b(2q_s + q_b)]}{4\mu_b} + (1-\omega_b)N, \end{aligned} \tag{61}$$

$$\begin{aligned} r(p_s R_a + q_s R_b + u_s) = {} & [\gamma_a(p_s + \eta q_s) - \omega_a \theta_a]R_a + (\gamma_b q_s - \omega_b \theta_b)R_b \\ & - \frac{[\omega_a \varepsilon_a + \alpha_a(p_s + \eta q_s)]^2}{2\mu_s} - \frac{(\omega_b \varepsilon_b + \alpha_b q_s)^2}{2\mu_s} - \frac{[\omega_a \delta_a + \beta_a(p_s + \eta q_s)][\omega_a \delta_a + \beta_a(p_s + \eta q_s + p_a + \eta q_a)]}{2\mu_a} \\ & - \frac{[(1-\omega_a)\delta_a + \beta_a(p_s + \eta q_s)]^2}{8\mu_a} - \frac{[\omega_b \delta_b + \beta_b q_s][\delta_b + \beta_b(q_b + q_s)]}{2\mu_b} \\ & - \frac{[(1-\omega_b)\delta_b + \beta_b(p_a + \eta q_a)]^2}{8\mu_b} + \omega_a M + \omega_b N. \end{aligned} \tag{62}$$

If equations (60)–(62) satisfy all $R_a \geq 0, R_b \geq 0$, it is easy to get

$$\begin{aligned} p_a &= -\frac{(1-\omega_a)\theta_a}{r + \gamma_a}, \\ p_b &= 0, \\ u_a &= -\frac{(1-\omega_a)[\varepsilon_a(r+\gamma_a) + \alpha_a \theta_a]\{\omega_a[\varepsilon_a(r+\gamma_a) + \alpha_a \theta_a] + (\eta r \alpha_a \omega_b \theta_b/(r+\gamma_b))\}}{\mu_s r(r+\gamma_a)^2} \\ & \quad - \frac{(1-\omega_a)[\delta_a(r+\gamma_a) + \beta_a \theta_a]\{(1+\omega_a)[\delta_a(r+\gamma_a) + \beta_a \theta_a] + (2\eta r \beta_a \omega_b \theta_b/(r+\gamma_b))\}}{4\mu_a r(r+\gamma_a)^2} + \frac{(1-\omega_a)M}{r}, \end{aligned} \tag{63}$$

$$
\begin{aligned}
p_b &= \frac{\lambda\gamma_a(1-\omega_b)\theta_b}{(r+\gamma_a)(r+\gamma_b)},\\
q_b &= -\frac{(1-\omega_b)\theta_b}{r+\gamma_b},\\
u_b &= -\frac{\eta\alpha_a(1-\omega_b)\theta_b\{\omega_a[\varepsilon_a(r+\gamma_a)+\alpha_a\theta_a]+(\eta r\alpha_a\omega_b\theta_b/(r+\gamma_b))\}}{\mu_s(r+\gamma_a)^2(r+\gamma_b)}-\frac{\omega_b(1-\omega_b)[\varepsilon_b(r+\gamma_b)+\alpha_b\theta_b]^2}{\mu_s r(r+\gamma_b)^2}\\
&\quad+\frac{(1-\omega_b)N}{r}-\frac{\eta\beta_a(1-\omega_b)\theta_b\{(1+\omega_a)[\delta_a(r+\gamma_a)+\beta_a\theta_a]+(2\eta r\alpha_a\omega_b\theta_b/(r+\gamma_b))\}}{2\mu_a(r+\gamma_a)^2(r+\gamma_b)}\\
&\quad-\frac{(1-\omega_b)(1+\omega_b)[\delta_b(r+\gamma_b)+\beta_b\theta_b]^2}{4\mu_b r(r+\gamma_b)^2},
\end{aligned}
\tag{64}
$$

$$
\begin{aligned}
p_s &= \frac{\lambda\gamma_a(1-\omega_b)\theta_b}{(r+\gamma_a)(r+\gamma_b)}-\frac{\omega_a\theta_a}{r+\gamma_a},\\
q_s &= -\frac{\omega_2\theta_b}{r+\gamma_b},\\
u_s &= -\frac{\{\omega_a[\varepsilon_a(r+\gamma_a)+\alpha_a\theta_a]+(\eta r\alpha_a\omega_b\theta_b/(r+\gamma_b))\}^2}{2\mu_s r(r+\gamma_a)^2}-\frac{\omega_b^2[\varepsilon_b(r+\gamma_b)+\alpha_b\theta_b]^2}{2\mu_s r(r+\gamma_b)^2}\\
&\quad-\frac{\{(1+\omega_a)[\delta_a(r+\gamma_a)+\beta_a\theta_a]+(2\eta r\beta_a\omega_b\theta_b/(r+\gamma_b))\}^2}{8\mu_a r(r+\gamma_a)^2}-\frac{(1+\omega_b)^2[\delta_b(r+\gamma_b)+\beta_b\theta_b]^2}{8\mu_b r(r+\gamma_b)^2}+\frac{\omega_a M+\omega_b N}{r}.
\end{aligned}
\tag{65}
$$

Substituting equations (63)–(65) into equations (57)–(59), the minimum environmental pollution losses functions of Local-gov A, Local-gov B, and Cent-gov can be obtained, they are

$$
\begin{aligned}
V_a^{**} &= \frac{(1-\omega_a)M}{r}-\frac{(1-\omega_a)\theta_a}{r+\gamma_a}R_a-\frac{(1-\omega_a)[\varepsilon_a(r+\gamma_a)+\alpha_a\theta_a]\{\omega_a[\varepsilon_a(r+\gamma_a)+\alpha_a\theta_a]+(\eta r\alpha_a\omega_b\theta_b/(r+\gamma_b))\}}{\mu_s r(r+\gamma_a)^2}\\
&\quad-\frac{(1-\omega_a)[\delta_a(r+\gamma_a)+\beta_a\theta_a]\{(1+\omega_a)[\delta_a(r+\gamma_a)+\beta_a\theta_a]+(2\eta r\beta_a\omega_b\theta_b/(r+\gamma_b))\}}{4\mu_a r(r+\gamma_a)^2},
\end{aligned}
\tag{66}
$$

$$
\begin{aligned}
V_b^{**} &= \frac{(1-\omega_b)N}{r}+\frac{\lambda\gamma_a(1-\omega_b)\theta_b}{(r+\gamma_a)(r+\gamma_b)}R_a-\frac{(1-\omega_b)\theta_b}{r+\gamma_b}R_b-\frac{\eta\alpha_a(1-\omega_b)\theta_b\{\omega_a[\varepsilon_a(r+\gamma_a)+\alpha_a\theta_a]+(\eta r\alpha_a\omega_b\theta_b/(r+\gamma_b))\}}{\mu_s(r+\gamma_a)^2(r+\gamma_b)}\\
&\quad-\frac{\omega_b(1-\omega_b)[\varepsilon_b(r+\gamma_b)+\alpha_b\theta_b]^2}{\mu_s r(r+\gamma_b)^2}-\frac{\eta\beta_a(1-\omega_b)\theta_b\{(1+\omega_a)[\delta_a(r+\gamma_a)+\beta_a\theta_a]+(2\eta r\alpha_a\omega_b\theta_b/(r+\gamma_b))\}}{2\mu_a(r+\gamma_a)^2(r+\gamma_b)}\\
&\quad-\frac{(1-\omega_b)(1+\omega_b)[\delta_b(r+\gamma_b)+\beta_b\theta_b]^2}{4\mu_b r(r+\gamma_b)^2},
\end{aligned}
\tag{67}
$$

$$
\begin{aligned}
V_s^{**} &= \frac{\omega_a M+\omega_b N}{r}+\left[\frac{\lambda\gamma_a(1-\omega_b)\theta_b}{(r+\gamma_a)(r+\gamma_b)}-\frac{\omega_a\theta_a}{r+\gamma_a}\right]R_a-\frac{\omega_2\theta_b}{r+\gamma_b}R_b\\
&\quad-\frac{\{\omega_a[\varepsilon_a(r+\gamma_a)+\alpha_a\theta_a]+(\eta r\alpha_a\omega_b\theta_b/(r+\gamma_b))\}^2}{2\mu_s r(r+\gamma_a)^2}-\frac{\omega_b^2[\varepsilon_b(r+\gamma_b)+\alpha_b\theta_b]^2}{2\mu_s r(r+\gamma_b)^2}\\
&\quad-\frac{\{(1+\omega_a)[\delta_a(r+\gamma_a)+\beta_a\theta_a]+(2\eta r\beta_a\omega_b\theta_b/(r+\gamma_b))\}^2}{8\mu_a r(r+\gamma_a)^2}-\frac{(1+\omega_b)^2[\delta_b(r+\gamma_b)+\beta_b\theta_b]^2}{8\mu_b r(r+\gamma_b)^2}.
\end{aligned}
\tag{68}
$$

At this time, the total environmental pollution regional losses are

$$
\begin{aligned}
V^{**}(R_a, R_b) &= V_a^{**} + V_b^{**} + V_s^{**} \\
&= \frac{M+N}{r} + \left[\frac{\lambda\gamma_a\theta_b}{(r+\gamma_a)(r+\gamma_b)} - \frac{\theta_a}{r+\gamma_a}\right]R_a - \frac{\theta_b}{r+\gamma_b}R_b \\
&- \frac{\{\omega_a[\varepsilon_a(r+\gamma_a)+\alpha_a\theta_a] + (\eta r\alpha_a\omega_b\theta_b/(r+\gamma_b))\}\{(2-\omega_a)[\varepsilon_a(r+\gamma_a)+\alpha_a\theta_a] + (\eta r\alpha_a(2-\omega_b)\theta_b/(r+\gamma_b))\}}{2\mu_s r(r+\gamma_a)^2} \\
&- \frac{\omega_b(2-\omega_b)[\varepsilon_b(r+\gamma_b)+\alpha_b\theta_b]^2}{2\mu_s r(r+\gamma_b)^2} \\
&- \frac{\{(1+\omega_a)[\delta_a(r+\gamma_a)+\beta_a\theta_a] + (2\eta r\beta_a\omega_b\theta_b/(r+\gamma_b))\}\{(3-\omega_a)[\delta_a(r+\gamma_a)+\beta_a\theta_a] + (2\eta r\beta_a(2-\omega_b)\theta_b/(r+\gamma_b))\}}{8\mu_a r(r+\gamma_a)^2} \\
&- \frac{(3-\omega_b)(1+\omega_b)[\delta_b(r+\gamma_b)+\beta_b\theta_b]^2}{8\mu_b r(r+\gamma_b)^2}.
\end{aligned}
\tag{69}
$$

The partial derivatives of equations (65)–(68) are calculated and then substituted into the results of equations (47), (48), and (50)–(53) to obtain equations (39)–(44).

Under the Stackelberg game model, the environmental pollution control level of Local-gov A is

$$
\begin{cases}
R_a^{**}(t) = \dfrac{1}{\gamma_a}\left[\dfrac{\alpha_a}{\mu_s}\left[\omega_a\left(\varepsilon_a + \dfrac{\alpha_a\theta_a}{r+\gamma_a}\right) + \dfrac{\eta r\alpha_a\omega_b\theta_b}{(r+\gamma_a)(r+\gamma_b)}\right] + \dfrac{\beta_a}{\mu_a}\left[\dfrac{1+\omega_a}{2}\left(\delta_a + \dfrac{\beta_a\theta_a}{r+\gamma_b}\right) + \dfrac{\eta r\beta_a\omega_b\theta_b}{(r+\gamma_a)(r+\gamma_b)}\right] - e^{-\gamma_a t + D_a}\right], \\
R_a^{**}(0) = R_a.
\end{cases}
\tag{70}
$$

The environmental pollution control level of Local-gov B is

$$
\begin{cases}
R_b^{**}(t) = \dfrac{\eta}{\gamma_b}\left\{\dfrac{\alpha_a}{\mu_s}\left[\omega_a\left(\varepsilon_a + \dfrac{\alpha_a\theta_a}{r+\gamma_a}\right) + \dfrac{\eta r\alpha_a\omega_b\theta_b}{(r+\gamma_a)(r+\gamma_b)}\right] + \dfrac{\beta_a}{\mu_a}\left[\dfrac{1+\omega_a}{2}\left(\delta_a + \dfrac{\beta_a\theta_a}{r+\gamma_a}\right) + \dfrac{\eta r\alpha_a\omega_b\theta_b}{(r+\gamma_a)(r+\gamma_b)}\right] - e^{-\gamma_a t + D_a}\right\} \\
+\dfrac{1}{\gamma_b}\left[\dfrac{\omega_b\alpha_b}{\mu_s}\left(\varepsilon_b + \dfrac{\alpha_b\theta_b}{r+\gamma_b}\right) + \dfrac{(1+\omega_b)\beta_b}{\mu_b}\left(\delta_b + \dfrac{\beta_b\theta_b}{r+\gamma_b}\right) - e^{-\gamma_b t + D_b}\right], \\
R_b^{**}(0) = R_b, \\
e^{D_a}\& = \dfrac{\alpha_a}{\mu_s}\left[\omega_a\left(\varepsilon_a + \dfrac{\alpha_a\theta_a}{r+\gamma_a}\right) + \dfrac{\eta r\alpha_a\omega_b\theta_b}{(r+\gamma_a)(r+\gamma_b)}\right] + \dfrac{\beta_a}{\mu_a}\left[\dfrac{1+\omega_a}{2}\left(\delta_a + \dfrac{\beta_a\theta_a}{r+\gamma_a}\right) + \dfrac{\eta r\alpha_a\omega_b\theta_b}{(r+\gamma_a)(r+\gamma_b)}\right] - \gamma_a R_a,
\end{cases}
\tag{71}
$$

By comparing equation (7) and (39), equations (8) and (40), we know that under the Stackelberg game model, the effort levels of the local government E_a, E_b are positively correlated with the distribution ratio of environmental pollution losses ω, but the impact degree is less than the Nash game model, while other influencing factors and influence direction are consistent with the Nash game model.

By comparing equations (9) and (41), equations (10) and (42), it can be seen that under the Stackelberg game model, the effort level of Cent-gov and the related influencing factors are consistent with the Nash game model. In other words, the government must comprehensively consider its own environmental pollution governance level, impact ability, and execution ability to make decisions.

Equations (43) and (44) show that the funding ratio chosen by the Cent-gov depends on the sharing ratio of environmental pollution losses. When the Cent-gov bears less environmental pollution losses $(0 \le \omega \le (1/3))$, it will not consider sharing costs through the subsidy mechanism; when the Cent-gov bears more environmental pollution losses, it will consider improving the efficiency of environmental pollution control through special subsidy, which reflects the Cent-gov's "Economic person" characteristics. □

4.3. The Cooperative Game Model. The Coase theorem shows that if transaction costs are low enough, the rational participants can achieve Pareto optimal allocation through voluntary bargaining. Under appropriate conditions, governments can achieve economies of scale and policy spillovers through cooperation. As the intergovernmental relations gradually develop in all directions, in many fields, and at a deeper level, the governments should build an intergovernmental coordination model. In order to further improve the efficiency of environmental pollution control, the Cent-gov cooperates with Local-gov A and Local-gov B to jointly determine the optimal effort strategy, improve the environmental pollution control level, and reduce environmental pollution losses.

Proposition 3. *Under the situation of full communication and cooperation between the Cent-gov, Local-gov A, and Local-gov B, their optimal equilibrium strategies are*

$$E_a^{***} = \frac{1}{\mu_a}\left[\delta_a + \frac{\beta_a\theta_a}{r+\gamma_a} + \frac{\eta r \beta_a \theta_b}{(r+\gamma_a)(r+\gamma_b)}\right], \tag{72}$$

$$E_b^{***} = \frac{1}{\mu_b}\left(\delta_b + \frac{\beta_b\theta_b}{r+\gamma_b}\right), \tag{73}$$

$$E_{as}^{***} = \frac{1}{\mu_s}\left[\varepsilon_a + \frac{\alpha_a\theta_a}{r+\gamma_a} + \frac{\eta r \alpha_a \theta_b}{\mu_s(r+\gamma_a)(r+\gamma_b)}\right], \tag{74}$$

$$E_{bs}^{***} = \frac{1}{\mu_s}\left(\varepsilon_b + \frac{\alpha_b\theta_b}{r+\gamma_b}\right). \tag{75}$$

Proof. When the relationship between the Cent-gov, Local-gov A, and Local-gov B is transformed into collaboration, all parties aim at minimizing environmental pollution losses regionally and jointly determine the optimal values of E_a, E_b, E_{as}, and E_{bs}. The total environmental pollution losses can be expressed as

$$T = \int_0^\infty e^{-rt}\left\{\begin{array}{c} M - \varepsilon_a E_{as} - \delta_a E_a - \theta_a R_a + N - \varepsilon_b E_{bs} - \delta_b E_b - \theta_b R_b \\ +\frac{1}{2}\left(\mu_a E_a^2 + \mu_b E_b^2 + \mu_s E_{as}^2 + \mu_s E_{bs}^2\right) \end{array}\right\} \mathrm{d}t. \tag{76}$$

Supposing there is a continuous bounded differential income function $V(R_a, R_b)$ that satisfies the HJB equation for all $R_a \ge 0, R_b \ge 0$,

$$r \cdot V(R_a, R_b) = \min_{\substack{E_{as}\ge 0; E_a \ge 0 \\ E_{bs}\ge 0; E_b\ge 0}} \left\{\begin{array}{c} M - \varepsilon_a E_{as} - \delta_a E_a - \theta_a R_a + \frac{\mu_s}{2}E_{as}^2 + \frac{\mu_a}{2}E_a^2, \\ N - \varepsilon_b E_{bs} - \delta_b E_b - \theta_b R_b + \frac{\mu_s}{2}E_{bs}^2 + \frac{\mu_b}{2}E_b^2 \\ -\left(\frac{\partial V}{\partial L_1} + \eta\frac{\partial V}{\partial L_2}\right)(\alpha_a E_{as} + \beta_a E_a - \gamma_a R_a) - \frac{\partial V}{\partial L_2}(\alpha_b E_{bs} + \beta_b E_b - \gamma_b R_b). \end{array}\right\} \tag{77}$$

In equation (77), calculating the first-order partial derivatives of E_{as}, E_{bs}, E_a, E_b and making them equal to 0, we can get

$$E_a = \frac{\delta_a + \beta_a((\partial V/\partial R_a) + \eta(\partial V/\partial R_b))}{\mu_a}, \quad (78)$$

$$E_b = \frac{\delta_b + \beta_b(\partial V/\partial R_b)}{\mu_b}, \quad (79)$$

$$E_{as} = \frac{\varepsilon_a + \alpha_a((\partial V/\partial R_a) + \eta(\partial V/\partial R_b))}{\mu_s}, \quad (80)$$

$$E_{bs} = \frac{\varepsilon_b + \alpha_b(\partial V/\partial R_b)}{\mu_b}. \quad (81)$$

Substituting the formulas (78)–(81) into formula (77) for simplification yields

$$\begin{aligned} r\cdot V = {} & \left[\gamma_a\left(\frac{\partial V}{\partial R_a} + \eta\frac{\partial V}{\partial R_b}\right) - \theta_a\right]R_a + \left(\gamma_b\frac{\partial V}{\partial R_b} - \theta_b\right)R_b - \frac{[\varepsilon_a + \alpha_a((\partial V_s/\partial R_a) + \eta(\partial V_s/\partial R_b))]^2}{2\mu_s} \\ & - \frac{(\varepsilon_b + \alpha_b(\partial V_s/\partial R_b))^2}{2\mu_s} - \frac{[\delta_a + \beta_a((\partial V/\partial R_a) + \eta(\partial V/\partial R_b))]^2}{2\mu_a} - \frac{(\delta_b + \beta_b(\partial V/\partial R_b))^2}{2\mu_b} + \omega_a M + \omega_b N. \end{aligned} \quad (82)$$

From equation (81), we can see that the linear optimal income functions about R_a, R_b are the solutions of the HJB equation, let

$$V(R_a, R_b) = pR_a + qR_b + u, \quad (83)$$

where p, q, u are constants. Deriving equation (83) and substituting the results into equation (82), it can be obtained that

$$\begin{aligned} r(pR_a + qR_b + u) = {} & [\gamma_a(p + \eta q) - \theta_a]R_a + (\gamma_b q - \theta_b)R_b - \frac{[\varepsilon_a + \alpha_a(p + \eta q)]^2}{2\mu_s} - \frac{(\varepsilon_b + \alpha_b q)^2}{2\mu_s} \\ & - \frac{[\delta_a + \beta_a(p + \eta q)]^2}{2\mu_a} - \frac{(\delta_b + \beta_b q)^2}{2\mu_b} + \omega_a M + \omega_b N. \end{aligned} \quad (84)$$

If formula (84) satisfies all $R_a \geq 0, R_b \geq 0$, we can get

$$\begin{aligned} p &= \frac{\lambda\gamma_a\theta_b}{(r + \gamma_a)(r + \gamma_b)} - \frac{\theta_a}{r + \gamma_a}, \\ q &= -\frac{\theta_b}{r + \gamma_b}, \\ u &= -\frac{[\varepsilon_a(r + \gamma_a) + \alpha_a\theta_a + (\eta r\alpha_a\theta_b/(r + \gamma_b))]^2}{2\mu_s r(r + \gamma_a)^2} - \frac{[\varepsilon_b(r + \gamma_b) + \alpha_b\theta_b]^2}{2\mu_s r(r + \gamma_b)^2} - \frac{[\delta_a(r + \gamma_a) + \beta_a\theta_a + (\eta r\beta_a\theta_b/(r + \gamma_b))]^2}{2\mu_a r(r + \gamma_a)^2} \\ &\quad - \frac{[\delta_b(r + \gamma_b) + \beta_b\theta_b]^2}{2\mu_b r(r + \gamma_b)^2} + \frac{\omega_a M + \omega_b N}{r}. \end{aligned} \quad (85)$$

Substituting equation (85) into equation (83), the optima benefit function can be obtained as

$$V^{***}(R_a, R_b) = \frac{M+N}{r} - \left[\frac{\theta_a}{r+\gamma_a} - \frac{\lambda\gamma_a\theta_b}{(r+\gamma_a)(r+\gamma_b)}\right]R_a - \frac{\theta_b}{r+\gamma_b}R_b - \frac{\left[\varepsilon_a(r+\gamma_a)+\alpha_a\theta_a+(\eta r\alpha_a\theta_b/(r+\gamma_b))\right]^2}{2\mu_s r(r+\gamma_a)^2}$$
$$- \frac{\left[\varepsilon_b(r+\gamma_b)+\alpha_b\theta_b\right]^2}{2\mu_s r(r+\gamma_b)^2} - \frac{\left[\delta_a(r+\gamma_a)+\beta_a\theta_a+(\eta r\beta_a\theta_b/(r+\gamma_b))\right]^2}{2\mu_a r(r+\gamma_a)^2} - \frac{\left[\delta_b(r+\gamma_b)+\beta_b\theta_b\right]^2}{2\mu_b r(r+\gamma_b)^2}. \tag{86}$$

By deriving (86) and substituting the results into equations (78)–(81), equations (72)–(75) can be obtained.

At this time, the environmental pollution control level of Local-gov A is

$$\begin{cases} R_a^{***}(t) = \dfrac{1}{\gamma_a}\left[\dfrac{\alpha_a}{\mu_s}\left(\varepsilon_a + \dfrac{\alpha_a\theta_a}{r+\gamma_a} + \dfrac{\eta r\alpha_a\theta_b}{(r+\gamma_a)(r+\gamma_b)}\right) + \dfrac{\beta_a}{\mu_a}\left(\delta_a + \dfrac{\beta_a\theta_a}{r+\gamma_b} + \dfrac{\eta r\beta_a\theta_b}{(r+\gamma_a)(r+\gamma_b)}\right) - e^{-\gamma_a t + D_a}\right], \\ R_a^{***}(0) = R_a. \end{cases} \tag{87}$$

The environmental pollution control level of Local-gov B is

$$\begin{cases} R_b^{**}(t) = \dfrac{\eta}{\gamma_b}\left\{\dfrac{\alpha_a}{\mu_s}\left[\varepsilon_a + \dfrac{\alpha_a\theta_a}{r+\gamma_a} + \dfrac{\eta r\alpha_a\theta_b}{(r+\gamma_a)(r+\gamma_b)}\right] + \dfrac{\beta_a}{\mu_a}\left[\delta_a + \dfrac{\beta_a\theta_a}{r+\gamma_a} + \dfrac{\eta r\alpha_a\theta_b}{(r+\gamma_a)(r+\gamma_b)}\right] - e^{-\gamma_a t + D_a}\right\} \\ +\dfrac{1}{\gamma_b}\left[\dfrac{\alpha_b}{\mu_s}\left(\varepsilon_b + \dfrac{\alpha_b\theta_b}{r+\gamma_b}\right) + \dfrac{\beta_b}{\mu_b}\left(\delta_b + \dfrac{\beta_b\theta_b}{r+\gamma_b}\right) - e^{-\gamma_b t + D_b}\right], \\ R_b^{**}(0) = R_b, \\ e^{D_a} = \dfrac{\alpha_a}{\mu_s}\left[\varepsilon_a + \dfrac{\alpha_a\theta_a}{r+\gamma_a} + \dfrac{\eta r\alpha_a\theta_b}{(r+\gamma_a)(r+\gamma_b)}\right] + \dfrac{\beta_a}{\mu_a}\left[\delta_a + \dfrac{\beta_a\theta_a}{r+\gamma_a} + \dfrac{\eta r\alpha_a\theta_b}{(r+\gamma_a)(r+\gamma_b)}\right] - \gamma_a R_a. \end{cases} \tag{88}$$

From equations (72)–(75), it can be seen that under the Cooperative model, the optimal efforts of the Cent-gov and Local-gov A no longer involve the distribution ratio of environmental pollution losses, and other influencing factors are consistent with the Nash game model and the Stackelberg model. □

5. Comparative Analysis of Equilibrium Results

This section compares the equilibrium results, environmental pollution control levels, and environmental pollution losses in the three models, and analyzes whether the Nash game model and the Cooperative model can effectively promote the local governments' environmental pollution control efforts, improve governance level, and reduce environmental pollution losses.

5.1. Analysis of Game Equilibrium Strategy. The comparison of the optimal effort strategies of the Cent-gov and local governments under three models is as follows.

Proposition 4. *When* $(1/3) < \omega \leq 1$, ① *the optimal effort of Local-gov A:* $E_a^* < E_a^{**} \leq E_a^{***}$; ② *the optimal effort of Local-gov B:* $E_b^* < E_b^{**} \leq E_b^{***}$; ③ *the optimal effort of Cent-gov:* $E_{as}^* = E_{as}^{**} \leq E_{as}^{***}$, $E_{bs}^* = E_{bs}^{**} \leq E_{bs}^{***}$; *and* ④ *the Cent-gov's optimal funding for local governments:* $\lambda_a^{**} = (E_a^{**} - E_a^*)/E_a^{**}$, $\lambda_b^{**} = (E_b^{**} - E_b^*)/E_b^{**}$.

Proof. ① According to equations (7), (39), and (72), we can get

$$\begin{aligned} E_a^{**} - E_a^{*} &= \frac{3\omega_a - 1}{2\mu_a}\left(\delta_a + \frac{\beta_a\theta_a}{r+\gamma_a}\right) + \frac{\eta r\beta_a\omega_b\theta_b}{\mu_a(r+\gamma_a)(r+\gamma_b)} > 0,\\ E_a^{***} - E_a^{**} &= \frac{1-\omega_a}{2\mu_a}\left[\delta_a + \frac{\beta_a\theta_a}{r+\gamma_a} + \frac{\eta r\beta_a\theta_b}{(r+\gamma_a)(r+\gamma_b)}\right] + \frac{\eta r\beta_a(1-\omega_b)\theta_b}{(r+\gamma_a)(r+\gamma_b)} \geq 0. \end{aligned} \tag{89}$$

Therefore, $E_a^{*} < E_a^{**} \leq E_a^{***}$ is established.

② According to equations (8), (40), and (73), we can get

$$\begin{aligned} E_b^{**} - E_b^{*} &= \frac{3\omega_b - 1}{2\mu_b}\left(\delta_b + \frac{\beta_b\theta_b}{r+\gamma_b}\right) > 0,\\ E_b^{***} - E_b^{**} &= \frac{1-\omega_b}{2\mu_b}\left[\delta_b + \frac{\beta_b\theta_b}{r+\gamma_b} + \frac{\eta r\beta_a\theta_b}{(r+\gamma_a)(r+\gamma_b)}\right] + \frac{\eta r\beta_b(1-\omega_b)\theta_b}{\mu_b(r+\gamma_a)(r+\gamma_b)} \geq 0. \end{aligned} \tag{90}$$

Therefore, $E_b^{*} < E_b^{**} \leq E_b^{***}$ is established.

③ According to equations (9), (41), and (74), we can get

$$\begin{aligned} E_{as}^{*} &= E_{as}^{**},\\ E_{as}^{***} - E_{as}^{**} &= \frac{1-\omega_a}{\mu_s}\left[\varepsilon_a + \frac{\alpha_a\theta_a}{r+\gamma_a} + \frac{\eta r\alpha_a\omega_b\theta_b}{(r+\gamma_a)(r+\gamma_b)}\right] \geq 0. \end{aligned} \tag{91}$$

Therefore, $E_{as}^{*} = E_{as}^{**} \leq E_{as}^{***}$ is established.

According to equations (10), (42), and (75), we can get

$$\begin{aligned} E_{bs}^{*} &= E_{bs}^{**},\\ E_{bs}^{***} - E_{bs}^{**} &= \frac{1-\omega_b}{\mu_s}\left(\varepsilon_b + \frac{\alpha_b\theta_b}{r+\gamma_b}\right) \geq 0. \end{aligned} \tag{92}$$

So, $E_{bs}^{*} = E_{bs}^{**} \leq E_{bs}^{***}$.

④ According to equations (7), (39), and (43), we can get

$$\begin{aligned} E_a^{**} - E_a^{*} &= \frac{3\omega_a - 1}{2\mu_a}\left(\delta_a + \frac{\beta_a\theta_a}{r+\gamma_a}\right) + \frac{\eta r\beta_a\omega_b\theta_b}{\mu_a(r+\gamma_a)(r+\gamma_b)}\\ &= E_a^{**}\cdot\lambda_a^{**} > 0. \end{aligned} \tag{93}$$

According to equations (8), (40), and (44), we can get

$$E_b^{**} - E_b^{*} = \frac{1-\omega_b}{2\mu_b}\left[\delta_b + \frac{\beta_b\theta_b}{r+\gamma_b} + \frac{\eta r\beta_a\theta_b}{(r+\gamma_a)(r+\gamma_b)}\right] + \frac{\eta r\beta_b(1-\omega_b)\theta_b}{\mu_b(r+\gamma_a)(r+\gamma_b)} = E_b^{**}\cdot\lambda_b^{**}. \tag{94}$$

The proof is completed.

Proposition 4 shows that when transitioning from the Nash game model to Stackelberg game model, the effort level of the Cent-gov will remain unchanged, while the effort level of Local-gov A and Local-gov B will increase, and the degree of improvement is related to the funding from Cent-gov.

Under the Cooperative game model, all parties have the highest effort level, and the involvement of the Cent-gov has given a positive signal to protect the environment. The local governments tend to actively implement priority strategies and policies promoted by the Cent-gov, otherwise they may be held accountable for inaction. In order to effectively coordinate the allocation of regional environmental pollution control resources, the Cent-gov boosts environmental governance investment through policy leverage. □

5.2. Analysis on the Environmental Pollution Control Level. Comparison of environmental pollution control level between Local-gov A and Local-gov B under three models.

Proposition 5. *When* $(1/3) < \omega \leq 1$, ① *comparison of environmental pollution control levels of Local-gov A is* $R_a^{*} \leq R_a^{**} \leq R_a^{***}$ *and* ② *comparison of environmental pollution control levels of Local-gov B is* $R_b^{*} \leq R_b^{**} \leq R_b^{***}$.

Proof. ① According to equations (34), (70), and (87), we can get

$$\begin{cases} R_a^{**}(t) - R_a^{**}(t) = \dfrac{\left(1-e^{-\gamma_a t}\right)\beta_a}{\gamma_a\mu_a}\left[\dfrac{3\omega_a-1}{2}\left(\delta_a+\dfrac{\beta_a\theta_a}{r+\gamma_b}\right)+\dfrac{\eta r\beta_a\omega_b\theta_b}{(r+\gamma_a)(r+\gamma_b)}\right]\geq 0, \\ R_a^{*}(0) = R_a^{**}(0), \end{cases}$$
$$\begin{cases} R_a^{***}(t) - R_a^{**}(t) = \dfrac{1-e^{-\gamma_a t}}{\gamma_a}\left\{\dfrac{\alpha_a}{\mu_s}(1-\omega_a)\left(\varepsilon_a+\dfrac{\alpha_a\theta_a}{r+\gamma_a}\right)+\dfrac{\beta_a}{2\mu_a}\left[(1-\omega_a)\left(\delta_a+\dfrac{\beta_a\theta_a}{r+\gamma_b}\right)+\dfrac{\eta r\beta_a(1-\omega_b)\theta_b}{(r+\gamma_a)(r+\gamma_b)}\right]\right\}\geq 0, \\ R_a^{*}(0) = R_a^{**}(0). \end{cases} \tag{95}$$

So, $R_a^{*} \leq R_a^{**} \leq R_a^{***}$.

② According to equations (34), (71), and (88), we can get

$$\begin{cases} R_b^{**}(t) - R_b^{*}(t) = \dfrac{1}{\gamma_b}\left\{\dfrac{\eta\beta_a\left(1-e^{-\gamma_a t}\right)}{\mu_a}\left[\dfrac{3\omega_a-1}{2}\left(\delta_a+\dfrac{\beta_a\theta_a}{r+\gamma_a}\right)+\dfrac{\eta r\alpha_a\omega_b\theta_b}{(r+\gamma_a)(r+\gamma_b)}\right]+\dfrac{(1+\omega_b)\beta_b\left(1-e^{-\gamma_b t}\right)}{2\mu_b}\left(\delta_b+\dfrac{\beta_b\theta_b}{r+\gamma_b}\right)\right\}\geq 0, \\ R_b^{*}(0) = R_b^{**}(0), \end{cases}$$
$$\begin{cases} R_b^{***}(t) - R_b^{**}(t) \\ = \dfrac{\eta\left(1-e^{-\gamma_a t}\right)}{\gamma_b}\left\{\left[\dfrac{\alpha_a(1-\omega_a)}{\mu_s}\left(\varepsilon_a+\dfrac{\alpha_a\theta_a}{r+\gamma_a}\right)+\dfrac{\eta r\alpha_a\omega_b\theta_b}{(r+\gamma_a)(r+\gamma_b)}\right]+\dfrac{\beta_a}{\mu_a}\left[\dfrac{1-\omega_a}{2}\left(\delta_a+\dfrac{\beta_a\theta_a}{r+\gamma_a}\right)+\dfrac{\eta r\alpha_a(1-\omega_b)\theta_b}{(r+\gamma_a)(r+\gamma_b)}\right]\right\} \\ +\dfrac{1-e^{-\gamma_b t}}{\gamma_b}\left[\dfrac{\alpha_b(1-\omega_b)}{\mu_s}\left(\varepsilon_b+\dfrac{\alpha_b\theta_b}{r+\gamma_b}\right)+\dfrac{\beta_b(1-\omega_b)}{2\mu_b}\left(\delta_b+\dfrac{\beta_b\theta_b}{r+\gamma_b}\right)\right]\geq 0, \\ R_b^{**}(0) = R_b^{***}(0). \end{cases} \tag{96}$$

So, $R_b^{*} \leq R_b^{**} \leq R_b^{***}$.

Proposition 5 shows that compared with the Nash game model, the Stackelberg game model can better promote the improvement of environmental pollution control level for Local-gov A and Local-gov B. In the Cooperative game model, with the maximization of the effort level of the Cent-gov and local governments, the environmental pollution control level has also reached the highest level.

The Cooperative game model is an effective mechanism to improve the local environmental pollution control level. That is to say, under appropriate circumstances, it is possible for governments to achieve economies of scale and policy spillover effects through cooperation. □

5.3. Analysis of Minimum Environmental Pollution Losses. A comparative analysis about environmental pollution losses of Local-gov A, Local-gov B, and Cent-gov under three models.

Proposition 6. *For any* $R_a \geq 0, R_b \geq 0$, $(1/3) < \omega \leq 1$, ① *comparison of the optimal environmental pollution losses of Local-gov A:* $V_a^{*}(R_a, R_b) \geq V_a^{**}(R_a, R_b)$; ② *comparison of the optimal environmental pollution losses of Local-gov B:* $V_b^{*}(R_a, R_b) \geq V_b^{**}(R_a, R_b)$; ③ *comparison of the optimal environmental pollution Losses of Cent-gov:* $V_s^{*}(R_a, R_b) \geq V_s^{**}(R_a, R_b)$; *and* ④ *comparison of the total* *environmental pollution losses:* $V^*(R_a,R_b) \geq V^{*}(R_a,R_b) \geq V^{**}(R_a,R_b)$.

Proof. ① According to the formulas (30) and (66), we can get

$$V_a^*(R_a,R_b) - V_a^{**}(R_a,R_b) = \left[\frac{\omega_a\theta_a}{r+\gamma_a} - \frac{\lambda\gamma_a\theta_b}{(r+\gamma_a)(r+\gamma_b)}\right](R_a^{**}-R_a^*) + \frac{\omega_2\theta_b}{r+\gamma_b}(R_b^{**}-R_b^*) + \frac{(1-\omega_a)[\delta_a(r+\gamma_a)+\beta_a\theta_a]\{(3\omega_a-1)[\delta_a(r+\gamma_a)+\beta_a\theta_a]+2\eta r\beta_a\omega_b\theta_b/r+\gamma_b\}}{4\mu_a r(r+\gamma_a)^2} \geq 0. \tag{97}$$

So, $V_a^*(R_a,R_b) \geq V_a^{**}(R_a,R_b)$.

② According to the formulas (31) and (67), we can get

$$V_b^*(R_a,R_b) - V_b^{**}(R_a,R_b) = \left[\frac{\omega_a\theta_a}{r+\gamma_a} - \frac{\lambda\gamma_a\theta_b}{(r+\gamma_a)(r+\gamma_b)}\right](R_a^{**}-R_a^*) + \frac{\theta_b}{r+\gamma_b}(R_b^{**}-R_b^*) + \frac{\eta\beta_a(1-\omega_b)(3\omega_a-1)\theta_b[\delta_a(r+\gamma_a)+\beta_a\theta_a]}{2\mu_a(r+\gamma_a)^2(r+\gamma_b)} + \frac{\eta^2 r\alpha_a\beta_a\omega_b(1-\omega_b)\theta_b^2}{\mu_a(r+\gamma_a)^2(r+\gamma_b)} + \frac{(1-\omega_b)(3\omega_b-1)[\delta_b(r+\gamma_b)+\beta_b\theta_b]^2}{4\mu_b r(r+\gamma_b)^2} \geq 0. \tag{98}$$

So, $V_b^*(R_a,R_b) \geq V_b^{**}(R_a,R_b)$.

③ According to the formulas (32) and (68), we can get

$$V_s^*(R_a,R_b) - V_s^{**}(R_a,R_b) = \left[\frac{\omega_a\theta_a}{r+\gamma_a} - \frac{\lambda\gamma_a\theta_b}{(r+\gamma_a)(r+\gamma_b)}\right](R_a^{**}-R_a^*) + \frac{\theta_b}{r+\gamma_b}(R_b^{**}-R_b^*) + \frac{\{(3\omega_a-1)[\delta_a(r+\gamma_a)+\beta_a\theta_a]+(2\eta r\beta_a\omega_b\theta_b/(r+\gamma_b))\}^2}{2\mu_a(r+\gamma_a)^2(r+\gamma_b)} + \frac{(3\omega_b-1)^2[\delta_b(r+\gamma_b)+\beta_b\theta_b]^2}{8\mu_b r(r+\gamma_b)^2} > 0. \tag{99}$$

Thus, $V_s^*(R_a,R_b) \geq V_s^{**}(R_a,R_b)$.

④ $V^*(R_a,R_b) \geq V^{**}(R_a,R_b)$ is easy to get from ①, ②, and ③.

According to the formulas (69) and (86), we can get

$$V^{**}(R_a,R_b) - V^{***}(R_a,R_b) = \left[\frac{\omega_a\theta_a}{r+\gamma_a} - \frac{\lambda\gamma_a\theta_b}{(r+\gamma_a)(r+\gamma_b)}\right](R_a^{***}-R_a^{**}) + \frac{\theta_b}{r+\gamma_b}(R_b^{***}-R_b^{**}) + \frac{\{(1-\omega_a)[\varepsilon_a(r+\gamma_a)+\alpha_a\theta_a]+\eta r\alpha_a(1-\omega_b)\theta_b/r+\gamma_b\}^2}{2\mu_s(r+\gamma_a)^2} + \frac{(1-\omega_b)^2[\varepsilon_b(r+\gamma_b)+\alpha_b\theta_b]^2}{2\mu_s(r+\gamma_b)} + \frac{\{(1-\omega_a)[\delta_a(r+\gamma_a)+\beta_a\theta_a]+2\eta r\beta_a(1-\omega_b)\theta_b/r+\gamma_b\}^2}{8\mu_a(r+\gamma_a)^2} + \frac{(1-\omega_b)^2[\delta_b(r+\gamma_b)+\beta_b\theta_b]^2}{2\mu_b r(r+\gamma_b)^2} \geq 0. \tag{100}$$

Thus, $V^*(R_a,R_b) \geq V^{**}(R_a,R_b) \geq V^{***}(R_a,R_b)$.

Proposition 6 shows that compared with the Nash game model, the Stackelberg game model promotes the Pareto improvement of all parties, and the environmental pollution losses of all parties are reduced. The Stackelberg game model is better than the Nash game model. From a holistic point of

Table 1: The effort levels of Cent-gov and local governments under the three models.

	E_a	E_b	E_{as}	E_{bs}
Nash game model	4.50	4.30	3.17	2.18
Stackelberg game model	6.96	5.02	3.17	2.18
Cooperative game model	9.53	7.17	6.33	5.44
Analysis	$E_a^* < E_a^{**} < E_a^{***}$	$E_b^* < E_b^{**} < E_b^{***}$	$E_{as}^* = E_{as}^{**} < E_{as}^{***}$	$E_{bs}^* = E_{bs}^{**} < E_{bs}^{***}$

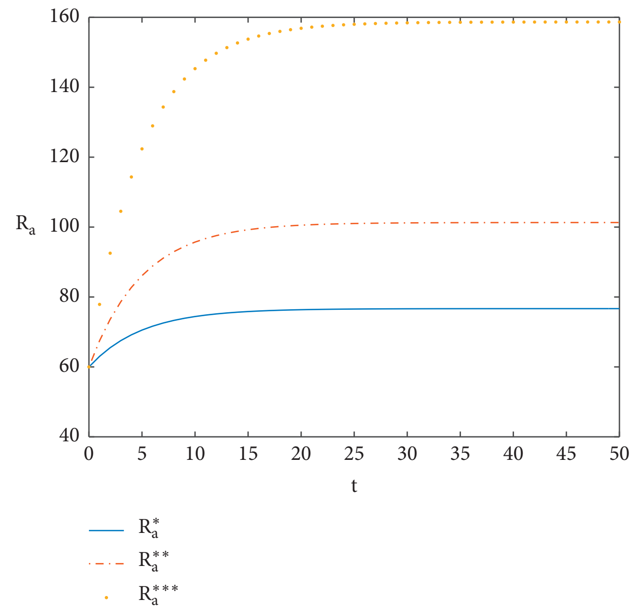

Figure 1: The environmental pollution control level of Local-gov A.

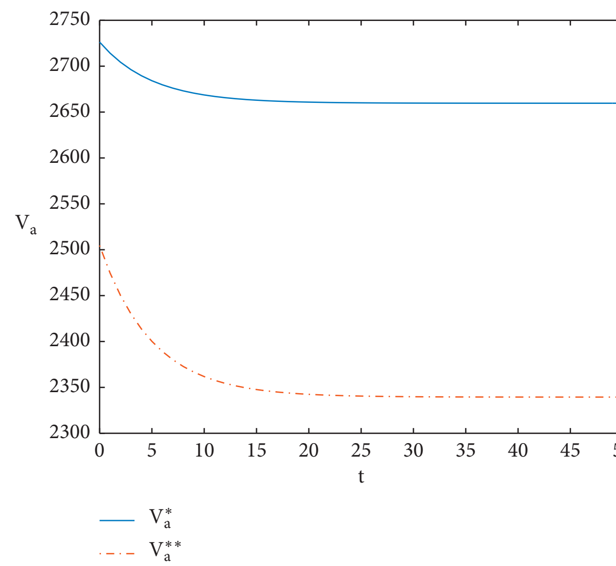

Figure 3: Comparison of environmental pollution losses of Local-gov A.

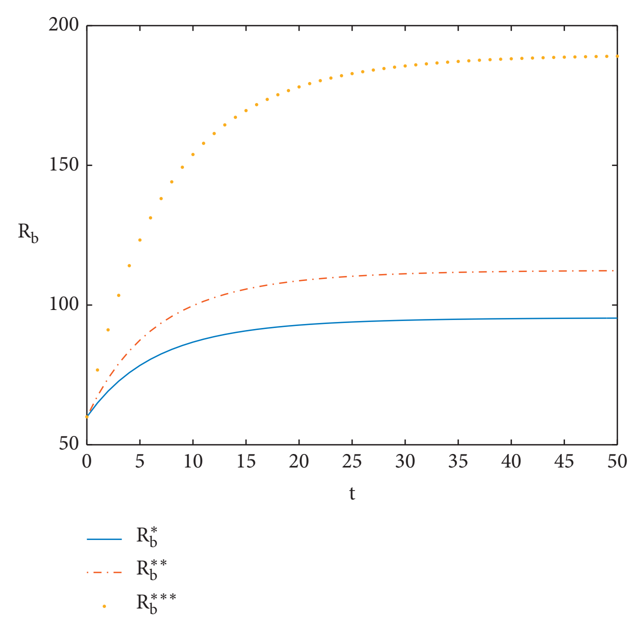

Figure 2: The environmental pollution control level of Local-gov B.

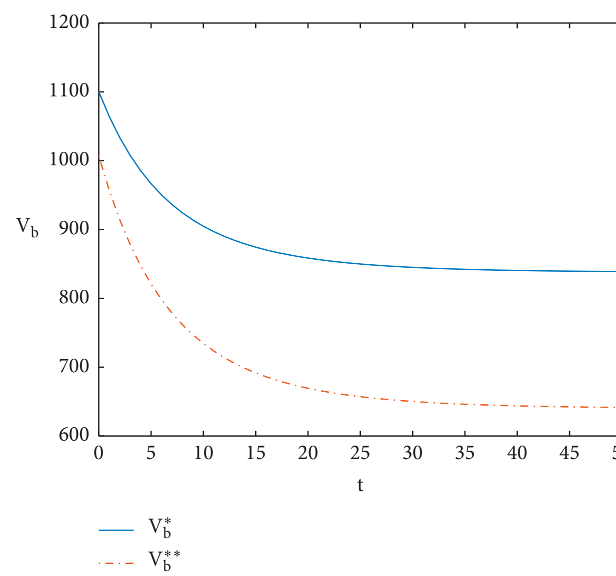

Figure 4: Comparison of environmental pollution losses of Local-gov B.

view, if a reasonable environmental pollution losses commitment scheme can be formulated, the Cooperative game model is better than the other two models.

In summary, under the Nash game model, the Cent-gov and local governments as subjects with relatively independent interests and responsibilities choose the optimal effort level from the perspective of minimizing their own environmental losses, without considering the overall interests of the region. In order to improve the local environment and promote local economic development, local governments will take proactive actions to control environmental pollution. However, due to the division of administrative power and the positive externality of environmental governance, local governments have a negative attitude towards matters involving multiple administrative regions. The environmental pollution emergency linkage benefits are almost negligible. In the Stackelberg game model, the intervention of the Cent-gov can effectively solve the market failure caused by the externalities of environmental pollution, optimize resource allocation to a certain extent, and effectively reduce environmental pollution losses. By formulating a clear financial subsidy system, the central government strengthens financial support to local governments, which can effectively reduce the self-interested behavior of local governments, consolidate the trust between the local government and the central government, and promote more effective cooperation between the two parties. The Cooperative game model, which aims at minimizing the environmental pollution losses, is the best choice for Cent-gov, Local-gov A, and Local-gov B during environmental governance, and can effectively control the environmental pollution losses. □

6. Numerical Analyses

Under the three modes, the optimal effort level, environmental pollution control level, and environmental pollution losses of Local-gov A, Local-gov B, and Cent-gov depend on the selection of various parameters in the models. If we assume that $R_a(0) = R_b(0) = 60$, in the models, discount rate $r = 0.05$, and the pollution losses distribution ratios are $\omega_1 = 0.5, \omega_2 = 0.4$, $\mu_s = 3, \mu_a = 2, \mu_b = 2$, $\alpha_a = 2, \alpha_b = 1$, $\beta_a = 2, \beta_b = 1$, the attenuation rates of environmental pollution control level are: $\gamma_a = 0.2, \gamma_b = 0.1$, $\varepsilon_a = 3, \varepsilon_b = 3$, $\delta_a = 2, \delta_b = 1$, $\theta_a = 2, \theta_b = 2$, $\eta = 0.2$. Under the three models, the effort levels of Cent-gov and local governments are shown in Table 1.

In the Nash game model, environmental pollution control efforts of the Cent-gov and local governments are always the lowest; in the Stackelberg game model, the environmental pollution control effort of the Cent-gov is consistent with that in the Nash game model. However, the environmental pollution control efforts of Local-gov A and Local-gov B have improved to some extent; in the Cooperative game model, the efforts of all parties have significantly improved and reach the highest state, which are consistent with the conclusions of Proposition 4.

In the Nash game model, the environmental pollution control level of Local-gov A is $R_a^* = 76.67 - 16.67e^{-0.2t}$, the environmental pollution control level of Local-gov B is $R_b^* = 95.44 - 18.67e^{-0.2t} - 16.78e^{-0.1t}$, the minimum environmental pollution losses of Local-gov A is $V_a^* = 2966.31 - 4R_a$, the minimum environmental pollution losses of Local-gov B is $V_b^* = 1503.4 + 1.28R_a - 8R_b$, the minimum environmental pollution losses of Cent-gov is $V_s^* = 4034.32 - 3.15R_a - 5.33R_b$, the total environmental pollution losses in the region is $V^* = 8504.04 - 5.87R_a - 13.33R_b$; in the Stackelberg game model, the environmental pollution control level of Local-gov A is $R_a^{**} = 101.3 - 41.3e^{-0.2t}$, the environmental pollution control level of Local-gov B is $R_b^{**} = 112.46 - 28.52e^{-0.2t} - 23.94e^{-0.1t}$, the minimum

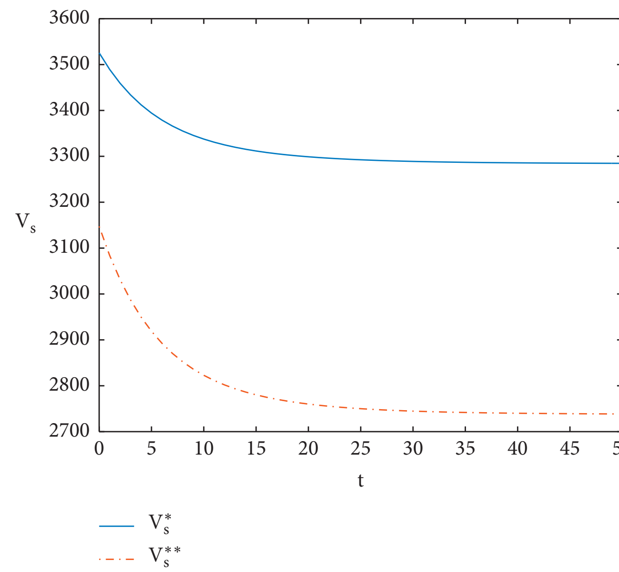

Figure 5: Comparison of environmental pollution losses of Cent-gov.

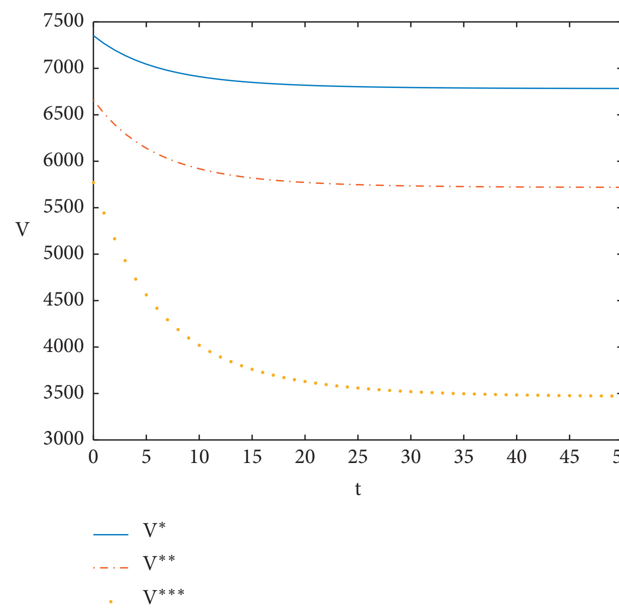

Figure 6: Comparison of total environmental pollution losses in the region.

environmental pollution losses of Local-gov A is $V_a^{**} = 2744.61 - 4R_a$, the minimum environmental pollution losses of Local-gov B is $V_b^{**} = 1410.24 + 1.28R_a - 8R_b$, the minimum environmental pollution losses of Cent-gov is $V_s^{**} = 3656.16 - 3.15R_a - 5.33R_b$, the total environmental pollution losses in the region is $V^{**} = 7811.01 - 5.87R_a - 13.33R_b$; in the Cooperative game model, the environmental pollution control level of Local-gov A is $R_a^{***} = 158.67 - 98.67e^{-0.2t}$, the environmental pollution control level of Local-gov B is $R_b^{***} = 189.58 - 51.47e^{-0.2t} - 78.11e^{-0.1t}$, the total environmental pollution losses in the region is $V^{***} = 6923.59 - 5.87R_a - 13.33R_b$.

The trends of environmental pollution control levels of Local-gov A and Local-gov B are shown in Figures 1 and 2. Under the three models, the improvement of environmental pollution control level tends to be stable over time. In Nash game model, the environmental pollution control levels are the lowest; in the Stackelberg game model, the environmental pollution control levels have been improved; and in the Cooperative game model, the environmental pollution control levels have always been higher than the other two models, which are consistent with the conclusions of Proposition 5.

Before the improvement of environmental pollution control level stabilizes, the growth rate of the environmental pollution control level in the Nash game model is the slowest, the growth rate of the Stackelberg game model is medium, and the growth rate of the Cooperative game model is the fastest.

In the three models, the trend of environmental pollution losses of Local-gov A, Local-gov B, Cent-gov, and the region over time is shown in Figures 3–6. Under the Stackelberg game model, the environmental pollution losses of Local-gov A, Local-gov B, and Cent-gov increase over time and tend to be stable, and are always lower than that under the Nash game model; The regional total environmental pollution losses under the Cooperative game model is always lower than the environmental pollution losses of Local-gov A under the Nash game model and the Stackelberg game model, which are consistent with the conclusions of Proposition 6.

7. Conclusions and Policy Recommendations

7.1. Conclusions. This paper constructs two functions about the environmental pollution control level and environmental pollution losses, which are used to study the environmental pollution control problem between the Cent-gov and the two local governments. The local governments improve environmental pollution control levels through their own efforts and the Cent-gov's funding and seek to minimize environmental pollution losses in an infinite time zone.

This paper constructs a tripartite differential game model, and considers the equilibrium results, environmental pollution control level, and minimum pollution losses of the Cent-gov and the two local governments in the three models, and then carries out the comparative analysis. The result shows the following:

(1) In three situations, the cost coefficient of all governments, the attenuation coefficient of environmental pollution control level, and the discount rate are inversely proportional to the environmental pollution effort; the government's ability to influence and govern are directly proportional to environmental pollution effort.

(2) In the process of environmental pollution control, the parties put in more efforts in the Cooperative game model than the other two models.

(3) From the perspective of environmental pollution control level and regional total pollution losses, the Cooperative game model is superior to the Nash game model and the Stackelberg model, which can achieve the Pareto optimal of the system.

(4) This paper quantitatively analyzes the relationship between central government funding and the proportion of environmental pollution losses, the effort level of local government, and the environmental pollution control level. The Cent-gov's special subsidy can effectively encourage local governments to put in more environmental pollution control efforts and reduce all parties' pollution losses and achieve Pareto optimal.

7.2. Policy Recommendations

(1) Reform the fiscal decentralization system and improve the performance evaluation standards of local governments. For a long time, the performance evaluation standards of local governments have always been around GDP growth. Local governments have paid more attention to local economic development and paid less attention to nonproductive expenditures such as environmental protection. Expenditure on economic construction has greatly squeezed out expenditure on energy conservation and environmental protection, and ecological and environmental protection has been neglected in the process of economic development. Therefore, the Cent-gov should completely abandon the "GDP-only" performance evaluation system, accelerate the inclusion of environmental protection and sustainable development indicators into the evaluation system, promote the coordinated and healthy development of the economy and the environment, and achieve green fiscal competition.

(2) Strengthen the cooperation of governments at all levels to promote the equalization of local environmental governance. The environmental protection requires a large amount of capital investment, and only relying on local fiscal revenue to ensure the growth of environmental protection expenditure cannot be sustained. The research results of this paper show that government special subsidies can effectively encourage local governments to take more environmental protection efforts and reduce environmental pollution losses

from all parties. Therefore, the Cent-gov must strengthen special transfer payments to local governments for environmental protection, and use special funds to solve the contradiction between the local government's environmental protection needs and the shortage of financial funds, and establish a horizontal transfer payment system. Because environmental pollution is transboundary and environmental protection has positive externality, the central government should formulate an environmental compensation mechanism between local governments, and regions that benefit from environmental protection should provide compensation to regions that provide environmental protection.

(3) Improve the transparency of fiscal expenditures and strengthen social supervision and central supervision. On the one hand, the Cent-gov should further strengthen fiscal transparency, regulate fiscal revenue and expenditure, harden budget constraints, and mobilize social supervision; on the other hand, it should emphasize fiscal incentives for green investment in enterprises, and use policy guidance to help prevent and control environmental pollution. Through local finance, companies that invest in environmental protection are provided with indirect tax reductions, and companies that use pollution-free equipment in the production process directly enjoy tax credits, so that companies can develop advanced technologies and factories to reduce environmental pollution.

With the development of global economic integration, environmental pollution and destruction are not only a domestic cross-administrative regional cooperative governance problem but also an international cross-border cooperative governance problem [39]. For example, a large amount of greenhouse gas emissions have caused global warming. Water pollution of the Rhine River caused widespread death of aquatic life in coastal countries. The environmental governance investment, as a typical international public goods supply, has significant positive externality, and the benefits and costs brought by it are seriously unequal, which makes it difficult to achieve international cooperation and international coordination. Therefore, certain measures need to be taken to promote international government cooperation. We can start from the following aspects:

(1) Enhance the linkage effect of ecological cooperation between countries. All countries should continuously improve their domestic ecological protection policies and institutional systems, provide policy support for environmental protection, and actively participate in the construction of ecological civilization; all countries should formulate mutually supportive policy systems and carry out in-depth cooperation to reduce national barriers toward the implementation of environmental protection policies; strengthen the role of international organizations in providing public goods, expand the sources of environmental protection funds, and ensure the adequacy and continuity of capital investment.

(2) Call on all countries to strengthen ecological and environmental protection. On the one hand, international organizations represented by the United Nations should actively promote the global action concept of ecological civilization construction, continuously create an atmosphere of common action and common governance around the world, and increase the enthusiasm and initiative of each country to participate in environmental changes; on the other hand, developed countries should play an exemplary role, follow historical logic, actively assume common but differentiated responsibilities, and work with developing countries to solve the ecological and environmental dilemmas faced by mankind.

(3) Improve the cost-sharing mechanism and compensation mechanism for environmental protection. The benefits of environmental protection investment have the characteristics of lagging and being risky, and may not be able to obtain benefits in the short term. Then, other countries should share and compensate the countries that invested in the early stage, so as to form a long-term cooperative relationship. The "free rider" problem in the supply of international public goods can be solved, and the "prisoner's dilemma" can be transformed into a cooperative game.

The shortcomings of this paper are the following three points: Firstly, this paper only considers the intergovernmental relationship between the Cent-gov and the two local governments. In reality, the process of regional environmental pollution control will involve more than two local governments; secondly, this paper only considers the impact of major participants' efforts and environmental pollution control levels on environmental pollution losses; however, in reality, many factors are contributing to the losses due to environmental pollution, and they are mutually connected and also affected; finally, for the convenience of solving, this paper assumes that all parameters in the models are not related to time, the subsequent research can use a differential game model to solve the nondegenerate problem.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Authors' Contributions

All authors contributed equally to this paper.

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Research Article

Evolutionary Game Analysis of Three Players on Behavioural Strategy of P2P Lending Participants: A Sustainable Operations Perspective

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In China, most of peer-to-peer (P2P) lending platforms do not possess operational sustainability due to excessive defaults. To address this problem, the conflict of interests among P2P lending participants is discussed using a stakeholder approach. An evolutionary game model (EGM) of three players is developed to analyse the interactions among regulatory authorities, P2P lending platforms, and borrowers. Then, the asymptotic of the equilibrium and evolutionary stability strategies of the EGM are analysed. Results indicate that either the P2P lending platforms or borrowers will choose "noncompliant operation" or "default" strategies from a short-term perspective, and the strict supervision of the P2P lending platform in the short term is necessary for the sustainable operation of the platform. When supervision is intensified in the early stage and regulatory pressure becomes a normal state, P2P lending platforms and borrowers will actively select "compliant operation" and "repayment" strategies even if there is a lack of regulation in the future. Meanwhile, the behavioural strategies of P2P lending participants can be changed to conform to the sustainability of P2P lending by reducing the costs of strict supervision and increasing the damage caused by general supervision, reward and punishment coefficient for P2P lending platforms, repayment incentives of borrowers, and defaulting opportunity costs. Finally, suggestions for regulating the behaviours of P2P lending participants and promoting sustainability of P2P lending industry are discussed.

1. Introduction

Peer-to-peer (P2P) lending, as a supplement to the modern financial system, deals with the financing difficulties for small and medium-sized enterprises (SMEs). It plays an important role in promoting inclusive finance [1]. The number of P2P lending platforms has increased significantly in many countries. In China, the P2P lending industry has increased 60 times from 2013 to 2017 [2]. However, P2P lending has been increasingly regulated in recent years [3], and most of P2P lending platforms do not possess operational sustainability due to the excessive defaults. By the beginning of 2021, the number of normal operational P2P lending platforms was only six in China, more than 6000 platforms have gone bankrupt, and the transaction volume of the P2P lending has dropped by nearly 80% compared with the peak in 2017 [4]. That is to say, the sustainability issue of the P2P lending industry is becoming a challenge of the P2P lending in China. In this context, it is significant to understand the interests and interactions of the P2P lending stakeholders. In practice, most of the P2P lending platforms cannot coordinate the interests of P2P participants to ensure the sustainable operation of P2P lending. Therefore, it is an important and interesting topic to focus on the behaviours and interactions of P2P lending stakeholders from a sustainable operation perspective.

More specifically, P2P lending includes many stakeholders, where regulatory authorities, P2P lending platforms, and borrowers are considered to be the three critical P2P lending participants [5, 6]. The three participants often face a conflict of interest when pursuing their maximum interests, respectively. For example, in the case of weak regulation, P2P lending platforms can often obtain some extra benefits through noncompliant operations. Meanwhile, the total return of the society will become smaller, which is not aligned with the regulatory expected revenue and damages the interests of regulatory authorities. According to García-Pérez et al. [7] and Cao et al. [8], sustainability can be seen as the result of the coordination of interests among multiple stakeholders. It is almost impossible to achieve the sustainable operation of P2P lending if the conflict of interest among P2P lending participants is not balanced [9]. Besides, due to a lack of legal and regulatory systems of the P2P lending [10], inadequate regulatory basis [11], and high regulatory costs and rent-seeking behaviour [12], the regulation of P2P lending market usually receives a great uncertainty. Therefore, the sustainable operation of the P2P lending market depends on the strategic game among the regulations by regulatory authorities, compliant behaviours of P2P lending platforms, and repayment behaviours of borrowers.

In recent years, issues about the behaviour of P2P lending participants have received increasing attention, but it is still in its early stages. First, most researchers are keen to study the herding behaviour in the P2P [13–15], defaulting behaviour of borrowers in P2P lending [16, 17], and operational behaviour of P2P lending platforms [18]. These studies generally focus on the characteristic and influencing factors of the behaviour of a single participant, but the interactions with each other of P2P lending participants with regard to the operations are ignored. This evokes an interesting question on how behaviours of P2P lending participants affect the sustainability of the P2P lending. Second, the researches on the interest coordination among the P2P lending participants are still limited in the previous literature. For instance, the interest-coordination mechanisms between multiple participants, such as lenders and platform [19], borrowers and lenders [20], and platforms and government [12, 21], are generally studied. However, the interest-coordination mechanisms are only for two players and cannot illustrate how to perform well for P2P lending participants to achieve sustainability of the P2P lending industry. Third, from the perspective of sustainable operations, it is necessary to coordinate the interest of each P2P lending participant and ensure that the participants can be profitable. For analysing the conflict of interest, an evolutionary game model (EGM) emphasizing bounded rationality and dynamic decision-making processes was formulated to study the interest-coordination mechanism among P2P lending participants. On the one hand, due to incomplete information and information asymmetry [20], regulatory authorities, P2P lending platforms, and borrowers fail to acknowledge the decision of each other (e.g., compliant operation or noncompliant operation, repayment, or default), and they show bounded rationality to make their decision according to the previous interactions among them. On the other hand, since the returns and costs vary in different games among regulatory authorities, P2P platforms, and borrowers, each participant will continuously change their strategies in the decision-making system. For example, regulatory authorities enhance the regulations because of the increasing returns, while the regulations are reduced by the growth of costs [22]. Similarly, borrowers adopt repayment strategy owing to rewards from the platforms [23], while they change the decision of repayment into default because of the reduction of defaulting cost. Thus, the behavioural system among regulatory authorities, P2P platforms, and borrowers should be captured by dynamic decision-making processes using the EGM. It is important and interesting to investigate the dynamical decision-making processes by using EGM.

According to an overview of the studies on the behaviour of the P2P lending participants, the research questions and openings that motivate this research are summarized as follows.

(i) What is the conflict of interest among regulatory authorities, P2P lending platforms, and borrowers? How to formulate and solve an EGM of three-player to balance the interests of the three participants?

(ii) How do behavioural strategies of P2P lending participants affect the evolutionary results? What are the optimal behaviour strategies for regulatory authorities, P2P lending platforms, and borrowers from the perspective of sustainable operations?

(iii) What is the impact of the relevant parameters on behavioural strategies of the three P2P lending participants?

To address the aforementioned issues, by adopting stakeholder approach, the conflicts of interest among regulatory authorities, P2P lending platforms, and borrowers are analysed in this paper. Besides, due to the asymmetric information available, short-sightedness, and self-interest [24, 25], P2P lending participants may show bounded rationality in multistage games. An EGM is developed, and the asymptotic of the equilibrium and evolutionary stability strategies of the EGM are analysed. Meanwhile, the interactions and the interest-coordination mechanisms among P2P lending participants are analysed.

The contributions include the following three points. (1) An EGM of three players is developed to explore interactions among regulatory authorities, P2P lending platforms, and borrowers, which overcomes the limitations of two-player evolutionary game mechanism in previous studies. (2) The interest-coordination mechanism among P2P lending participants is designed to guide each participant to choose the behavioural strategy, which is beneficial to the sustainability of P2P lending. The behavioural strategies of P2P lending participants are theoretically and numerically analysed, and the conclusions contributing to the sustainability of P2P lending are obtained. For instance, we find that the strict supervision of the P2P platform in the short term is necessary for the sustainable operation of the platform. (3) We investigate the influencing factors of the behaviours and interactions of P2P lending participants systematically and analyse the impact of rewards and penalties by regulatory authorities, repayment incentives, and defaulting opportunity costs on the evolutionary stability strategies, and we propose suggestions for sustainable development of the P2P lending industry.

The rest of this paper is organized as follows: Section 2 reviews the existing literature concerning the behaviour of P2P lending participants, conflict of interest among P2P lending stakeholders, and evolutionary game theory. In Sections 3 and 4, an EGM of three-player is proposed to analyse the interactions among regulatory authorities, P2P lending platforms, and borrowers. Section 5 presents the numerical study and discusses the computational results. Section 6 provides conclusion and directions for future research.

2. Related Work

In recent years, many scholars have paid attention to study the P2P lending. In line with the title and structure of this paper, the related work is reviewed from the aspects of behaviour of P2P lending participants, conflict of interest among P2P lending participants, and evolutionary game theory.

First, the behaviour of P2P lending participants is the main focus of this work. In previous studies, Berkovich proved that there is a herding behaviour in P2P lending [26]. Herzenstein et al. found that there is an obvious herding effect in the P2P loans closing to full bids, while the herding effect is weakened in loans that have full bids [27]. Liu et al. pointed out that friends with close offline relationships would have a stronger herding effect than friends with ordinary offline relationships in P2P lending [13]. Jiang et al. found that the automatic bidding mechanism can weaken the herding effect and present reasonable herding behaviour in P2P lending [28]. Kim pointed out that the rationality of investors' herding behaviour in P2P lending is not deterministic but changes with the investors' credit evaluation methods in each market [29]. Yang et al. pointed out that better operational capabilities, profitability, and platform security can help to improve investors' investment behaviour [30]. Ding et al. proved that a good reputation can reduce the defaulting probability of borrowers and effectively restrain their defaulting behaviour of borrowers [16]. Ge et al. pointed out that social media behaviours of borrowers, especially self-disclosure behaviours, have an important impact on the defaulting probability of borrowers on P2P lending websites [17]. Du et al. found that text message reminders, which convey lenders' positive expectations, considerably increase the possibility of borrower's repayment [31]. Yu and Shen conducted a study of existing P2P lending regulatory system in China and found that the strict regulations of P2P lending platforms limit their ability to maintain the role of a broker, which in turn jeopardized the commercial sustainability of P2P lending platform [32].

Second, the conflict of interests among the P2P lending participants is another important stream in this paper. The stakeholder is defined broadly as any group or individual that can influence the achievement of an organization's goals or be affected by the achievement thereof [9]. Bachmann analysed the external stakeholders in the P2P lending platform through the method proposed by Freeman [5]. Wei and Lin divided the main stakeholders involved in P2P lending market into borrowers, lenders, and P2P lending platforms and developed a game model based on the general characteristics of the market and stakeholders' incentives [19]. Cohen and Sundararajan divided the stakeholders of P2P sharing economic platform into governmental and nongovernmental stakeholders and noted that the regulatory issues on P2P sharing economic platform can be resolved through self-regulation [33]. In this paper, we divided the P2P lending stakeholders into regulatory authorities, P2P lending platforms, borrowers, and investors. There are obvious conflicts of interest among them. For instance, Chen and Tsai pointed out that noncompliant operations and fraudulent behaviour of P2P lending platforms would force investors to encounter the defaulting risk and loss of interests [10]. Zhang and Wang found that the high regulatory costs and rent-seeking behaviours of regulatory authorities posed the operational risk to the P2P lending platforms and damage the interests of platforms [12].

Third, the third stream of the literature review is the introduction of EGM and its applications. Evolutionary game theory was proposed in the 1970s, which emphasized on the importance of replicator dynamics when players with bounded rationality would adjust their strategies in line with their previous actions, especially through successful strategies [34, 35]. In recent years, evolutionary game theory is widely used in the field of economics and finance. For instance, Antoci et al. constructed an EGM between visitors and firms with replicator dynamics and found that such a dynamic process may lead to welfare-improving attractive Nash equilibrium [36]. Zhao et al. adopted an EGM to explore the cooperation or competition between Chinese e-commerce financial institutions and commercial banks [37]. Zhang et al. analysed the investment decision process in cyber offender–defender interaction by an EGM [38]. Li et al. used the two-player EGM to simulate the performance of supply chain members under the environment of financial risk [39]. Yang and Fu constructed an EGM to analyse the equilibrium strategies of inclusive financial institutions and the poor in poverty-reduction activities [40]. Liu and Xia constructed an EGM between borrowers and lenders in P2P lending market to study the impact of evolutionary equilibrium strategies of lenders and borrowers' behavioural strategies on the risk to the P2P lending platforms under bounded rationality [20].

To sum up, although the aforementioned literature has discussed either the behaviour of the P2P lending participant or the EGM, there are still limitations that need to be addressed. The following conclusions can be summarized.

(1) An empirical approach [26–30] or a qualitative approach [31, 32] to investigate the behaviour of a single participant in the P2P lending is popular in the existing literature. However, a quantitative approach to study the interaction among multiple P2P lending participants regarding sustainable operations is ignored. In this paper, we studied the interaction and interest-cooperation mechanisms among the P2P lending participants to achieve sustainability of P2P lending.

(2) There are conflicts of interest among the major P2P lending participants [10, 12]. Thus, it is necessary to understand the interest and interactions of P2P lending participants to coordinate the interest among them for achieving sustainable development of the P2P lending industry.

(3) According to the aforementioned literature, the EGM of two game groups or two players is often applied in studies [20, 36–40]. However, practical cases usually involve more than two participants. In this context, we formulate an EGM of three players including regulatory authorities, P2P lending platforms, and borrowers for the sustainability of P2P lending.

3. Model Formulation

3.1. Problem Description. P2P lending participants include regulatory authorities, P2P lending platforms, borrowers, and investors, as shown in Figure 1. The behaviour of investors is significantly affected by both P2P lending platforms and borrowers [41, 42]. In detail, a good reputation can attract more investors to invest in P2P lending [43]. Moreover, the lack of regulation, noncompliant operation of P2P lending platforms, and defaulting behaviour of borrowers are the main causes of chaos in P2P lending industry. Thus, regulatory authorities, P2P lending platforms, and borrowers are considered to be the three most influential stakeholders for the sustainability of P2P lending industry. The research on the sustainability of the P2P lending can also simplify the discussion of behavioural strategy chosen by regulatory authorities, P2P lending platforms, and borrowers in their conflict of interests.

More specifically, regulatory authorities are the makers of rules and policies in the P2P lending industry and play an important role in regulating the normal operation of the P2P lending market and ensuring the safety of funds of all participants. Meanwhile, regulatory authorities, as the participants in P2P lending market, have their own goals and interests and influence the expectations and actions of other participants. P2P lending platforms are the operational entity for the P2P lending market and the medium of P2P lending users. P2P lending platforms need to follow the competition rules of the market, regulate their own behaviour according to the policies and regulations of the Internet finance, and ensure the security of P2P lending transactions. The borrowers are companies or individuals who apply for a loan to an idle fund investor through a P2P lending platform. These aforementioned three participants often have conflict of interest when pursuing their maximum interests respectively. The conflict of interest among the three participants will affect the order of the P2P lending market.

In addition, with the existence of information asymmetry [20], it is difficult for regulatory authorities to use fragmented or even erroneous information to determine whether a P2P lending platform is operating in compliance. Furthermore, the platforms fail to know if the borrowers adopt a "repayment" strategy due to the incomplete borrowing information. Similarly, borrowers also do not know any information about other participants. Thus, a dynamic game exists in the interaction among regulatory authorities, platforms, and borrowers. In other words, since the three participants are bounded rationality, the behavioural decision is closely related to their previous behaviours. Therefore, developing an EGM on how to balance the interests among the three participants with incomplete information is the main focus of the work described as follows.

3.2. Assumptions and Parameter Setting

Assumption 1. The EGM has only three participants, where the regulatory authorities conduct supervision and inspection of the operation of the P2P lending platforms and formulate corresponding regulatory policies; P2P lending platforms are responsible for the release of loan information and reviewing borrowers' information and the borrowers' loan through the P2P lending platforms.

Assumption 2. The three P2P lending participants aim to achieve a self-benefit maximization. As the regulator in the financial market, the regulatory authorities achieve the goal of maximizing the benefits of regulation. P2P lending platforms, as financial intermediaries, aim to pursue maximum profit. Borrowers pursue their own maximum income.

Assumption 3. The three participants of P2P lending are bounded to rationality. We abandon the classical game theory and choose the evolutionary game theory as the main research method, because the bounded rationality of the P2P lending participants is more aligned with the actual situation.

Assumption 4. The set of strategies of the regulatory authorities is $G = \{\text{strict supervision, general supervision}\}$. The set of strategies of P2P lending platforms is $P = \{\text{compliant operation, noncompliant operation}\}$. The set of strategies of P2P lending borrowers is $B = \{\text{repayment, default}\}$. The game among the three participants is based on incomplete information: x represents the possibility of regulatory authorities choosing "strict supervision" strategy; then, $1 - x$ represents the possibility of regulatory authorities choosing "general supervision" strategy, and $0 \leq x \leq 1$. y represents the possibility of P2P lending platforms choosing "compliant operation" strategy; then, $1 - y$ represents the possibility of

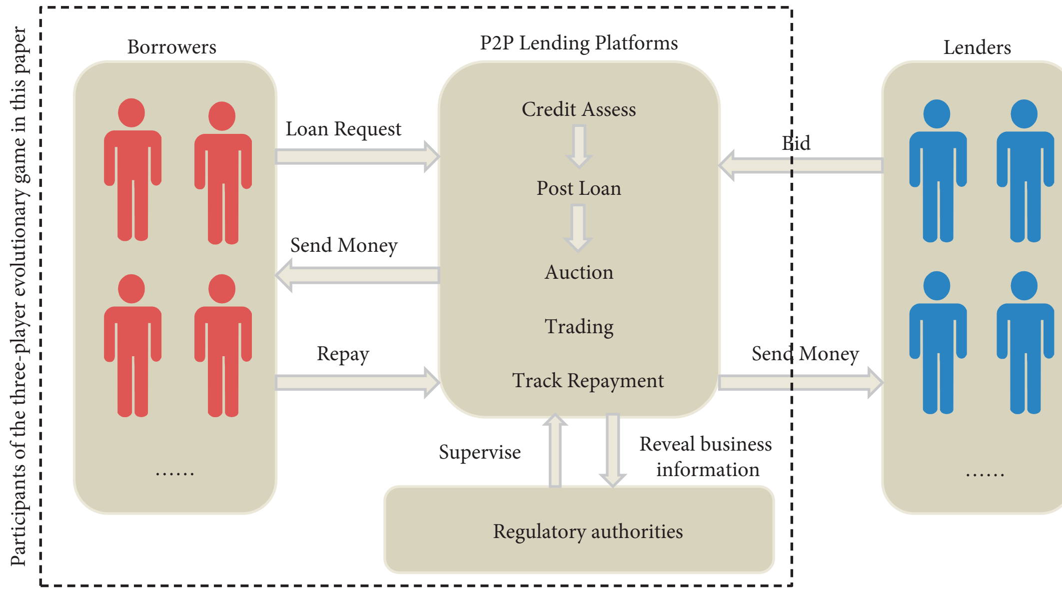


Figure 1: The working mechanism of P2P lending.

P2P lending platforms choosing "noncompliant operation" strategy, and $0 \leq y \leq 1$. z represents the possibility of P2P borrowers choosing "repayment" strategy; then, $1 - z$ represents the possibility of P2P borrowers choosing "default" strategy, and $0 \leq z \leq 1$.

According to the aforementioned assumptions, the main factors that are considered by the regulatory authorities, P2P lending platforms, and borrowers in the behavioural strategies, are clarified, and the parameters involved in the model are defined, as shown in Table 1.

3.3. Return Matrix of a Three-Player Evolutionary Game Model

Case 1 {strict supervision, compliant operation, repayment}. The regulatory cost of regulatory authorities is C_1, and the reward of regulatory authorities for compliant P2P lending platforms is wR. Therefore, the revenue of regulatory authorities of strict supervision is $-C_1 - wR$. The normal revenue of the P2P lending platforms is R, and the reward obtained by a compliant P2P lending platforms is wR, so the revenue of platforms is $(1 + w)\ R$. The incentive for repayment of P2P borrowers is V, and the sum of principal and interest required is H. Therefore, the revenue of the borrowers who choose repayment is $V - H$.

Case 2 {strict supervision, noncompliant operation, repayment}. The normal revenue of P2P lending platforms is R, and the extra revenue gained by P2P lending platforms through noncompliant operation is ΔR. The punishment coefficient of the regulatory authorities for noncompliant P2P lending platforms is θ, so the return of platforms is $(1 - \theta)\ (R + \Delta R)$. Meanwhile, the regulatory cost of regulatory authorities is C_1. Therefore, the revenue of regulatory authorities of strict supervision is $-C_1 + \theta(R + \Delta R)$. The sum of principal and interest required is H. Therefore, the revenue of the borrowers who choose repayment is $-H$.

Case 3 {general supervision, compliant operation, repayment}. The regulatory cost of regulatory authorities is C_2, and the damage caused by general supervision of regulatory authorities is E. Therefore, the revenue of regulatory authorities of general supervision is $-C_1 - E$. The revenue of P2P lending platforms is R. The incentive for repayment of P2P borrowers is V, and the sum of principal and interest required is H. Therefore, the revenue of the borrowers who choose repayment is $V - H$.

Case 4 {general supervision, noncompliant operation, repayment}. The regulatory cost of regulatory authorities is C_2, and the damage caused by regulatory authorities general supervision is E. Therefore, the revenue of regulatory authorities of general supervision is $-C_1 - E$. The normal revenue of P2P lending platforms is R, and the extra revenue gained by P2P lending platforms through noncompliant operation is ΔR, so the revenue of P2P lending platforms is $R + \Delta R$. The sum of principal and interest required is H. Therefore, the revenue of the borrowers who choose repayment is $-H$.

Case 5 {strict supervision, compliant operation, default}. The regulatory cost of regulatory authorities is C_1. The reward of regulatory authorities for compliant P2P lending platforms is wR. Therefore, the revenue of regulatory authorities of strict supervision is $-C_1 - wR$. The normal revenue of P2P lending platforms is R, and the reward obtained by compliant P2P lending platforms is wR. The loss coefficient of P2P lending platforms due to P2P borrowers default is f, so the revenue of P2P lending platforms is $(1 + w)\ (1 - f)\ R$. The sum of the principal and interest required is H, and the defaulting opportunity cost of P2P borrowers is D.

Table 1: Symbols and descriptions of the parameters.

Items	Parameter	Description
Regulatory authorities	x	The possibility of regulatory authorities choosing “strict supervision” strategy, and $0 \leq x \leq 1$
	C_1	The costs incurred by regulatory authorities for strict supervision of P2P lending platforms
	C_2	The costs incurred by regulatory authorities for general supervision of P2P lending platforms, and $C_2 < C_1$
	E	The damage caused by regulatory authorities general supervision of P2P lending platforms
P2P platforms	y	The possibility of P2P lending platforms choosing “compliant operation” strategy, and $0 \leq y \leq 1$
	R	Normal returns obtained from operation of P2P lending platform
	ΔR	The extra revenue gained by P2P lending platforms through noncompliant operation
	w	The reward coefficient of regulatory authorities for the compliant P2P lending platforms in the case of strict supervision, and $0 < w < 1$
	θ	The punishment coefficient of regulatory authorities for the noncompliant P2P lending platforms in the case of strict supervision, and $0 < \theta < 1$
	f	The loss coefficient of operational income of P2P lending platforms due to P2P borrowers default, and $0 < f < 1$
Borrowers	z	The possibility of P2P borrowers choosing “repayment” strategy, and $0 \leq z \leq 1$
	H	The sum of principal and interest that P2P borrowers need to repay in the case of the loan
	V	The positive incentives of P2P lending platforms for P2P borrowers’ repayment in case P2P lending platforms operate in compliance
	D	The defaulting opportunity cost of P2P borrowers

Therefore, the revenue of the borrowers who choose default is $H - D$.

Case 6 {strict supervision, noncompliant operation, default}. The normal revenue of P2P lending platforms is R, the extra revenue gained by P2P lending platforms through noncompliance operation is ΔR, the punishment coefficient of regulatory authorities for noncompliant P2P lending platforms is θ, and the loss coefficient of P2P lending platforms due to P2P borrowers default is f, so the revenue of platforms is $(1-\theta)(1-f)(R+\Delta R)$. At same time, the regulatory cost of regulatory authorities is C_1. Therefore, the revenue of regulatory authorities of strict supervision is $-C_1 + \theta(R+\Delta R)$. The sum of principal and interest required is H, and the defaulting opportunity cost of P2P borrowers is D. Therefore, the revenue of the borrowers who choose default is $H - D$.

Case 7 {general supervision, compliant operation, default}. The regulatory cost of regulatory authorities is C_2, and the damage caused by regulatory authorities general supervision is E. Therefore, the benefit of regulatory authorities’ strict supervision is $-C_1 - E$. The normal revenue of P2P lending platforms is R, and the loss coefficient of P2P lending platforms due to the default of P2P borrowers is f, so the revenue of P2P lending platforms is $(1-f)R$. The sum of principal and interest required is H, and the defaulting opportunity cost of P2P borrowers is D. Therefore, the revenue of the borrowers who choose default is $H - D$.

Case 8 {general supervision, noncompliant operation, default}. The regulatory cost of regulatory authorities is C_2, and the damage caused by regulatory authorities of general supervision is E. Therefore, the revenue of regulatory authorities of strict supervision is $-C_1 - E$. The normal revenue of P2P lending platforms is R, the extra revenue gained by P2P lending platforms through noncompliance operation is ΔR, and the loss coefficient of P2P lending platforms due to P2P borrowers’ default is f, so the revenue of platforms is $(1-f)(R+\Delta R)$. The sum of principal and interest required is H, and the defaulting opportunity cost of P2P borrowers is D. Therefore, the revenue of the borrowers who choose default is $H - D$.

As shown in Figure 2, the return matrix of the EGM among regulatory authorities, P2P lending platforms, and borrowers can be obtained according to the aforementioned statements. It is shown in Table 2.

4. Model Analysis

4.1. Regulatory Authorities

4.1.1. Replicator Dynamic Equation and Evolutionary Stability Analysis. Assume that the expected returns of regulatory authorities adopting “strict supervision” strategy are π_{G1}, the expected returns of regulatory authorities adopting “general supervision” strategy are π_{G2}, and the average expected returns of regulatory authorities under the mixed strategies are π_G. Then,

$$\begin{aligned}
\pi_{G1} &= yzA_1 + (1-y)zA_2 + y(1-z)A_5 + (1-y)(1-z)A_6 = -wyR - C_1 + (1-y)\theta(R+\Delta R),\\
\pi_{G2} &= yzA_3 + (1-y)zA_4 + y(1-z)A_7 + (1-y)(1-z)A_8 = -(C_2+E),\\
\pi_G &= x\pi_{G1} + (1-x)\pi_{G2} = -xywR - xC_1 + x(1-y)\theta(R+\Delta R) - (1-x)(C_2+E).
\end{aligned} \tag{1}$$

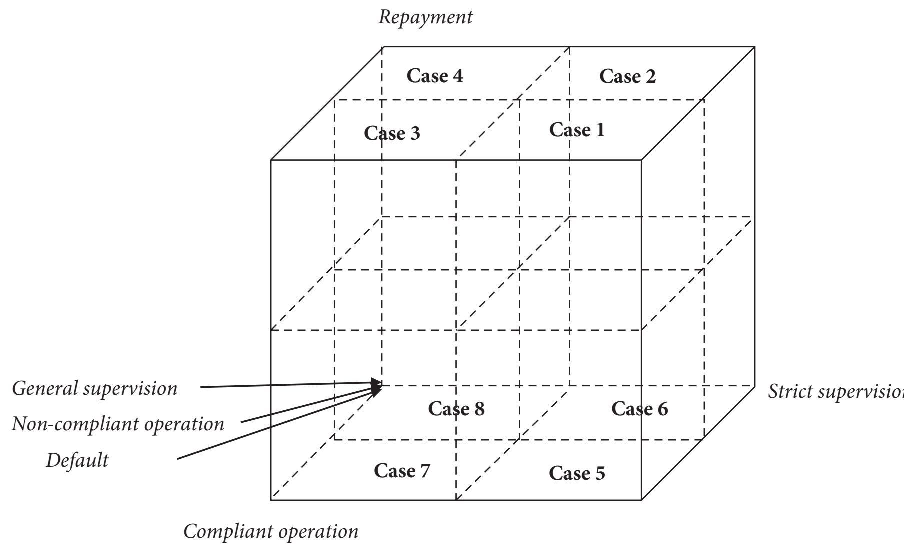


FIGURE 2: The EGM among regulatory authorities, P2P lending platforms, and borrowers.

TABLE 2: Return matrix of the three players: regulatory authorities, P2P lending platforms, and borrowers.

Regulatory authorities		Strict supervision (x)		General supervision ($1-x$)	
	P2P lending platforms	Compliant operation (y)	Noncompliant operation ($1-y$)	Compliant operation (y)	Noncompliant operation ($1-y$)
Borrowers	Repayment (z)	$\begin{bmatrix} -C_1 - wR \\ (1+w)R \\ V-H \end{bmatrix}$	$\begin{bmatrix} -C_1 + \theta(R+\Delta R) \\ (1-\theta)(R+\Delta R) \\ -H \end{bmatrix}$	$\begin{bmatrix} -C_2 - E \\ R \\ V-H \end{bmatrix}$	$\begin{bmatrix} -C_2 - E \\ R+\Delta R \\ -H \end{bmatrix}$
	Default ($1-z$)	$\begin{bmatrix} -C_1 - wR \\ (1+w)(1-f)R \\ H-D \end{bmatrix}$	$\begin{bmatrix} -C_1 + \theta(R+\Delta R) \\ (1-\theta)(1-f)(R+\Delta R) \\ H-D \end{bmatrix}$	$\begin{bmatrix} -C_2 - E \\ (1-f)R \\ H-D \end{bmatrix}$	$\begin{bmatrix} -C_2 - E \\ (1-f)(R+\Delta R) \\ H-D \end{bmatrix}$

According to EGM, the replicator dynamics system emphasizes the adjustment of the respective probabilities of choosing two strategies based on the previous results of games. It is denoted by the differential equation and can be used to describe the frequency or the frequency of such strategies in a population [44].

$$F(x) = \frac{dx}{dt} = x(\pi_{G1} - \pi_G) = x(1-x)[-ywR - C_1 + (1-y)\theta(R+\Delta R) + (C_2 + E)]. \quad (2)$$

For convenience of calculation, make $y_0 = ((\theta(R+\Delta R) + C_2 + E - C_1)/(wR + \theta(R+\Delta R)))$.

① When $y = y_0$, then $F(x) \equiv 0$; this shows that all levels are stable

② When $y \neq y_0$, make $F(x) = 0$; then, $x = 0$, $x = 1$ are two stable points

Let $F'(x)$ be the derivative of x and derived from $F(x)$:

$$F'(x) = \frac{dF(x)}{dx} = (1-2x)[-ywR - C_1 + (1-y)\theta(R+\Delta R) + (C_2 + E)]. \quad (3)$$

According to the requirements of the evolutionary stability strategy (ESS), $F'(x) < 0$. Therefore, $\theta(R+\Delta R) + C_2 + E - C_1$ are analysed, because $0 < x < 1$, $0 < y < 1$, and $0 < z < 1$, and ESSs are obtained considering the following two scenarios.

Scenario 1. When $\theta(R+\Delta R) + C_2 + E - C_1 < 0$, $-ywR - C_1 + (1-y)\theta(R+\Delta R) + (C_2 + E) < 0$. Therefore, when $x = 0$, $F'(x) < 0$; when $x = 1$, $F'(x) > 0$; therefore, $x = 0$ is an ESS.

Scenario 2. When $\theta(R+\Delta R) + C_2 + E - C_1 > 0$, scilicet, $\theta(R+\Delta R) + C_2 + E > C_1$. If $y > y_0$, then, when $x = 0$, $F'(x) < 0$; when $x = 1$, $F'(x) > 0$. So, $x = 0$ is an ESS. If $y < y_0$, then, when $x = 0$, $F'(x) > 0$; when $x = 1$, $F'(x) < 0$. Therefore, $x = 1$ is an ESS.

According to the analysis, the dynamic evolutionary trend of regulatory authorities is shown in Figure 3, and thereby, Propositions 1 and 2 are obtained.

Proposition 1. *When the initial state of the behavioural strategy of the regulatory authorities is in space V_1, that is, $\theta(R+\Delta R) + C_2 + E - C_1 < 0$, $x = 0$ is the equilibrium point, and the regulatory authorities will adopt the strategy of "general supervision." Therefore, when the cost of strict supervision by*

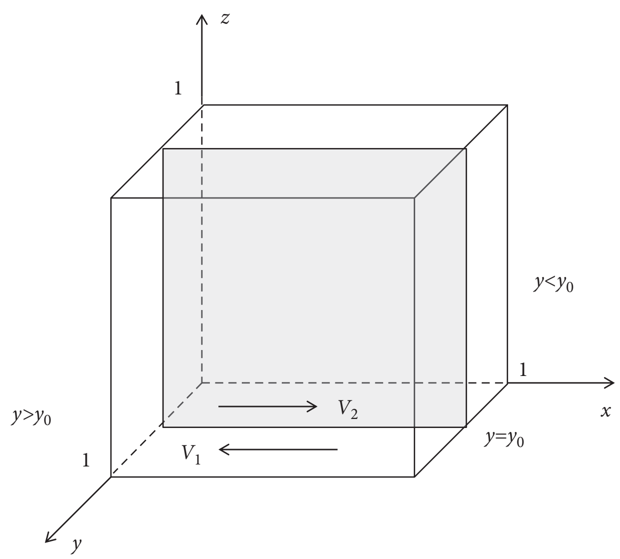


Figure 3: The dynamic trend diagram of regulatory authorities.

the regulatory authorities exceeds the benefits obtained, the regulatory authorities will adopt the strategy of "general supervision."

Proposition 2. *When the initial state of the behavioural strategy of regulatory authorities is in space V_2, that is, $\theta (R + \Delta R) + C_2 + E - C_1 > 0$, $x = 1$ is the equilibrium point, and the regulatory authorities will adopt the strategy of "strict supervision." Therefore, when the cost of strict supervision by the regulatory authorities is less than the benefits obtained, the regulatory authorities will adopt the strategy of "strict supervision."*

4.1.2. Parameter Analysis. As shown in Figure 3, when other parameters are fixed, w is increased, and y_0 becomes smaller. When y_0 becomes smaller, space of V_1 becomes larger. That is to say, when the incentive of the regulatory authorities for the compliant P2P lending platforms increases, the regulatory authorities tend to select the strategy of "general regulation." Additionally, this shows that when the rewards of regulatory authorities for the compliant P2P lending platforms increase, P2P lending platforms will select the strategy of "compliant operation," so the regulatory authorities adopt the strategy of "general supervision" at this point. Similarly, when C_1 increases, space of V_1 becomes larger; in other words, when the cost of strict supervision by regulatory authorities increase, the pressure of high regulatory costs will be imposed on the regulatory authorities, which would prompt them to adopt the strategy of "general supervision."

4.1.3. Evolutionary Analysis of Regulatory Authorities. The two aforementioned scenarios are aligned with the current regulatory situation of P2P lending industry in China. Due to the high cost of strict supervision, the regulatory authorities adopted the "general supervision" strategy in the early stage of the P2P lending industry, which directly prompted chaos therein. When the P2P lending industry is in trouble, the regulatory authorities raises the threshold to the entry of the P2P lending industry, which damages the openness and sustainability of the P2P lending industry. In addition, this explains the reasons why the P2P lending industry is in trouble from the perspective of regulation in China. In order to overcome this dilemma, the following measures can be taken. On the one hand, the central regulatory authority should formulate development policies and regulatory system to provide guidance for the local regulatory authorities. On the other hand, local regulatory authorities should be responsible for the standard guidance, filing management, risk prevention, and disposal concerning the P2P lending platforms, by adopting modern financial technology to optimize the regulatory approach of the P2P lending platforms, improve regulatory efficiency, reduce regulatory costs, and achieve a balance between efficiency and economy in regulation of the P2P lending industry.

4.2. P2P Lending Platforms

4.2.1. Replicator Dynamic Equation and Evolutionary Stability Analysis. Assume that the expected returns of the P2P lending platforms adopting "compliant operation" strategy are π_{P1}, the expected returns of the P2P lending platforms adopting "noncompliant operation" strategy will be π_{P2}, and the average expected returns of P2P lending platforms under the mixed strategies will be π_P. Then,

$$\begin{aligned}
\pi_{P1} &= xzB_1 + (1-x)zB_3 + x(1-z)B_5 + (1-x)(1-z)B_7 = (xw+1)(1-f+zf)R,\\
\pi_{P2} &= xzB_2 + (1-x)zB_4 + x(1-z)B_6 + (1-x)(1-z)B_8 = (R+\Delta R)(1-x\theta)(1-f+zf),\\
\pi_P &= y\pi_{P1} + (1-y)\pi_{P2} = (1-f+zf)[yR(xw+1) + (1-y)(R+\Delta R)(1-x\theta)].
\end{aligned} \tag{4}$$

The replicator dynamics equation of P2P lending platforms is shown in

$$F(y) = \frac{dy}{dt} = y(\pi_{P1} - \pi_P) = y(1-y)(1-f+zf) \cdot [(xw+1)R - (R+\Delta R)(1-x\theta)]. \quad (5)$$

For convenience of calculation, make $x_0 = (\Delta R/(wR + \theta R + \theta\Delta R))$.

① When $x = x_0$, then $F(y) \equiv 0$; this shows that all levels are stable

② When $x \neq x_0$, make $F(y) = 0$; then $y = 0$ and $y = 1$ are two stable points

Let $F'(y)$ be $F(y)$ the derivative of y and derived from $F(y)$:

$$F'(y) = \frac{dF(y)}{dy} = (1-2y)(1-f+zf)[(xw+1)R - (R+\Delta R)(1-x\theta)]. \quad (6)$$

According to the requirements of the ESS, $F'(y) < 0$, and $0 < z < 1$, $0 < f < 1$, so $1 - f + zf > 0$. Therefore, $(xw+1)R - (R+\Delta R)(1-x\theta)$ are analysed, and ESSs are obtained considering the following two scenarios.

Scenario 3. When $x_0 > 1$, scilicet, $(1-\theta)\,\Delta R > (w+\theta)\,R$, constant $x < x_0$. Therefore, when $y = 0$, $F'(y) < 0$; when $y = 1$, $F'(y) > 0$; therefore, $y = 0$ is an ESS.

Scenario 4. When $x_0 < 1$, scilicet, $(1-\theta)\,\Delta R < (w+\theta)\,R$. If $x > x_0$, then, when $y = 1$, $F'(y) < 0$; when $y = 0$, $F'(y) > 0$. So $y = 1$ is an ESS. If $x < x_0$, then, when $y = 1$, $F'(y) > 0$; when $x = 0$, $F'(y) < 0$; therefore, $y = 0$ is an ESS.

To clearly describe the results, the dynamic evolution trend of P2P lending platforms is presented in Figure 4, from which Propositions 3 and 4 are obtained.

Proposition 3. *When the initial state of the behavioural strategy of the P2P lending platforms is in space V_3, that is, $(1-\theta)\,\Delta R > (w+\theta)\,R$, $y = 0$ is the equilibrium point, the P2P lending platforms will adopt the strategy of "noncompliant operation." Therefore, considering rewards and punishments of the local regulatory authorities for P2P lending platforms, when the revenue of the P2P lending platforms through compliant operations is less than that obtained through noncompliant operations, and P2P lending platforms will eventually select the strategy of "noncompliant operation."*

Proposition 4. *When the initial state of the behavioural strategy of the P2P lending platforms is in space V_4, that is $(1-\theta)\,\Delta R < (w+\theta)\,R$, $y = 1$ is the equilibrium point, the P2P lending platforms will adopt the strategy of "compliant operation." Therefore, considering rewards and punishments of the local regulatory authorities for the P2P lending platforms, when the revenue of P2P lending platforms through compliant operations exceeds what was obtained through noncompliant operations, P2P lending platforms will eventually choose the strategy of "compliant operation."*

4.2.2. Parameter Analysis. As shown in Figure 4, the initial state space V_3, V_4 of the operational strategy of the P2P lending platform is related to the size of x_0. When w is increased, x_0 turns smaller, and the space of V_4 turns larger. This indicates that when regulatory authorities increase the incentives of compliant P2P platforms, P2P lending platforms will be more inclined to operate in noncompliance. Similarly, when θ increases, x_0 becomes smaller and the space of V_4 becomes larger. In other words, P2P lending platforms are more inclined to operate in compliance when regulatory authorities increase penalties for noncompliant P2P lending platforms. When R is larger, x_0 becomes smaller, and the space of V_4 becomes larger. This shows that when the revenue of compliant P2P lending platforms increases, P2P lending platforms will be more inclined to operate in compliance. In addition, When R increases, x_0 becomes larger, and the space of V_3 becomes larger, indicating that P2P lending platforms tend to be noncompliant when P2P lending platforms earn more benefits through noncompliant operation.

4.2.3. Evolutionary Results Analysis of P2P Lending Platforms. According to the previously mentioned analysis, P2P lending platforms choose their own strategies for the purpose of maximum profit. Therefore, to enable P2P lending platforms to adopt the strategy of "compliant operation" actively, their operational profit should be increased. By adjusting relevant parameters to make $(1-\theta)\,\Delta R < (w+\theta)\,R$, the following measures can be taken. The reward coefficient for compliant P2P lending platforms should increase. The penalties for noncompliant P2P lending platforms should also increase. The regulatory authorities should build a good business environment for compliant P2P lending platforms, such as providing preferential policies, increasing publicity about compliant P2P lending platforms, punishing noncompliant P2P lending platforms, and guiding investors to invest in compliant P2P lending platforms.

4.3. P2P Borrowers

4.3.1. Replicator Dynamic Equation and Evolutionary Stability Analysis. Assume that the expected returns of P2P borrowers adopting "repayment" strategy are π_{B1}, the expected returns of P2P borrowers adopting "default" strategy are π_{B2}, and the average expected returns of P2P borrowers under mixed strategies are π_B. Then,

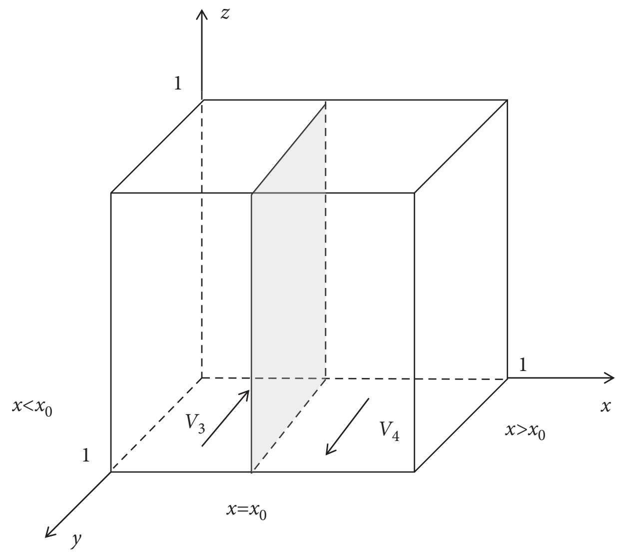


Figure 4: The dynamic trend diagram of P2P lending platforms.

$$\begin{aligned}\pi_{B1} &= xyC_1 + x(1-y)C_2 + y(1-x)C_3 + (1-x)(1-y)C_4 = yV - H,\\ \pi_{B2} &= xyC_5 + x(1-y)C_6 + y(1-x)C_7 + (1-x)(1-y)C_8 = H - D,\\ \pi_B &= z\pi_{B1} + (1-z)\pi_{B2} = z(yV-H) + (1-z)(H-D).\end{aligned} \tag{7}$$

The replicator dynamics equation of P2P borrowers is shown and presented by

$$F(z) = \frac{\mathrm{d}y}{\mathrm{d}t} = y\left(\pi_{P1} - \pi_P\right) = z(1-z)(yV + D - 2H). \tag{8}$$

For ease of calculation, make $y_1 = ((2H - D)/V)$.

① When $y = y_1$, then $F(z) \equiv 0$; this shows that all levels are stable

② When $y \neq y_1$, make $F(z) = 0$; then, $z = 0$ and $z = 1$ are two stable points

Let $F'(z)$ be $F(z)$ the derivative of z and derived from $F(z)$:

$$F'(z) = \frac{\mathrm{d}F(z)}{\mathrm{d}z} = (1-2z)(yV + D - 2H). \tag{9}$$

According to the requirements of the ESS, $F'(z) < 0$, and $0 < y < 1$. Therefore, $yV + D - 2H$ are analysed, and ESSs are obtained considering the following two scenarios.

Scenario 5. When $y_1 > 1$, scilicet, $V + D < 2H$, constant $y < y_1$. Therefore, when $z = 0$, $F'(z) < 0$; when $z = 1$, $F'(z) > 0$; therefore, $z = 0$ is an ESS.

Scenario 6. When $y_1 < 1$, scilicet, $V + D > 2H$. If $y > y_1$, then, when $z = 0$, $F'(z) > 0$; when $z = 1$, $F'(z) < 0$. So, $z = 1$ is an ESS. If $y < y_1$, then, when $z = 0$, $F'(z) < 0$; when $z = 1$, $F'(z) > 0$. Therefore, $z = 0$ is an ESS.

To explicitly analyse the results, the dynamic evolution trend of the P2P borrowers is depicted in Figure 5. Besides, from Figure 5, Propositions 5 and 6 are obtained.

Proposition 5. *When the initial state of the behavioural strategy of P2P borrowers is in space V_5, that is $V + D < 2H$, $z = 0$ is the equilibrium point, P2P borrowers will adopt the strategy of "default." Therefore, considering the positive incentives of compliant P2P lending platforms for borrowers' repayment and the defaulting opportunity cost of borrowers, when the revenue of P2P borrowers through default exceeds that obtained through repayment, P2P borrowers will eventually choose the strategy of "default."*

Proposition 6. *When the initial state of the behavioural strategy of P2P borrowers is in space V_6, that is $V + D > 2H$, $z = 1$ is the equilibrium point, the P2P borrowers will adopt the strategy of "repayment." Therefore, considering the positive incentives of compliant P2P lending platforms for P2P borrowers' repayment and the defaulting opportunity cost of borrowers, when the revenue of P2P borrowers through repayment exceeds that obtained through default, P2P borrowers will eventually choose the strategy of "repayment."*

4.3.2. Parameter Analysis. As shown in Figure 5, the initial state space V_5, V_6 of repayment strategy of P2P borrowers is related to the size of y_1. When V increases, y_1 becomes smaller, and space V_6 will become larger. This indicates that P2P borrowers are more inclined to repay when positive incentive of compliant P2P lending platforms for P2P borrowers' repayment increases. Similarly, when D

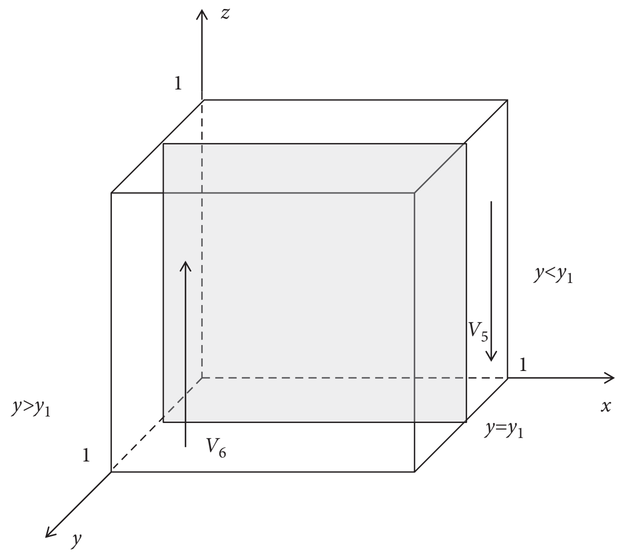


Figure 5: The dynamic trend diagram of P2P lending borrowers.

increases, y_1 becomes smaller, and space V_6 becomes larger. That is, when the defaulting opportunity costs of borrowers increases, P2P borrowers will be more willing to choose repayment. In addition, when H increases, y_1 becomes larger, and space V_5 becomes larger. That is, the more the principal and interest P2P borrowers need to repay, the more the P2P borrowers tend to default.

4.3.3. Evolutionary Results Analysis of P2P Borrowers. When P2P lending platforms lack the necessary repayment incentive and the defaulting opportunity costs of borrowers are low, the borrower is more willing to choose the "default" strategy. Therefore, given the nature of the "economic man" among P2P borrowers, for P2P borrowers to choose the "repayment" strategy, the benefits of their repayments and the defaulting cost should increase. By adjusting the corresponding parameters to make $V + D > 2H$, P2P lending platforms can take relevant measures. First, the loan amount of the repaying borrowers should be increased. The credit rating and positive incentive of repaying borrowers should also increase. Second, the information disclosure system should be improved. Borrowers who default by escaping debts should be announced to the public in a timely manner, and their names added to the list of untrustworthy persons. The defaulting opportunity cost of borrowers should increase to restrain the behaviour of borrowers.

4.4. Comprehensive Analysis of the Three P2P Lending Participants. The aforementioned three P2P lending participants should be regarded as a system for comprehensive analysis, and the impact of P2P lending participants' behavioural strategies on the sustainability of P2P lending is also explored. Figures 3–5 show that the dynamic evolutionary trend of regulatory authorities, P2P lending platforms, and borrowers are divided into two spatial sets, respectively. The initial state of each participant is arranged and combined to obtain the equilibrium points of the three players in each space, as shown in Table 3.

Table 3: The behavioural strategies of three P2P lending participants in each space.

Space	V_1		V_2	
	V_3	V_4	V_3	V_4
V_5	(0, 0, 1)	(0, 1, 0)	(1, 0, 0)	(0, 0, 1)
V_6	(0, 0, 1)	(0, 1, 1)	(1, 0, 1)	(0, 0, 1)

When the initial state of three P2P lending participants is located in the intersection of space V_2, V_3, and V_4, the behavioural strategies of the participants will converge to (1, 0, 0). That is, in the early stage of P2P lending industry development, since there are short-sightedness and self-interest, most of P2P lending platforms engaged in non-compliant operation to gain the extra revenue. Without the necessary incentives and penalties, even if the regulatory authorities adopt strict regulatory measures, P2P lending platforms will eventually adopt the strategy of "non-compliant operation." Therefore, in this case, the regulatory authorities should formulate corresponding punishment and incentive policies for P2P lending platforms to achieve sustainability of P2P lending. So, the proportion of P2P lending platforms engaged in compliant operation will be greatly increased. Meanwhile, P2P borrowers will also choose the strategy of "default" due to the lack of necessary incentives. P2P lending platforms should also give repayment incentives to improve the rate of repayment.

When $x = 1$, $y = 1$, $z = 1$, that is, the regulatory authorities choose strict supervision, P2P lending platforms choose compliant operation, and borrowers choose repayment, which is also the regulatory goal of P2P lending industry in China. In the early stage of P2P lending industry development, strict supervision by regulatory authorities is indispensable. As can be seen from Figures 3 and 4, this evolution equilibrium state occurs when y_0 is large and x_0 is small. That is, when P2P lending industry is in early stage, only regulatory authorities can ensure P2P lending platforms to operate in compliance by carrying out strict supervision, and P2P lending platforms can ensure borrowers to repayment by adopting incentive measures. In this way, the sustainability of P2P lending industry can be achieved.

When the initial state of P2P lending participants is in the intersection of spaces V_1, V_4, and V_6, the behavioural strategies of the participants will converge to (0, 1, 1). That is, from a long-term perspective, when the initial group proportion of P2P lending platforms engaged in compliant operations and the borrowers adopting repayment strategy is sufficiently high, P2P lending industry has already formed a certain degree of self-discipline. Even without strict supervision by regulatory authority, P2P lending platforms and borrowers will also take the "compliant operation" and "repayment" strategies, which is the goal of achieving sustainable development of P2P lending industry.

5. Numerical Analysis

To further validate the proposed model, computational studies are used to analyse the impact of changes in parameters on the evolutionary results. This paper refers to the transaction data of China's P2P lending platform in 2019 to set the interval range of each parameter. By the end of 2019, there were 343 good-performance platforms and 6156 problem platforms in China (see https://m.wdzj.com). The total transaction value of Chinese P2P lending platform in 2019 was ¥ 96.49 billion. The operating return of the general platform approximately equals 0.5 to 1 percent of the transaction value. That is, the average unit revenue of the normal operation of each platform is ¥ 742,345~1,484,690. In order to facilitate the calculation, the normal returns from compliance operation of the P2P lending platform are scaled down by 1/100,000 and are denoted by $R \in [7.4, 14.8]$. Assume that the extra revenue gained by the platform through noncompliant operations accounts for 50 percent of normal operating returns, and the extra revenue of P2P lending platforms through noncompliant operation is set to $\Delta R \in [3.7, 7.4]$. Besides, due to frequent "thunderstorm incidents" of the P2P lending platforms in 2019, the unit loss of investors' investment was ¥ 10,000~50,000. We can regard these losses as social damage caused by previous general supervision. The damage caused by the general supervision of regulatory authorities is scaled down by 1/100,000 and is located at interval [0.10, 0.50] ($E \in [0.10, 0.50]$). According to Pang et al. [22], a medium-sized P2P lending platform pays ¥ 2 million for the normal operation costs (e.g., website construction cost, operating cost, and customer acquisition cost per year), assuming that the repayment incentives for borrowers paid by platforms account for 5~25 percent of the normal cost, (e.g., ¥ 100,000~500,000). The positive incentives for P2P borrowers' repayment are scaled down by 1/100,000 and are denoted by $V \in [1, 5]$. The defaulting opportunity cost of P2P borrowers is set to $D \in [0.5, 1.8]$.

According to the notice about penalties for the P2P-related illegal platforms, most of the punishments located at interval from 10,000 to 50,000 yuan. For instance, Shenzhen Jinhai loan financial service company was fined ¥ 12,000. China Anhui Juyun Technology Co., Ltd. was suspected of violating the regulations and was imposed an administrative penalty of ¥ 40,000. Based on the previously mentioned information, it is assumed that the unit cost of general supervision by the regulatory authorities is between 10,000 and 50,000 yuan. The unit cost of strict supervision by the regulatory authorities is 60,000 to 100,000 yuan. They are scaled down by 1/100,000 and are bounded to $C_1 \in [0.60, 1]$, $C_2 \in [0.10, 0.50]$. Since the supervision of P2P lending platforms is enhanced by the regulatory authorities after 2018, the reward coefficient and punishment coefficient of the regulatory authorities for P2P lending platforms are at interval [0.17, 0.61] ($w \in [0.17, 0.61]$) and [0.34, 0.91] ($\theta \in [0.34, 0.91]$). In Figures 6–10, x (0), y (0), and z (0) indicate the initial proportion of strict supervision, compliance operations, and repayment.

Figure 6 shows the numerical analysis, which concerns the impact of the initial population ratio of the P2P lending participants' strategy selections on the evolutionary results. In Figure 6, it is obvious that the evolutionary equilibrium results of regulatory authorities, P2P lending platforms, and borrowers are mutually influential. The convergence results of the three P2P lending participants are not only related to the initial proportion of their groups choosing behavioural strategies, but they are also affected by the behavioural strategies made by other participants. The probability of behavioural strategies chosen by the participants exhibits periodicity, either converging to 0 or tending to 1. At the end, the three P2P lending participants do not reach a fixed equilibrium state. This shows that the strategic game among the regulatory authorities, P2P lending platforms, and borrowers has no evolutionary equilibrium strategy.

Figure 7 shows the three P2P lending participants choose different strategies in different initial states. In Figure 7, the evolutionary results of the three P2P lending participants only consider the impact of the initial state of behavioural strategy of each participant, whereas the mutual influence of the three participants is not considered. In Figure 7(a), $x(0) = 0.2$, $y(0) = 0.7$, and $z(0) = 0.5$, in Figure 7(b), $x(0) = 0.1$, $y(0) = 0.5$, and $z(0) = 0.3$, in Figure 7(c), $x(0) = 0.6$, $y(0) = 0.7$, and $z(0) = 0.3$, and in Figure 7(d), $x(0) = 0.7$, $y(0) = 0.7$, and $z(0) = 0.3$. From Figures 7(a) and 7(b), we can conclude that when the supervision is lacking or the initial proportion of regulatory authorities adopting "strict supervision" strategy is low in the early stage of P2P lending industry, the behavioural strategies of P2P lending platforms and borrowers will evolve towards "noncompliant operation" and "default." It increases the operational risk to the P2P lending platforms [12]. In spite of the fact that the regulatory authorities are pushing for regulatory pressures later, P2P lending platforms and borrowers would not change the initial behavioural strategy due to the less regulatory pressure before. On the contrary, as shown in Figure 7(c), when the initial proportion of regulatory authorities adopting "strict supervision" strategy is high in the early stage of P2P lending industry, P2P lending platforms and borrowers will be subject to greater regulatory pressure, and the behavioural strategies of P2P lending platforms and borrowers will evolve towards "compliant operation" and "repayment." In Figure 7(d), it denotes that when regulatory pressure becomes a normal state, even after regulatory authorities adopt deregulation, P2P lending platforms and borrowers will follow the strategies of "compliant operation" and "repayment." Therefore, the strict supervision is necessary in the early stage of the P2P lending industry. Such a viewpoint is also supported by Shao and Bo [45] and Wang et al. [46].

Figure 8 shows the impact of changes in the costs of strict supervision and the damage caused by general supervision on the evolutionary result of regulatory authorities' strategy selection. In Figure 8, we changed the values of parameters C_1 and E. In Figure 8(a), $C_1 = 1$, and $E = 0.1$, and in Figure 8(b), $C_1 = 0.6$, and $E = 0.5$. It can be seen from Figure 8 that when the initial proportion of behavioural strategies of P2P lending participants is the same, the final evolutionary result of regulatory authorities can be changed by changing C_1 and E. In detail, in Figure 8(a), regulatory authorities choose the "general supervision" strategy, P2P lending platforms and borrowers choose "noncompliant operation" and "default" strategies, respectively. In Figure 8(b), the initial proportion of the participants' behavioural strategies remains unchanged. When the costs of strict supervision dropped from 1.0 to 0.6, and the damage caused by general

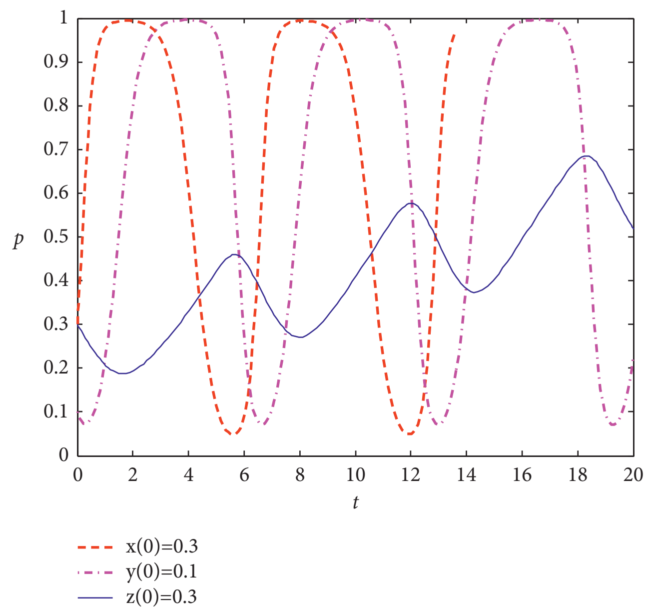


Figure 6: Evolutionary equilibrium results under different initial states.

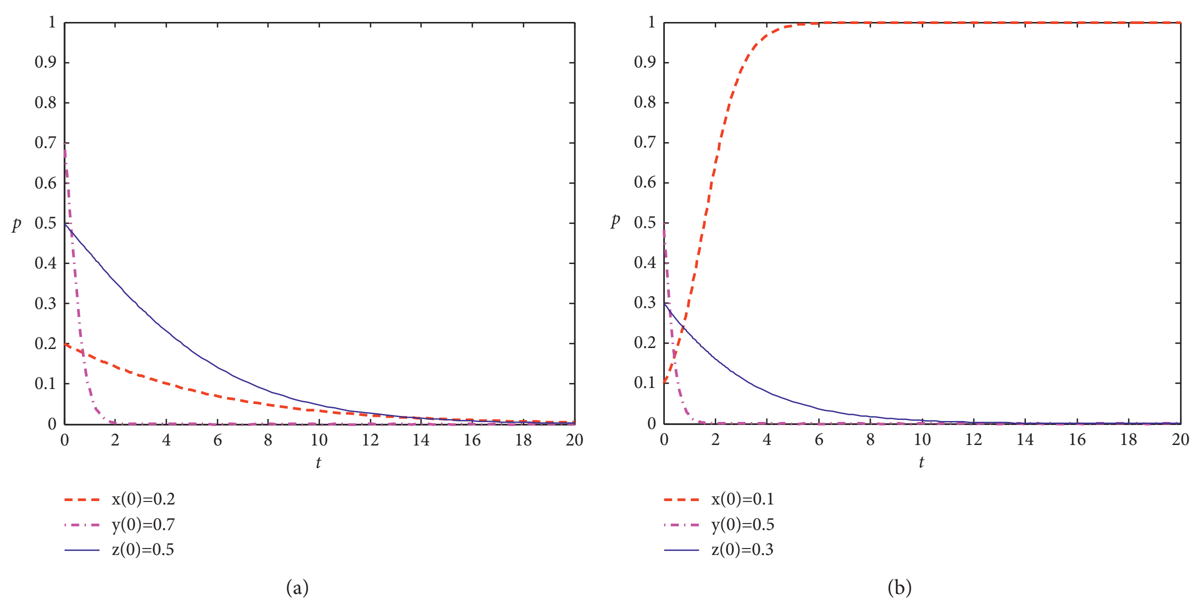
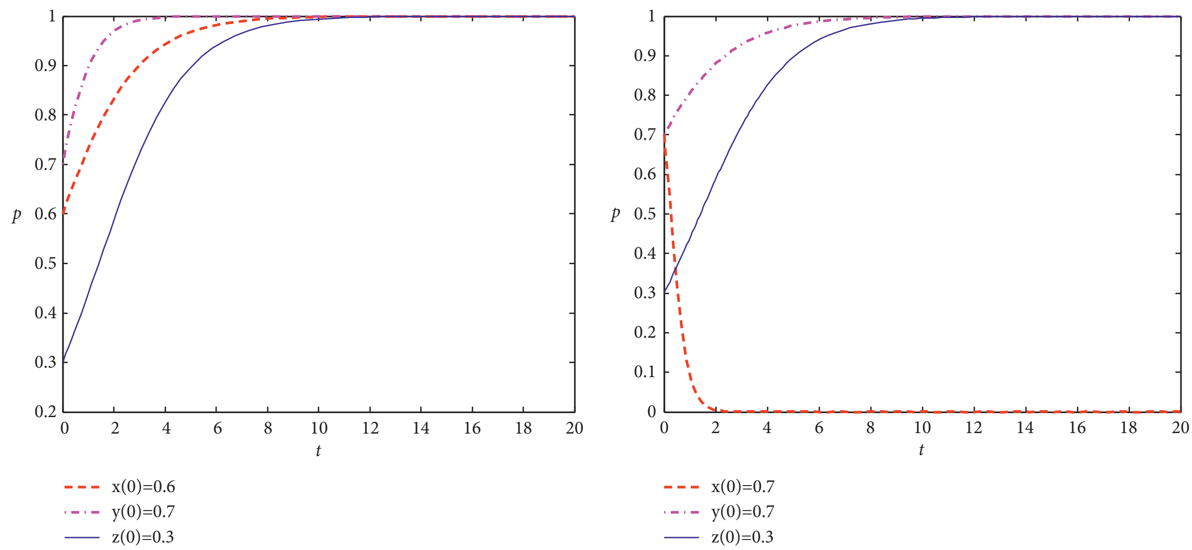
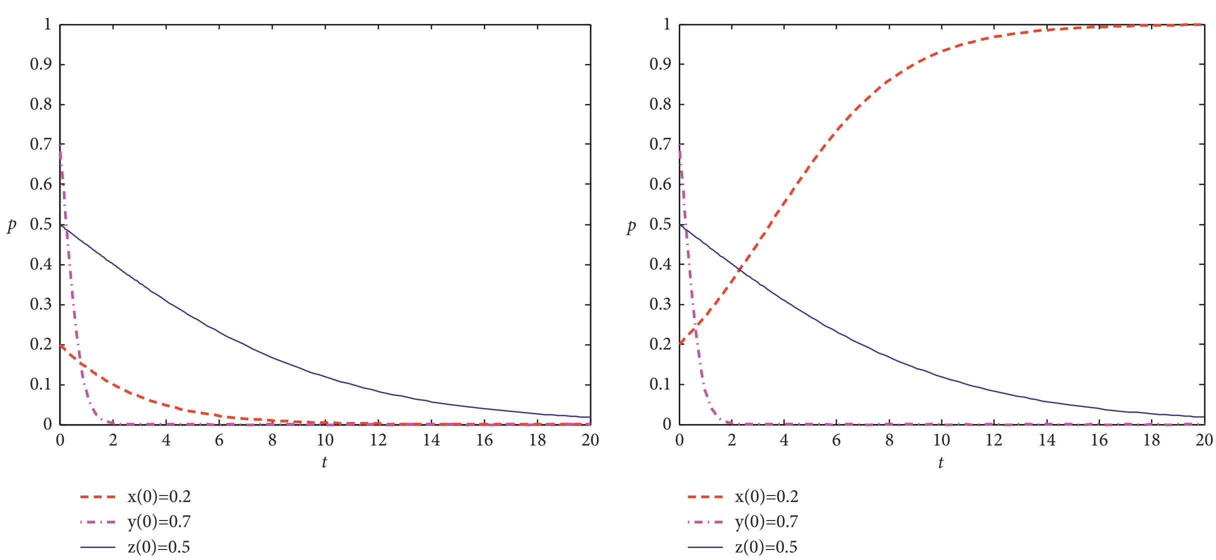


Figure 7: Continued.



(c) (d)

FIGURE 7: Strategy choices under different initial states. (a) $x\ (0) = 0.2$, $y\ (0) = 0.7$, and $z\ (0) = 0.5$. (b) $x\ (0) = 0.1$, $y\ (0) = 0.5$, and $z\ (0) = 0.3$. (c) $x\ (0) = 0.6$, $y\ (0) = 0.7$, and $z\ (0) = 0.3$. (d) $x\ (0) = 0.7$, $y\ (0) = 0.7$, and $z\ (0) = 0.3$.



(a) (b)

FIGURE 8: The impact of the costs of strict supervision and the damage caused by general supervision on evolutionary results. (a) $C_1 = 1$, and $E = 0.1$. (b) $C_1 = 0.6$, and $E = 0.5$.

supervision increases from 0.1 to 0.5, the behavioural strategy of regulatory authorities change from "general supervision" to "strict supervision" strategy, which is caused by $\theta\ (R + \Delta R) + C_2 + E - C_1 > 0$. This result is in line with Proposition 2 and is supported by Pang et al. [22]. It denotes that through reducing the costs of strict supervision and increasing the damage caused by general supervision, regulatory authorities will eventually tend to the strategy of "strict supervision."

Figure 9 shows the impact of changes in regulatory authorities' rewards and penalties for P2P platforms on the evolutionary result of P2P lending platforms' strategy selection. In Figure 9, while other parameters remain unchanged, we changed the values of parameters ω and θ and assessed the impact of changes of parameters ω and θ on the evolutionary results of the behavioural strategies of P2P lending platforms. In Figure 9(a), $\omega = 0.2$, and $\theta = 0.4$, and in Figure 9(b), $\omega = 0.4$, and $\theta = 0.8$. It can be seen from Figure 9 that when the initial proportion of behavioural strategies of P2P lending participants is the same, by changing ω and θ, the final evolutionary result of P2P lending platforms can be changed. More specifically, in Figure 9(a), regulatory

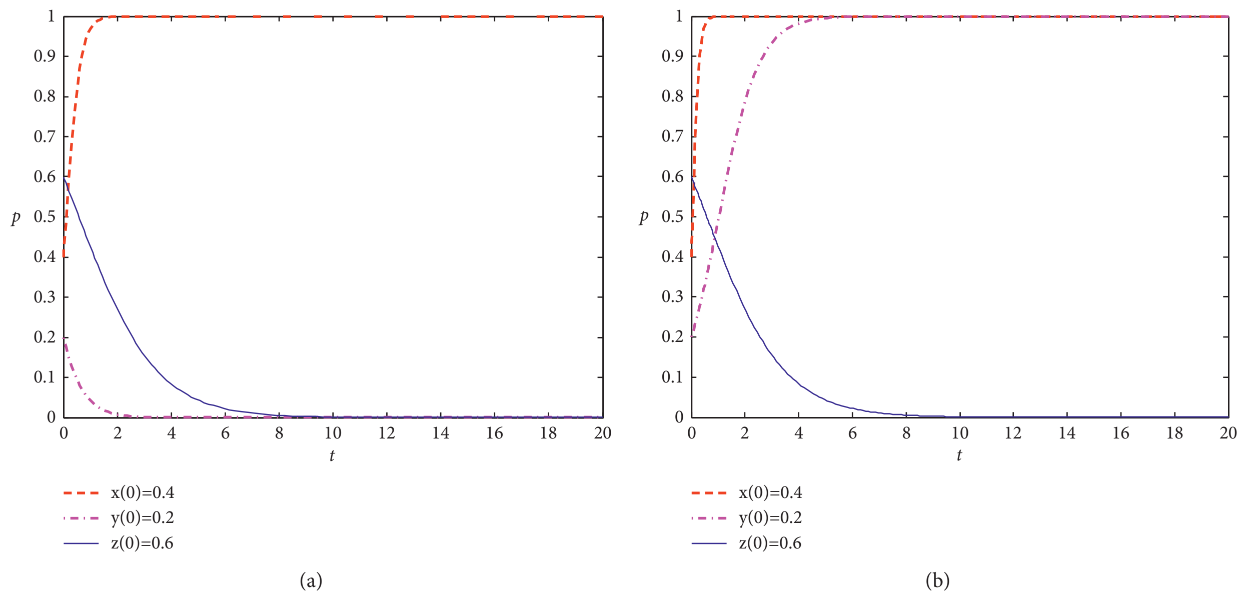


FIGURE 9: The impact of regulatory authorities' rewards and penalties for P2P lending platforms on the evolutionary result. (a) $w = 0.2$, and $\theta = 0.4$. (b) $w = 0.4$, and $\theta = 0.8$.

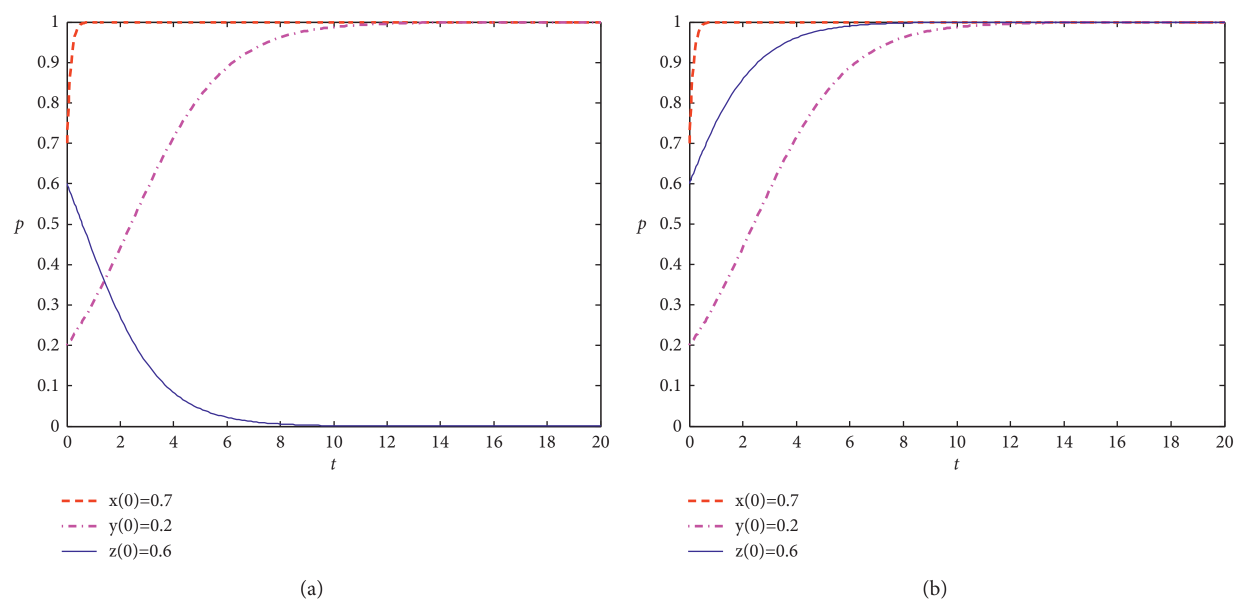


FIGURE 10: The impact of repayment incentives and defaulting opportunity costs on evolutionary results. (a) $V = 1$, and $D = 0.8$. (b) $V = 4$, and $D = 1.6$.

authorities choose the "strict supervision" strategy, and P2P lending platforms and borrowers choose "noncompliant operation" and "default" strategies, respectively. In Figure 9(b), the initial proportion of the participants' behavioural strategies remains unchanged. When regulatory authorities increase P2P lending platform rewards and penalties coefficients by a factor of two, the evolutionary results of regulatory authorities and borrowers remain unchanged, which makes $(1 - \theta)\ \Delta R < (w + \theta)\ R$, and the behavioural strategy of P2P lending platforms change from "noncompliant operation" to "compliant operation" strategy. This result is in line with Proposition 4. It denotes that through increasing rewards and penalties for P2P lending platforms, the benefit of compliant P2P lending platforms increases, the return of noncompliant P2P lending platforms decrease, and P2P lending platforms will eventually tend to the strategy of "compliant operation." In other words, increasing the rewards and penalties for the platform can improve the self-discipline of platform operations. Zhang and Wang show a better support for such a viewpoint [12].

Figure 10 shows the impact of changes in the repayment incentive given by the compliant P2P lending platforms and the opportunity costs of the borrowers' default on the evolutionary result of borrowers' strategy selection. In Figure 10, with other parameters being unchanged, we change the values of parameters V and D. In Figure 10(a), $V = 1$, and $D = 0.8$, and in Figure 10(b), and $V = 4$, $D = 1.6$. Then, it can be seen from Figure 10 that when the initial group proportion of behavioural strategies of the three participants is the same, by changing V and D, the evolutionary result of behavioural strategies of P2P borrowers can be changed. In Figure 10(a), regulatory authorities, P2P lending platforms, and borrowers choose "strict supervision," "compliant operation," and "default" strategies, respectively. In Figure 10(b), the initial proportion of the behavioural strategies of the three participants remains unchanged. When the compliant P2P lending platforms increase the repayment incentives of borrowers by a factor of four, and the defaulting opportunity cost of borrowers increases by two times, and the behavioural strategies of borrowers would change from "default" to "repayment" strategy, which is caused by $V + D > 2H$. This result corresponds to Proposition 6. It indicates that when the P2P lending platforms increase the repayment incentives and defaulting opportunity costs of borrowers, the cost of borrowers choosing "default" strategy will increase. Because the repayment incentives increase, the revenue of borrowers choosing "repayment" strategy will also increase, so borrowers will eventually choose the "repayment" strategy. Brihaye et al. [23] and Pang et al. [47] showed a better support for such results mentioned onwards.

6. Conclusions and Implications for Future Research

We have discussed the interaction and cooperation among P2P lending participants from the sustainable perspective. Conflicts of interest among the regulatory authorities, P2P lending platforms, and borrowers are analysed. Afterwards, the evolutionary trends of the three participants' behavioural strategies are analysed using an evolutionary game model of three players. Finally, the impacts of relevant factors on the evolutionary result of behavioural strategies of participants are investigated. The conclusions are shown as follows.

(1) The strict supervision of the P2P lending platform is necessary for the sustainable operation of the platform in the short term. According to the numerical analysis, there are significant differences in the results of the game of three players with different initial states. It is denoted that the P2P lending platforms and borrowers will choose the "noncompliant operation" and "default" strategies when the regulatory system is insufficient in the early stage of the P2P lending industry. Even after the regulatory authorities strengthen their regulatory intensity, the P2P lending platforms and borrowers will also choose the "noncompliant operation" and "default" strategies. On the contrary, when intense supervision is imposed in the early stage and regulatory pressure by regulatory authorities becomes a normal state, even if there is a lack of regulation in the future, the P2P lending platforms and borrowers will still actively choose the "compliant operation" and the "repayment" strategies.

(2) Given the conflict of interest among regulatory authorities, the P2P lending platforms and the borrowers (e.g., the platform operating incompliance for the extra income damages the interests of the regulatory authorities [22]), the interests of the three participants can be transformed into revenues and costs to formulate an EGM. The replicator dynamics equation is used to solve the equilibrium solution of the EGM. The behavioural strategies of the three participants can be changed into strict supervision, compliant operation, and repayment to balance the interests of the participants by adjusting the parameters (e.g., C_1, E, w, θ, V, and D).

(3) Through reducing the costs of strict supervision and increasing the damage caused by general supervision, regulatory authorities will eventually choose the "strict supervision" strategy. By increasing the incentives and penalties for the P2P lending platforms, the P2P lending platforms will eventually choose the "compliant operation" strategy. Meanwhile, when the P2P lending platforms increase the repayment incentives and the defaulting opportunity costs of borrowing, then, borrowers will eventually choose the "repayment" strategy.

The conclusions of this study have an important practical significance for the sustainable development of the P2P lending industry in China. In detail, when P2P lending emerged in China, the risks in the industry (e.g., absconding with the money and fraudulent risks) soared due to the lack of regulations of this industry [48]. As such, a series of policies have begun to be issued to gradually stabilize the P2P lending industry since 2016 [22]. Throughout the past three years, Chinese regulatory authorities raised the threshold to the entry of P2P lending platforms, the noncompliant platforms were gradually eliminated, and the standardization of the P2P lending industry has improved [12]. In fact, this confirms the necessity of strict supervision by regulatory authorities in the early stage of the P2P lending industry. In addition to the regulatory measures, the support policies (e.g., financial support and priority projects) should be adopted to encourage the compliant P2P lending platforms to ensure the competitive advantages. Meanwhile, penalties for illegal platforms should be increased to further eliminate the noncompliant P2P platforms. When most of platforms can operate in compliance, the regulatory intensity can be appropriately reduced. Moreover, it is necessary to improve the credit system of the individuals and enterprises. A public credit information service platform should be established and improved, to provide centralized inquiry services for the whole society. It plays the role of credit restraint to encourage the P2P lending platforms and borrowers to keep trustworthy.

This study provides several insights on the behavioural theory of the P2P lending participants regarding sustainable operation. First, a theoretical link between sustainable principle and behaviour of P2P lending participants is proposed to balance the interests of the participants. Second, this paper aims to design an interest-coordination mechanism among P2P lending participants to guide each participant to choose the behavioural strategy, which is beneficial to the sustainability of P2P lending. Third, meaningful suggestions are provided for regulatory authorities' regulation of P2P lending industry, which not only ensure the sustainable development of P2P lending industry but also provide insights for the supervision of other emerging industries (e.g., electronic currency).

This study can be further extended. First, in order to prevent P2P borrowers from defaulting, most of P2P lending platforms began to establish an information disclosure system of borrowers and use this system to construct the defaulting punishment of borrowers. Thus, the penalty of default based on the information disclosure can be used as an influencing factor to add to the three-player EGM. Besides, the altruistic preference behaviour has an important impact on the decision-making of multiparticipants system and can be used as an adjustment tool to achieve system coordination [49, 50]. Therefore, the altruistic preference behaviour can be introduced into the interest-coordination mechanism among P2P lending participants for the sustainability of P2P lending. Finally, this paper, considers only the three participants, including regulatory authorities, P2P lending platforms, and borrowers, but the investors are indispensable in the P2P lending process. Investors will be unable to introduce and extend the three-player EGM to the four-player EGM.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

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Research Article

Research on Business Environment Risk Governance Based on Occupational Claims: 1784 Cases of Food Safety Disputes

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There are disputes on the legal acceptance of occupational claims and the risk of occupational claim spoiling business environment is skyrocketing. How to manage the risk of occupational claims in the business environment is the subject of urgent research, especially COVID-19 is ravaging the world and the risk of economic crisis is increasing dramatically. In this study, we collected 1784 cases of food occupational claims from the Chinese legal documents website. Using Excel, Review Manager 5.0 and SPSS 19.0, the number of cases prosecuted as “consumers” were obtained by means of textual analysis, and the development process was directly influenced by occupational claims, with 2017 as a great value point (watershed); the rate of losing occupational claim cases has been climbing since 2018; and the risk of losing occupational claims is higher than that of true meaningful consumer advocacy cases ($Z = 6.99$, $p < 0.001$), and in 2019, the risk of losing a case was 33.34 times higher than that of an ordinary consumer. The proportion of occupational claims in the total number of food safety disputes is positively correlated with official protective behavior; the failure rate of occupational claims is positively correlated with official regulatory behavior. The results show that occupational claims are being reexamined by society; the continued rise in the number of unsuccessful occupational claims cases indicates a lack of regulatory guidance for their profit-making behavior, the existence of malicious reporting complaints against business behavior, damage to the business environment, and a certain lack of legality. Therefore, it is proposed that laws and regulations should be in line with international standards, highlight the legal thinking and the concept of the rule of law, return to the original legislative intent, and build a five-in-one mechanism of “consumers, operators, media, government, and justice” to coordinate the management of occupational claims, crack down on occupational claims, and contribute to the creation of a good business environment.

1. Introduction

The 19th National Congress of the Communist Party of China reported the scientific improvement of the food safety governance system and the construction of a new pattern of social governance with universal participation and shared governance of food safety [1]. Xi Jinping emphasized the importance of preventing and resolving governance risks in food safety and other areas, fostering new opportunities amid challenges and making new advances amid changes. In the author’s view, the attributes of occupational claims in the process of food safety governance are evolving, developing through three stages: “indeterminate attributes in the budding stage, positive attributes in the middle stage, and negative attributes in the later stage.” The risk management of occupational claims requires the participation of the society, government, and judiciary in multiple dimensions.

Occupational claim is the act of claiming compensation from the operator by purchasing defective products (such as label markings, additives, and shelf life) from a self-cognitive perspective with the purpose of profit, based on the punitive damages provisions in the Law of the PRC on the Protection of the Rights and Interests of Consumers, the Food Safety Law, and other laws and regulations [2]. Punitive damages were first introduced in the UK in 1763 and developed in the US in 1784 as one of the most important systems in the civil and criminal fields [3, 4]. In 1994, it was introduced into China, forming the punitive provision of Article 49, "return one to compensate one," of the Law on the Protection of the Rights and Interests of Consumers, and the occupational claims represented by "Case of Wang Hai" were inaugurated in China. Combined with the basic national conditions in the 1990s, the low level of science and technology, the backward economic development, and the numerous product quality defects [5], occupational claims behavior objectively forced the improvement of commodity quality and played a positive role in the innovation of consumer perceptions and operators' concepts. On December 9, 2013, the Supreme People's Court issued regulations on the application of the law to the trial of food and drug disputes, making it clear for the first time that "knowingly buying a fake" is protected by law. The revision of the Law on the Protection of the Rights and Interests of Consumers, which explicitly provides for "3 times compensation," and the Food Safety Law, which provides for "10 times compensation," had further boosted the wave of occupational claims [6]. According to the disclosure of Shanghai Municipal Administration of Industry and Commerce, the number of occupational claims cases increased by an average of 364% per year between 2013 and 2016. The huge increase in the number of occupational claims cases due to the interest-driven punitive damages led to a sudden increase in the number of occupational claims complaints from the grassroots administration and occupational claims disputes in the courts, resulting in a serious waste of administrative resources and an imbalance between administrative costs and benefits.

With low threshold and utilitarian nature, occupational claims have become gang-oriented, large-scale, and professional in operation and even distorted the organizational form of building personnel with clear division of labor and process-oriented claims [7]. The negative impact of the profit-making nature of their occupational claim behavior far outweighs the positive impact. In March 2016, the Chongqing Senior People Court took the lead in issuing the "Answers to Several Questions on the Trial of Consumer Rights and Interests Protection Disputes," which states that a person who purchases goods or services knowing that they have quality problems is a consumer. However, the court will not support a request for punitive damages from a person who purchases goods or services knowing that they have quality problems, because it is against the principle of integrity. On December 6, 2016, the Jiangsu Senior People Court proposed the provisions of the Discussion Minutes (2016) No. 10 on Several Issues regarding the Trial of Consumer Rights and Interests Protection Disputes: for the field of food consumption, the elements of punitive damages are that the seller operates food that he knows does not meet food safety standards, except for natural persons, legal persons, or other organizations that purchase it for the purpose of profit.

To this point, the jurisprudential disputes between occupational claims and distributors have continued [8]. We have been organized based on the line of jurisprudential development of food safety disputes, as shown in Table 1.

Occupational claims have always been wandering in the edge of violation of law, and it is controversial whether the behavior of occupational claimants upholds social justice or undermines the business environment. The regulation of occupational claimants' behavior is directly related to the risk management of the healthy development of the business environment.

2. Subjects and Methods

2.1. Subjects. We comprehensively searched the database from 2011 to 2019 using the Chinese legal documents website, a public database of court closing case. Following keyword terms were searched in the database: referee year ('2011', '2012', '2013', '2014', '2015', '2016', '2017', '2018', '2019′), civil case, sales, and purchase contract disputes and type of instrument ("judgment" and "ruling"). The criteria to qualify are as follows: (a) topics are food defects; (b) the plaintiff is an individual. Exclusions are as follows: (a) case filed in 2010 and closed in 2011; (b) case filed in 2019 and closed in 2020; (c) topics are drug defects; (d) the defendant is a pharmaceutical company.

2.2. Data Extraction. The following data were extracted from the included studies: year of case occurrence, classification of case attributes (the number of cases made by the same subject is 2 or more which was defined as occupational claims, occupational claims were recorded as 1, and non-occupational claims were recorded as 0), result of the case (1 for a successful case' −1 for an unsuccessful case), and behavior of occupational claims official regulation (in this article, official refers to the justice, government, and media; issuance of n country-level documents noted as $2n$%; protective documents are counted as positive values, and regulatory documents are counted as negative values; the relevant documents that are not available are recorded as 0; the provincial and ministerial level documents are assigned 50% of the national level documents; the media monitoring is assigned 50% of the national level documents). Two researchers independently evaluated the legal instruments and reached consensus on all data. Data were matched using a double-entry method to ensure error-free data entry.

2.3. Methods. Using Excel software to fit data to the distribution of the sample data, explore the trend of the number of occupational claims and analyze the trial results of food safety disputes. Review Manager 5.0 software was used to analyze the risk of losing an occupational claim. SPSS 19.0 software [9–12] was employed to explore the correlation between official behavior and year, the share of occupational claims in the total number of food safety disputes and official protective behavior, and the failure rate of occupational claims and official regulatory behavior. Excel software was used to explore the moderating effect of official regulation of

Table 1: Food safety dispute jurisprudence development line.

Time node	Judicial behavior	Official behavior	Media behavior
January 1, 1994	Refund 1 to compensate 1		
February 28, 2009	10 times compensation		
March 15, 2014	Refund 1 to compensate 3		
March 25, 2016	CSPC		
December 6, 2016	SIRTCRIPD		
May 19, 2017	REOCOB		
November 7, 2018		OCOCCAP	
December 29, 2018	10 times compensation*		
March 13, 2019			COCPBE
March 18, 2019		LMMVBPEFF	
May 9, 2019		CDMRIPMB	
August 8, 2019		CDEFAC	
November 26, 2019		RPOC	
December 1, 2019		IFSMS	
December 6, 2019			Beijing TV
December 7, 2019			Metro Newspaper
April 20, 2020		FPMRBSME	
December 11, 2020			China Central Television News

Note. Refund 1 to compensate 1: the fourth session of the Standing Committee of the 8th National People's Congress adopted the Law of the People's Republic of China on the Protection of Consumer Rights and Interests, proposing "refund 1 to compensate 1"; 10 times compensation: the seventh session of the Standing Committee of the Eleventh National People's Congress voted on the Food Safety Law of the People's Republic of China, proposing "10 times compensation"; refund 1 to compensate 3: the fifth session of the Standing Committee of the 12th National People's Congress passed the Law on the Protection of Consumer Rights and Interests, proposing "refund 1 to compensate 3"; CSPC: Chongqing Senior People Court's "Answers to Several Questions on the Trial of Consumer Rights and Interests Protection Disputes" provides for punitive damages for consumers: "if a person who purchases goods or services knowing that there are quality problems requests punitive damages, the people's court shall not support it because it is against the principle of integrity"; SIRTCRIPD: restrictions on obtaining punitive damages in the Jiangsu Senior People Court's Discussion Minutes (2016) No. 10 on Several Issues regarding the Trial of Consumer Rights and Interests Protection Disputes; REOCOB: suggestions of the Supreme People's Court on guiding and regulating occupational counterfeiting, proposing to "reexamine occupational claims and other behaviors"; OCOCCAP: Shanghai Market Supervision Bureau, Shanghai Municipal Office of Legal Affairs and other seven departments jointly issued the "Guidance on Effective Response to Occupational Claims and Occupational Reporting Behavior to Maintain the Business Environment" (Shanghai Municipal Administration of Industry and Commerce (2018) No. 910), proposing to differentiate "occupational claims and ordinary consumers," and to classify and apply policies; 10 times compensation∗: the seventh session of the Standing Committee of the Eleventh National People's Congress voted on the Food Safety Law of the People's Republic of China, proposing 10 times compensation for violations under informed conditions; COCPBE: Hong Mingji, a member of the National Committee of the Chinese People's Political Consultative Conference (CPPCC), proposed a motion on "combating occupational claims and optimizing the business environment"; LMMVBPEFF: Shanghai introduced the "list of minor market violations of business practices exempt from fines"; CDMRIPMB: the State Council issued "opinions on deepening reforms to strengthen food safety," proposing to crack down on malicious reporting illegal profit-making behavior; CDEFAC: the General Office of the State Council issued the "Guidance on Promoting the Standardized and Healthy Development of the Platform Economy," proposing to effectively protect the legitimate rights and interests of participants in the platform economy and to crack down on extortion in the name of "fighting against counterfeit"; RPOC: the State Administration for Market Regulation issued "Interim Measures for Handling Market Supervision and Administration Complaints and Reports" to put forward restrictive provisions for occupational claims, officially implemented since January 1, 2020; IFSMS: the State Council issued "Regulations on the Implementation of the Food Safety Law of the People's Republic of China" to improve the food safety management system; Beijing TV: Beijing TV promotes the spirit of "the General Office of the CPC Central Committee and the State Council demands to crack down on occupational claimants"; Metro Newspaper: Metro Newspaper wrote "stopping occupational claims"; FPMRBSME: Guiding Opinions of the Supreme People's Court on "Several Issues concerning the Proper Trial of Civil Cases Involving the Novel Coronavirus Pneumonia Epidemic According to Law (I)," which proposed "flexible preservation measures to reduce the burden of the small and microenterprises"; China Central Television News: China Central Television News propagated "market supervision and management complaints and reports processing interim measures" of the restrictive provisions of occupational claims, clearly cracking down on occupational claimants.

occupational claims on the number of occupational claims and that of unsuccessful occupational claims. $p < 0.05$ was considered to be statistically significant.

3. Results

3.1. Current Development of Food Safety Dispute. The search years ranged from January 1, 2011, to December 31, 2019, with a cumulative total of 1,784 cases regarding food disputes during the 9-year period, with an upward trend in the number of cases, reaching a peak during 2017–2018 and then declining. The development trend is shown in Figure 1.

Before 2017, the number of cases won by consumers as plaintiffs was on an upward trend; since 2017, it had been on a downward trend, and the winning rate in 2018–2019 was significantly lower than that in 2017–2018. The number of unsuccessful plaintiffs in case trials was on a steady upward trend.

3.2. Trends of Occupational Claims in Food Safety Disputes. The search years ranged from January 1, 2009, to December 31, 2019, and the number of lawsuits initiated by occupational claimants was as high as 1,530, accounting for 85.76% of the food safety lawsuits.

Combining Figures 1 and 2, it is easy to see that the trend in the number of occupational claims is directly related to the trend of food safety disputes. Figure 2 shows that the total number of occupational claims has generally shown a fluctuating increase, peaking in 2018. The number of successful

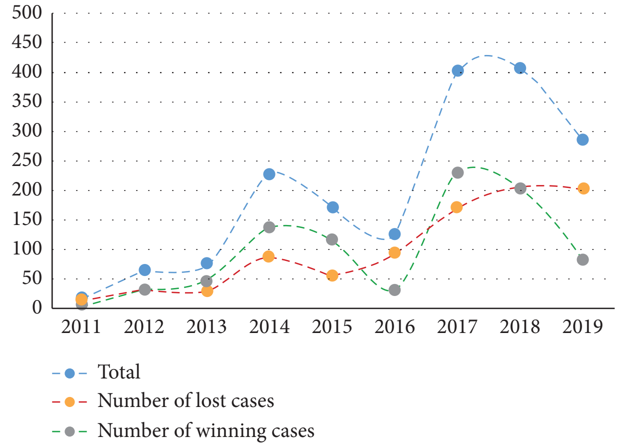

Figure 1: The trial trends of food safety disputes.

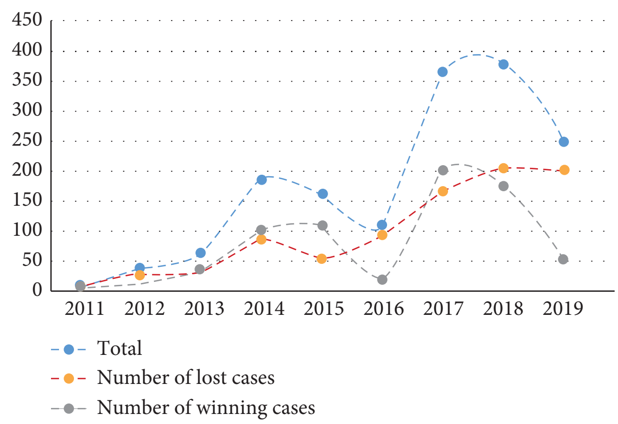

Figure 2: The trial trends of occupational claims disputes.

occupational claims cases continued to be high until 2015, before hitting a low point for the first time in 2016. In 2017, occupational claimants once again worked rampantly and the number of successful cases climbed sharply; since the start of 2018, the number of successful occupational claims has plummeted. The number of lost occupational claims cases had been climbing since 2011, and the current data estimate that the number of that will reach its peak in 2020.

3.3. Trends in the Failure Rate of Occupational Claims in Food Safety Disputes. During the period of 2011–2019, there were 2 maximum values and 2 minimal values in the trial loss rate of occupational claims in food safety disputes, with the maximum values in 2012 and 2016 and the minimal values in 2015 and 2017, respectively, and the occupational claims trial loss rate had continued to climb since 2018. See Figure 3 for details.

3.4. Analysis of the Risk of Losing Occupational Claims in Food Safety Disputes. Using Review Manager 5.0 software [13], we conducted a study on the risk of losing a trial for the full set of food safety disputes from 2011 to 2019 and found that there was a statistically significant difference in the rate of losing an occupational claim and a true consumer rights

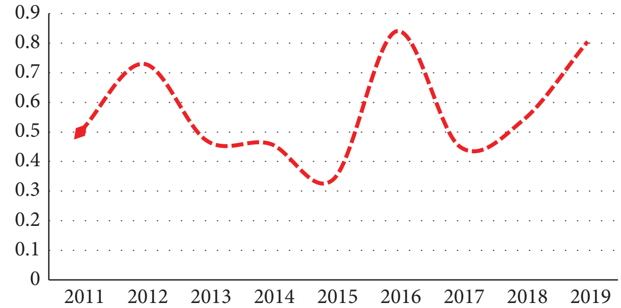

Figure 3: Rate of lost cases in occupational claims disputes.

defeat rates ($Z = 6.99$, $p < 0.001$). In 2019, the risk of losing an occupational claim is 33.34 times that of losing a consumer rights claim in the true sense (see Figure 4).

3.5. The Moderating Effect of Official Regulatory Behavior on Occupational Claims Trials. Analysis by SPSS 19.0 software showed a negative correlation between official behavior and year ($r = -0.63$, $p < 0.05$); the share of occupational claims in the total number of food safety disputes was positively correlated with official protection behavior ($r = -0.90$, $p < 0.05$), and the rate of losing occupational claims was positively correlated with official regulatory behavior ($r = 0.53$).

On this basis, we used Excel software to explore the moderating effects of official behaviors (protective and regulatory behavior) on rate of lost cases in occupational claims and percentage of occupational claims in total, respectively. The specific results are shown in the following series of graphs.

The trend line in Figure 5 shows that official protective policies are relatively stable and the introduction of regulatory policies for occupational claims is relatively delayed. Throughout the consumer rights protection process, there has been a fluctuating increase in the rate of losing occupational claims. Official protective policies increase the winning rate of occupational claims. The more obvious the official regulatory behavior, the higher the likelihood of losing an occupational claim. There is a time lag in the effectiveness of official behavior.

The trend line in Figure 6 shows that throughout the consumer rights protection process, continued growth in occupational claims as a share of total food safety dispute cases was stably drove by official protective policies.

The trend line in Figure 7 shows that throughout the consumer rights protection process, official regulatory policies had steadily constrained the share of occupational claims in the total number of food safety disputes.

4. Discussion

The results of the study show that food safety issues are taken seriously by society and that the number of food safety disputes is generally on an increasing trend. One of the possible reasons is that, based on China's national conditions, the country's technological level was not high at the

Study or subgroup	Experimental Events	Experimental Total	Control Events	Control Total	Weight (%)	Odds ratio M-H, random, 95% CI
SPAN 2012	25	34	8	30	11.8	7.64 [2.51, 23.21]
SPAQ 2011	3	6	2	13	5.0	5.50 [0.61, 49.54]
SPAQ 2013	28	60	3	17	9.7	4.08 [1.06, 15.69]
SPAQ 2014	84	182	5	45	13.1	6.86 [2.59, 18.17]
SPAQ 2015	53	158	3	19	10.3	2.69 [0.75, 9.65]
SPAQ 2016	90	107	4	20	10.8	21.18 [6.30, 71.16]
SPAQ 2017	164	362	8	41	15.1	3.42 [1.54, 7.60]
SPAQ 2018	201	374	4	32	12.2	8.13 [2.80, 23.64]
SPAQ 2019	198	247	4	37	12.0	33.34 [11.28, 98.54]
Total (95% CI)		*1530*		*254*	*100.0*	*7.45 [4.24, 13.09]*
Total events	846		41			

Heterogeneity $tau^2 = 0.38$; $chi^2 = 17.16$, $df = 8$ ($P = 0.03$); $I^2 = 53\%$

Test for overall effect: $Z = 6.99$ ($P < 0.00001$)

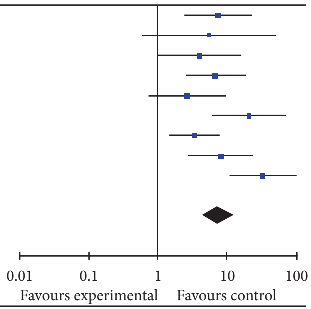

Figure 4: Risk of lost cases in occupational claims and actual consumers.

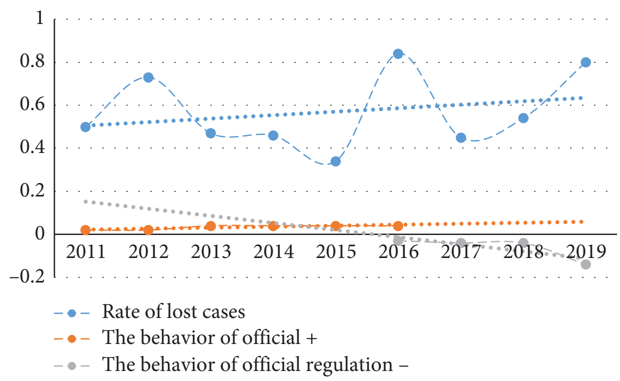

Figure 5: The moderating effect of official regulatory behavior on rate of lost cases in occupational claims.

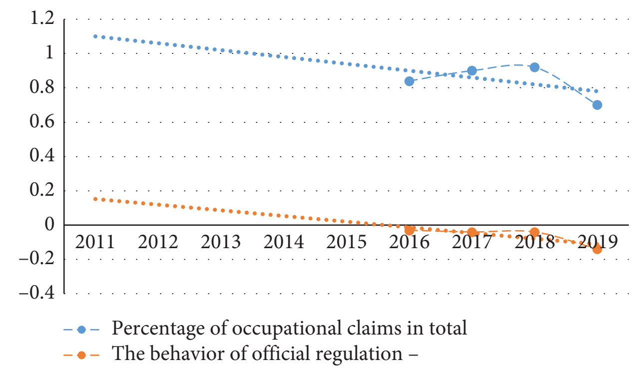

Figure 7: The moderating effect of official regulatory behavior on percentage of occupational claims in total.

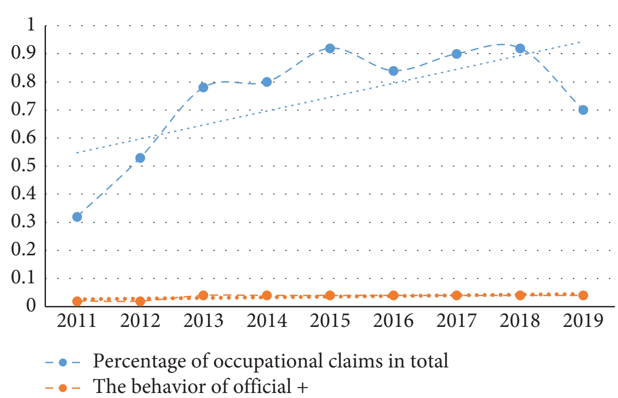

Figure 6: The moderating effect of official protective behavior on percentage of occupational claims in total.

end of the 20th century and the quality of food production needed to be improved. The second reason may be due to the conflict between the public's expectations of food safety production and the lack of actual production capacity in the society, combined with the official introduction of Protection of the Rights and Interests of Consumers and the publicity effect of the media, which has raised public awareness of safety [14, 15]. The third reason for this may be that the amendment and upgrading of the Consumer Protection Law, which introduced the provision of "refund 1 to compensate 1" to "refund 1 to compensate 3," have to a certain extent given rise to the phenomenon of occupational food safety claims, such as "Case of Wang Hai" [16]. The "10 times compensation" provision in the Food Safety Law, which was legislated in 2009, amended in 2013, and implemented in 2015, has largely become a "booster" for occupational claims. This may be the fourth possible reason, because a large number of small businesses or outlets, with little money involved, responded relentlessly and gave up responding to lawsuits, resulting in occupational claimants who can obtain 10 times the compensation without any effort and were happy to do so, pushing up the total number of food safety disputes. Other possible causes cannot be excluded.

The results of this study show that "occupational claims" account for 85.76% of food safety disputes, directly affecting the rational allocation of administrative and judicial resources. The number of unsuccessful occupational claims continues to climb. The possible reasons for this are that occupational claimants have exploited legal loopholes and abused the right to file complaints and reports, administrative review, and litigation. According to scientific statistics, occupational claims consume 4–5 times more administrative and judicial resources than normal consumer disputes. One of the reasons for the continued rise in the number of unsuccessful occupational claims is the upward trend in the total number of food safety disputes. The second reason may be related to occupational claimants "making profits in the name of fighting against counterfeiting."

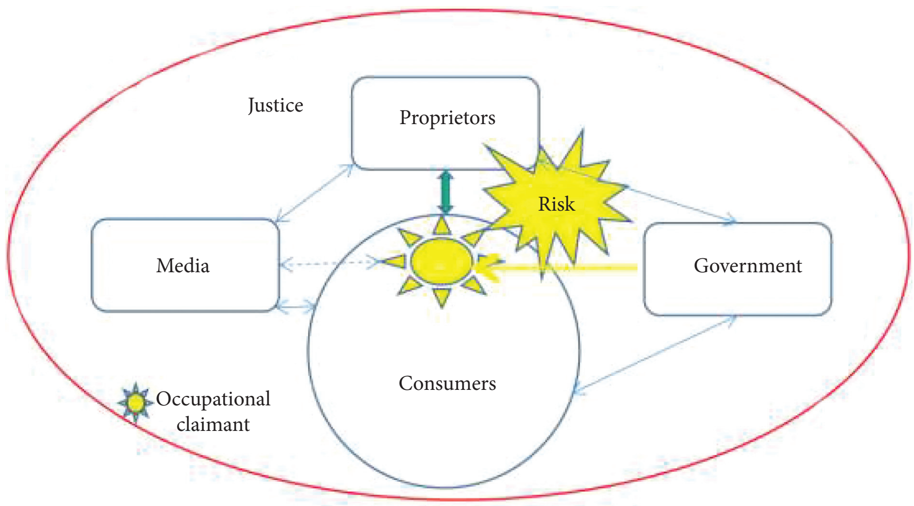

Figure 8: Five-in-one mechanism to coordinate the management of occupational claims.

Occupational claims behavior violates the principle of integrity, damages the market business environment, and is harmful to social stability and economic development.

The results of this study show that the loss rate of occupational claims first increased, then decreased, then increased, then decreased, and finally showed an increasing trend during the period 2011–2019, which is consistent with the law of social administrative intervention. Since the implementation of the Protection of the Rights and Interests of Consumers in 1994, the "refund 1 to compensate 1" rule has created "occupational counterfeiters" represented by "Wang Hai," occupational counterfeiters are welcomed by the public based on forcing product quality improvement. The role of "occupational counterfeiters" has changed to that of "occupational claimants" due to financial interests. Before 2011, there was an upward trend in the rate of losing occupational claims, probably due to inexperience with occupational claims. The newly revised Consumer Protection Law of 2011 with 3 times compensation and the Food Safety Law of 2009 with 10 times compensation accelerated the wave of occupational claims. Having the experience of losing occupational claims in the earlier period made it understandable that the loss rate had continued to decline from 2012 to 2015. The phenomenon of occupational claims is further exacerbated by the lure of financial gain and even the emergence of a large number of jobless people, specializing in occupational claims. The occupational claims represented by "Xing Zhihong" amounted to as much as 1 million, shocking the industry and causing concern of the national regulatory authorities. The public and official have re-examined the behaviors of the occupational claims and reconsidered the original legislative intent of the Protection of the Rights and Interests of Consumers and the Food Safety Law, and the outcome of the public and official reflections will negatively affect the outcome of the occupational claims trial. As a result, the rate of losing occupational claims reached a high point again in 2016. People can always find a way to cope with the government policies. Occupational claims have become gang-oriented, large-scale, and professional in operation and even distorted the organizational form of building personnel with clear division of labor and process-oriented claims, which brought the loss rate of occupational claims down again to 45% in 2017. This result may also be related to the "Regulations on the Implementation of the Consumer Rights Protection Law (Request for Comments)" issued by the State Administration for Industry and Commerce on August 5, 2016, which proposed to stipulate that "acts for profit are no longer protected by the Consumer Law." Nonetheless, at this time, there is regional variation in the outcome of domestic occupational claims trials, due in large part to the provision for punitive damages for consumers in March 25, 2016, Chongqing Senior People Court's "Answers to Several Questions on the Trial of Consumer Rights and Interests Protection Disputes": "if a person who purchases goods or services knowing that there are quality problems requests punitive damages, the people's court shall not support it because it is against the principle of integrity" and restrictions on obtaining punitive damages in the Jiangsu Senior People Court's Discussion Minutes (2016) No. 10 on Several Issues regarding the Trial of Consumer Rights and Interests Protection Disputes. Since the beginning of 2018, the rate of losing occupational claims had skyrocketed, and one of the reasons may be related to the fact that on May 19, 2017, the Supreme People's Court proposed to "reexamine occupational claims and other behaviors." The second reason may be related to the official regulatory behavior and social concern about the heat of occupational claimants, for example, the State Council issued a document on cracking down on occupational claimants, as well as the publicity coverage of Beijing TV, CCTV news, and other major media.

The results of this study point out that the risk of losing an occupational claim case is higher than that of normal consumption. The main reason for this is that the motivation of occupational claims is contrary to the original legislative intent of the Consumer Protection Law and the Food Safety Law, "the prevailing norm of international legislation is to use "fraud" as a premise for punitive damages" [17, 18]. The risk of losing an occupational claim in 2019 is 33.34 times higher than a normal consumer dispute, as evidenced by the fact that occupational claim losses are directly related to official regulatory behavior. The secondary reason may be that occupational claims are not in line with public sentiment and are contrary to socio-economic development. Further, it may be due to occupational claims overly pursuing financial interests and misclassifying the focus of the dispute. Most of the disputes belong to food unsafe under self-perception, rather than unsafe in the real sense. Other possible causes cannot be excluded.

The results of this study reveal that the government's protective behavior toward occupational claimants has a positive effect on the number of occupational claim cases and the government's regulatory behavior toward occupational claimants has a positive effect on the rate of losing occupational claim cases. The former can be confirmed by the relationship between the government's introduction of the Consumer Protection Law and the Food Safety Law and the timing of the amendments and the number of occupational claim cases. The latter can be confirmed from the data in Table 1, which shows the relationship between the official series of regulatory behaviors and social media involvement and the rate of losing occupational claim cases.

5. Conclusion

It is proposed that laws and regulations should be in line with international standards, highlight the legal thinking and the concept of the rule of law, return to the original legislative intent, refer to the Shanghai model, multisectoral linkage, and build a five-in-one mechanism of "consumers, operators, media, government, and justice" to coordinate the management of occupational claims (see Figure 8) and to crack down on extortion and abuse of the right to file complaints in the process of occupational claims and contribute to the creation of a good business environment.

We call for the government to introduce business norms and policies on rewards and penalties to promote social and economic development, protect consumers' legitimate consumption channels and improve people's livelihood, actively protect the legitimate rights and interests of consumers, clarify the negative attributes of occupational claims, regulate the phenomenon, and provide policy guarantees for the improvement of the business environment. The media should report fairly and impartially on the quality of the operator's products and truthfully expose the malpractice of occupational claims to contribute to the creation of a positive business environment, improve public confidence, and enhance public integrity. The judiciary should keep up with the times and actively amend the adaptive provisions of punitive laws and regulations in an effort to win social support and maintain social stability. Other individuals in the society should actively improve their moral cultivation, resolutely resist the consumption of poor quality products, firmly support laws and regulations, refrain from participating in occupational claims, take the initiative to report the phenomenon of occupational claims, and make contributions to progress of social civilization.

We propose that the official should be designed from the top to build a system of integrity and rights protection, remove the "fighting against counterfeit" halo from the head of occupational claims, clarify the negative characterization of occupational claims, and crack down on bad behavior such as maliciously reporting and filing a complaint against businesses, disrupting the normal working of the state administration, abusing the right to file complaints and report lawsuits, and undermining the business environment. Public security depatments, market supervision departments, and other relevant departments should jointly establish a list of occupational claimants, linked to personal integrity, and people with such behavior will have their credit scores deducted, and some of their rights will be restricted to a certain extent (such as restricting loans, restricting high-speed rail and airplane travel, restricting the purchase of luxury goods, and treating them differently in various aspects such as complaint handling, administrative punishment, and administrative review), thus creating a sense of self-restraint [19]. The illegal and criminal acts of malicious occupational claimants should be severely punished. Typical cases of malicious occupational claimants of illegal and criminal punishment should be widely publicized as an example to others.

The government should address possible loopholes of common themes of occupational claims from the perspective of law management rules, such as the scope of business, food safety, advertising, unfair competition, and other areas, introduce relevant regulations as soon as possible to regulate the behavior of manufacturers and distributors, and clarify that if the illegal act is minor and corrected in time without causing harmful consequences, no administrative penalty shall be imposed. There is no opportunity for occupational claimants to take advantage of laws and regulations, compressing their space to profit through complaints and reports. At the same time, the rules for identifying occupational claimants combining their characteristics should be clarified and the situation where normal consumers are tempted to enter the occupational claim trap because of the interests should be avoided.

We will try to implement a five-in-one mechanism of "consumers, operators, media, government, and justice" to manage occupational claims by starting to control the two main bodies of occupational claims, respectively. It is firmly believed that occupational claims will eventually step off the stage of history. The withdrawal of occupational claims is the basic guarantee for the normal operation of social economy and business and is also the inevitable result of the construction of social credit system and the healthy development of social civilization.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of Interest.

Acknowledgments

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Research Article

Dynamic Optimal Pricing of Ridesharing Platforms under Network Externalities with Stochastic Demand

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Ridesharing two-sided platforms link the stochastic demand side and the self-scheduling capacity supply side where there are network externalities. The main purpose of this paper is to establish the optimal pricing model of ridesharing platforms to dynamically coordinate uncertain supply and stochastic demand with network externalities in order to maximize platforms' revenue and social welfare. We propose dynamic pricing strategies under two demand scenarios that minimize order loss in the surge demand period and maximize social welfare in the declining demand period. The numerical simulation results show that dynamic pricing strategies could stimulate the supply to reduce delayed orders in the surge demand scenario and adjust the demand to maximize social welfare under declining demand scenario. Additionally, we further find that the direct network externalities positively influence the platforms' revenue, and the indirect network externalities have a negative effect on social welfare in the declining demand scenario, and a higher wage ratio cannot enhance the platforms' revenue.

1. Introduction

With the rapid growth of sharing economy, ridesharing platforms, which offer service to consumers via sharing idle social labors, have entered in our lives and have deep and long-lasting impact on transportation [1]. Ridesharing is becoming an important way for resident travelling in cities. In 2018, the ridesharing platforms provided services for 20 billion customers, which accounts for thirty-six percent of resident travelling market in China [2]. Ridesharing platforms connect consumers and drivers and make revenue by charging consumers "price" and build delivery capacity by providing drivers "wage." Lower price and convenience are the main reasons for consumers to order service on ridesharing platforms, but for drivers, except for wage, their participation decisions are usually influenced by the quantity of platform's orders and drivers [3, 4].

The ridesharing platforms are facing the challenge on coordination self-scheduling capacity supply with stochastic demand. The sharing drivers who provide delivery capacity for ridesharing platforms are part-time social labors with high mobility and instability. The self-scheduling social drivers [5] who can provide service and decide working hours by themselves can be far less controlled by ridesharing platforms. Meanwhile, the order demand of platform's consumers is stochastic, largely because customers could place the ride request order online at anytime and anywhere. Because consumers and drivers are sensitive to price and wage [6], a dynamic pricing strategy could be applied to effectively manage the stochastic demand and uncertain supply of the ridesharing platforms [7].

Moreover, dynamic pricing strategies for ridesharing platforms have complex demand scenarios of surge demand [7] in peak time, i.e., in the busy morning and declining demand [8] in the off-peak time, i.e., in the leisurely afternoon. Under surge demand scenario in the peak time, the demand of the ridesharing platforms extremely exceeds the capacity supply, which causes delayed orders. However, under declining demand scenario in the off-peak time, the demand of the ridesharing platforms is less than the capacity supply, which make some drivers idle. Then, for platforms, the balance between the supply and demand is not the only viable objective in many cases because of the delayed orders or the idle driver accumulation issue.

Meanwhile, ridesharing platforms are completely two-sided, which exhibit network externalities between customers' demand side and drivers' supply side. For instance, drivers will choose to join the ridesharing platforms for sufficient income when they observe large online orders of the platforms. In addition, drivers can view information about the idle drivers in the nearby zone in real-time on ridesharing platforms. Therefore, the self-scheduling capacity supply offered by sharing the social drivers might be influenced by indirect network externalities from the demand side of the quantity of platforms' orders and the direct network externalities within the supply side of other drivers' participation as well. Therefore, the network externalities of ridesharing platforms are worthwhile considered in a dynamic pricing strategy [9, 10].

Our research addresses these challenging issues for ridesharing platforms and tries to answer the following research questions:

(1) How to effectively manage the dynamic demand and supply of ridesharing platforms via dynamic pricing strategy?
(2) How to solve the delayed orders and idle drivers' problem for the platforms?
(3) How does network externalities influence the pricing strategy of the platforms?

To answer these questions, our research focuses on the dynamic pricing modeling considering network externalities in order to balance the demand and supply to maximize ridesharing platforms' revenue. Furthermore, we study the dynamic pricing strategies in two scenarios, which are the surge demand scenario in peak time to minimize the delayed order loss and the declining demand scenario in off-peak time to minimize idle drivers. Then, we conduct a numerical study to verify the dynamic pricing strategies and analyze the influence of network externalities.

Our study generates several contributions. First, this paper extends prior research on the dynamic pricing strategy of ridesharing platforms [5] to complex network externality circumstances. We build the pricing model with network externalities and illuminate the impact of network externalities on the dynamic pricing strategy and ridesharing platforms' revenue. Second, we put forward dynamic pricing strategies for ridesharing platforms not only under surge demand scenario [5, 11, 12] but also under declining demand scenario in which the idle drivers are reduced to maximize the social welfare. Third, the optimal control theory [13, 14] is applied to optimize the pricing strategy more precisely. In our research, the ridesharing service price is taken as the control variable. The delayed orders and idle drivers are state variables, respectively, in two scenarios, which are minimized in pricing optimization with objectives of maximum revenue and social welfare. Furthermore, our study also contributes to the general ridesharing pricing literature [5] by illustrating the importance for platforms to develop dynamic pricing strategies to adapt to the complex and dynamic environment with temporary and lasting features of evolution. Our study has managerial implications to optimize the ridesharing platforms' performance.

The rest of the paper is organized as follows: in Section 2, we review the related literature and search the research gap. Section 3 describes the problem and puts forward assumptions. In Section 4, we build a dynamic pricing model under surge demand scenario and analyze the pricing strategy. Section 5 analyzes the dynamic pricing model in the declining demand scenario. In Section 6, the dynamic pricing models are verified with numerical study in which the effect of network externalities and wage ratio are analyzed. Finally, Section 7 concludes this paper.

2. Related Literature

Our research is closely related to three streams of literature: ridesharing platforms, dynamic pricing, and network externalities.

2.1. Ridesharing Platforms. Ridesharing, in a real sense, originates from Uber founded in 2009 and is sharing self-scheduling drivers, which is very different from that of regular taxi. The ridesharing platforms have changed the travel mode and eased traffic pressure, but it is almost inevitable that the development of the online peer to peer ridesharing service has also brought various problems waiting to be resolved. The researchers have done various studies on ridesharing from the perspective of spatial dimension. Some researchers consider the ridesharing services as solutions to pressure due to the traffic congestion. Li et al. [15] built a path-based equilibrium model to describe the decision-making of travelers and examine how the ridesharing program will reshape the spatial distribution of traffic congestion in the presence of the ridesharing program. Meanwhile, Tafreshian and Masoud [16] proposed a new market model to address the ride-matching problem, which outputs matching, role assignment, and pricing to analyze an opportunity cost of missed social welfare or revenue for a P2P ridesharing system. In addition, passengers' mobility preferences are also viewed as the service strategies; for example, Bian et al. [17] proposed a novel mechanism, namely, "mobility-preference-based mechanism with baseline price control" (MPMBPC) to promote consumers' participation in the on-demand first-mile ridesharing accounting for mobility preferences including arrival deadlines, maximum willing-to-pay prices, and detour tolerances. Some researchers proposed the approach to balance between user privacy and utility. Mejia and Parker [18] explored whether the operational transparency is beneficial with potentially biased service providers in the context of ridesharing platforms through an experiment. Avodji et al. [19] developed a privacy-preserving service to compute meeting points in ridesharing with each user in control of his location data. Ridesharing platform pricing is also especially important to address the traffic issue from time dimension in the demand side. Wei et al. [20] modelled a multimodal network with ridesharing services, where two types of travelers who have their own cars or not could have different choices. Based on the doubly dynamical framework, two different congestion pricing schemes are proposed to reduce network congestion and improve traffic efficiency. María et al. [21] analyzed user preferences toward pooled on-demand services regarding their time-reliability cost trade-offs, including value of time (VOT) and value of reliability(VOR) of the different trip stages.

2.2. Dynamic Pricing. Many researchers have studied the dynamic pricing model on perishable products [22–24] and electricity market. Herbon and Khmelnitsky [13] developed an inventory replenishment model with dynamic pricing, considering the interdependence of demand on price and time. Referred to Chen et al. [25], they compared four dynamic pricing models with and without menu costs for deteriorating products and analyzing the impact of menu costs on deteriorating products. Dynamic pricing is used in electricity market for load management in the peak period [26]. Sharifi et al. [27] studied optimal pricing strategies and demand response models for a pool-based electricity market based on the bilevel Stackelberg-based model in order to enhance retailer's profit and consumers' welfare during peak hours of power consumption. The economic demand response model [28] is also employed for residential consumers in liberalized electricity markets to change their consumption pattern from times of high energy prices to other times to maximize their utility functions. Abapour et al. [29] proposed a noncooperative game to obtain the best bidding strategy of demand response aggregators in the electricity market. The robust optimization method is used to optimize the robustness of the pricing strategies.

The dynamic pricing strategy plays an important role in coordinating the balance of the demand and supply for ridesharing platforms [30]. Bimpikis et al. [31] explored the role of spatial price discrimination in ridesharing networks and highlighted the effect of demand pattern. In addition, surge pricing should not be ignored, which is an effective mean to adjust the capacity in the peak time for ridesharing platforms. Cachon et al. [5] studied a revenue model in which the optimal contract of a service platform applies a surge pricing policy, considering self-scheduling of providers. In addition, Guda and Subramanian [11] analyzed the function of surge pricing on managing the platform service through considering workers' behavior of moving between adjacent zones, taking forecast communication and worker incentives into account as well.

Ridesharing platforms have stochastic demand and uncertain social supply. The load management by dynamic pricing strategies on electricity markets focuses on demand response and customer flexibility during peak hours of power consumption. Existing ridesharing literature mainly studies dynamic pricing of peak time in order to coordinate the supply with demand to maximum platforms' revenue. In this paper, we extend the existing literature on load management [27] and ridesharing [5] to minimize delayed order loss in peak time. Moreover, considering the social feature of ridesharing drivers, we study the dynamic pricing strategies in off-peak time to minimize idle drivers and maximize social welfare.

2.3. Network Externalities. Inevitably, with the development of technology and smartphone, two-sided ridesharing platforms linking customers and drivers have the characteristic of network externalities. Rohlfs [32] proposed the network externalities in the communication industry. Katz and Shapiro [9] redefined the concept and formulated a static, one-period model that uses market equilibria to capture network externalities, competition, and compatibility as vital elements. The network externalities exist in multiple situations [33, 34], such as retailers and manufacturers [35], green manufacturing [36], consumers and retailers in supply chain [37], social networks [38], and so on. The research is beginning to pay attention on network externalities in ridesharing platforms in recent years. Wu and Zhang et al. [10] develop an instantaneous pricing model in the context of two-sided market theory, and spatial differentiation and network externalities are considered as factors that affect the pricing mechanism of online car hailing platforms.

Ridesharing two-sided platforms connect customers' demand side and social drivers' supply, which have network externalities between two sides. We focus on the dynamic pricing strategy under network externalities in ridesharing platforms using optimal control theory. Optimal control theory is a systematic theory developed in 1950s, which is used in the field of control at the beginning. Now, the optimal control theory has been applied in the management field, such as production planning [14] and financial system [39]. The dynamic optimization of the optimal control theory can depict the dynamic pricing trajectory of platforms in continuous time; thus, it can improve the accuracy and timeliness of the pricing strategy by changing the state in continuous time [40]. Therefore, extending the work of Herbon and Khmelnitsky [13], this paper studies the dynamic pricing strategies under two scenarios (surge demand and declining demand) based on Pontryagin's maximum principle method of optimal control theory [41, 42], considering the network externalities. Meanwhile, in this paper, we innovatively take delayed orders and idle drivers as the state variables of two scenarios, respectively, instead of taking the inventory level as the state variable in the existing literature, aiming to reduce loss cost while coordinating the supply and demand to obtain more platform revenue. Furthermore, network externalities have analyzed the influence on dynamic pricing strategies of ridesharing platforms. Our research fills the theoretical gap in dynamic pricing of load management and ridesharing management.

3. Problem Formulation

3.1. Problem Description. Ridesharing platforms are typical two-sided markets. On the demand side, consumers pay "price" to obtain service in platforms. The online demand of consumers is stochastic and changes with time; it means they can request service at any time through the platforms. On the supply side, platforms pay "wage" to drivers for service capacity supply. Since drivers could decide participation and work time by themselves, the ridesharing platforms have self-scheduling capacity supply. Hence, it is more difficult for the platforms to control the self-scheduling supply and stochastic demand. In this case, the ridesharing platforms have exhibited significant network externalities. Drivers are inevitably effected by the network externalities in online ridesharing platforms. Figure 1 shows a brief operation process of the ridesharing platforms.

In Figure 1, the two sides represent the demand side and the supply side, respectively. The demand side requests service from platforms via pay "price", and the supply side offers service to get "wage", ridesharing platforms make revenue by paying "price" and charging "wage". Because consumers and drivers can choose whether to join platforms via observing price and wage, it is more convenient for platforms to manage both sides through dynamic pricing based on fixed commission contract. Unlike traditional taxi, the ridesharing platforms are transparent two-sided markets for demand side and supply side. In term of drivers, they can observe not only the number of idle drivers around this order (direct effect), but also the regional thermodynamic diagram, which displays platforms' orders (indirect effect). Obviously, drivers could be influenced by network direct network externalities from the same supply side and indirect network externalities from the demand side; in addition, network externalities influence the pricing strategy of ridesharing platforms.

Generally, ridesharing platforms might face two demand scenarios, which are surge demand scenario and declining demand scenario. The interaction clearly appears between consumers and drivers and occurs over the process of coordinating demand and supply. As shown in Figure 2, customers request ride demands to ridesharing platforms, and the platforms accept demand orders and evaluate the supply capacity. When order demand exceeds the supply capacity, the platforms adopt the surge pricing strategy to stimulate driver supply until a balance between demand and supply is reached. When supply capacity exceeds the demand, the platforms can adopt a dynamic pricing strategy to adjust customer demand until a balance between demand and supply is reached. The description of variables and parameters involved in ridesharing platforms is shown in Table 1.

3.2. Assumption. We study dynamic pricing strategies in two scenarios, which are surge demand scenario in peak time and declining demand scenario in off-peak time by taking the delayed orders and idle drivers as the state variables, respectively, of two scenarios, and taking the optimal price as the control variable. Second, we consider network externalities on the supply side, which are from the cross demand side of the quantity of orders and the same supply side of other drivers. On the supply side, drivers can view information about the idle drivers around nearby location in real-time through platforms (direct effect). On the demand side, driver's participation decision to the platforms depends on the order quantity (indirect effect). Hence, the network

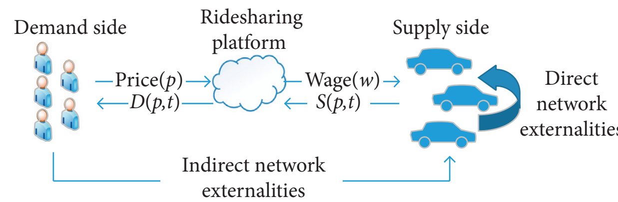

Figure 1: The two-sided ridesharing platforms.

externalities on the drivers' supply from both the demand side and supply are discussed in the paper considering the self-scheduling capacity of ridesharing platforms, which could be controlled by dynamic pricing to balance with the stochastic demand. Third, except for maximizing platforms' revenue, the platforms can ensure minimum order loss under surge demand and maximum social welfare under declining demand via controlling price.

Referring to Krishnamoorthy et al. [43] and Herbon and Khmelnitsky [13], we assume that the demand is a nonlinear time effect function, and the initial market demand is ae^{-bt} in time period $[0, T]$ ($b<0$ represents the negative-exponential time effect on demand and $b>0$ represents positive-exponential time effect, where b indicates the stochastic demand to some extent). The current demand of the ridesharing platforms is affected by rational and price-sensitivity consumers. Considering the price and time dependence of consumers, we assume that the demand is increasing under the surge demand period ($b<0$), and the demand is decreasing under the declining demand period ($b>0$). Specifically, the demand function is as follows:

$$D(p,t) = ae^{-bt} - \beta p(t). \tag{1}$$

For convenience, we adopt a fixed commission contract to connect wage and price, that is, wage $W(p,t)$ is linear with price $p(t)$, $W(p,t)=\gamma p(t)$ (Hu and Zhou [6]). Thus, the capacity supply of the platforms provided by drivers is similarly stimulated by the service price [10]. Given the effect of indirect network externalities, we also assume that μ_2 has a positive effect in all time period. Considering the effect of order quantity on drivers' decision, we assume that the direct network externalities μ_1 have a positive effect on the surge demand period because of insufficient driver supply and a negative effect on declining demand period due to idled drivers. Then, the supply function in the surge demand period is $S(p,t) = \varepsilon W(p,t) + \mu_1 S^e(p,t) + \mu_2 D(p,t)$. Let $S^e(p,t)$ denotes driver's rational expectation of supply at time t [9], $S(p,t) = S^e(p,t)$. To simplify the presentation, the joint dynamic pricing, time, and network externalities supply function is as follows:

$$S_p(p,t) = \frac{1}{1-\mu_1}\left(\varepsilon W(p,t) + \mu_2 D(p,t)\right). \tag{2}$$

Conversely, the supply function in declining demand is as follows:

$$S_o(p,t) = \frac{1}{1+\mu_1}\left(\varepsilon W(p,t) + \mu_2 D(p,t)\right). \tag{3}$$

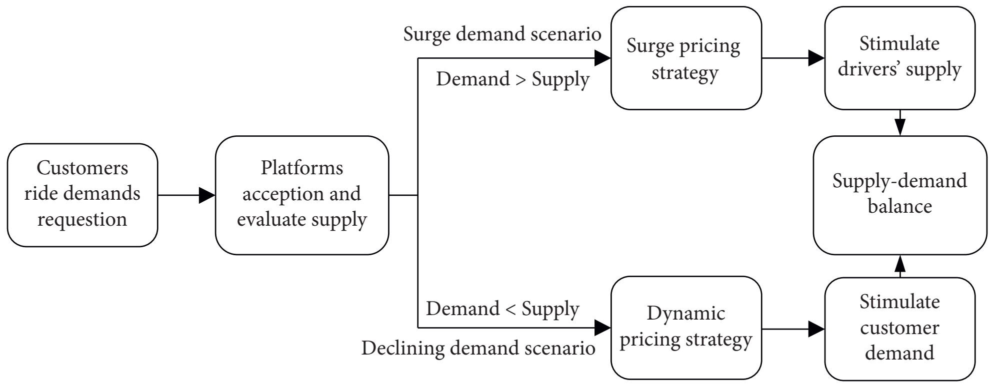

Figure 2: The flowchart of ridesharing platforms coordinating demand and supply process.

Table 1: Notion.

Parameters		Explanation
	a	Initial market demand of platforms
	b	Time-variation factor of market size
	β	Price-sensitivity coefficient of demand
	γ	Wage ratio, 0< γ <1
	ε	Price-sensitivity coefficient of supply
	μ_1	Direct network externalities among drivers, 0 < μ_1 <1
	μ_2	Indirect network externalities of demand on supply, 0 <<1
	h	Delayed order loss cost per unit
	c	Idle driver waiting cost per unit
Variables		
	$D(p, t)$	Demand level at time t for a given price p
	$S(p, t)$	Supply level at time t for a given price p
	$p(t)$	Price at time t
	$W(p, t)$	Wage of driver at time t
	$Y(t)$	Delayed order quantity at time t
	$I(t)$	Idle driver quantity at time t

Meanwhile, since orders of the demand side cannot be satisfied by drivers in the surge demand period, it results in the delayed order accumulation, $Y(t)$. We assume that the delayed order quantity at time T is φ_T, initial delayed order is φ_0, and the loss cost per unit of delayed order is h. In the declining demand period, it will be surplus in the supply side as the quantity of drivers exceeds orders, where $I(t)$ represents the quantity of idle drivers waiting for orders at time t. In addition, the waiting cost of the idle driver per unit is c. In addition, we assume that the initial idle driver quantity is ψ_0, and at time T it is ψ_T.

Therefore, we mainly control the optimal price trajectory to minimize the delayed order $Y(t)$ from φ_0 to φ_T in peak time, and idle driver $I(t)$ from ψ_0 to ψ_T in off-peak time, while maximizing the platforms' revenue and social welfare. In other words, we design the model for determining the optimal dynamic pricing strategy for the corresponding state variable (loss cost) by means of the optimal control theory subjected to the maximum revenue and social welfare. Then, this paper focuses on dynamic ridesharing pricing under two complex demand scenarios, surge demand and declining demand.

4. Surge Pricing Strategy to Minimize Delayed Order Loss under Surge Demand

This paper proposes dynamic ridesharing pricing strategies under two demand scenarios, which are surge demand and declining demand. The timeline of two scenarios are shown in Figure 3. In Section 4, we mainly discuss the surge pricing strategy under surge demand. And, Section 5 analyzes dynamic pricing strategy under declining demand Surge demand [7] in ridesharing platforms occurs in peak time. Generally speaking, it is when the order demand far exceeds the supply capacity and gradually increases. Due to the self-scheduling capacity characteristic of the supply side, ridesharing platforms could attract more drivers to actively join via increasing price, i.e., surge pricing. In the surge demand scenario, the demand side has a negative-exponential time effect. Through increasing price, the platforms stay at an equilibrium level. However, the delayed orders still exist in platforms, even though the delayed order rate reaches zero, that is, $\overline{Y}=0$, but $Y\neq 0$ at T_{pb}. Then, the platforms continue to simulate the supply side to reduce real-time orders and delayed orders. When $Y=0$ at T_{pm}, the platforms' revenue

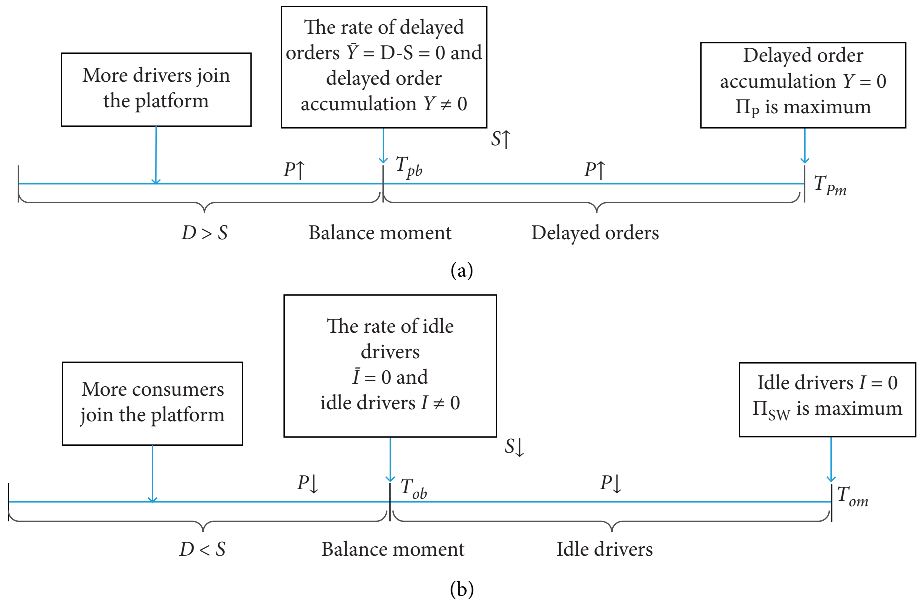

Figure 3: (a) The timeline of the surge demand in peak time. (b) The timeline of the declining demand in off-peak time.

reaches the maximum value. The timeline of the surge demand period is shown in Figure 3(a).

Referring to Herbon and Khmelnitsky [13], the ride-sharing service price $p(t)$ is taken as the control variable in the dynamic pricing model based on optimal control theory. The state variable $Y(t)$ is denoted as the delayed orders accumulated in the surge demand period while the demand exceeds the drivers' supply. The ridesharing service price is dynamically optimized by controlling the state variable of cumulative delayed orders decreased to zero in order to maximize the expected revenue of ridesharing platforms [13,41]. The changing rate $\overline{Y}(t)$ of the delayed orders is decreased with the difference between the demand and supply $(D(p,t) - S(p,t))$, which is indicated with a negative sign in the following state equation:

$$\begin{aligned} \overline{Y}(t) &= -(D(p,t) - S(p,t)), \\ Y(0) &= \varphi_0, \\ Y(T) &= \varphi_T. \end{aligned} \tag{4}$$

Theoretically, Wang et al. [12] have studied the price trajectory to minimize the cumulative delayed orders' loss cost in crowdsourcing platforms. Extending the work of Wang et al. [12] and considering the influence of network externalities, we obtain the objective function of platforms' expected revenue as follows:

$$\begin{aligned} \prod_P &= \max_{p(t)} \int_0^T [D(p,t)p(t) - D(p,t)W(p,t) - hY(t)]\mathrm{d}t \\ &= \max_{p(t)} \int_0^T [D(p,t)p(t)(1-\gamma) - h(\varphi_0 - (T-t)(D(p,t) - S(p,t)))]\mathrm{d}t. \end{aligned} \tag{5}$$

In order to obtain the optimal price of the platforms, we introduce the Lagrangian multiplier $\lambda(t)$, which is the costate variable, and the construct Hamilton function to the optimal control problem as follows:

$$\begin{aligned} H(Y(t), p(t), \lambda(t), t) &= D(p,t)p(t) - D(p,t)W(p,t) - hY(t) + \lambda(t)\overline{Y}(t) \\ &= D(p,t)p(t)(1-\gamma) - h\varphi_0 + (h(T-t) - \lambda)(D(p,t) - S(p,t)). \end{aligned} \tag{6}$$

Thereby, the second-order derivative for p from the Hamiltonian function is deducted as follows:

$$\frac{\partial^2 H}{\partial p^2} = -2\beta(1-\gamma) < 0. \tag{7}$$

Thus, the solution of the optimal price can maximize the Hamiltonian function. For a given pair of $0<\beta<1$, $0<\gamma<1$, platforms' expected profit is a concave function, which satisfies the maximum condition. By applying Pontryagin's maximum principle, the first-order conditions of maximum objective function (5) are given by

$$\begin{cases} \overline{Y}(t) = \dfrac{\partial H}{\partial \lambda}, \\ \overline{\lambda}(t) = -\dfrac{\partial H}{\partial Y}, \\ \dfrac{\partial H}{\partial p} = 0. \end{cases} \tag{8}$$

Based on the above mentioned conditions, we can obtain the optimal price $p^*(t)$, shadow price $\lambda^*(t)$, supply $S^*(t)$, and demand $D^*(t)$ with respect to time t as follows:

$$\begin{aligned} p^*(t) &= \frac{ae^{-bt}}{2\beta} + \frac{(\beta+\varepsilon\gamma-\beta\mu_1-\beta\mu_2)ht}{\beta(1-\mu_1)(1-\gamma)} - \frac{(\beta+\varepsilon\gamma-\beta\mu_1-\beta\mu_2)hT}{2\beta(1-\mu_1)(1-\gamma)} \\ &\quad + \frac{(\varphi_T-\varphi_0)(1-\mu_1)}{(\beta+\varepsilon\gamma-\beta\mu_1-\beta\mu_2)T} + \frac{a\left(1-e^{-bT}\right)(\beta-\varepsilon\gamma-\beta\mu_1-\beta\mu_2)}{2b\beta(\beta+\varepsilon\gamma-\beta\mu_1-\beta\mu_2)T}, \\ \lambda^*(t) &= ht + \frac{2\beta(\varphi_T-\varphi_0)(1-\mu_1)^2(1-\gamma)}{(\beta+\varepsilon\gamma-\beta\mu_1-\beta\mu_2)^2T} + \frac{a\left(1-e^{-bT}\right)(\beta-\varepsilon\gamma-\beta\mu_1-\beta\mu_2)(1-\mu_1)(1-\gamma)}{b(\beta+\varepsilon\gamma-\beta\mu_1-\beta\mu_2)^2T}, \\ S^*(t) &= \frac{ae^{-bt}(\varepsilon\gamma+\beta\mu_2)}{2\beta(1-\mu_1)} + \frac{(\beta+\varepsilon\gamma-\beta\mu_1-\beta\mu_2)(\varepsilon\gamma-\beta\mu_2)ht}{\beta(1-\mu_1)^2(1-\gamma)} - \frac{(\beta+\varepsilon\gamma-\beta\mu_1-\beta\mu_2)(\varepsilon\gamma-\beta\mu_2)hT}{2\beta(1-\mu_1)^2(1-\gamma)} \\ &\quad + \frac{(\varphi_T-\varphi_0)(\varepsilon\gamma-\beta\mu_2)}{(\beta+\varepsilon\gamma-\beta\mu_1-\beta\mu_2)T} + \frac{a\left(1-e^{-bT}\right)(\beta-\varepsilon\gamma-\beta\mu_1-\beta\mu_2)(\varepsilon\gamma-\beta\mu_2)}{2b\beta(\beta+\varepsilon\gamma-\beta\mu_1-\beta\mu_2)(1-\mu_1)T}, \\ D^*(t) &= \frac{ae^{-bt}}{2} - \frac{(\beta+\varepsilon\gamma-\beta\mu_1-\beta\mu_2)ht}{(1-\mu_1)(1-\gamma)} + \frac{(\beta+\varepsilon\gamma-\beta\mu_1-\beta\mu_2)hT}{2(1-\mu_1)(1-\gamma)} \\ &\quad - \frac{\beta(\varphi_T-\varphi_0)(1-\mu_1)}{(\beta+\varepsilon\gamma-\beta\mu_1-\beta\mu_2)T} - \frac{a\left(1-e^{-bT}\right)(\beta-\varepsilon\gamma-\beta\mu_1-\beta\mu_2)}{2b(\beta+\varepsilon\gamma-\beta\mu_1-\beta\mu_2)T}. \end{aligned} \tag{9}$$

This section mainly focuses on the dynamic pricing trajectory under the balance moment and the minimum order loss. Thus, we assume that the balance moment of demand and supply is T_{pb}, which means $S(p, T_{pb}) = D(p, T_{pb})$. At time T_{pb}, $\overline{Y}(T_{pb}) = 0$ but $Y(T_{pb}) > 0$, and it shows that delayed orders still exist. Therefore, the platforms take some time to increase the service price and motivate the drivers. Meanwhile, we assume that T_{pm} is the moment of minimum order loss, where $Y(T_{pm}) = 0$, and the accumulated delayed order quantity decreases to zero. In doing this, we propose the following theorem.

Theorem 1. *$p^*_{T_{pm}}(t)$ is a strictly increasing function at time period $[0, T_{pm}]$.*

Proof. From equations (5) and (6), we obtain the optimal price $p^*_{T_{pm}}(t)$, shadow price $\lambda^*_{T_{pm}}(t)$, supply $S^*_{T_{pm}}(t)$, and demand $D^*_{T_{pm}}(t)$ at T_{pm}.

Then, the first-order of $p^*_{T_{pm}}(t)$ for t is

$$\frac{\partial p^*_{T_{pm}}(t)}{\partial t} = -\frac{abe^{-bt}}{2\beta} + \frac{(\beta+\varepsilon\gamma-\beta\mu_1-\beta\mu_2)h}{\beta(1-\mu_1)(1-\gamma)} > 0. \tag{10}$$

It shows that $p^*_{T_{pm}}(t)$ increases with respect to t in peak time. The larger is the demand order quantity, the higher is the price.

Theorem 1 shows that optimal price always increases and over time under surge demand. $b<0$ represents the increasing orders, and the demand side is greater than the supply capacity as a whole. The increasing price can directly motivate drivers, which is due to the fixed commission contract, further help to reduce real-time and delayed orders. Thus, Lemma 1 shows the variation trajectory of the supply side as the control parameter $p^*_{T_{pm}}(t)$ change. □

Lemma 1. *$S^*_{T_{pm}}(t)$ increases with $p^*_{T_{pm}}(t)$ for $\varepsilon\gamma \geq \beta\mu_2$.*

Proof. By simple deformation, the supply $S^*_{T_{pm}}(t)$ is

$$S^*_{T_{pm}}(t) = \frac{a\mu_2 e^{-bt}}{1-\mu_1} + \frac{\varepsilon\gamma - \beta\mu_2}{1-\mu_1} p^*_{T_{pm}}(t), \tag{11}$$

where the effect of the price incentive is greater than the indirect network externalities, and $S^*_{T_{pm}}(t)$ has a positive correlation with $p^*_{T_{pm}}(t)$. On the basis of Theorem 1, $p^*_{T_{pm}}(t)$ is a strict increasing function with time t. Obviously, the supply side also increases with time t.

Considering the direct effect of network externalities on optimal price, we further have insight into the influence of the network externalities on the supply trajectory. □

Theorem 2. *μ_1 and μ_2 have positive effect on capacity supply at T_{pb}.*

Proof. The results of $S_{T_{pb}}(t)$ in the following can be obtained from equation (12).

$$S_{T_{pb}}(t) = \frac{\mu_2 a e^{-bt}}{1-\mu_1} + \frac{\varepsilon\gamma - \beta\mu_2}{1-\mu_1} * p_{T_{pb}}(t) = \frac{a e^{-bT_{pb}}\varepsilon\gamma}{\beta + \varepsilon\gamma - \beta\mu_1 - \beta\mu_2}. \tag{12}$$

Then, the two first-order for μ_1 and μ_2 from $S_{T_{pb}}(t)$ are, respectively,

$$\frac{\partial S_{T_{pb}}(t)}{\partial\mu_1} = \frac{\partial S_{T_{pb}}(t)}{\partial\mu_2} = \frac{a e^{-bT_{pb}}\varepsilon\gamma\beta}{(\beta + \varepsilon\gamma - \beta\mu_1 - \beta\mu_2)^2} > 0. \tag{13}$$

Obviously, solving the two first-order conditions from $S_{T_{pb}}(t)$ yield $(\partial S_{T_{pb}}(t)/\partial\mu_1) \geq 0$ and $(\partial S_{T_{pb}}(t)/\partial\mu_2) \geq 0$, which represent that $S_{T_{pb}}(t)$ increases with respect to μ_1 and μ_2. Actually, drivers can observe the surge demand and insufficient supply by smartphone application, and the increasing price stimulates drivers to join the platforms, which could increase the capacity supply.

In addition, the ridesharing platforms revenue $\prod_p$ and the drivers revenue $\prod_s$ will be verified by numerical simulation in Section 6. □

5. Dynamic Pricing Strategy to Maximize Social Welfare under Declining Demand

The ridesharing platforms' demand is declining in the off-peak time, except for the surge orders, over a longer period of time [8]. Some drivers are idle in the declining demand period, which shows that the whole drivers exceed the order demand. When platforms decreases the price, more consumers will be attracted to choose the ridesharing service. Until the balance moment T_{ob}, the demand side and supply take some time to gradually reach equilibrium. However, the idle drivers still exist at T_{ob}, even though the idle driver rate reaches to zero, i.e., $\overline{I} = 0$, but $I \neq 0$. Then, the platforms continue to simulate the demand side by reducing the ridesharing price. When $I = 0$ at T_{om}, the social welfare can reach the maximum value with decreasing idle loss. The timeline of declining demand period can be referred to Figure 3(b) in Section 4.

Referring to Herbon and Khmelnitsky [13], the ridesharing service price $p(t)$ is taken as the control variable in the dynamic pricing model based on optimal control theory. The state variable I(t) denotes the idle drivers accumulated in the declining demand period ,while the drivers' supply exceeds demand. The ridesharing service price is dynamically optimized by controlling the state variable of cumulative idle drivers decreased to zero in order to maximize the social welfare [13, 41]. The idle drivers' changing rate $\overline{I}(t)$ decreases with the difference between the supply and demand $(S(p,t) - D(p,t))$, which is indicated with a negative sign in the following state equation:

$$\begin{aligned} &\overline{I}(t) = -(S(p,t) - D(p,t)),\\ &I(0) = \psi_0,\\ &I(T) = 0. \end{aligned} \tag{14}$$

The main goal for ridesharing platforms is to make profit like other companies. In fact, platforms still take into account the development issue especially during the off-peak time. Referring to Yu et al. [1], we propose the social welfare denoted by the sum of drivers' earnings and ridesharing platforms' revenue, where the ridesharing platforms revenue' is represented in equation (15) and drivers' earning is in equation (16). Then, our proposed optimal control problem of maximization social welfare (denoted by $\prod_{SW}$) is as follows:

$$\prod_p = \max_{p(t)} \int_0^T [D(p,t)p(t) - D(p,t)W(p,t)]\mathrm{d}t, \tag{15}$$

$$\prod_s = \max_{p(t)} \int_0^T [S(p,t)W(p,t) - cI(t)]\mathrm{d}t, \tag{16}$$

$$\prod_{\mathrm{SW}} = \prod_{p} + \prod_{s} = \max_{p(t)} \int_0^T [D(p,t)p(t) - D(p,t)W(p,t) + S(p,t)W(p,t) + ct(D(p,t) - S(p,t))]\mathrm{d}t. \tag{17}$$

We then introduce costate variable $\lambda(t)$ and construct Hamilton function of social welfare maximization,

$$\begin{aligned} H(I(t), p(t), \lambda(t), t) &= D(p,t)p(t) - D(p,t)W(p,t) + S(p,t)W(p,t) - cI(t) + \lambda(t)\overline{I}(t) \\ &= D(p,t)p(t) - D(p,t)W(p,t) + S(p,t)W(p,t) + (\lambda + ct)(D(p,t) - S(p,t)). \end{aligned} \tag{18}$$

Hamilton function is a differential and nonlinear equation. By applying Pontryagin's maximum principle, the first-order conditions of the Hamilton function are given by

$$\begin{cases} \overline{I}(t) = \dfrac{\partial H}{\partial \lambda}, \\ \overline{\lambda}(t) = -\dfrac{\partial H}{\partial I}, \\ \dfrac{\partial H}{\partial p} = 0. \end{cases} \tag{19}$$

Combining equations (18) and (19), we obtain the optimal price $p^*_{T_{om}}(t)$ and shadow price $\lambda^*_{T_{om}}(t)$, further obtaining the supply $S^*_{T_{om}}(t)$ and demand $D^*_{T_{om}}(t)$ as follows:

$$\begin{aligned} p^*_{T_{om}}(t) &= \frac{(\beta + \varepsilon\gamma + \beta\mu_1 - \beta\mu_2)ct}{\varepsilon\gamma^2 - \beta + \beta\gamma - \beta\mu_1 + \beta\mu_1\gamma - \beta\mu_2\gamma} - \frac{ae^{-bt}(1 + \mu_1 - \gamma - \mu_1\gamma + \mu_2\gamma)}{2(\varepsilon\gamma^2 - \beta + \beta\gamma - \beta\mu_1 + \beta\mu_1\gamma - \beta\mu_2\gamma)} \\ &\quad + \frac{\psi_0(1 + \mu_1)}{(\beta + \varepsilon\gamma + \beta\mu_1 - \beta\mu_2)T} + \delta, \\ \lambda^*_{T_{om}}(t) &= ct + \frac{2\psi_0(\varepsilon\gamma^2 - \beta + \beta\gamma - \beta\mu_1 + \beta\mu_1\gamma - \beta\mu_2\gamma)(1 + \mu_1)}{(\beta + \varepsilon\gamma + \beta\mu_1 - \beta\mu_2)^2 T} + \frac{a(1 - e^{-bT})(1 + \mu_1 - \gamma - \mu_1\gamma + \mu_2\gamma)}{b(\beta + \varepsilon\gamma + \beta\mu_1 - \beta\mu_2)T} \\ &\quad + \frac{2a(1 - e^{-bT})(1 + \mu_1 - \mu_2)(\varepsilon\gamma^2 - \beta + \beta\gamma - \beta\mu_1 + \beta\mu_1\gamma - \beta\mu_2\gamma)}{b(\beta + \varepsilon\gamma + \beta\mu_1 - \beta\mu_2)^2 T} - cT, \\ S^*_{T_{om}}(t) &= \frac{(\beta + \varepsilon\gamma + \beta\mu_1 - \beta\mu_2)(\varepsilon\gamma - \beta\mu_2)ct}{(\varepsilon\gamma^2 - \beta + \beta\gamma - \beta\mu_1 + \beta\mu_1\gamma - \beta\mu_2\gamma)(1 + \mu_1)} - \frac{ae^{-bt}(1 + \mu_1 - \gamma - \mu_1\gamma + \mu_2\gamma)(\varepsilon\gamma - \beta\mu_2)}{2(\varepsilon\gamma^2 - \beta + \beta\gamma - \beta\mu_1 + \beta\mu_1\gamma - \beta\mu_2\gamma)(1 + \mu_1)} \\ &\quad + \frac{a\mu_2 e^{-bt}}{1 + \mu_1} + \frac{\psi_0(\varepsilon\gamma - \beta\mu_2)}{(\beta + \varepsilon\gamma + \beta\mu_1 - \beta\mu_2)T} + \frac{(\varepsilon\gamma - \beta\mu_2)\delta}{1 + \mu_1}, \\ D^*_{T_{om}}(t) &= ae^{-bt} - \frac{\beta(\beta + \varepsilon\gamma + \beta\mu_1 - \beta\mu_2)ct}{\varepsilon\gamma^2 - \beta + \beta\gamma - \beta\mu_1 + \beta\mu_1\gamma - \beta\mu_2\gamma} + \frac{a\beta e^{-bt}(1 + \mu_1 - \gamma - \mu_1\gamma + \mu_2\gamma)}{2(\varepsilon\gamma^2 - \beta + \beta\gamma - \beta\mu_1 + \beta\mu_1\gamma - \beta\mu_2\gamma)} \\ &\quad - \frac{\beta\psi_0(1 + \mu_1)}{(\beta + \varepsilon\gamma + \beta\mu_1 - \beta\mu_2)T} - \beta\delta, \end{aligned} \tag{20}$$

where parameter δ satisfies the following equation:

$$\delta = -\frac{(\beta+\varepsilon\gamma+\beta\mu_1-\beta\mu_2)cT}{2\left(\varepsilon\gamma^2-\beta+\beta\gamma-\beta\mu_1+\beta\mu_1\gamma-\beta\mu_2\gamma\right)} + \frac{a\left(1-e^{-bT}\right)(1+\mu_1-\mu_2)}{b(\beta+\varepsilon\gamma+\beta\mu_1-\beta\mu_2)T} + \frac{a\left(1-e^{-bT}\right)(1+\mu_1-\gamma-\mu_1\gamma+\mu_2\gamma)}{2b\left(\varepsilon\gamma^2-\beta+\beta\gamma-\beta\mu_1+\beta\mu_1\gamma-\beta\mu_2\gamma\right)T}. \tag{21}$$

This section mainly focuses on the optimal pricing trajectory under declining demand scenario, where the model is proposed to maximize social welfare. Meanwhile, we obtain the minimum idle loss cost via controlling ridesharing price. In the declining demand, the drivers exceed order demand, which means some drivers are in an idle state to wait for limited orders. Then, dynamic pricing takes the role of controlling the drivers and attracting consumers.

Given the supply-demand balance moment, T_{ob}, where $S(p, T_{ob}) = D(p, T_{ob})$. At time T_{ob}, $\overline{I}\ (T_{ob}) = 0$, but $I(T_{ob}) \neq 0$, there still exists accumulated idle drivers on the platforms. The platforms continue to control price and stimulate consumers. We assume that T_{om} is the moment of minimum idle driver loss, where $I(T_{om}) = 0$, and accumulated idle driver quantity decreases to zero. Thus, the platforms can obtain the optimal social welfare at T_{om}. The proposed theorems are given as follows.

Theorem 3. *At the time interval [0, T_{om}], there exists a supply-demand balance moment T_{ob}, and the optimal price at T_{ob} is*

$$\begin{aligned} P^*_{T_{ob}}(t) = {} & \frac{(\beta+\varepsilon\gamma+\beta\mu_1-\beta\mu_2)ct}{\varepsilon\gamma^2-\beta+\beta\gamma-\beta\mu_1+\beta\mu_1\gamma-\beta\mu_2\gamma} - \frac{ae^{-bt}(1+\mu_1-\gamma-\mu_1\gamma+\mu_2\gamma)}{2\left(\varepsilon\gamma^2-\beta+\beta\gamma-\beta\mu_1+\beta\mu_1\gamma-\beta\mu_2\gamma\right)} \\ & - \frac{(\beta+\varepsilon\gamma+\beta\mu_1-\beta\mu_2)cT_{ob}}{\varepsilon\gamma^2-\beta+\beta\gamma-\beta\mu_1+\beta\mu_1\gamma-\beta\mu_2\gamma} + \frac{ae^{-bT_{ob}}(1+\mu_1-\gamma-\mu_1\gamma+\mu_2\gamma)}{2\left(\varepsilon\gamma^2-\beta+\beta\gamma-\beta\mu_1+\beta\mu_1\gamma-\beta\mu_2\gamma\right)} \\ & + \frac{ae^{-bT_{ob}}(1+\mu_1-\mu_2)}{\beta+\varepsilon\gamma+\beta\mu_1-\beta\mu_2}. \end{aligned} \tag{22}$$

Proof. At T_{ob}, $S(p, T_{ob}) = D(p, T_{ob})$, i.e., $((\varepsilon W(T_{ob}) + \mu_2(ae^{-bt} - \beta p(T_{ob})))/(1+\mu_1)) = ae^{-bt} - \beta p(T_{ob})$. Hence, the price at T_{ob} is $p(T_{ob}) = ((ae^{-bT_{ob}}(1+\mu_1-\mu_2))/(\beta+\varepsilon\gamma+\beta\mu_1-\beta\mu_2))$.

Substituting $p(T_{ob})$ into the optimal price equation $p^*_{T_{ob}}(t)$ and simplifying,

$$\begin{aligned} p^*_{T_{ob}}(t) = {} & \frac{(\beta+\varepsilon\gamma+\beta\mu_1-\beta\mu_2)cT_{ob}}{2\left(\varepsilon\gamma^2-\beta+\beta\gamma-\beta\mu_1+\beta\mu_1\gamma-\beta\mu_2\gamma\right)} - \frac{ae^{-bT_{ob}}(1+\mu_1-\gamma-\mu_1\gamma+\mu_2\gamma)}{2\left(\varepsilon\gamma^2-\beta+\beta\gamma-\beta\mu_1+\beta\mu_1\gamma-\beta\mu_2\gamma\right)} \\ & + \frac{\psi_0(1+\mu_1)}{(\beta+\varepsilon\gamma+\beta\mu_1-\beta\mu_2)T_{ob}} + \frac{a\left(1-e^{-bT_{ob}}\right)(1+\mu_1-\mu_2)}{b(\beta+\varepsilon\gamma+\beta\mu_1-\beta\mu_2)T_{ob}} \\ & + \frac{a\left(1-e^{-bT_{ob}}\right)(1+\mu_1-\gamma-\mu_1\gamma+\mu_2\gamma)}{2b\left(\varepsilon\gamma^2-\beta+\beta\gamma-\beta\mu_1+\beta\mu_1\gamma-\beta\mu_2\gamma\right)T_{ob}}, \end{aligned} \tag{23}$$

where ψ_0 satisfies the following equation:

$$\begin{aligned} \psi_0 = {} & \frac{ae^{-bT_{ob}}(1+\mu_1-\mu_2)T_{ob}}{1+\mu_1} - \frac{(\beta+\varepsilon\gamma+\beta\mu_1-\beta\mu_2)^2cT_{ob}^2}{2\left(\varepsilon\gamma^2-\beta+\beta\gamma-\beta\mu_1+\beta\mu_1\gamma-\beta\mu_2\gamma\right)(1+\mu_1)} \\ & + \frac{ae^{-bT_{ob}}(1+\mu_1-\gamma-\mu_1\gamma+\mu_2\gamma)(\beta+\varepsilon\gamma+\beta\mu_1-\beta\mu_2)T_{ob}}{2\left(\varepsilon\gamma^2-\beta+\beta\gamma-\beta\mu_1+\beta\mu_1\gamma-\beta\mu_2\gamma\right)(1+\mu_1)} - \frac{a\left(1-e^{-bT_{ob}}\right)(1+\mu_1-\mu_2)}{b(1+\mu_1)} \\ & + \frac{a\left(1-e^{-bT_{ob}}\right)(1+\mu_1-\gamma-\mu_1\gamma+\mu_2\gamma)(\beta+\varepsilon\gamma+\beta\mu_1-\beta\mu_2)}{2b\left(\varepsilon\gamma^2-\beta+\beta\gamma-\beta\mu_1+\beta\mu_1\gamma-\beta\mu_2\gamma\right)(1+\mu_1)}. \end{aligned} \tag{24}$$

From this, as well as Theorem 3, we can conclude that the solution for the optimal price does exist under declining demand. $\lambda^*_{T_{ob}}(t)$, $S^*_{T_{ob}}(t)$, and $D^*_{T_{ob}}(t)$ have to be considered along with the optimal control parameter.

Theorem 3 shows that the control parameter $p^*(t)$ exists and have effect on the platforms, including real-time and cumulative idle drivers' loss. Considering the effect of network externalities on drivers, we try to look for the correlation between them. □

Lemma 2. *$D^*_{T_{om}}(t)$ increases with decreasing $p^*_{T_{om}}(t)$.*

Proof. By simple deformation, the demand $D^*_{T_{om}}(t)$ is

$$D^*_{T_{om}}(t) = ae^{-bt} - \beta p^*_{T_{om}}(t). \quad (25)$$

Obviously, $D^*_{T_{om}}(t)$ has a negative correlation with $p^*_{T_{om}}(t)$. That is, the demand side shows an increasing trend when platforms decrease price. The decreasing price can stimulate consumers to join platforms. Wage has a direct effect on the optimal price. Then, we further prove the influence of the wage ratio on the optimal price trajectory. □

Theorem 4. *The optimal price $p^*_{T_{ob}}(T_{ob})$ is high initially and then decreases with γ over time.*

Proof. Note that the first-order of $p^*_{T_{ob}}(T_{ob})$ for γ is

$$\frac{\partial p^*_{T_{ob}}(T_{ob})}{\partial \gamma} = -\frac{ae^{-bT_{ob}}\varepsilon(1+\mu_1-\mu_2)}{(\beta+\varepsilon\gamma+\beta\mu_1-\beta\mu_2)^2} < 0. \quad (26)$$

Interestingly, we find that the higher wage ratio leads to a lower ridesharing price. In other words, $p^*_{T_{ob}}(T_{ob})$ decreases with the wage ratio. When platforms' price remains relatively stable, increasing γ means that drivers obtain more revenue, and more drivers prefer to stay on the platforms. Due to the complexity relationship between social welfare $\prod_{SW}$ and γ, μ_1 and μ_2 will be verified by simulation in the following section. □

6. Numerical Study

In Sections 4 and 5, we, respectively, present the dynamic pricing strategies under two scenarios of the surge demand in peak time and declining demand in off-peak time. Next, we examine the numerical study to analyze the optimal price, the supply, and the demand, even the revenue of ridesharing platforms and social welfare with and without considering network externalities. DiDi is a typical online ridesharing platform introduced in 2012, and gradually occupies most of ridesharing market share in China. We take DiDi as an example for numerical analysis. Without loss of generality, we adopt initial values $a = 10^6$, $b = 0.03$, $h = c = 0.2$, $\mu_1 = 0.5$, $\mu_2 = 0.2$, $\varphi_0 = \psi_0 = 10^5$, $\gamma = 0.2$, and $T_{pm} = T_{om} = 35$, i.e., time t is allowed to vary from 0 to 35. Meanwhile, given $\varepsilon = 40000$ and $\beta = 50000$ for $\varepsilon\gamma < \beta\mu_2$ and $\varepsilon = 90000$ and $\beta = 90000$ for $\varepsilon\gamma \geq \beta\mu_2$.

6.1. Price Strategy. Under surge demand and declining demand, the trends of the optimal price p^* become obviously different, which are subject to the supply, the demand, and especially parameter b of market size change, as shown in Figures 4–6.

In Figure 4, the optimal price p^* is steadily moving higher in the surge demand period with network externalities ($\mu_1 = 0.5$, $\mu_2 = 0.2$) and without considering network externalities μ_1 and μ_2. It is consistent with Theorem 1, thus we can obtain that the intensity of network externalities μ_1 and μ_2 has no effect on the overall trend of p^*, but have a major influence on the price range.

As shown in Figure 3(a) (surge demand), the price p^* is an increasing function for $b < 0$, which is in accordance with Theorem 1. Therefore, the ridesharing platforms entail to raise price to increase drivers' supply when the demand increases with t in peak time. As shown in Figure 4 (declining demand), the ridesharing price p^* in off-peak time is strictly concave with t. In addition, the price p^* is a decreasing function for $b > 0$. Therefore, it is consistent with the actual market, and illustrates the difference between the network externality case and nonnetwork externality case in the considered two scenarios. The ridesharing platforms reduce price to increase the demand when the demand side decreases with t.

Furthermore, Figure 5, respectively, shows that the trends of order demand and driver supply varies with the optimal ridesharing price during two scenarios of surge demand and declining demand. The supply cannot satisfy the order requirements when $b < 0$ (surge demand) in Figure 5(a), then the ridesharing platforms increase price to stimulate drivers' supply when the price is more attractive to drivers $\varepsilon\gamma \geq \beta\mu_2$. It is consistent with Lemma 1. Interestingly, in the declining demand period when $b > 0$, the demand curve shows an overall upward trend as shown in Figure 5(b), the trend is consistent with Lemma 2. It indicates that the decreasing ridesharing price could increase the demand in the declining demand period. Concretely speaking, the price can effectively coordinate the demand and supply of the ridesharing platforms.

Figure 6, except for cost loss, also shows the state trajectory in which the state variables $Y(t)$ and $I(t)$ gradually decrease to zero with the change in the control variable. Obviously, the control of dynamic pricing is directed toward avoiding a certain loss cost for further earnings. According to Figure 6, the ridesharing platforms achieve the minimum order loss at T_{pm} in the surge demand period, and reaches maximum social welfare at T_{om} in the declining demand period. Therefore, the dynamic pricing strategy could reduce the cost loss to maximize the platforms' revenue and social welfare.

6.2. Effect of Network Externalities. According to Sections 4 and 5, the network externalities μ_1 and μ_2 have influence on self-scheduling drivers supply side, which is a typical characteristic of online ridesharing platforms. As shown in Figure 7, for all b, the indirect network externalities μ_2 always has a positive effect on drivers' supply. In other words,

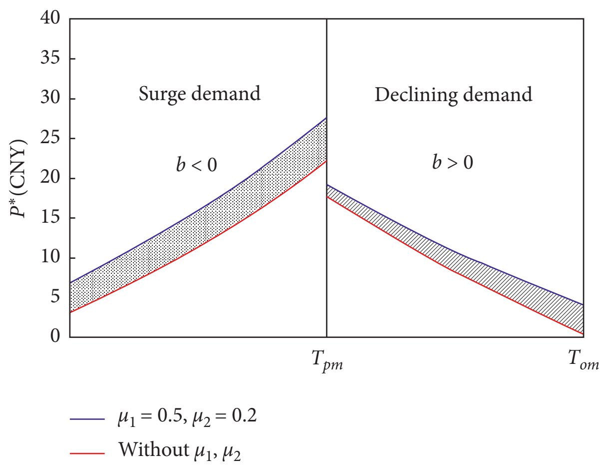

Figure 4: The optimal price p^* in surge demand and declining demand periods.

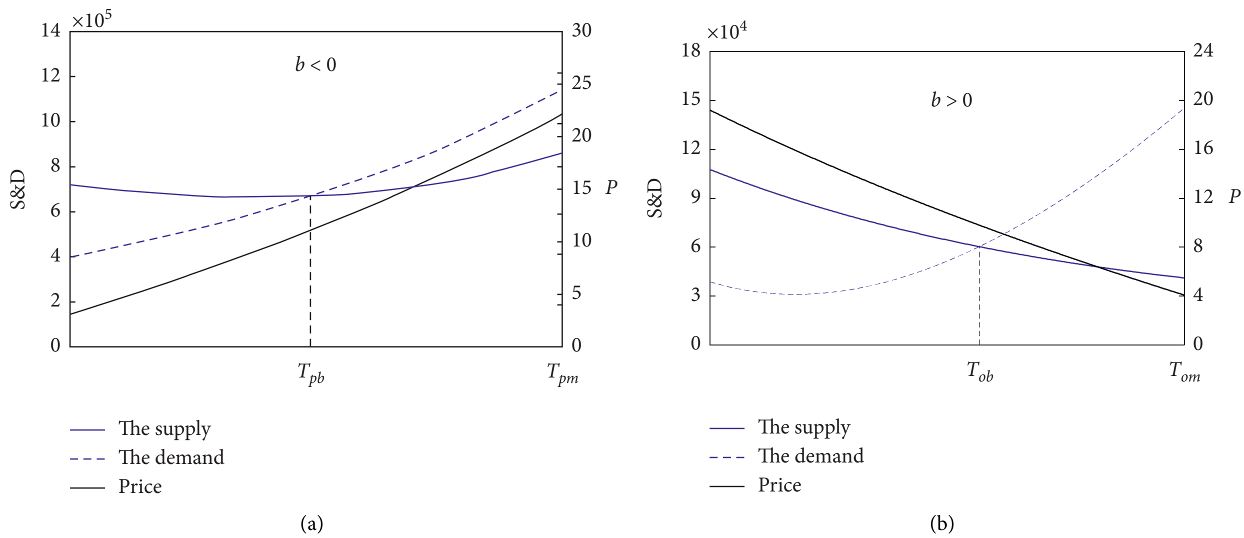

Figure 5: The dynamic change in demand and supply with p^*. X axis is the time t, Y axis (left) is the supply and demand, and Y axis (right) is the optimal price p^*. (a) Surge demand($b < 0$). (b) Declining demand($b > 0$).

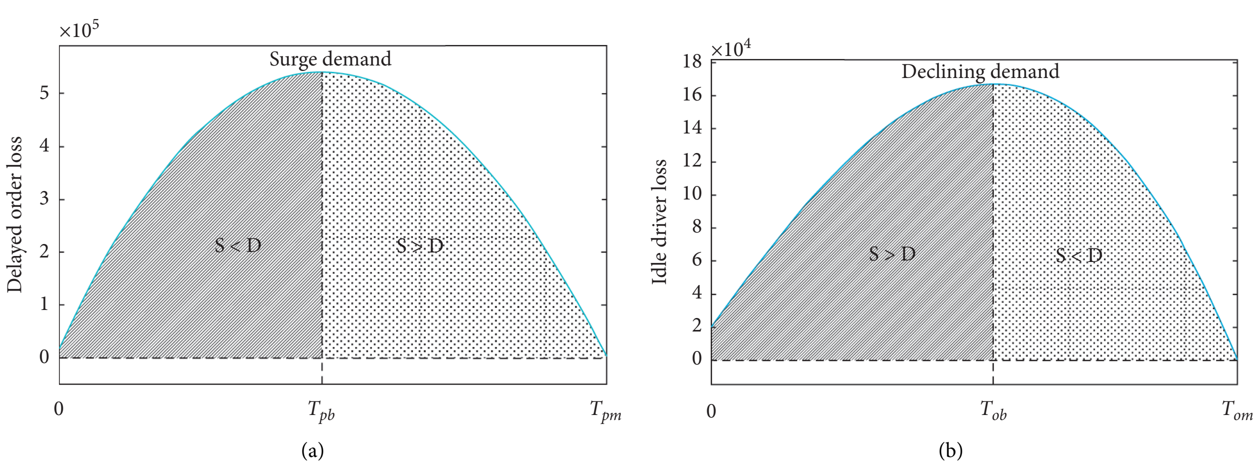

Figure 6: Delayed order loss cost (surge demand) and idle driver waiting cost (declining demand).

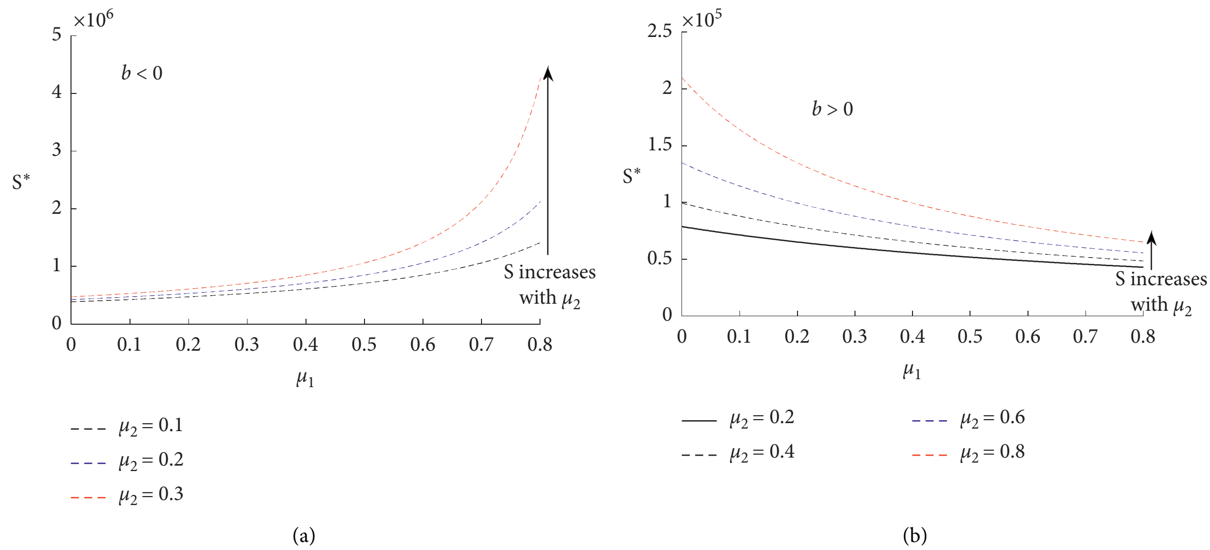

Figure 7: The effect of μ_1 and μ_2 on the supply side. (a) Surge demand. (b) Declining demand.

the overall trend means that large orders can encourage drivers to join the platforms. For the direct network externalities μ_1, S^* increases with μ_1 in surge demand, and decreases in declining demand. When the demand in the surge demand period increases, it attracts more drivers to provide service for ridesharing platforms. On the contrary, excessive idle drivers in the declining demand period make the drivers adopt a wait-and-see attitude or quit platforms.

Next, we consider the change in $\prod_P$ and $\prod_S$, which is influenced by μ_1 and μ_2. Simultaneously, there is no doubt that μ_1 and μ_2 have strong increasing effect on revenue for $b < 0$. In Figure 6, we can see the supply trend with μ_1 and μ_2. Figures 7 and 8 further compares the μ_1 and μ_2 influence on revenue $\prod_P$ and $\prod_S$ in the surge demand period. When $b < 0$, S^* always increases with μ_1 (Figure 7(a)), and $\prod_P$ and $\prod_S$ increase under satisfying orders. However, the supply side gradually exceeds the demand with μ_1, where the revenue of idle drivers suffers cost loss as $\prod_P$ declines. Similarly, $\prod_P$ and $\prod_S$ gradually increase with μ_2.

In the declining demand period, μ_1 always has a positive effect on social welfare $\prod_{SW}$. Hence, $\prod_{SW}$ increases with μ_1 as shown in Figure 9. We redefine the social welfare, which is the total revenue of platforms and drivers, and the quantity of other drivers is always beneficial to the supply side. However, under the declining demand, we can see that the curves of different μ_2 move down greater. Drivers need to share the limited orders in the declining demand period, and they usually choose to exit the platforms. Thus, μ_2 has a negative effect on $\prod_{SW}$. Therefore, lower μ_2 and higher μ_1 appropriately can contribute to the revenue.

6.3. Effect of Wage Ratio. In self-scheduling supply side, we use fixed commission contract to manage and determine the revenue level of drivers. In other words, γ directly influences the price and social welfare. Although the ridesharing platforms have been widely controlled at the level of optimal

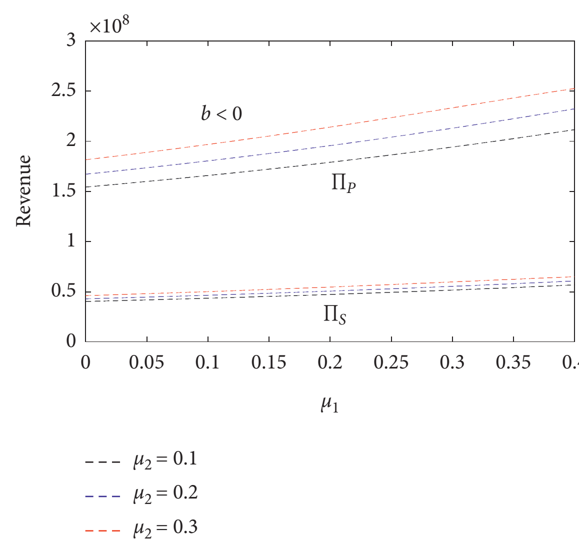

Figure 8: The relation between μ_1, μ_2 and $\prod_P$, $\prod_S$ (surge demand).

dynamic pricing, the relation between drivers and pricing under network externalities is fairly recent. To explore the effect of wage fully, we study equally the sensitivity of γ to resort to numerical analysis.

From the price perspective, the higher ridesharing price allocates the driver a higher wage, which may motivate more sharing drivers to join platforms. From Figure 10, we can obtain that p^* and S^* without considering network externalities still present the same trends. In declining demand, p^* shows a decreasing trend with γ, instead S^* increases with γ. Thus, it proves that the high wage ratio is extremely attractive to drivers. However, the higher wage ratio could increase the gap between the supply and the demand. Then, within a certain range, the wage ratio can benefit to the platforms. Ridesharing platforms should not only rely on the wage ratio to coordinate the demand and supply.

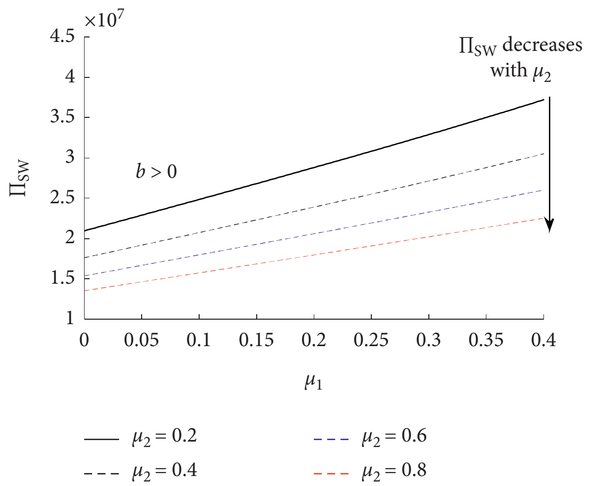

FIGURE 9: The effect of μ_1 and μ_2 on $\prod_{SW}$ (declining demand).

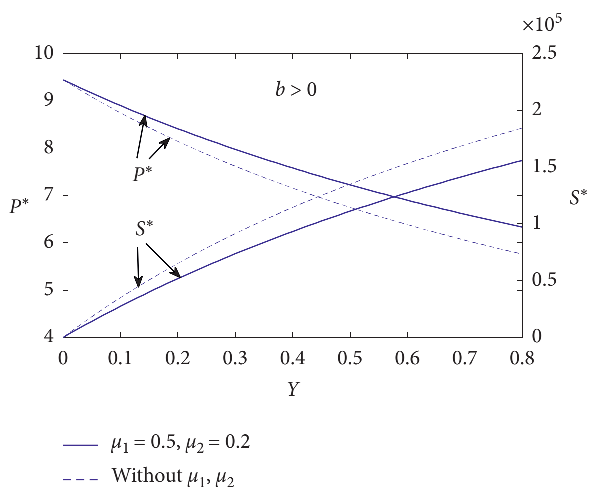

FIGURE 10: The effect of γ on P^* and S^* (declining demand). The X axis refers to the wage ratio γ, Y axis (left) refers to the optimal price P^*, and Y axis (right) refers to the supply capacity.

Furthermore, the analysis of the wage ratio is discussed for platforms' revenue, drivers' earning, and social welfare. In Figure 11, increasing γ is always beneficial to drivers, so $\prod_S$ increases with γ. Similar to the increasing effect on supply, social welfare always presents the positive trend. By comparison, as the wage ratio increases, the revenue of ridesharing platforms gradually increases and then decreases. Then, the whole trend is consistent with the actual platforms. Thus, appropriate increase in γ is beneficial to attract drivers and the development of ridesharing platforms.

In ridesharing platforms, the demand and supply are highly flexible; this model quickly offers the real-time price according to the market situation. Likewise, these strategies compensate the loss cost and helps secure the maximum revenue. Then, our model is evaluated in the numerical study. In the coordinating process between two sides, the network externalities between the demand side and the supply side make the dynamic pricing for ridesharing

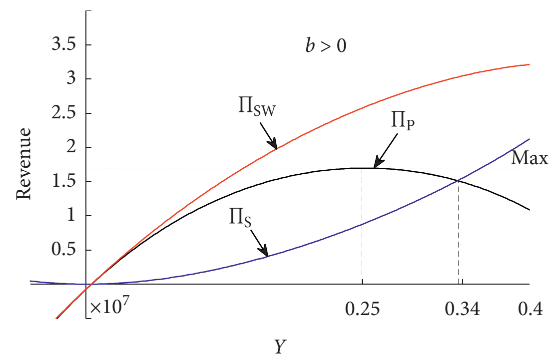

FIGURE 11: The effect of γ on $\prod_P$, $\prod_S$, and $\prod_{SW}$ (declining demand).

platforms more complicated. In summary, the model based on optimal control theory was proposed to create a dynamic pricing strategy by ridesharing platforms to increase platforms' revenue and social welfare under two demand scenarios. Specifically, the surge pricing model can decrease the speed of the surging demand, and increase the quantity of the supply side. The decreasing pricing model of the declining demand can control the decreasing demand to rise slowly. Meanwhile, the loss cost of two periods can be reduced to zero via optimal dynamic pricing. The application of optimal control has important management significance to dynamically coordinate demand and supply for the real ridesharing platforms. These studies benefit to our better understanding of the dynamic characteristics of the ridesharing platforms.

7. Conclusions

This paper mainly focuses on the dynamic optimal pricing model involved in network externalities applying optimal control theory. We discuss that platforms take the pricing strategy to maximize platforms' own revenue as the objective function under surge demand and take the maximization of social welfare under declining demand. Compared with the previous studies on ridesharing platforms, the loss cost caused by delayed orders and idle drivers is simultaneously optimized. The results show that the optimal price and platforms' revenue considering the effect of network externalities have changed significantly. Our model is implemented for the actual ridesharing platform pricing and social welfare, which is one step closer to reality.

The simulation result draws the following conclusions:

(1) Optimal price has changed gradually with time, which is associated with loss cost and revenue. During the surge demand period, increasing price can reduce real-time orders and digest cumulative orders. Meanwhile the existing order loss signifies that the platforms entail to continually increase price to motivate drivers. During the declining demand period, ridesharing platforms opt to decrease price to attract consumers and avoid idle drivers' loss. These results reveal the reason why the optimal price continues the original trend to increase or decrease

after the balance moment of demand and supply. In addition, ridesharing platforms can simultaneously reach the minimum delayed order loss and idle driver loss via control pricing.

(2) Network externalities simultaneously influence the optimal price, supply side, and revenue. In terms of the direct effect of network externalities on the supply side, it means that platforms may pay more effort for management. The dynamic price model combining network externalities can endogenously control the changes of platforms.

(3) Wage ratio parameter identifies the vital position. The higher is the wage ratio, the higher is the supply capacity level, which means that the higher wage will give drivers more motivation to join platforms. Within a certain range, the wage ratio benefits to platforms and social welfare.

The results indicate that the optimal dynamic pricing considering network externalities provide reference values to ridesharing platforms, and offers the evidence for the market to achieve robust and orderly development. However, this paper only studies the optimal pricing on the single platform with the constraint of a fixed commission contract, that is, our model is applicable to a single platform. Thus, future work can study the dynamic pricing strategy under the competition between two or more ridesharing platforms with dynamic commission contract.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Review Article

Deterrence of Punitive Measures on Collusive Bidding in the Construction Sector

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Collusive bidding has been a deep-seated issue in the construction market for a long time. The strategies implemented by bid riggers are deliberate, interactive, and complex, suggesting that antitrust authorities have difficulty preventing collusive behaviors. Based on game payoff matrixes, this study proposes a system dynamics (SD) model to present the deterrence of punitive measures, namely the certainty of punishment (CoP) and the severity of punishment (SoP), on regular bidders' to-collude decision-making. Data were collected from the Chinese construction industry to test the proposed SD model. While the model was supported, the results indicate that the CoP has a greater impact than the SoP on deterring regular bidders from making to-collude decisions. Furthermore, these two punitive measures cannot be replaced by each other, given the same deterrence effects. Thus, the study demonstrates the usefulness of deterrence theory to inhibit collusive bidding in the construction sector. It also sheds some light on the formulation of competition policy from the perspective of deterrence.

1. Introduction

Bidding is a primary means of auctioning public goods worldwide [1–3]. Recently, this kind of auction has witnessed the proliferation of collusive bidding in many industries such as manufacturing, construction, and services [4–6]. As noted in previous studies, collusive bidding is notorious for charging a heavy toll on the soul of fair competition [7], damaging the interest of purchasers [8], and breaching the right of regular bidders [9–11]. Besides, the imperfect competition incurred by collusive bidding is unfavorable for industrial innovation, and it jeopardizes the sustainable growth of industry [12]. Most countries, including the US [13, 14], China [15–17], Australia [9, 18], the UK [19], and the Netherlands [12], have thus exhibited a strong ambition to thwart collusive bidding.

There are two kinds of approaches, preventive and punitive, for antitrust authorities to impose controls over the outbreak of collusive bidding [20, 21]. The preventive approaches are ex ante, which entails establishing an efficient bidding system [22–25]and promoting bidders' ethical behaviors [18, 26]. Previous studies have affirmed the effectiveness of inhibiting collusive bidding in different bid pricing systems [27, 28]. The derived findings suggest that an efficient and transparent bidding system can normalize bidders' behaviors by rewarding the most eligible bidders [29]. By comparison, the promotion of bidders' ethics to alleviate collusion depends on whether the values and legal rules serve as the basis for competitive behaviors [30]. The punitive approaches are ex post, denoting antitrust authorities' determination of imposing financial fines and imprisonment on those bid riggers that have been identified

[31]. On occasions, tailoring current bidding rules to fluctuating market conditions is impracticable, and the hedges that bid riggers take against the existing rules are often encountered [4, 32–34]. Consequently, the punitive approaches have gained antitrust authorities' closer attention in the manipulation of collusive bidding [1, 35].

The rationales for utilizing punitive approaches to deter susceptible bid riggers are releasing a strong signal of competition regulations to market players by detecting and punishing incumbent bid riggers [36]. Such reasoning resembles noncooperation in public goods games [37, 38], where the deterrence effects are determined by the certainty of punishment (CoP) and the severity of punishment (SoP) [39]. The CoP refers to the success rate of detecting bid riggers over the projects that have gone through bidding procedures [40]. The SoP delineates the magnitude of fines that antitrust authorities impose on bid riggers [39]. While both play a due role in crime deterrence, many countries prefer to use the SoP to deter regular bidders from initiating collusion [41, 42]. Meanwhile, excessive punishment turns out to be a diminished deterrent effect, namely over-deterrence [43], and the CoP owns more complicated deterrence effects than the SoP [44–47]. Although previous studies have confirmed the values of punitive approaches to deter collusive bidding, little consensus has been reached hitherto.

Bid riggers are composed of two strands of actors: the convenor and participants. The less business competition caused by bid-rigging facilitates these two actors to enjoy a higher winning probability, motivating the convenor to fortify collusive relationships [9, 48, 49]. If bid-rigging benefits are larger than expected, the convenor will undertake collusive bidding. By contrast, the convenor may be reluctant to conduct collusive bidding if benefits from the collusion are not very attractive. Therefore, it is worth investigating what means prevent bid riggers, either the convenor or its participants, from making such a decision. Doing so can inhibit the launch of collusive bidding. While such a claim can be aware in the literature, previous studies have not made sufficient efforts to explore the deterrent difference between the CoP, the SoP, and a combination of both in hindering the occurrence of collusive bidding [31, 50, 51].

In appreciating the research gaps presented above, this study aims to examine the deterrence of punitive measures on collusive bidding regarding the certainty and severity of punishment. A model is proposed to account for deterrence-based decision-making mechanisms from the angles of the convenor, participants, and antitrust authorities. We collected data from the Chinese construction context to test the effectiveness of the proposed model. To this end, the remainder of this article is structured as follows. Section 2 presents a review of deterrence theory and the essence of collusive bidding to lay a theoretical foundation for the study. Section 3 describes the establishment of a system dynamics model. Section 4 elaborates the simulation process. Section 5 summarizes the results and discusses the findings. Finally, the research conclusions and recommendations for future research are given in Section 6.

2. Literature Review

2.1. Deterrence Theory. Deterrence theory originated from the utilitarian doctrine of crime, and it views crime as making rational choices to strike a cost-benefit trade-off [36, 52]. The benefits are concerned with the money they gain from crime. The costs involve the disqualification to participate in business competition, financial fines posed by antitrust authorities, and ruined reputations in the niche market. A punishment may enhance the total cost of crime to unacceptable levels, making criminals feel unnecessary and risky to launch another one. However, the crimes shall not pay the penalty if they eschew being detected. The main thoughts of deterrence related to criminal offending are that punitive measures deter individuals from conducting crime, and punishing offenders help deter other potential offenders. Thus, an experienced criminal knows to gauge crime costs by multiplying the certainty and severity of punishment. The larger the crime costs, the higher the deterrence, and the less the to-be crime in the market.

2.2. Attributes of Collusive Bidding. In economists' opinions, collusive bidding is a specific form of monopoly in the field of auction. Although collusive bidding is diversified, such as winner rotation [35] and price manipulation [53], they have in common the operation process. The convenor first searches for potential bidders and desires to establish a bid-rigging group with them [13]. The success of doing so depends on whether both sides reach agreements on the incomes they are about to receive from the illegal competition. The convenor agrees to redistribute collusive profits among bid riggers in an effort to unify all participants for targeted projects [54–56]. Hence, there is a vacuum of competition between the convenor and their participants, favoring them to guarantee a high success rate of collusion [9].

Collusive bidding is a serious crime that undermines the cornerstone of auction mechanisms and has been known for social irresponsibility [57]. Due to the illegality nature, collusive behaviors must be concealed as far as possible [54, 55], forming an obstacle for antitrust authorities to detect them. Researchers have proposed several approaches to overcoming the obstacle, such as diagnosing the anomalies of bidding prices [56–58], identifying bidders' networks and their inherent relationships [59, 60], and applying machine learning methods for mapping bidders [61]. Nevertheless, these approaches appear to be end-of-pipe solutions as they rarely address the formation and complexity of collusive bidding [62]. Moreover, few of them spell out the benefits and costs of bid riggers and the extent to which society has to accept the negative impacts of collusive bidding [54]. In practice, signals of collusion are often released and intercepted by antitrust authorities. It is thus considered that whether antitrust authorities utilize the signals to deter future collusive bidding without consuming too many public resources.

2.3. Deterring Collusive Bidding in Construction. An all-pervasive distribution of collusive bidding results in market competition disorder and the shrinkage of social welfare. Construction work bidding is project-based, one-off, and locationless. Unsurprisingly, collusive bidding in the construction sector is becoming a key area of competition in policy discourse, and consequently, they spurred heated discussion on their regulations [63]. Given effective monitoring, mitigating collusive bidding is an overwhelming challenge in the construction sector [8, 64]. As usual, antitrust authorities are responsible for encapsulating collusion-free scenarios to expedite construction business transactions [41, 65, 66]. In light of deterrence theory, it is considered valuable to use punitive approaches to deter bidders from making to-collude decisions. Thus, collusive bidding can be prevented at an earlier stage.

Deterrence theory has been applied to develop and improve measures for dealing with property crimes [67]. It functions as a cornerstone for examining the substitution between the certainty and severity of punishment in the area of collusive bidding [45]. For instance, in line with deterrence theory, Landes suggested that increasing the likelihood of being caught deter more usefully than those that enhance punishment, and thus, an optimal criterion to calculate the numerical size of fines deserves attention [68]. Connor and Lande argued that punishing bid riggers is inadequate to discourage conspiracies [69]. Posner applied deterrence theory to antitrust examination and recognized that the alternative relationship between the certainty and severity of punishment is still valid for deterring monopolies [42]. Seemingly, both the certainty and severity of punishment have different deterrence effects, and they are interchangeable [45]. Therefore, the study embraces a combination of them for further analysis.

3. Model Development

3.1. Game Analysis. According to the principle of deterrence, bid riggers' to-collude decision revolves around the cost-benefit trade-off. Therefore, a game model is proposed to reflect such a decision-making mechanism as follows:

(a) **The convenor:** Each collusive bidding has a nominal winner (say, the convenor), whose role is to maneuver the whole collusion process. Most of the convenor's efforts are in liaison with bid riggers to reach income-sharing agreements. The convenor anticipates profits from collusive bidding but still needs potentially to pay a fine for organizing collusive bidding and benefit fees to all participants [70, 71]. Specifically, the convenor must count the cost for searching for and negotiating with bid riggers [72]. If their collusive bidding is affirmed, the convenor will be stripped of illegal incomes and punished for violating business competition. Since not all bid-rigging groups can be established as planned, the convenor might eventually assume a regular bidder role.

(b) **Participants:** Participants' main duties are implementing bidding strategies as required by the convenor. They request compensation for being nominally disqualifying from attending business competition [73].

(c) **Antitrust authorities:** Antitrust authorities have to input public resources to detect collusion [74], another type of social cost. The penalties that antitrust authorities receive can be deemed compensation for the generation of social costs caused by collusive bidding [39].

A total of 12 collusive scenarios (Table 1) were listed to differentiate situations in which the convenor undertakes collusion, participants are engaged in the collusion, and antitrust authorities' detection is effective. The table elaborates a benefits matrix for three actors involved in a collusive bidding case.

The probability of the convenor deciding to initiate collusive bidding is x; the probability of a participant deciding to participate in collusive bidding is y. The probability of regulations by antitrust authorities is z, and the success rate of detection is k. The expected benefits per actor (Table 2) are calculated using the benefits matrix shown in Table 1.

3.2. A System Dynamics Model. Based on the relationships between the convenor, participants, and antitrust authorities, a system dynamics (SD) model is established to simulate the effects of the certainty and severity of punishment on collusive bidding inhibition. The SD model has three subsystem modes, as shown in Figure 1. Each subsystem comprises one state variable, one rate variable, and several auxiliary variables to present actors' decision-making process. Thus, three state variables, three rate variables, seventeen auxiliary variables, and fourteen constants are synthesized into the SD model. We interviewed twelve experts to verify the proposed SD model. For simplicity, the verification process is briefly summarized in this section.

(a) Decision-making mode: bid riggers know to draw on past experiences to support decision-making. They will forecast the payoff of ongoing collusion cases using historical data. A mixture of income disparities (Table 2) and the previously made decisions determine the ratio reflecting the variation of decision-making.

(b) Profit calculation mode: collusive bidding increases the convenor's probability of being awarded contracts. Ceiling bid prices specified in tender documents are adopted as a benchmark to calculate the winning prices. Thereby, profits are calculated for collusive and noncollusive bidding.

(c) Punishment determination mode: punishment relates to the turnover of collusive bidding as

Table 1: The benefit matrix for all actors.

Detecting collusive bidding		Benefits per subject	The convenor initiates collusive bidding		The convenor does not initiate bidding	
			Participant decided to participate in collusive bidding	Participant not decided to participate in collusive biddings	Participant decided to participate in collusive bidding	Participant not decided to participate in collusive bidding
Antitrust authorities detect collusive bidding	Success	The convenor	$-N_pG-F_c-C_c$	wP_n-C_c	wP_n	wP_n
		Participants	$-F_p-C_p$	0	$-C_p$	0
		Antitrust authorities	$P_c-P_n+F_c+N_pF_p-C_g$	$P_c-P_n-C_g$	$P_c-P_n-C_g$	$P_c-P_n-C_g$
	Failure	The convenor	$P_c-N_pG-C_c$	wP_n-C_c	wP_n	wP_n
		Participants	$G-C_p$	0	$-C_p$	0
		Antitrust authorities	$P_n-P_c-C_g$	$P_c-P_n-C_g$	$P_c-P_n-C_g$	$P_c-P_n-C_g$
Antitrust authorities do not detect collusive bidding		The convenor	$P_c-N_pG-C_c$	wP_n-C_c	wP_n	wP_n
		Participants	$G-C_p$	0	$-C_p$	0
		Antitrust authorities	P_n-P_c	P_c-P_n	P_c-P_n	P_c-P_n

Table 2: Expected benefits for collusion decision.

Subjects	Expected benefits for action decision	Expected benefits for inaction decision
The convenor	$-kzy(P_c+F_c)+y(P_c-wP_n-N_pG)+wP_n-C_c$	wP_n
Participants	$-kxz(G+F_p)+xG-C_p$	0
Antitrust authorities	$kxy(2P_c-2P_n+F_c+N_pF_p)-2xy(P_c-P_n)-C_g$	$1-2xy(P_c-P_n)$

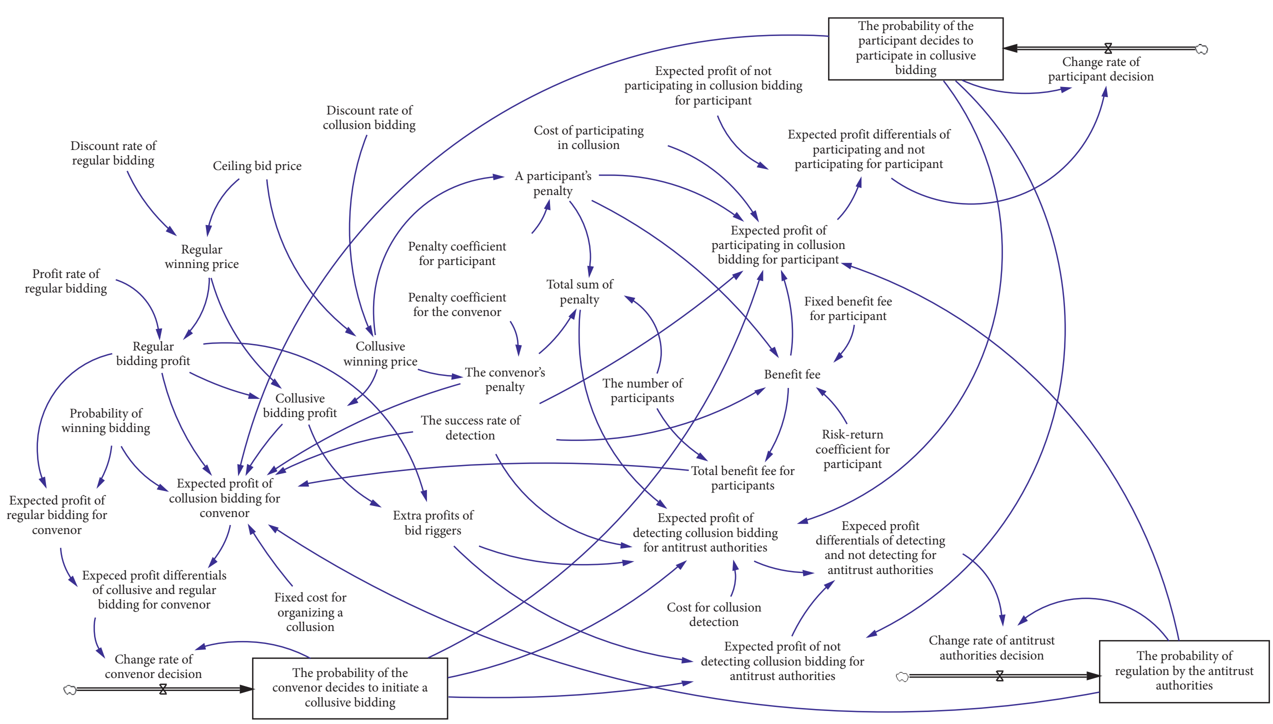

Figure 1: Stock and flow diagram for the dynamic system model. The dynamic system model combined with three subsystem modes simulates the decision-making process of different actors. In addition, the dynamic system model was established surrounding three key variables: "punishment coefficient for a participant", "punishment coefficient for the convenor", and "the success rate of detection".

calculated by benchmarking prices with a punishment coefficient. The coefficient is calculated to mirror the different roles of the convenor and their participants in collusive bidding.

(d) Benefit fee calculation mode: participants are given a fixed payment or benefit fee. However, they might additionally claim fees depending on what fines they are going to face. The convenor has to pay all expenses to its participants to maintain the stability of bid-rigging groups.

4. Simulation

4.1. Parameter Setting and Data Collection. In the study, we interviewed eight professionals with considerable experience in construction business collusion to assign an initial value for the SD model. The interviewees were composed of one engineer, two consultants, three bidding agents, and two project managers. As the interviewees advised, a ceiling bid price is suitable to measure bidders' competitiveness. Those regular bidders ought to win the bid with the lowest price, usually 80% of the ceiling price. Thus, the discount rate of regular bidding (say, 0.8) was considered an initial value. In addition, the noncollusive bidders have a 20% chance of winning the bid, with an average return of 8%. Illegal competition help bid riggers increase the bid price to 90% of the ceiling bid price. The scenario assumed here similarly appeared in some countries. As reported by Priemus, bid prices are increased by 8.8% as caused by collusion in the Netherlands [75]. Signor et al. revealed that the bid price increases by 20%. Therefore, it is acceptable to develop the following equations [76]:

Regular winning price = Ceiling bid price × Discount rate of regular bidding, where the initial rate is 0.8

Regular bidding profit P_n = Regular winning price × Profit rate

Collusive winning price = Ceiling bid price × Discount rate of regular bidding, where the initial rate is 0.9

Collusive bidding profit P_c = Additional profits from collusive bidding + Regular profit P_n

Collusive winning profit = Collusive winning price − Regular winning price + Regular profit

Additional profits = Collusive winning price − Regular winning price

As the interviewees recalled, finding participants per collusive bidding case usually costs the convenor RMB 100 thousand (US$13.6 thousand), and the benefit fee that the convenor delivers to its participants is a fixed benefit payment of about RMB 100 thousand (US$13.6 thousand) and an additional fee that participants claim for risk compensation. The fixed payment covers the bidding expense, about RMB 5 thousand (US$0.68 thousand). The additional fee can be calculated by multiplying the success rate of detection k with potential punishment F_p.

Benefit fee G = Fixed benefit fee + Additional fee

Additional fee = Risk-return coefficient T × Expected punishment E_p

Expected punishment E_p = Probability of successful detection k × Potential punishment F_p

We collected one hundred sixteen collusion cases and four media reports with detailed information from the Chinese construction industry for 2010–2017. The data analysis results reveal that those projects with a size of RMB 22 million (US$3 million) are more intended for collusive bidding; participants in a collusive bidding team are on average thirteen. According to China's antitrust law, a punishment shall be imposed on bid riggers, depending on the punishment coefficient and the winning bid price. For example, the coefficient for the convenor f_c is 1%, and the coefficient for a participant f_p is 0.5%. Therefore, the amount of punishment is calculated as follows:

Convenor's punishment F_c = Punishment coefficient for the convenor f_c × Winning bid price

Participant's punishment F_p = Punishment coefficient for a participant f_p × Winning bid price

Vensim was used to build the subsystem flows and the entire SD model. Decision probabilities for the convenor, participants, and antitrust authorities fall in the range of 0–100% with an initial value of 50%.

4.2. Simulation on the Certainty of Punishment. The simulation serves to detect how the certainty of punishment, or the success rate of detection, affects the convenor's decision-making. The system is assumed to set an initial value, where f_c is 1% and f_p is 0.5%. The success rate of detection starts from 0 and increases by 0.1% per time until it reaches 100%. The following four scenarios are included:

(a) **Scenario 1:** Given the SoP, the threshold for the success rate of detection is 30.3%. If the success rate of detection is lower than 30.3%, antitrust authorities have to detect all project bidding thoroughly. However, since the success rate of detection is low, the convenor can initiate collusive bidding and benefit from bid-rigging. As a result, their collusive willingness might surge to 100%. The decision-making curves are shown in Figure 2, suggesting that deterrence may not be guaranteed when the success rate of detection is low.

(b) **Scenario 2:** Assumed that the success rate of detection increases to 30.3%, antitrust authorities find it worthy of detecting collusion cases, which means that bid riggers' benefits will be shrunk, and "to-be" bid riggers will abandon collusion (Figure 3). Furthermore, with the success rate of detection soaring to 31.9% (Figure 4), antitrust authorities find it effective to deter and image no collusive bidding in the market. Due to the restricted budget of collusion detection, antitrust authorities will tend to undo detection frequency.

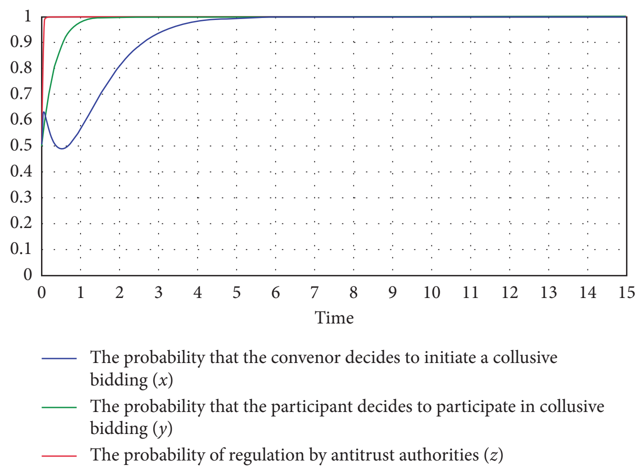

Figure 2: The curves of decision-making for three actors given the success rate of detection $k = 30.0\%$. The probability of regulation by antitrust authorities (red line) ascends to 100% immediately; the probability of collusive (green and blue lines) rises to 100% eventually.

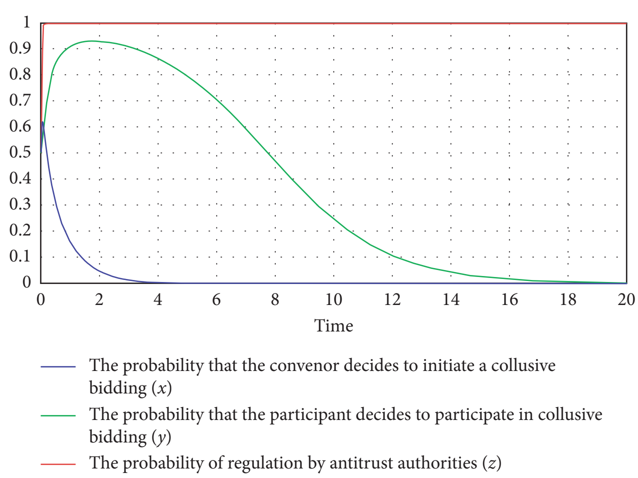

Figure 3: The curves of decision-making for three actors given the success rate of detection $k = 30.3\%$. The probability of collusive (green and blue lines) that decreases to 0 keeps the probability of regulation by antitrust authorities (red line) at 100%.

(c) **Scenario 3:** The success rate of detection is assumed 33.2% (Figure 5). Antitrust authorities can deter collusion and relax the detection frequency as none of the collusive bidding has been encountered in the market. However, the market will again see the emergence of collusive bidding and the increase of governmental determination to detect bid-rigging. As Figure 6 indicates, with a further augment in the success rate of detection beyond 35.5%, the market becomes stable after two regulation periods. The willingness to inhibit collusion erodes once again, at which point the market equilibrium is realized, and no more collusion appears.

(d) **Scenario 4:** The success rate of detection rises to 44.1% (Figure 7). Bid riggers find it impossible to earn extra profits and prefer not to collude. Due to the withdrawal of the convenor, the number of potential bid riggers will also decrease. Antitrust authorities do not need to detect collusive bidding, and the detection frequency drops.

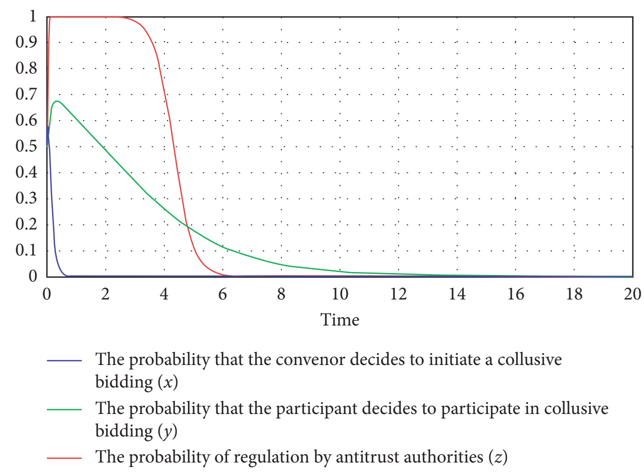

Figure 4: The curves of decision-making for three actors given the success rate of detection $k = 31.9\%$. The probability of the convenor initiates collusive bidding (blue line) decreases to 0 in a short time. This phenomenon indicates antitrust authorities (red line) can detect collusion cases effectively, while antitrust authorities will undo the detection after believing no collusive bidding practices in the market.

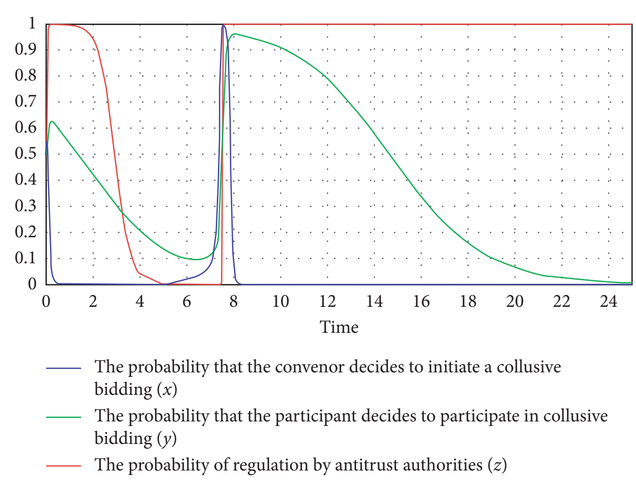

Figure 5: The curves of decision-making for three actors given the success rate of detection $k = 33.2\%$. The time to maintain 100% detection by antitrust authorities (red line) is too short of establishing a new balance. The convenor (blue line) with participants (green line) restarts to initiate collusive bidding at the moment of no regulation. Therefore, antitrust authorities have to promote the probability of regulation to 100%.

To summarize, the above four scenarios present a real situation in the construction market, namely (a) Scenario 1: strong willingness to detect but poor detecting capacity. (b) Scenario 2: long-time market detection with gentle pressure.

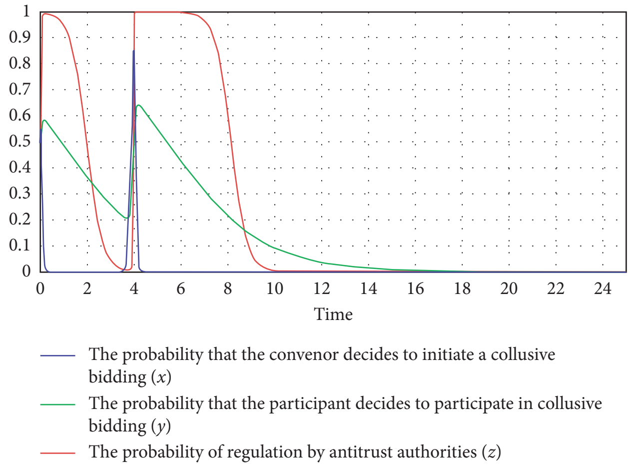

Figure 6: The curves of decision-making for three actors given the success rate of detection $k = 35.5\%$. Like Figure 5, repeated governance is revealed again in this figure. However, due to a higher rate of successful detection, antitrust authorities do not need to maintain regulation probability (red line) to 100% until the end.

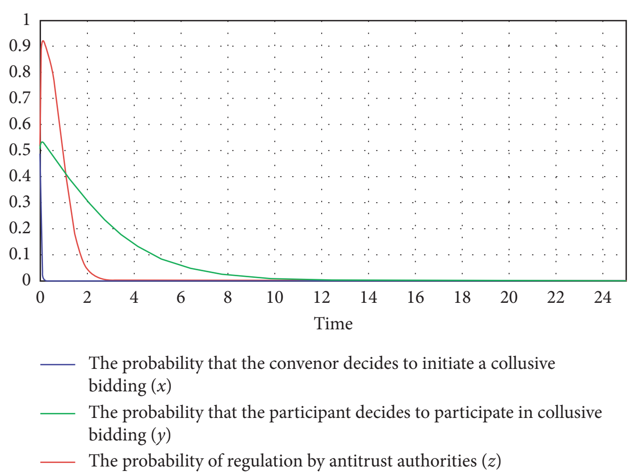

Figure 7: The curves of decision-making for three actors given the success rate of detection $k = 44.1\%$. Because of the high success rate of detection, the benefits of collusive bidding are unobtainable for bid riggers. The probability of collusive (green line and blue line) decreases to 0 directly, and antitrust authorities (red line) will undo the detection.

(c) Scenario 3: periodic regulation under moderate pressure. In practice, collusion cases draw social concerns, and antitrust authorities must immediately intensify detection to a higher rate. (d) Scenario 4: high detection frequency and no opportunities for bid riggers to survive.

4.3. Simulation on the Severity of Punishment. Collusive bidding will be significantly reduced when the success rate of detection reaches a threshold. However, it is unclear whether detection efforts are worth continuing and the SoP's roles in detecting collusive bidding. Therefore, the deterrence of the SoP is considered in this study. The SoP is quantified using two ranges of values: one is 0–100% for the convenor f_c, and the other is 0–50% for participants f_p. All of the simulations are based on the presumption that the success rate of detection ($k = 30.3\%$, $f_c = 1\%$, and $f_p = 0.5\%$) can be guaranteed. Consequently, the success rate of detection and the corresponding punishment coefficients are connected to create a surface, as shown in Figure 8. Any point on the surface has the same deterrence effects, indicating that the success rate of detection that antitrust authorities take suffices to prevent the convenor and their participants from making a to-collude decision.

We took a point (f_c, f_p) on the surface shown in Figure 8 with the same success rate of detection to form a concatenation; a contour plot of the surface projection is derived as given in Figure 9.

The results show the SoP for the convenor and their participants at any threshold of the success rate of detection as follows:

$$f_c = -\frac{f_p}{26} + b, \tag{1}$$

where the constant (26) is the multiplication of participant number N_p with the risk-return coefficient T that participants claim. Thus, equation (1) is rewritten as follows:

$$f_c = -\frac{f_p}{T \times N_p} + b, \tag{2}$$

where parameter b refers to the linear intercept, showing a reversed correlation with the success rate of the detection threshold. We used the regression analysis to model the relationship between b and k, with a goodness of fit $R^2 = 0.999$, as follows:

$$k = \frac{0.003759}{\left(b/\sqrt{1 + (-(1/26))^2}\right) + 0.007079}. \tag{3}$$

Equations (2) and (3) are further combined as follows:

$$k = \frac{0.003759}{\left(\left(\left(T \times N_p\right) f_p + f\right)/\sqrt{1 + \left(T \times N_p\right)^2}\right) + 0.007079}. \tag{4}$$

$T = 2$ and $N_p = 13$ as indicated in the data collection section are substituted into equation (4). Hence, the relationship between the convenor's punishment coefficient, participants' punishment coefficient, and antitrust authorities' success rate of detection is rephrased as follows:

$$k = \frac{0.003762}{f_p + 0.03846 f_c + 0.007083}. \tag{5}$$

We defined the combination (f_c, f_p) in equation (4) as the comprehensive punishment coefficient f for a collusive team; then

$$f = \frac{\left(T \times N_p\right) f_p + f_c}{\sqrt{1 + \left(T \times N_p\right)^2}}. \tag{6}$$

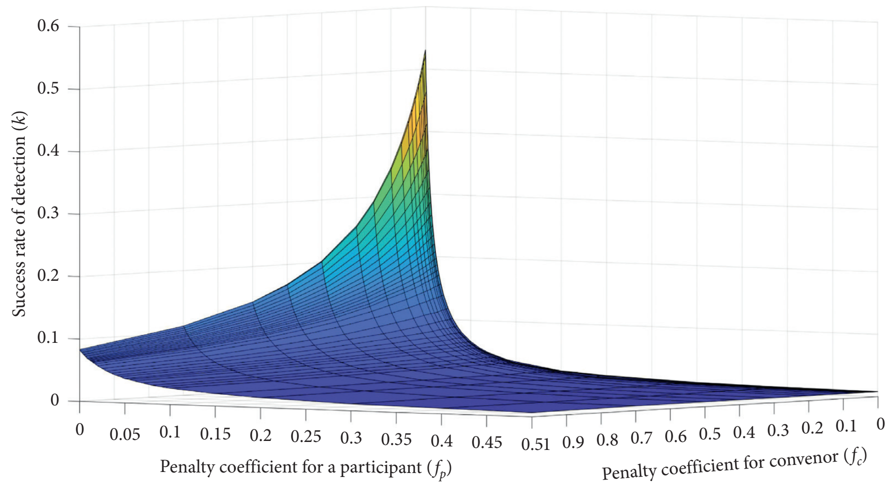

FIGURE 8: The surface diagram shows the combination of three coefficients (the success rate of detection k punishment coefficient for the convenor f_c and punishment coefficient for participant f_p), given a deterrence effect. Each point in the surface means the three coefficients that can reach an effective detection threshold ($k = 30.3\%$, $f_c = 1\%$, and $f_p = 0.5\%$).

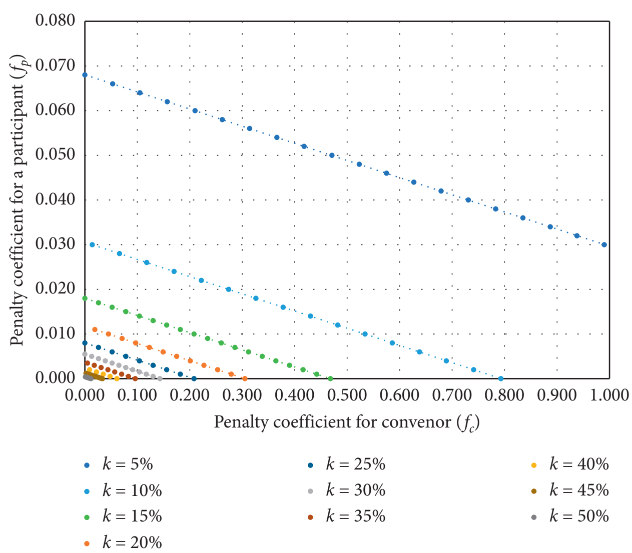

FIGURE 9: Contour plot of the surface projection shows the relationship of punishment coefficient between the convenor f_c and their participant f_p in the changing success rate of detection k, given a deterrence effect. All lines mirror a negative linear correlation between f_c and f_p.

At this point, the relationship between the SoP and the success rate of detection exhibits an inverse proportional relationship as follows:

$$k = \frac{0.003759}{f + 0.007079}. \quad (7)$$

It is noted that when the SoP is less than 5.423%, the punishment coefficient will produce a better outcome than the success rate of detection. At that moment, the threshold of the success rate of detection will be 6.13%, suggesting that when the SoP $f < 5.423\%$, an increase in the SoP increases the efficiency of regulation. Provided that f equates to 0, equation (7) will have the maximum value of 75.01, implying that the SoP reaches a maximum of 75.01 times detection frequency. Consequently, an increase in the SoP coincides with enhancing the success detection rate by 75 times. The sensitivity of the SoP is 24.22 times the sensitivity of the success rate of detection when $f_c = 1\%$ and $f_p = 0.5\%$ are synthesized to be $f = 0.5380\%$.

5. Findings and Discussion

5.1. Deterrence Effects of Punitive Measures. The above simulations are centered on three parameters: the SoP for the convenor, the SoP for its participants, and the CoP for antitrust authorities. As Figure 8 indicates, an increase in the CoP or the SoP promotes the deterrence effects on collusive bidding. Enhancing any of the three parameters will give rise to better deterrence effects, suggesting that collusive bidding can be deterred by implementing punitive measures. The results also indicate a mode of diminishing marginal deterrence effects. These findings demonstrate the usefulness of deterrence theory to address the role of punishment in inhibiting collusive bidding and outline many implications to policy formulation for improving competition regulation efficiency. Since deterrence theory has been mostly considered in criminal justice, this study can provide empirical evidence to link deterrence theory to collusive bidding [77–79]. Therefore, the research lays a theoretical foundation for future studies on the promotion of collusive bidding monitoring and the application of punitive measures to deter collusive bidding.

The research findings outline the threshold value of punitive measures, a reference to promote collusion regulations. The results show that the comprehensive punishment coefficient $f = 0.5380\%$ is smaller than the threshold $f = 5.423\%$, signifying that the SoP deserves wider applications in the Chinese construction market [44], echoing Connor and Lande's views [69]. As indicated by equation (1), an increase in the SoP for participants has better deterrence effects than that for the convenor. The reasons can be that the convenor has to bear participants' anticipated loss, and the convenor's expense ascends with more participants involved. The research findings indicate that participants' upscaling of collusion cost frustrates the convenor to implement collusive bidding. Therefore, antitrust authorities' efforts can be made towards participants to realize better deterrence. However, this does not mean that the convenor's role in collusive bidding may be overlooked [80, 81].

5.2. Replaceability between Two Punitive Measures. Previously, researchers employed the multiplication of the CoP by the SoP to gauge the deterrence effects of punitive measures [39], implying that the certainty and severity of punishment are replaceable in creating deterrence effects. However, the findings of the current study pose some challenges to previous studies. According to equation (7), the certainty and severity of punishment are in an adjusted inversely proportional relationship. This implies that these two measures are not fully replaceable in deterring collusive bidding.

As Feess et al. discussed, the reason for the weak replaceability is that an increase in the SoP facilitates antitrust authorities to reduce the CoP, while the overall deterrence effects stay unchanged [82]. When the success rate of detection decreases to 0, the SoP becomes completely invalid. Simultaneously, when the SoP is 0, deterrence effects may still be guaranteed by increasing the detection success rate to over 53.1%. Thus, the severity and certainty of punishment are not fully substitutable for each other. As Figure 8 indicates, the replaceability between the CoP and the SoP is confined to a defined boundary as disclosed in accounting control research [83]. Referred to the diminishing effects of marginal deterrence (Section 5.1), an effective strategy to inhibit collusive bidding is finding an effective combination of the certainty and severity of punishment rather than merely choosing one, concurring with the work by Polinsky and Shavell [84].

5.3. Improving the Efficiency of Punitive Measures. In the study, an increase in detection success rate represents an improvement of detection efficiency, depending on an unchanged detection cost level. Based on the four scenarios mentioned above, the success rate of detection is classified as follows: inefficient measures ($k < 30.3\%$), less efficient measures ($30.3\% \leq k < 31.9\%$), neutrally efficient measures ($31.9\% \leq k < 44.1\%$), and highly efficient measures ($k \geq 44.1\%$). The derivation of these four scenarios paves the way for improving the deterrence effects of the less efficient measures and the neutrally efficient measures.

Regarding the deterrence effects of the less efficient measures, reducing detection costs is not useful enough for rendering a shift to neutrally efficient measures. If the less efficient measures are sometimes be exerted [85], it is vital to include a high detection frequency to ensure the deterrence effects. Therefore, antitrust authorities must conduct 100% detection. Furthermore, regarding the deterrence effects of the neutrally efficient measures, reducing detection costs helps antitrust authorities to render highly efficient measures. It seems that a longer-lasting of neutrally efficient measures may also inhibit the backlash against collusive bidding. Consequently, this finding indicates that antitrust authorities shall calculate collusive detection costs exactly to improve the deterrence of punitive measures.

6. Conclusions

Does a punitive measure prevent collusive bidding in the construction sector? If so, how and to what extent? This study demonstrates that increasing the certainty and severity of punishment can improve collusive bidding deterrence, indicating the usefulness of punitive measures to combat collusive bidding. The deterrence effects are reflective of a diminishing marginal mode. Besides, the certainty and severity of punishment cannot fully replace one for another in deterring collusive bidding. Furthermore, realizing a shift from less efficient measures to neutrally efficient measures shall address the changes in detection costs regarding their deterrence effects. The research findings enlighten antitrust authorities to evaluate the effectiveness of competition policy for the inhibition of collusive bidding. The implication is that antitrust authorities shall strike the trade-off between enhancing punishment and improving policy enforcement capacity.

The study has a few limitations. First, the model considers the effects of punitive measures on collusive bidding inhibition. Future research is recommended to account for more factors such as contract reward [29] and ethics [30]. Second, the case data were subject to the uniqueness of China's construction industry. Model parameters are open for amendment in other national contexts. Third, the study can take into account short-term returns when investigating all actors' decision-making. The model shall be revised to ensure that actors' pursuit of long-term returns is embedded into the decision-making process.

Data Availability

The data supporting the conclusions of the study can be accessed by request.

Conflicts of Interest

The authors state that no conflicts exist among all relevant interests.

Acknowledgments

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Research Article

The Complexity of Technological Innovation Decision-Making in Emerging Industries

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It is well known that innovation-driven emerging industries have gradually become the main driving force of global economic recovery and growth. Technological innovation decision-making is a complex and dynamic system, which is affected by various factors inside and outside an enterprise. In this dynamic system, how to make the optimal technological innovation investment decisions is a key concern for enterprises and governments. As an investment activity, technological innovation largely depends on the amount of external financing obtained by enterprises. However, financial constraints have increasingly become an obstacle to enterprises' technological innovation. At the same time, technological innovation is also affected by the external political and economic environment, such as changes in economic policy, government subsidy policies, and institutional environmental policies. Can these external environments reduce the negative impact of financing constraints on technological innovation? In this study, based on the data of listed companies in China's strategic emerging industries, we adopt a panel negative binomial regression model to investigate the complexity of technological innovation decision-making from the perspective of financing constraints. Our main findings include the following. First, financing constraints significantly inhibit the input and output of technological innovation in emerging industries. Second, the inhibition effect on the output of substantive innovations is more pronounced than that on the output of strategic innovations. Third, based on the analysis of enterprise heterogeneity in different dimensions, we show that this inhibition has a selective effect among different industries. Finally, we show that economic policy and marketization can help alleviate the inhibition effect of financing constraints on technological innovation.

1. Introduction

Innovation is a key issue of economic development and has become a driving force for high-quality development [1]. Innovation can bring more efficient technologies and promote social development [2]. No high-quality development is possible without the important supporting role of technological innovation. Furthermore, strategic emerging industries is the key forces of technological innovation. The cultivation and development of strategic emerging industries are of great practical significance for building a modern economic system and realizing high-quality economic development [3, 4].

As an important investment activity, technological innovation is inevitably affected by a variety of factors inside and outside an enterprise. One is from the internal perspective of the enterprise, such as its nature, property rights, governance structure, strategy, equity incentives, size, age, investment strategies, and financial constraints. The other is from the external perspective of the enterprise, such as economic policy uncertainty and marketization process. In fact, technological innovation depends to a large extent on the amount of external financing an enterprise can secure. The external political and economic environment influences its financing constraints and ultimately affects its technological innovation decision-making. How to effectively incorporate internal and external factors when studying the dynamic decision-making of enterprise technological innovation will be the focus of this article.

Technological innovation activities cannot be separated from the support of financing. The R&D and innovation activities of enterprises depend to a large extent on whether they can obtain sufficient external equity financing and debt financing [5, 6]. In the face of large investments in technological innovation, the biggest obstacle faced by enterprises is capital constraints. Many technological innovation projects are subject to capital constraints and eventually are shelved. In a perfect capital market, information is completely symmetrical and there are no transaction costs and financing costs, so companies can easily raise the funds from the capital market. However, there are often financing constraints in the actual capital market due to information asymmetry, moral hazard, and adverse selection, which increase the cost and difficulty of external financing for enterprises. Compared with general investment, the information asymmetry in technological innovation is more severe. Moreover, technological innovation requires a greater amount of investment and longer R&D cycle. As a result, it is more difficult for enterprises to obtain external financing for technological innovation. This can cause serious financing constraints. Then, do financing constraints affect the company's technological innovation decisions? Is this effect related to enterprise and industry characteristics? How do economic policy environment and marketization work under such effect? In this study, we aim to analyze these problems. Our results can provide theoretical support for building a financial system suitable for technological innovation and providing guidance for better implementing the innovation-driven development strategy.

In this study, we exploit the listed companies in China's strategic emerging industries over the period 2009 to 2019 to study the decision-making of technological innovation in emerging industries. We focus on strategic emerging industries because these industries are the main forces in technological innovation.

Given that technological innovation is also affected by the external political and economic environment, such as economic policy fluctuations, and institutional environmental policies, whether these external environments can minimize the negative effects of financing constraints on technological innovation, stimulate enterprises' investment in technological innovation, and enhance enterprises' technological innovation capability is also a key aspect of national policy attention. Hence, we add economic policy uncertainty and marketization environment variables as the moderator to test whether they can alleviate financing constraints on technological innovation. Our findings do indicate economic policy uncertainty and marketization can weaken the negative effects of financing constraints on technological innovation. Specifically, the higher the marketization, the smaller the inhibition effect, and the greater the uncertainty of economic policy, the smaller the inhibition effect of financing constraints on technological innovation.

In this study, we make three major contributions. Firstly, in the literature, most scholars analyzed the financing constraints through investment-cash flow sensitivity based on the idea of Fazzri et al. [7]. However, more recent studies found that the investment-cash flow sensitivity has its own drawbacks. In this study, financing constraints index (referred to as FC in the text) is constructed through a series of financial indicators to measure the financing constraints, which are then incorporated into the overall analytical framework of technological innovation as an influencing factor. Secondly, the influence of financing constraints on technological innovation is studied from both the input and output of technological innovation. In particular, we analyze the impact of financing constraints on the innovation output of different types (strategic innovation and substantive innovation). It is found that the inhibitory effect of financing constraints on substantive innovation, such as invention patent, is more pronounced than that of strategic innovation. Thirdly, we reveal the roles of economic policy uncertainty and the marketization in regulating the negative correlation between financing constraints and technological innovations. This helps to realize the connection of the microbehaviour and macro policy and provide the micro-evidence at the enterprise level on how the macropolicy drives the investment.

The rest of the article is organized as follows. Section 2 presents a literature review; Section 3 develops the research hypotheses; Section 4 discusses the data and methodology, including sample selecting, procedure, data sources, and model specification; and the empirical results and related discussions are described in Section 6. Finally, Section 2 presents the conclusion and policy implications.

2. Literature Review

Innovation and financial development are both core factors affecting sustainable development of economy. In the 21st century, technological innovation plays a more important role in the country's comprehensive competitiveness, while financial constraints also become an increasingly serious obstacle in the process of enterprise development. In this context, scholars began to focus on the impact of financial development on the technological innovation of enterprises. The literature generally affirmed the promoting effect of financial development on technological innovation [8, 9]. However, there was no consensus on the mechanism of financial influence innovation. One view held that financial development promotes technological innovation by alleviating financing constraints faced by enterprises, that is, reducing financing costs and broadening financing channels [10, 11]. The other view maintains that financial development boosts technological innovation by improving the efficiency of capital allocation [12]. These studies focused on the relationship between financial development and technological innovation from a macroperspective and do not explore its micromechanism in more detail. However, technological innovation is always the behavior of enterprises at the microlevel. The transmission mechanism of financial development to technological innovation still needs to be investigated on the motivation and specific behavior of enterprises.

As information economics took off, scholars began to study financial constraints under the condition of information asymmetry. Since Fazzari, Hubbard, and Petersen first proposed to measure the financing constraints using the investment-cash flow sensitivity [7], this method was subsequently extended to research and development investment and other investment fields to seek stronger theoretical support of financing constraints from the perspective of cash flow. On the basis of this theory, a large number of scholars discussed the relationship between financing constraints and technology innovation investment from the perspective of the cash flow. However, there were great differences in the development of capital markets and innovation investment in various countries. When different countries were used as samples to study the relationship between financing constraints and technological innovation, there were some differences in the conclusions. Hall believed that it is precisely because of the difficulties in raising funds from outside for innovation investment that companies mainly rely on internal financing for innovation [13]. Hall, Himmelberg, and Petersen, and He studied American companies and found a strong positive correlation between R&D investment and cash flow sensitivity [14–16]. Mulkay et al. held that the sensitivity of innovation investment to cash flow in the United States is more pronounced than that in France and Japan [17]. Harhoff showed that there is a statistically significant but weak relationship between R&D investment and cash flow of German companies [18]. Bond and Harhoff held that there is no significant relationship between R&D investment and cash flow in German and the UK [19]. Bloch believed that R&D investment expenditures of Danish companies are significantly affected by internal cash flow, and R&D investment has investment-cash flow sensitivity [20].

With the advancement of technology and the expansion of production scale, it is difficult to meet the capital needs of enterprises solely by relying on internal financing for projects with large investment such as technological innovation, and external financing has gradually become the main financing channel for technological innovation. Researchers began to focus on the financing constraints of technological innovation from the perspective of external financing. External funds for R&D projects are believed to be relatively scarce, mainly due to the serious information asymmetry in the financing process. The uncertainty and strategic nature of R&D may restrict managers from disclosing relevant information about R&D projects to external investors in order to prevent the information from being known to competitors [21–23].

Hall pointed out that despite the adoption of measures such as intellectual property protection, government subsidies, and tax incentives, technological innovation investment is still difficult to finance or the financing cost is high. There is often a big gap between the rate of return required by enterprises to use their own capital and the rate of return required by outside investors, which leads to the high cost of external capital, and some innovation projects cannot even be financed from outside [24]. Brown and Petersen believed that the output of innovation activities is characterized by nonexclusive indivisibility and uncertainty, leading to the social optimal investment level much higher than the private optimal level, which seriously hinders the enterprises from using all the internal funds for R&D [25]. Li held that, compared with general investment, R&D investment is more inflexible, and R&D-intensive companies facing financing constraints are more likely to pause or cut off R&D projects. The risk of R&D-intensive companies increases with the degree of financing constraints [26]. Mina et al. believed that the uncertainty of innovation activities have a negative impact on financial supply, which is related to the expectation of enterprises to take risky projects, leading to higher external capital costs and possible access to suboptimal external financial resources [27].

In addition to the internal characteristics of the enterprise, the external environment will inevitably have an impact on innovation decisions. Relevant literature concentrates on research from the perspective of economic policies, government subsidies, and marketization. There are two views on the impact of economic policy uncertainty on technological innovation. One view is that economic policy uncertainty can have an incentive effect on technological innovation. This is because economic policy uncertainty represents an opportunity to increase revenue in the future [28]. Under the motive of pursuing profit, uncertainty is beneficial to enterprises to increase R&D investment [29]. The other view, based on the analysis of the physical budget theory, believes that the uncertainty of economic policies inhibits the technological innovation [30]. Regarding the effect of marketization, most scholars have affirmed the role of marketization in the process of technological innovation and believed that the improvement of marketization is generally conducive to promoting technological innovation [31–33]. Nonetheless, no consensus has been reached on which systems play a role in promoting technological innovation.

When studying the impact of financing constraints on technological innovation, most scholars only focused on innovation input and rarely paid close attention to the impact of financing constraints on technological innovation output. However, technological innovation output is the key to promote the development of social productivity, especially substantive innovation (invention patents). Therefore, the impact of financing constraints on technological innovation output is worth of social attention. In view of the above considerations, the impact of financing constraints on technological innovation should be extended from technological innovation input to technological innovation output, aiming to comprehensively analyze the impact of financing constraints on technological innovation activities in strategic emerging industries. At the same time, most scholars rarely took the external political and economic environment of the firm into account, and there was a lack of research on the combining financing constraints with environmental factors such as economic policy uncertainty and institutional environment. In fact, technological innovation depends to a large extent on the amount of external financing that a company obtains. Economic policy uncertainty and institutional environment both affect the company's external financing environment and then affect the company's financing constraints, and ultimately affect the company's technological innovation activity.

3. Research Hypotheses

Arrow believed that technological innovations have externalities, showing spillover effects and diffusion effects, which make technological innovation show strong nonexclusive and limited exclusivity. The diffusion of externalities enables the competitors to acquire technology at a lower cost than innovators in order to improve their productivity and innovation [34]. The enterprises undertaking technological innovation burden the high cost, but they fail to access all the benefits. Under the spillover effect of technological innovation, some of the profits are occupied by other enterprises, so the enterprises are less motivated to engage in technological innovation and even have the idea of free rider.

According to the theory of net present value, the principle of optimal investment decision is that marginal revenue equals marginal cost. Financing constraints disable the enterprise to make optimal investment decisions and inhibit technological innovation. There are two main reasons. One reason is that, due to the limited internal funds, external financing is required. However, companies will weigh the cost of financing and their benefits [35]. Once the company faces financing constraints, the cost of external funds will be higher than the cost of internal funds, which increases the cost of technological innovation. When such investment cost increases to the present value of the project's expected cash flow, the enterprise may cease its investment in technological innovation, thus delaying the innovation project that could have been implemented. The other reason is the difficulty of external financing , which prevents enterprises from obtaining the funds they need. Then, even if the marginal revenue of an enterprise is greater than its marginal cost, technological innovation projects cannot be implemented due to capital constraints.

It can be seen that, under the influence of the external characteristics of technological innovation, enterprises' willingness to undertake technological innovation is not high. When the financing constraints become tighter, the enterprise's investment cost in technological innovation will increase correspondingly. Then, the willingness of enterprises to undertake technological innovation activities will also decline. Therefore, Hypothesis 1 is put forward.

Hypothesis 1. Financing constraints negatively affect the technological innovation. In other words, financing constraints have an inhibitory effect on the enterprise's technological innovation.

Strategic emerging industries consist of nine subindustries. Since the characteristics of financing constraints and technological innovation vary in different industries, the impact of financing constraints on technological innovation must be different to some extent in certain industries. Therefore, Hypothesis 2 is put forward.

Hypothesis 2. The influence of financing constraint on different subindustries of strategic emerging industries is different.

Due to the great difference between the output of the manufacturing industry and that of the nonmanufacturing industry, there are different characteristics in innovation. The manufacturing industry is dominated by technological innovation, while the nonmanufacturing industry is dominated by service innovations, such as organizational innovation, normative innovation, and characteristic innovation. These service innovations have little to do with technological innovation. Meanwhile, the strategic position of technological innovation in enterprises also varies greatly. Yuan pointed out that there is an obvious difference in the dependence of the manufacturing industry and service industry on R&D. The manufacturing industry has a relatively large investment in technological innovation, and R&D investment plays a decisive role. Many companies even have set up specialized R&D departments, while the service industry has a smaller dependence on R&D, and the investment in technological innovation is far lower than that of the manufacturing industry [36]. Therefore, the manufacturing industry has a strong desire to improve the productivity of enterprises through technological innovation. It can then be inferred that the inhibitory effect of financing constraints on the manufacturing industry is smaller than that on the nonmanufacturing industry. Therefore, Hypothesis 3 is put forward.

Hypothesis 3. The negative impact of financing constraint on manufacturing industry is less than that on nonmanufacturing industry.

Rajan and Zingales constructed the industry's external financing dependence, which was used to measure the industry's dependence on external funds, and they analyzed 36 industries in US industrial companies [10]. They came to a conclusion that traditional industries generally rely less on external financing while emerging industries mostly rely more on external financing. The top three industries with the highest external financing dependence are drugs and pharmaceuticals, plastics, and computing. The three industries with the lowest external financing dependence are the tobacco, pottery manufacturing, and leather industries. According to the definition and scope of strategic emerging industries in China, it can be found that most strategic emerging industries are highly dependent on external financings, such as the new generation of the information technology industry and the biomedical industry. Based on the industry's external financing dependence, we put forward the following expectations: the deterioration of the financing environment will have a greater impact on the computer industry and other industries with higher external financing dependence than those with low dependence on external financing. Therefore, Hypothesis 4 is put forward.

Hypothesis 4. The negative impact of financing constraints on the industries with low external financing dependence is less than that on the industries with medium- and high-level external financing dependence.

For general investment, scholars generally believe that the economic policy uncertainty inhibits enterprises' investment, but technological innovation differs from general investment, and thus, the impact of economic policy uncertainty may vary correspondingly. Technological innovations are full of high uncertainty, which also means that there are many market opportunities in the future. It is the source of future profits for enterprises. The future profit opportunities will disappear if these uncertainties are removed while enterprises pursue high profits. Uncertainty will stimulate their innovation behaviors and encourage entrepreneurs to pursue greater profits. From this perspective, the uncertainty of economic policy means not only risks and challenges but also opportunities and benefits. For entrepreneurs with an innovative spirit, they will make full use of the opportunities brought by the economic policy uncertainty, avoid risks, create profits for enterprises, and enable the enterprises to develop and grow stronger. Furthermore, the adjustment cost of technical innovation is higher than that of physical capital investment [24]. Therefore, enterprises can save a lot of "adjustment costs" by keeping R&D investment stable. Then, in the face of economic policy uncertainty, enterprises will tend to make use of the opportunities and keep the stable investment of technological innovation so that they can maintain continuous investment in technological innovation. Therefore, Hypothesis 5 is put forward.

Hypothesis 5. The restraining effect of financing constraints in periods of high economic policy uncertainty is less than that in periods of low economic policy uncertainty, that is, financing constraints have a more restraining effect on technological innovation in periods of low economic policy uncertainty.

Generally speaking, in the highly marketized regions, there are more mature and effective laws and regulations, less government interventions, a more effective financial system, and an open and transparent information disclosure, which provides a proper external political environment for technological innovation. As for the reasons, first, the market-oriented institutional environment helps to alleviate the information asymmetry between enterprises and investors, reduce the cost of external financing, and broaden the financing channels of enterprises, thereby optimizing the external financing structure of enterprises and making up for the lack of funds for technological innovation [37]. Second, the market-oriented system enhances the function of the market in resource allocation. It not only reduces the government's intervention and possibility of rent-seeking but also improves the specificity of innovation, stimulates the current R&D investment, and enhances the innovation initiative through a perfect patent protection system (Wu and Tang) [38]. Third, the market-oriented system can provide more sensitive price information for enterprises and make the capital flow to the sectors with high-efficiency investment, thereby improving the allocation efficiency of capital and reducing the distortion of capital price and the risk premium of capital to a certain extent. Fourth, the market-oriented system increases the labor remuneration of technical innovation personnel through income distribution and the rate of return on the technology of technical personnel, stimulates the innovation enthusiasm of technical personnel, and promotes the technological innovation. Fifth, the improvement of the market-oriented system can effectively promote China's foreign trade. Through the import and export of commodities, it is conducive to the introduction and absorption of technology by Chinese companies. Under the influence of technology spillover effects, it can promote innovation activities of Chinese enterprises (Li and Liu) [33]. Therefore, the market-oriented institutional environment is conducive to alleviate the negative effect of financial constraints on technological innovation. Therefore, Hypothesis 6 is put forward.

Hypothesis 6. The restraining effect of financing constraints on technological innovation in high-market-oriented areas is less than that in low-market-oriented areas, that is, it has a more restraining effect on enterprises in low-market-oriented areas.

4. Data and Methodology

4.1. Model Specification. In order to test Hypothesis 1, we construct two models from the perspectives of input and output of technological innovation. The model of technological innovation input is as follows:

$$\text{Innovating}_{i,t} = +_0 + \alpha_1 F\text{constraints}_{i,t-1} + \sum \theta_i x_{i,t-1} + \text{ind}_{i,t} + \theta_t + \varepsilon_{i,t}. \quad (1)$$

In view of the continuity of technological innovation activities, when setting the model in this study, explanatory variables and control variables will lag by one period (except the variable of company age). $\text{Innovating}_{i,t}$ represents the technological innovation input of the company i in the year t. $F\text{constraints}_{i,t-1}$ represents the variable of financing constraints, indicating the financing constraints of the company i in the year $t-1$. $\sum \theta_i x_{i,t-1}$ represents the vector combination of control variables. $\text{ind}_{i,t}$ represents the industrial effect, θ_t represents the time effect, and $\varepsilon_{i,t}$ represents the comprehensive error.

Since the number of patent applications, which is the explained variable to measure the technological innovation output, is a discrete variable and does not necessarily meet the assumption of linear regression, we adopt the panel counting model. According to the distribution characteristics of the number of patent applications, there is a huge difference between the variance and the mean, and the variance is obviously greater than the mean. There may be excessive data dispersion, and it is difficult to satisfy Poisson regression condition that expectation and variance are equal. Therefore, the negative binomial regression model of panel data is adopted.

It is assumed that the number of patents filed by an enterprise is Y_{it} (the subscripted variable i represents the enterprise observed, and the subscripted variable t represents the year observed), and its conditional distribution function is as follows:

$$P(Y_{it} = y_{it}|x_{it}) = \frac{e^{-\lambda_{it}}\lambda_{it}^{y_{it}}}{y_{it}!}, \quad (y_{it} = 0, 1, 2, \ldots), \tag{2}$$

where $\lambda_{it} > 0$ represents the average occurrence times of the event. In order to ensure that λ_{it} is a nonnegative figure, it is assumed that

$$\lambda_{it} = \exp\ (x'_{it}\beta + u_i) = \exp(x'_{it}\beta)\exp(u_i) \equiv v_i \exp(x'_{it}\beta), \tag{3}$$

where x_{it} does not contain constant term. $v_i \equiv \exp(u_i)$ represents the individual effect in the form of product. In the case that it satisfies the condition that $v_1 = v_2 = \cdots v_n$, it means that there is no individual effect. More generally, the existence of individual effect is allowed. In other words, different individuals have different values of v_i. The probability density of the negative binomial regression model is

$$f(Y_{it}|\mu_{it}, \alpha) = \frac{\Gamma(y_{it} + \alpha^{-1})}{\Gamma(y_{it} + 1)\Gamma(\alpha^{-1})}\left(\frac{\alpha^{-1}}{\alpha^{-1} + \mu_{it}}\right)^{\alpha^{-1}}\left(\frac{\mu_{it}}{\alpha^{-1} + \mu_{it}}\right)^{\alpha^{-1}}, \quad y_{it} = 0, 1, \ldots, \tag{4}$$

where $\Gamma(\cdot)$ represents the gamma distribution function and α represents the overdispersion parameter. $E(Y_{it}|x_{it}) = \mu_{it}$ and $\mathrm{Var}(Y_{it}|x_{it}) = \mu_{it} + \alpha\mu_{it}^2 > \mu_{it}$. y_{it} represent the number of patents applied by the enterprise i in the year t. μ_{it} represents the average value of the patents applied by the enterprise. After introducing relevant control variables, the negative binomial regression model of the technological innovation output is

$$\mu_{i,t} = \exp\left(\alpha_1 F\text{constraints}_{i,t-1} + \sum \theta_i x_{i,t-1} + \varepsilon_{it}\right). \tag{5}$$

To test Hypothesis 2 to Hypothesis 4, we group the samples according to their characteristics and compare the magnitude and significance of financing constraint coefficient. To test Hypothesis 5 and Hypothesis 6, we introduce economic policy uncertainty or marketization as the moderator based on model (1) and set the following econometric model:

$$\begin{aligned}\text{Innovationg}_{i,t} &= \alpha_0 + \alpha_1 F\text{constraints}_{i,t-1} + \sum \theta_i x_{i,t-1} \\ &+ \alpha_2 M_{i,t} + \alpha_3 M_{i,t} \times F\text{constraints}_{i,t-1} + \text{ind}_{i,t} + \theta_t + \varepsilon_{i,t},\end{aligned} \tag{6}$$

where $M_{i,t}$ represents the economic policy uncertainty or the marketization. If the estimate of the interaction coefficient α_3 is significantly positive, the hypotheses H_5 and H_6 are supported. If α_3 is significantly negative, it means the economic policy uncertainty or the marketization increases the negative effect of financing constraints on technological innovation.

4.2. Variable

4.2.1. Explained Variable. The explained variable is technical innovation. Technical innovation can be measured from the perspectives of input and output. For innovation input, we measure the company's technological innovation activities by the R&D expense and use the R&D concentration (the proportion of R&D expenses to the total assets of the current period) and the R&D intensity (the proportion of R&D expenses to current sales revenue). In terms of the technical innovation output, following Hall and Harhoff [39], we measure the output of technological innovation by the number of patent applications.

4.2.2. Explanatory Variable. The core explanatory variable is the financing constraints. Following Owen [40] to calculate KZ index and considering the characteristics of listed companies in China, the measurement method of FC index of the Chinese listed companies financing constraint is established. The first step is to classify the samples by year and calculate medians of the annual operating net cash flow (CF), cash dividends (DIV), cash holding/last term's assets (CashH), the leverage ratio (LEV), and Tobin's Q (TobinQ). Then, we assign a value to the variable. CF, DIV, and CashH are expected to be negative correlation with financing constraints, while LEV and TobinQ are positively correlated with financing constraints. The values are determined according to the following principles. If CF, DIV, and CashH are lower than their medians that year, the corresponding indicator value is taken as 1; otherwise, it is taken as 0, expressed as FC_1, FC_2, and FC_3. If LEV and TobinQ are higher than their medians that year, the corresponding indicator value is taken as 1; otherwise, it is taken as 0, expressed as FC_4 and FC_5. The third step is to calculate the value of FC, according to the equation $FC = CF_1 + FC_2 + FC_3 + FC_4 + FC_5$. The fourth step is to use the panel sorting logistic regression model for regression. The dependent variable is FC, and the explanatory variables are the original values of CF, DIV, CashH, LEV, and TobinQ. The regression coefficients of these explanatory variables are estimated, and the expression of the FC index is obtained. In the end, the actual values of CF, DIV, CashH, LEV, and TobinQ are substituted into the regression model, and the predicted FC value of the enterprise is calculated, which was the FC index of the enterprise. The higher the FC index is, the more serious financing constraints is.

According to the process above for calculating the FC index, the measurement result of the financing constraints is FC = 11.35CF − 45.72DIV − 4.04CashH + 5.38LEV +0.16TobinQ. Moreover, the regression coefficients of the five variables are all significant at the significance level of 1%, and the overall significance of the model also passes the statistical test. It is illustrated that the five variables, namely, CF, DIV, CashH, LEV, and TobinQ, are the effective proxy variables affecting the financing constraints. In addition, CF, DIV, and CashH are negatively correlated with financing constraints, while LEV and TobinQ are positively correlated with the financing constraints. It means that listed companies with high operating cash flow, high cash holding, high dividends, low leverage ratio, and low investment opportunities face less serious financing constraints. In contrast, listed companies with low operating cash flow, low cash holding, low dividends, high leverage ratio, and high investment opportunities face more severe financing constraints.

Two other important variables in this study are economic policy uncertainty and marketization. There are many measurement indicators of economic policy uncertainty. We adopt the economic policy uncertainty index constructed by Baker et al. [41]. This index has been widely used in recent macropolicy literature and has been proved to be comprehensive and objective to reflect the fluctuation of China's economic policy. Since the index is a monthly index, we use the monthly arithmetic average to convert the monthly economic policy uncertainty index into an annual economic policy uncertainty index. We use variable EPU to represent the economic uncertainty index. Marketization is mostly measured by the marketization index proposed by Fan et al., which consists of the relationship between the government and the market, the development of the nonstate economy, the development of the product market, the development of the factor market, and the development of market intermediary organizations [31]. The five aspects of the legal system environment can fully reflect all aspects of marketization. Therefore, marketization index is used to measure the level of marketization in each region. Since the sample in this article is data of listed companies in strategic emerging industries, it is not possible to directly obtain the corresponding market index of each listed company. The method is to find the market index of the corresponding province according to the province where each listed company is registered. We use marketization variable to represent the marketization index.

4.2.3. Control Variable. Control variables involved are Size representing the size of enterprises, Age representing the age of enterprises, TobinQ, Concentr representing equity concentration, Sgrowth representing the sales growth rate, and Cflow representing the cash flow ratio.

4.3. The Data. Our samples are the companies listed on the main board of China in strategic emerging enterprise from over 2009 to 2019. As there are no strategic emerging industries in the industry classification of the China Securities Regulatory Commission, it is impossible to obtain the sample of listed companies of strategic emerging industries directly. In order to gather the samples of listed companies in strategic emerging industries, the following steps are followed.The initial sample is selected from the sample stocks of China Strategic Emerging Industries Composite Index ("Emerging Composite Index") released by China Securities Index Co., Ltd., and Shanghai Stock Exchange in 2017, covering a total of 1117 companies listed as A-shares in Shanghai and Shenzhen Stock Exchanges, on the SMEs board (Small and Medium Enterprise Board), the second-board market, and the new OTC market (new over-the-counter market). Due to the small amount of data disclosed by listed companies on the new OTC market and the poor comparability compared with other listed companies, such companies are removed from the sample frame. Next, some filter conditions are set in the sample frame. The ST and ∗ST listed companies within the sample period are deleted. Then, the listed companies in the financial and insurance industry are deleted. At last, the samples with missing values of some indexes are deleted. After the steps detailed above, the final samples are 757 listed companies in the strategic emerging industries over the period of 2009 to 2019.

5. Empirical Results and Discussions

5.1. The Inhibitory Effect of Financing Constraints. We focus on the impact of financing constraints on technical innovation. Columns 2 and 3 of Table 1 report the impact of financing constraints on technological innovation input. As shown in Table 1, financing constraints negatively affect the concentration and intensity of R&D at the significance level of 5%. That is, financing constraints inhibit technological innovation input. For listed companies, technological innovation is a very important investment decision for enterprises, involving large capital investment and a long time of capital occupation. When enterprises face serious financing constraints, their internal and external funds cannot meet the capital demand for technological innovation, so enterprises' technological innovation activities will be postponed.

The impact of financing constraints on technological innovation output is also vital. According He and Zhang [42] and Li and Zheng [43], the patent applications for measuring the technological innovation are divided into two types. One is the substantive innovation with a higher technological level represented by invention patents, aiming to promote social and technological progress and occupy a competitive advantage in the industry. Andrea pointed out that financing constraints have a significant negative effect on fundamental innovation [44]. The other is strategic innovations with low

Table 1: Regression results of the influence of financing constraints on technical innovation.

Variable	R&D concentration	R&D intensity	Number of patent applications	Number of invention patents	Number of noninvention patents
L.FC	−0.031**	−0.114***	−0.024*	−0.038**	−0.002
	(0.014)	(0.032)	(0.012)	(0.015)	(0.014)
L.size	−0.287***	−0.629***	0.357***	0.378***	0.348***
	(0.051)	(0.119)	(0.044)	(0.050)	(0.058)
L.TobinQ	−0.009	−0.029	0.024***	0.030***	0.009
	(0.013)	(0.029)	(0.006)	(0.010)	(0.010)
L.Concentr	−0.009**	−0.025***	−0.000	0.002	0.002
	(0.004)	(0.009)	(0.003)	(0.003)	(0.003)
L.Sgrowth	−0.011	−0.165***	−0.000	−0.000	0.000
	(0.024)	(0.054)	(0.000)	(0.000)	(0.000)
Age	−0.037**	−0.160***	0.045***	0.071***	0.024*
	(0.015)	(0.036)	(0.011)	(0.010)	(0.014)
L.Cflow			−0.003**	−0.005**	−0.000
			(0.002)	(0.002)	(0.002)
Constant	9.033***	17.980***	−7.436***	−8.479***	−7.302***
	(1.203)	(2.798)	(0.922)	(1.058)	(1.203)
Time effect	Controlled	Controlled			
Industry effect	Controlled	Controlled			
Sample size	757	757	628	625	608

Notes: ***, **, and * mean significant at the significance level of 1%, 5%, and 10%, respectively. The figures in parentheses are standard errors, the same as below. L.variables represent variables with a lag of one period.

technical level represented by utility model patents and design patents, most of which aim to obtain other benefits. Then the influence of financing constraints on the different types of patent applications is studied. Columns 4 to 6 of Table 2, respectively, report the impact of financing constraints on the number of patent applications, invention applications, and noninvention applications. In order to determine whether negative binomial regression is a fixed effect or a random effect, the Hausmann test is carried out. The results show that the p value is less than 0.01, which strongly rejected the negative binomial regression of random effect. Therefore, the fixed-effect negative binomial regression is adopted. Hilbe pointed out that, in the counting model, the marginal effect of variables is more significant than that of the regression coefficient [45]. We use the marginal effect to analyze the impact of the unit change of the explanatory variable on the explained variable. Columns 4 and 5 of Table 1 show that, in terms of both the number of patent applications and the number of invention patents, financing constraints inhibit technological innovation output at the significance level of 10%. Column 6 of Table 1 shows that the influence of financing constraints on the number of nonpatent applications is negative but not significant. The above results indicate that therestraint of financing constraints on the inventionpatent is greater than that of noninvention patent, mainly because of the different nature of the two types of patents. The invention patent can improve the production efficiency of enterprises, enable enterprises to obtain competitive advantages in the industry, and represent the core competitiveness of enterprises. However, invention patents usually require a lot of investment and last a long time before they come out.

On the contrary, the purpose of noninvention patents is to echo the innovation strategy of enterprises and national innovation policies, and the companies pay more attention to the “speed” and “quantity” of innovation. Noninvention patents involve a relatively small investment, a relatively short duration cycle, and a relatively little influence by capital. Due to the essential differences between invention patents and noninvention patents, enterprises have different attitudes towards the two kinds of patents, which ultimately leads to the difference in the degree of influence of financing constraints on the two kinds of patents. This conclusion is consistent with Khan et al. [46].

The results above indicate that financing constraints not only inhibit the technological innovation input in emerging industries but also inhibit the technological innovation output of the enterprise in emerging industries, and thus, Hypothesis 1 has been supported.

5.2. The Heterogeneous Influence of Financing Constraints

5.2.1. Analysis by Industry. Considering that different subindustries in strategic emerging industries have different characteristics of financing constraints and technological innovation, the sensitivity of technical innovation to financing constraints may be heterogeneous. We further analyze by industry in order to find out the difference in the impact of financial constraints on technical innovation of various subindustries in strategic emerging industries. Since there are many subindustries in the strategic emerging industries, only R&D intensity is used as the explained variable to analyze by industry.

Table 2: Regression analysis of different subindustries in strategic emerging industries.

Variable	Next-generation information technology	Advanced equipment manufacturing	New material industry	Biological industry	New energy automobile industry	New energy industry	Environmental protection industry
L.FC	-0.238^{***} (0.066)	-0.084^{*} −0.049	−0.011 (0.039)	0.211 (0.170)	-0.126^{*} (0.073)	0.178 (0.143)	−0.005 (0.041)
L.size	−0.098 (0.273)	-0.586^{***} (0.161)	-0.642^{***} (0.136)	−0.579 (0.723)	−0.065 (0.211)	−0.077 (0.212)	-1.002^{***} (0.204)
L.TobinQ	0.025 (0.054)	0.002 (0.060)	0.082^{*} (0.042)	0.004 (0.149)	0.037 (0.134)	1.011^{**} (0.496)	-0.263^{***} (0.058)
L.Concentr	−0.021 (0.020)	-0.025^{**} (0.012)	0.008 (0.009)	−0.075 (0.055)	−0.008 (0.014)	0.006 (0.013)	0.009 (0.008)
L.Sgrowth	0.009^{***} (0.002)	−0.000 (0.001)	0.006^{***} (0.002)	−0.002 (0.007)	−0.001 (0.003)	0.008 (0.006)	−0.001 (0.001)
Age	-0.276^{***} (0.073)	-0.096^{*} (0.050)	0.020 (0.039)	−0.249 (0.179)	−0.036 (0.056)	0.041 (0.031)	-0.071^{*} (0.040)
Sample size	290	257	95	43	19	14	24

Notes: according to the Guiding Catalogue of Key Products and Services for Strategic Emerging Industries (2016 Edition) issued by the National Development and Reform Commission in 2017, the strategic emerging industries are divided into nine sectors (including related service industries). Considering the small number of samples of digital cultural and creative industries and related service industries, they are not separately analyzed by industry.

Columns 2 to 8 of Table 2 report the effects of financing constraints in different subindustries in strategic emerging industries on technological innovation. It is found that there are pronounced industry differences in the impact of financing constraints on technological innovation. Except for the biological industry and new energy industry, the impact of financing constraints on technological innovation investment in the other five industries is uniformly negative. In the new generation information technology industry, advanced equipment manufacturing and new energy vehicle industry with high R&D intensity, the negative impact is statistically significant, but not in the new material industry and energy conservation and environmental protection industry with relatively low R&D intensity. This is because the higher the R&D intensity is, the more the money for R&D investment will be, and the stronger the influence of financing constraints will be. In the regression analysis of the biological industry and the new energy industry, the financing constraints' coefficient is not negative. The main reason is that these two industries are industries with relatively small financing constraints and are less affected by financial factors. Therefore, financing constraints have no obvious inhibitory effect on technological innovation, and thus, Hypothesis 2 has been verified.

5.2.2. Whether It Is a Manufacturing Enterprise. We divide the listed companies in strategic emerging industries into manufacturing and nonmanufacturing industries according to the classification standards of China's high-tech industries. The regression results of Table 3 show that the inhibitory effect of the financing constraints on the technological innovation input and output of the manufacturing industry is lower than that of the nonmanufacturing industry. The possible reason is that China's labor costs have risen sharply, which has seriously affected the operating profits of enterprises in the labor-intensive and capital-intensive manufacturing industries. Therefore, the manufacturing industry is more willing to improve labor productivity through technological innovation, and technological innovation is of greater significance to manufacturing enterprises. Manufacturing companies invest more in R&D and have a longer cycle for capital recovery. Once the technical innovation project is launched, the funds need to be continually invested. Otherwise, the invested cost will become a sunk cost and cannot be recovered. The characteristic of high adjustment cost of R&D input is more obvious in the manufacturing industry, and manufacturing enterprises will pay more attention to the sustainability of R&D. Therefore, technological innovation will not react so sensitively to the capital situation. Even if the financing constraints are intensified, the technological innovation in the manufacturing industry will not be reduced rapidly but need a long time to adjust. However, nonmanufacturing industries are mostly asset-light enterprises, which involve relatively less investment in technological innovation, with low R&D intensity and less dependence on technological innovation. Therefore, in these enterprises, technological innovation is more sensitive to the financial situation, and thus, Hypothesis 3 has been verified.

5.2.3. Level of the Dependence of Industry External Financing. The companies are divided into two groups according to the external financing dependence in the industry to test whether the inhibitory effect of financing constraints on technological innovation is related to the external financing dependence of the industry. One group are the companies with low external financing dependence and the other are the companies with medium- and high-level external financing dependence. The grouping results of the sample in Table 4 show that only a few strategic emerging enterprises

Table 3: The classification test results of manufacturing enterprises and nonmanufacturing ones.

Variable	R&D concentration		R&D intensity		Number of patent applications	
	Manufacturing	Nonmanufacturing	Manufacturing	Nonmanufacturing	Manufacturing	Nonmanufacturing
L.FC	−0.015 (0.012)	−0.094** (0.043)	−0.100*** (0.035)	−0.151** (0.075)	−0.021* (0.012)	−0.061* (0.034)
All controls	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled
Sample size	543	214	543	214	484	144

Table 4: The classification test result of the level of the external financing dependence in the industry.

Variable	R&D concentration		R&D intensity		Number of patent applications	
	Low external financing dependence	Medium- and high-level external financing dependence	Low external financing dependence	Medium- and high-level external financing dependence	Low external financing dependence	Medium- and high-level external financing dependence
L.FC	0.107 (0.113)	−0.034** (0.014)	−0.060 (0.117)	−0.116*** (0.033)	−0.003 (0.088)	−0.021* (0.013)
All controls	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled
Sample size	14	743	14	743	14	614

are in the industries with low-level external financing dependence, with only 14 samples, accounting for 1.9% of the total samples. It indicates that most enterprises in the strategic emerging enterprises are in the industries with high external financing dependence. The regression results in Table 4 show that the negative effect of financing constraints on the technical innovation input and output is not significant in the samples of industries with low external financing dependence. However, in the industry with medium- and high-level external financing dependence, the impact of financing constraints on the technical innovation's input and output is significant at the 10% significance level, and thus, Hypothesis 4 has been verified.

5.3. *The Moderating Effect of the External Environment*

5.3.1. The Economic Uncertainty as the Moderator. As an external factor affecting enterprises' technological innovation, economic policy has an impact on the technological innovation activities of enterprises from a macroperspective. Once a country's economic policy changes, enterprises' innovation activities will inevitably be affected by the policy.

Columns 2 and 3 in Table 5 are the regression results after adding the cross terms of economic policy uncertainty and financing constraints to the regression model. It shows that the negative effect of financing constraints on technological innovation is still significant, and the coefficient of the cross term is significantly positive, indicating that economic policy uncertainty alleviates the inhibitory effect of financing constraints on technological innovation. Specifically, when the uncertainty of the economic policy environment increases, the inhibitory effect of financing constraints on the technological innovation input may be reduced. There are two main explanations. On the one hand, the increasing uncertainty of economic policy means that enterprises' business environment will change significantly.

Table 5: The moderating effect of economic policy uncertainty.

Variable	R&D concentration	R&D intensity
L.FC	−0.069*** (0.026)	−0.286*** (0.060)
L.size	−0.273*** (0.050)	−0.592*** (0.120)
L.TobinQ		−0.022 (0.029)
L.Concertr	−0.009** (0.004)	−0.025*** (0.009)
L.Sgrowth	−0.000 (0.000)	−0.002*** (0.001)
Age	−0.037** (0.015)	−0.160*** (0.036)
EPU*L.FC	0.000* (0.000)	0.001*** (0.000)
EPU	0.003*** (0.001)	0.013*** (0.002)
Constant	8.409*** (1.162)	15.80*** (2.775)
Sample size	757	757

This is both an opportunity and a challenge, and the survival of the fittest among enterprises will be presented. Only those enterprises with high production efficiency and strong competitiveness can finally survive in the industry. Furthermore, innovation ability is the key factor for enterprises to enhance their core competitiveness. Enterprises can make use of the opportunities brought by the economic policy uncertainty and improve their core competitiveness by increasing the input in technological innovation activities so as to boost their chances of winning in the future market competition. On the other hand, the uncertainty of economic policies will then spread to the external financing market, leading to the fluctuation of the capital market, and then affect the external financing of technological innovation. According to the research of Li and Yang [47], it can be seen that the economic policy uncertainty inhibits general investment activities. Therefore, when economic policy uncertainty increases, ordinary investment activities will not be active, and there will be abundant capital in the capital market. However, technological innovation was fraught with uncertainty and the future is full of opportunities. When the economic policy uncertainty increases, financing for technological innovation is more likely compared with general investment activities. Therefore, economic policy uncertainty can ease the inhibitory effect of financing constraints on technological innovation, and thus, Hypothesis 5 has been verified.

5.3.2. The Marketization as the Moderator. Columns 2 and 3 in Table 6 are the regression results after adding the cross terms of marketization and financing constraints to the regression model. It shows that the coefficient of financing constraints is significantly negative, the coefficient of marketization is significantly positive, and the coefficient of a cross term is significantly positive, indicating that the marketization can help to alleviate the inhibitory effect of financing constraints on technological innovation. Specifically, when the market environment improves, the inhibitory effect of financing constraints on technological innovation will be reduced. Therefore, the more the market-oriented, the lower the inhibitory effect of financing constraints on technological innovation and vice versa. In the end, the Matthew effect occurs when the strong get stronger and the weak get weaker. Under such effect, the differences in technological innovation between regions are constantly widened. The possible explanation is as follows.In highly market-oriented regions, there are a sound legal system, high information transparency, a more robust financial system sound, and abundant financial resources. Such a perfect institutional environment can ease the enterprise's financing constraints, provide a proper external financing environment for technological innovation, and better escort the enterprise's technological innovation, which is conducive to encourage enterprises to carry out technological innovation. In regions with less market-oriented, it is impossible to provide a strong institutional guarantee for technological innovation. For an enterprise facing financing constraints, this adverse institutional environment intensifies the inhibitory effect of financing constraints on technological innovation and is not conducive to the enterprise's technological innovation, and thus, Hypothesis 6 has been verified.

Table 6: The moderating effect of the marketization.

Variable	R&D concentration	R&D intensity
L.FC	-0.036^{***} (0.012)	-0.168^{***} (0.030)
Marketization	0.838^{***} (0.266)	1.319^{**} (0.658)
Marketization*L.FC	0.017^{***} (0.005)	0.024^{*} (0.013)
All controls	Controlled	Controlled
Sample size	757	757

5.4. Robustness Test

5.4.1. Solutions to Endogenous Problems. Financial constraints inhibit enterprises' technological innovation activities, and technological innovation may make financial constraints of enterprises get more serious, thus leading to a bidirectional causal relationship between financial constraints and technical innovation. In order to avoid possible reverse causality, all control variables and the explanatory variables are delayed by one period. Simultaneously in the study, to avoid the endogenous problems caused by the omitted variables, the industry and time fixed effects are controlled in the empirical analysis.

5.4.2. Recalculation of Financing Constraint Index. In the empirical analysis, we use the FC index to measure the financing constraints. However, there are various methods to measure the constraints with different emphases. In order to ensure robust conclusions, the SA index proposed by Hadlock and Pierce [48] is used to remeasure the financing constraints. That is, $SA = -0.737\,\text{Size} + 0.043\,\text{Size}^2 - 0.04\,\text{Age}$. The above empirical process is then repeated to check whether the financing constraints have an inhibitory effect on technological innovation.

The SA index is generally negative. The greater the absolute value of SA is, the more serious the financing constraints faced by the enterprise will be. Therefore, the SA index is negatively correlated with the level of financing constraints. The regression results in Table 7 show that the SA index is positively correlated with technological innovation at the significance level of 5%, indicating the more serious the financing constraints is, the stronger the inhibitory effect on technological innovation activities will be. This is consistent with the conclusion of the test based on the FC index, which once again verifies that financing constraints have an inhibitory effect on technological innovation.

5.4.3. Recalculation of the Technological Innovation Output. The increment of intangible assets is adopted to remeasure the technological innovation output following Ju et al. [49]. Moreover, the ratio of the increment of intangible assets to the total assets at the end of the period is used as the proxy variable of the technological innovation output to remeasure the technological innovation output. Finally, the empirical results of the influence of financing constraints on the technological innovation output are shown in Table 8.

The results in Table 8 show that financing constraints have a significant inhibitory effect on the technological innovation output, regardless of if the FC index or SA index is used. It is consistent with the conclusion where the number of patent applications is adopted as the technological innovation output.

5.4.4. The Ordinary Panel Model as the Counting Model. The panel counting model is used to study the influence of financing constraints on the technical innovation output, which shows that financing constraints have a significant inhibitory effect on the technological innovation output. In order to test the robustness of the results, the number of patent applications as the explained variable is taken as a continuous common variable, and then the ordinary panel model is used for empirical analysis. The empirical results are shown in Table 9.

As shown in Table 9, the conclusion obtained using the ordinary panel model is that the financing constraints significantly inhibit the technological innovation output. After

Table 7: Regression results of the impact of financing constraints on technological innovation through the SA index.

Variable	R&D concentration	R&D intensity	Number of patent applications
L.SA	0.351*** (0.135)	0.995*** (0.316)	0.300* (0.182)
L.LEV	−0.444* (0.240)	−4.102*** (0.549)	−0.003 (0.002)
L.TobinQ	0.003 (0.013)	−0.039 (0.030)	−0.005 (0.012)
L.Concentr	−0.010** (0.004)	−0.020** (0.0098)	−0.000 (0.0037)
L.Cflow	0.004* (0.003)	−0.004 (0.006)	
L.tangibility	0.011*** (0.003)	0.002 (0.006)	
L.Sgrowth	−0.011 (0.023)	−0.118** (0.053)	
Constant	2.159*** (0.592)	5.283*** (1.360)	−9.301*** (1.361)
Sample size	757	757	628

Table 8: Robustness test results of intangible assets increment.

Variable	FC index	SA index
L.FC	−0.042** (0.019)	0.249** (0.108)
L.size	0.000 (0.041)	
L.TobinQ	0.039** (0.019)	0.037* (0.019)
L.Concentr	0.000 (0.003)	0.002 (0.003)
L.Cflow	−0.014*** (0.004)	−0.012*** (0.001)
L.Sgrowth	−0.009 (0.042)	0.004 (0.042)
Age	−0.039*** (0.008)	
L.tangibility		0.000 (0.003)
Constant	0.508 (1.039)	0.316 (0.593)
Sample size	757	757

Table 9: Robustness test results of the ordinary panel model.

Variable	Number of patent applications	Number of invention patents	Number of noninvention patents
L.FC	−0.045*** (0.012)	−0.059*** (0.012)	−0.028** (0.013)
L.TobinQ	−0.003 (0.008)	0.002 (0.008)	−0.018** (0.009)
L.Concertr	0.005** (0.002)	0.004 (0.003)	0.006** (0.003)
L.Sgrowth	−0.000 (0.000)	−0.000 (0.000)	−0.000 (0.000)
L.lev	0.017*** (0.002)	0.017*** (0.002)	0.016*** (0.002)
Age	0.003 (0.009)	0.012 (0.010)	−0.004 (0.010)
L.Cflow	−0.004** (0.002)	−0.005*** (0.002)	−0.003 (0.004)
Sample size	691	691	691

dividing the number of patent applications into invention patents and noninvention patents, we find that the inhibitory effect of the financing constraints on the invention patents is significantly higher than that of the noninvention patents, which is consistent with the conclusion obtained using the negative binomial regression model of panel data.

6. Conclusions and Implications

As the world economy enters a stage of innovation competition, the decision-making problem of technological innovation in emerging industries is a practical problem worthy of research and attention. Based on the panel data of the listed companies in China's strategic emerging industries from 2009 to 2019, we adopt the negative binomial regression model of panel data and empirically study the technological innovation decision-making issues of emerging industries from the perspective of financing constraints. Our results show that the financial constraints in strategic emerging industries in China significantly inhibit technological innovation in terms of technological innovation inputs and outputs. What is more, the inhibitory effect of substantive innovation like the invention patent is more pronounced than that of strategic innovation like the noninvention patent. The influence of financing constraints on technological innovation varies significantly between industries within strategic emerging industries, manufacturing industries and nonmanufacturing industries, and among industries with different external financing dependence. However, the economic policy uncertainty and the marketization can help to alleviate the inhibitory effect of financing constraints on technological innovation.

Our research conclusions lead to the following policy implications. First of all, the government should focus on solving the financial constraints by speeding up the reform of the financial system. Promoting the reform of the financial supply side, improving the efficiency of financial resource allocation, and reducing the financing cost should also be emphasized. In addition, it is necessary to expand the coverage of financial services, to develop financing platforms and tools exclusive to R&D intensive industries, such as strategic emerging industries, and to encourage venture capital and long-term capital to invest in technological innovation projects. A technological innovation financing system based on the market mechanism, guided by government investment, dominated by enterprises and widely participated by social funds, should be established. More financial resources can flow to technological innovation projects and to enterprises with technological innovation activities.

Second, at present, China's economy is in a "new normal" that requires innovation. In view of the selective effect of financing constraints on innovation activities, relevant departments should make effort to build a good external financing environment and use effective financial policies and administrative methods to help enterprises release their innovative vitality more fully. For example, relevant departments should pay attention to building a good market-oriented system and increase institutional guarantees for innovative activities, so as to improve the operating conditions of enterprises and promote high-quality innovative activities. When companies face financing constraints, these measures that are conducive to improving operating conditions will help to stimulate innovation.

Finally, since the financing constraints have a more obvious restraining effect on enterprises' substantive innovation of high quality, the government should encourage enterprises to increase R&D investment in substantive innovation [50–53], while guiding them to pursue high-quality innovation, so as to avoid such innovations that emphasize only the quantity and speed. In addition, the government also should continue to increase financial investment in basic research for making up for the lack of substantive innovation of enterprises and aiming to truly improve innovation ability and quality of the enterprise.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this study.

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Research Article

Sovereign CDS Premiums' Reaction to Macroeconomic News: An Empirical Investigation

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We assess the efficiency of the sovereign credit default swap (CDS) market by investigating how sovereign CDS spreads react to macroeconomic news announcements. Contrary to the vast majority of the existing literature, one of our main findings supports the hypothesis that news announcements reduce market uncertainty and, thus, that both better- and worse-than-expected news lower CDS prices during our sample period. In addition, we find that CDS spreads respond differently to the four macroindicators across the three different regions. Our findings might help investors in these areas to interpret the surprises of macronews announcements when making decisions in CDS markets.

1. Introduction

Sovereign credit default swaps (CDS) are deemed to accurately capture the inherent credit risk within a country's economy. The sovereign CDS market has been under intense scrutiny in the last decade, following the European sovereign debt crisis that started in 2008 with the collapse of Iceland's banking system and then spread to other countries such as Greece and Portugal during 2009. Whether the spread of sovereign CDS can efficiently reflect the risk related to a country's economy is of great importance [1]. In this paper, we conduct an event study to assess the efficiency of the sovereign CDS market by investigating how the sovereign CDS spread reacts to four types of macroeconomic news: gross domestic product (GDP), consumer price index (CPI), unemployment rate, and consumer sentiment announcements. Our empirical study also aims to test whether news announcements increase or decrease the uncertainty of the sovereign CDS market.

Our paper fits into two streams in the literature. The first is the study of the financial markets' reactions to macro news announcements. For instance, Andersen et al. [2] investigated the incorporation of macroeconomic fundamentals into different security prices and found that the dynamics of the exchange rates are linked to fundamentals. Balduzzi et al. [3] consider the effect of 26 macroeconomic variables on the US Treasury bond prices ascertaining the significance of 17 public releases as well as an aftermath drift due to the new information. Bond prices are investigated by Beetsma et al. [4] who found that bond yield spreads are deemed to be volatile during announcement speeches with consistent spillover effects. Andritzky et al. [5], Arru et al. [6], and Kurov and Stan [7] modeled the bond volatilities in emerging markets and the US bond market. Vrugt [8] tested whether macroeconomic announcements play a role in the determination of conditional means, variances, and covariances in the stock and bond markets. The answer is affirmative, and the author also found a postannouncement drift towards the direction of the news.

The second stream focuses on the sovereign CDS spread and is relatively newer than the first stream but still includes a broad range of studies performed in the past two decades. For instance, Heinz and Sun [9] and Chebbi and Sarraj [10] investigated the variables underlying the movements of the sovereign CDS spreads focusing on the Euro area countries after the subprime mortgage financial crises. They found that the sovereign market moves from three different viewpoints: global investor sentiment proxied by the VIX index, the liquidity in the CDS market represented by the CDS bid-ask spreads, and a set of macroeconomic indicators such as the GDP growth rate, predicted fiscal deficit, and forecast of current account balance and public debt to GDP ratio. All these factors are highly significant in the determination of the sovereign market movements both before and after 2012. Longstaff et al. [11] investigated the sovereign credit risk by CDS and bond yield spreads between 2007 and 2010. They found theoretical evidence of global factors, risk premiums, and investment flows accounting for movements in the sovereign credit risk more than the country-specific factors such as macroeconomic fundamentals. Narayan and Bannigidadmath [12] found that CDS spreads changes are dominated by forecasting models that use positive news as a predictor.

Our paper complements the extant macroeconomic news and sovereign CDS theoretical contributions. It additionally deepens the knowledge about the sovereign CDS premiums' behaviour. We take inspiration from related studies, yet our work differs from the previous studies in some aspects.

Specifically, instead of using straight news announcements, we focus on the way that better/worse-than-expected news (i.e., news surprise) affects sovereign CDS quotes. Better/worse-than-expected news contains a greater/smaller released value than the economic consensus. By analysing the effects of news in this manner, it is possible to test the informational efficiency of the market and the promptitude with which sovereign CDS prices incorporate new information.

Additionally, the majority of the past works including the aforementioned papers typically concentrate on the determinants of market returns or CDS spread and employ regression analysis to test the significance of multiple variables. In this paper, we employ an event study approach that allows us to evaluate not only the overall magnitude of the effect on the announcement day but also the effect in the long run. To the best of our knowledge, to date, no event study that focuses on the global sovereign CDS market and public news surprises about contingent countries' fundamentals has been performed. Therefore, we mainly base this work on few reference studies trying to advance with respect to the analytic procedures and interpretations of the economic results. Greatrex [13] conducts an event study that investigates the CDS and stock corporate markets' efficiency in absorbing corporate earnings surprises. The authors found that news has a significant impact on both markets and that CDS prices are inversely correlated with good and bad news. Furthermore, market efficiency is examined, and it is reported that both CDS and stock prices anticipate the news as confirmed by abnormal returns. Kim et al. [14] carry out an analysis based on the domestic and spillover news effect on the US, China, and the eurozone sovereign CDS market. In addition to the central focus on the international responses to domestic news, they ascertain that good news has an economic and statistically greater impact on CDS prices than bad news.

For the sake of developing a deeper understanding of what drives sovereign CDS premiums, this study aims to address 3 main research questions that are based on the conventional literature intuitions proposed by Beetsma et al. [4] and Conrad et al. [15] and go beyond them, focusing the analysis on the specific macroeconomic indicators as described in Heinz and Sun [9]:

First, we note that there is some very recent literature on the effects of news announcement from an information theoretic approach. For instance, Ehrmann et al. [16] found that release of public information may increase or decrease the uncertainty of the market, depending on how central banks reflect the news. See also Kurov and Stan [7] for empirical results on reactions of equity and the crude oil market to the fluctuations of uncertainty due to the release of macro news. Since the sovereign CDS market is supposed to capture the risk related to a country's economic environments, we hypothesise that the announcement of the four macroeconomic indicators will reduce the uncertainty and thus lower the CDS price. Second, we also check if individual variables are effective enough to produce abnormal CDS spread changes. Third, we investigated whether the reaction of the CDS market to macroeconomic fundamentals is the same across three geographic regions, namely, Europe, the Middle East, and Africa (EMEA) region, and the American and Asian Pacific countries.

The event study enables us to obtain the following interesting findings. Better-than-expected news and worse-than-expected news both lower sovereign credit default swap prices within the sample interval. This finding appears odd, and we give some explanations for this finding below. However, the magnitude of the effect does vary with reference to the event window considered. The reaction to positive surprises is valued more by market participants than negative deviations. Moreover, single macroeconomic fundamentals provoke different drifts in the credit derivative market quotations. Gross domestic product and unemployment rate announcements reflecting the current economic situation are found to be ineffective in conditioning CDS prices. In contrast, consumer price index and consumer sentiment releases have a robust effect over the estimated economic period. Macroregional factors represent a further viewpoint from which to evaluate the impact of news. The EMEA region is more receptive to negative releases, whereas American and Asian countries appear to need longer to incorporate the news with evidence of informational leaks.

Overall, we try to obtain evidence that the subprime mortgage financial crisis and the European sovereign debt crisis had a significant impact on the perception of news announcement by the market. The fact that macroeconomic fundamentals' impact on security prices is time-varying is unanimously agreed upon in the literature. Hence, it seems worthwhile to extend the past research and examine whether the effectiveness of the considered variables has substantially changed over time.

The remainder of this paper is organised as follows. The dataset and news indices are given in Section 2. The employed methodology to answer the three questions mentioned above is outlined in Section 3. Section 4 gives the main results of the event study, while Section 5 concludes the paper.

2. Data and Descriptive Statistics

2.1. CDS Spread Patterns and Changes. The global sample takes into account sovereign CDS historical prices downloaded from Thomson Reuters DataStream. We select the average bid-ask quotations of sovereign CDS premiums, denominated in EUR and USD, with a 5-year maturity written on a senior debt reference obligation. This choice is because 5-year maturity assets are the most liquid and traded in the sovereign CDS market and are the dataset with continuous time observations. The number of contributors and the bid-ask spread generally represent two proxies for CDS market liquidity. Hence, the 5-year credit default swap exhibits a smaller bid-ask differential than longer maturities. The sample consists of 18 countries, representing 3 different macroregions: ten EMEA countries (France, Germany, Greece, Italy, Portugal, Spain, United Kingdom, Ukraine, Russia, and Turkey), as well as four American countries (Brazil, Colombia, Mexico, and Venezuela.), and four Asian Pacific countries (Australia, China, Indonesia, and Philippines.). The average of the daily CDS premiums is shown in Figure 1. The selection of the countries is the result of an accurate picking-up process. First, the countries have been chosen based on the availability of historical CDS prices. The second factor is the frequency of the key fundamentals' statements. For the nations in the sample, both the announced value and economic consensus of the specific macroeconomic indicator are reported. Moreover, the susceptibility to news played an important role in the determination of the series as well as the geographical location of the aforementioned states. Last, all the countries in the sample appear in the member list of the two sovereign CDS indices that we use to compute the market return proxy.

Although a large part of literature has focused on the analysis of CDS spread responsiveness to news during the subprime mortgage crisis and the subsequent months, we concentrate on the economic period (June 1, 2009, to June 1, 2016) that coincides with the European sovereign debt crisis and its consequences over the following years to date.

By examining the CDS prices at level, we can spot similar macroregional patterns within the analysed time period. EMEA region countries show a recovery trend from the subprime mortgage crisis in the first sample half and are characterised by the European sovereign debt crisis in the second half. Focusing on individual countries, Germany presents the lowest mean CDS spreads, with 25.20 basis points per annum (bps) over the analysis period, whereas Greece exhibits the highest values (2904.02 bps). American countries exhibit low volatility between 2010 and 2015. However, these countries show an interesting downturn that began in the second half of 2015 due to a sharp depreciation of home currencies, an increase in foreign exchange market volatility, and a plunge in oil prices. Brazil, Colombia, and Mexico present a similar level of riskiness, with a mean CDS spread of 185.73 bps, 152.17 bps, and 135.96 bps, respectively, whereas Venezuela stands out with an average of 2041.56 bps as it has recently experienced economic distress due to oil supply and prices. Asian countries are more tranquil. Insurance on Australian and Chinese issued debt (respectively, 51.53 bps and 95.50 bps as average annually paid premium) is found to be less risky than Indonesian and Philippine reference obligations (respectively, 203.79 bps and 142.90 bps on average).

For the purpose of the analysis, following Andres et al. [17] and Bouzgarrou and Chebbi [18], we define the daily relative spread changes as

$$\Delta SC_{i,t} = \ln\left(SC_{i,t}\right) - \ln\left(SC_{i,t-1}\right), \quad (1)$$

where $SC_{i,t}$ is the level of CDS spread for country i at time t. Descriptive statistics for $\Delta SC_{i,t}$ are shown in Table 1. It is important to note that consistent with the literature ([14, 19], among others), CDS daily relative spread changes are nonnormally distributed, are either positively or negatively skewed, and exhibit excess kurtosis.

2.2. CDS Indices. For the event study investigating *abnormal* change in the CDS spread, we need to obtain the *normal* CDS performance. For this purpose, we compute an *ad hoc* market return index as the normal CDS spread:

$$I = \frac{\text{iTraxx SWE index} + \text{CDX index}}{2}. \quad (2)$$

So, I is the average of two of the main sovereign CDS indices quoted daily by the Markit: iTraxx SOVX Western Europe (SWE) and CDX index (indices taken from Bloomberg.). The first index contains 14 of the most relevant Western European countries in the member list, and the CDX index specifically applies to emerging markets (the Markit iTraxx SOVX Western Europe index is composed of the credit default swaps written on the following countries: Austria, Belgium, Denmark, Finland, France, Germany, Ireland, Italy, Norway, Portugal, Spain, Sweden, The Netherlands, and United Kingdom. The reference entities composing the Markit CDX Index are as follows: Argentina, Brazil, Chile, China, Colombia, Indonesia, Malaysia, Mexico, Panama, Peru, South Africa, the Philippines, Turkey, Russia, and Venezuela). The reason behind this choice is motivated by the fact that with the exception of the USA and Australia, all the sample countries are listed in the member count of the indices. Hence, averaging the two indices enables us to represent the general level of normal return of the studied CDS sovereign market as a whole.

2.3. News Announcements. Although the vast majority of the literature takes into account forward-looking indicators, we assess the CDS premiums' reaction to the gross domestic product, consumer price index, unemployment rate, and consumer sentiment announcements. There are several reasons behind this choice. First, we want to test whether economic publication reflecting the current health of the economy can cause abnormal CDS spread changes in the sovereign market. Second, recalling that both CDS quotations and sovereign bond yield spreads can be used as indicators for country-specific default risk, we investigate whether the principal bond yield movers, as outlined in Goldberg and Leonard [20], can account for the movements

Figure 1: Mean daily CDS spreads for the sample countries.

Table 1: Descriptive statistics for the CDS relative spread changes.

Country/stat.	Mean	Maximum	Minimum	Std. dev.	Skewness	Kurtosis	Observations
Australia	51.5334	185.0000	25.0000	22.9668	2.3237	10.2637	1935
Brazil	185.7271	500.7400	90.9200	93.2134	1.5661	4.5322	1935
China	95.4965	259.5000	52.0000	32.2197	1.9379	8.2059	1935
Colombia	152.1739	499.1804	73.8500	68.8704	2.1985	8.9345	1935
France	50.8484	171.5600	14.0060	33.0462	1.3910	4.2849	1935
Germany	25.2047	92.5000	6.6400	16.8817	1.1769	4.0890	1935
Greece	2904.0200	26466.1700	102.9000	4565.8880	2.9355	12.5862	1935
Indonesia	203.7914	700.0000	124.7800	96.2232	3.2830	14.6363	1935
Italy	166.5527	498.6599	48.0000	102.1450	1.4038	4.1151	1935
Mexico	135.9627	491.6130	64.1700	60.8877	2.8531	13.1588	1935
Philippines	142.9045	485.0000	80.4000	64.6305	2.5458	10.9291	1935
Portugal	359.4365	1521.4500	37.0000	321.3420	1.4492	4.0329	1935
Russia	227.9381	793.2000	105.7100	122.1865	2.2847	9.3000	1935
Spain	160.7141	492.0698	45.4200	101.5039	0.9712	3.1203	1935
Turkey	196.7231	515.1567	99.9160	62.7601	1.8561	8.7117	1935
UK	47.9505	165.0000	11.6600	27.3410	1.1637	4.9223	1935
Ukraine	1231.7000	8943.8200	409.1700	987.3895	2.4701	10.4437	1935
Venezuela	2041.5590	10995.6700	571.4189	1953.1060	1.7593	5.0619	1935

in the national CDS market. Third, as explained by the European Commission in the "Key Economic Indicators" report, the variables represent four different key macroeconomic indicators. Whereas GDP and CPI are the most relevant indicators for the national output and prices, unemployment rate and consumer sentiment are proxies for the labour market and private consumption. We exclude the announcements with a lower value than 60% in the Bloomberg relevance index (the Bloomberg relevance index shows the country-related percentage of importance given to a specific news announcement). According to the employed methodology, we are only concerned about the specific variable's releasing date, expectation, and realisation.

To overcome the problem of different units of measurement among the variables and facilitate meaningful comparisons, we apply the approach in Balduzzi et al. [3] and Andersen et al. [2], which computes standardised news as follows:

$$S_{k,t} = \frac{A_{k,t} - E_{k,t}|\Omega_{t-1}}{\sigma_k}, \quad (3)$$

where $S_{k,t}$ is the standardised news value of the indicator k at time t, $A_{k,t}$ is the actual and unrevised announcement of the indicator k at time t, $E_{k,t}$ is the Bloomberg survey median for the release of indicator k at time t used as the expected value (Vrugt [8] suggests that the economic consensus is usually accurate as it is computed through a transparent process. The expectations are collected through surveys and it is easily possible to differentiate the analysts' individual perspectives. Once the predicted values are gathered, the median of the sample will represent what it is known as "market economic consensus" for a particular variable.) based on information available Ω_{t-1} prior to the releases of the indicator, and σ_k is the standard deviation of $(A_{k,t} - E_{k,t})$ over the sample period.

To clarify the news standardisation procedure, consider an example where k = GDP. On September 28, 2011, the quarterly announced French GDP year-over-year (YoY) value was $A_{k,t} = 0.017$. This observation compared to the expected economic consensus $E_{k,t} = 0.016$ based on the public information gives a differential of 0.001. Considering that the differential is positive, we can interpret it as a release of positive surprise. Therefore, we can categorise it as *positive news*. Considering that the computed sample standard deviation is $\sigma_k = 0.00064$, we obtain $S_{k,t} = 1.56$. As another example, we can compute the standardised German monthly unemployment rate news published on October 27, 2010, which is $S_{k,t} = 1.52$. Since a greater unemployment rate than the economic forecast indicates a negative outlook, we can interpret this result as *negative news*.

These numerical examples help to provide an overview of how we categorise the announced value. The next step in our methodology is the determination of a threshold that represents a delimiting point in the computation of the positive, negative, and no news indices. Since many studies such as that of Greatrex [13] use a threshold of ±2.5%, which is adapted to the specific conducted analysis, we set this value at ±0.455. We compute this ad hoc delimiter because the absolute value of the range of positive standardised news goes from 0 to 3.46, whereas that for negative news goes from 0 to 4.69. Therefore, we want to create indices that have as balanced a number of observations as possible in order to avoid biasing our estimation because of a disproportionate news dataset (if we use the same delimiters as Greatrex [13], we will have a very unbalanced pool of good news and bad news).

The first index takes into account the statements in which the released value overperforms the expectation. Therefore, we refer to this index as the "good" or "better than expected" news index. Mathematically, we only count standardised surprise values greater than 0.455. Economically, we include greater than expected GDP and consumer confidence values and smaller than expected CPI and unemployment rate observations. In contrast, we estimate a "bad" or "worse than expected" news index using lower than expected GDP and consumer confidence value as well as greater than expected CPI and unemployment rate. In this case, the delimiter is the ad hoc computed value −0.455. As stated above, this specific value is not taken from the literature. Hence, we reasonably introduce an alternative approach in order to check if it will lead to additional economically significant results. The better-than-expected news index comprises 970 announcements, whereas 775 releases compose the worse-than-expected news index. All the remaining announcements that are not part of the aforementioned indices are labelled "no news" because of a lack of effectiveness on the CDS spreads. These values are not taken into account in the analysis.

Tables 2 and 3 show the news announcements for each country grouped by the respective macroregions.

3. Methodology

The methodology that we employ to test the effects of macroeconomic announcements on the sovereign CDS prices is an event study that aims to measure the impact of an event on financial asset prices or firm's value. The first task in an event study is the determination of the occurrence to investigate over a predetermined period known as the event window. Consistent with Greatrex [13], the main event window [−1; 1] starts one trading day before the event date and ends on the subsequent day. Additionally, we extend the event window [−20; 20] to 20 trading days before and after the event date. The usefulness of a very short window can be identified from the fact that given the informational rationality of the market, security prices will reflect the new events immediately. Moreover, it is possible to evaluate the investor's reaction after the market closes. A longer observation interval will allow us to test the efficiency of the CDS sovereign market through the detection of information leaks, nonimmediate effects, and premiums drifts.

The estimation window starts 100 trading days (we assume that 100 trading days before the announcement represent a long enough time interval to estimate the normal performance without the price pattern being affected by any event effect. The estimation window stops 21 trading days prior the release day in order not to overlap with the preannouncement interval) before the event date and all of the relevant dates are represented in Figure 2.

The estimation window goes from 100 trading days to 21 days before the event date. A longer window takes into account 20 trading days before and after the announcement, whereas a shorter window only focuses on 3 trading days around the release day.

The next step in the event study procedure is the calculation of the normal performance of the sovereign CDS. This is a fundamental part of the analysis and consists of simulating what the CDS price path would have been without the impact of the event. Many different approaches for the computation of the normal performance have been introduced in the literature, and we adopt the market model cited in MacKinlay [21]. It first uses the data from the estimation period to regress the actual CDS spread changes $\Delta SC_{i,t}$ on a constant and the market index premiums changes ΔI_t, where I_t is defined as in (2):

$$\Delta SC_{i,t} = \alpha_i + \beta \Delta I_t + \varepsilon_{i,t}, \quad (4)$$

where $\varepsilon_{i,t}$ is a homoscedastic disturbance term with zero mean. In this case, we should not be concerned about the overlapping effect between the different countries because the normal performance is estimated independently for each state.

Once the intercept and the beta coefficient are estimated, we calculate the abnormal spread changes $\Delta ASC_{i,t}$ for each announcement as

$$\Delta ASC_{i,t} = \Delta SC_{i,t} - \widehat{\alpha}_i - \widehat{\beta} \Delta I_t. \quad (5)$$

The last step consists of the calculation of the cumulative abnormal spread changes ($\Delta CASC$) of country i, which corresponds to the sum of the $\Delta ASC_{i,t}$ within the event window:

$$\Delta CASC_i = \sum_{t=1}^{T} \Delta ASC_{i,t}. \quad (6)$$

Since there are 18 countries in the sample, we compute $\Delta CASC$ for each country and then the average value. By doing so, we estimate the cumulative average (in Sections 4.1 and 4.2, we take the average of all of the countries in our

Table 2: Number of announcements for each EMEA country.

Europe, Middle East, and Africa					
Variable	Frequency	N. events	Variable	Frequency	N. events
	France			*Russia*	
GDP YoY	Quarterly	25 (4, 6, 15)	GDP YoY	Quarterly	7 (3, 0, 4)
CPI YoY	Quarterly	82 (38, 17, 27)	CPI YoY	Quarterly	72 (15, 8, 49)
UR	Monthly	25 (11, 6, 8)	UR	Monthly	75 (30, 10, 35)
CS	Monthly	146 (61, 49, 36)	CS	Monthly	0 (0, 0, 0)
	Germany			*Spain*	
GDP YoY	Quarterly	26 (0, 0, 26)	GDP YoY	Quarterly	24 (4, 4, 16)
CPI YoY	Quarterly	78 (1, 11, 66)	CPI YoY	Quarterly	77 (2, 14, 61)
UR	Monthly	78 (23, 8, 47)	UR	Monthly	26 (6, 7, 13)
CS	Monthly	178 (60, 47, 71)	CS	Monthly	0 (0, 0, 0)
	Greece			*Turkey*	
GDP YoY	Quarterly	2 (1, 1, 0)	GDP YoY	Quarterly	25 (13, 5, 7)
CPI YoY	Quarterly	12 (3, 5, 4)	CPI YoY	Quarterly	77 (23, 28, 26)
UR	Monthly	48 (16, 9, 23)	UR	Monthly	51 (18, 15, 18)
CS	Monthly	0 (0, 0, 0)	CS	Monthly	7 (3, 1, 3)
	Italy			*United Kingdom*	
GDP YoY	Quarterly	26 (8, 12, 6)	GDP YoY	Quarterly	77 (17, 31, 29)
CPI YoY	Quarterly	76 (12, 14, 50)	CPI YoY	Quarterly	77 (25, 23, 29)
UR	Monthly	25 (10, 5, 10)	UR	Monthly	77 (29, 16, 32)
CS	Monthly	168 (59, 43, 66)	CS	Monthly	89 (26, 27, 36)
	Portugal			*Ukraine*	
GDP YoY	Quarterly	22 (7, 6, 9)	GDP YoY	Quarterly	0 (0, 0, 0)
CPI YoY	Quarterly	46 (15, 11, 20)	CPI YoY	Quarterly	75 (11, 14, 50)
UR	Monthly	0 (0, 0, 0)	UR	Monthly	0 (0, 0, 0)
CS	Monthly	0 (0, 0, 0)	CS	Monthly	0 (0, 0, 0)

This table shows the macroeconomic fundamentals announcements for each EMEA country from June 1, 2009, to June 1, 2016. We report the name of the variable, the frequency of the announcement, and the number of events. In the brackets, we express the number of better-than-expected news announcements, the number of worse-than-expected news announcements, and the announcements correctly anticipated by the market consensus.

Table 3: Number of announcements for each American and Asian Pacific country.

	Americas			Asia Pacific	
Variable	Frequency	N. events	Variable	Frequency	N. events
	Brazil			*Australia*	
GDP YoY	Quarterly	26 (7, 12, 7)	GDP YoY	Quarterly	26 (12, 5, 9)
CPI YoY	Quarterly	77 (18, 20, 39)	CPI YoY	Quarterly	26 (10, 5, 11)
UR	Monthly	72 (32, 15, 25)	UR	Monthly	77 (37, 15, 25)
CS	Monthly	5 (2, 2, 1)	CS	Monthly	0 (0, 0, 0)
	Colombia			*China*	
GDP YoY	Quarterly	25 (8, 4, 13)	GDP YoY	Quarterly	26 (15, 6, 5)
CPI YoY	Quarterly	77 (22, 23, 32)	CPI YoY	Quarterly	77 (29, 29, 19)
UR	Monthly	77 (22, 22, 33)	UR	Monthly	0 (0, 0, 0)
CS	Monthly	30 (8, 12, 10)	CS	Monthly	81 (15, 23, 43)
	Mexico			*Indonesia*	
GDP YoY	Quarterly	26 (6, 9, 11)	GDP YoY	Quarterly	26 (7, 5, 14)
CPI YoY	Quarterly	76 (34, 23, 19)	CPI YoY	Quarterly	78 (31, 20, 27)
UR	Monthly	77 (28, 25, 24)	UR	Monthly	0 (0, 0, 0)
CS	Monthly	89 (22, 31, 36)	CS	Monthly	0 (0, 0, 0)
	Venezuela			*Philippines*	
GDP YoY	Quarterly	19 (7, 4, 8)	GDP YoY	Quarterly	26 (10, 6, 10)
CPI YoY	Quarterly	42 (10, 13, 19)	CPI YoY	Quarterly	77 (33, 12, 32)
UR	Monthly	1 (1, 0, 0)	UR	Monthly	0 (0, 0, 0)
CS	Monthly	0 (0, 0, 0)	CS	Monthly	0 (0, 0, 0)

This table shows the macroeconomic fundamentals announcements for each American and Asian Pacific country from June 1, 2009, to June 1, 2016.

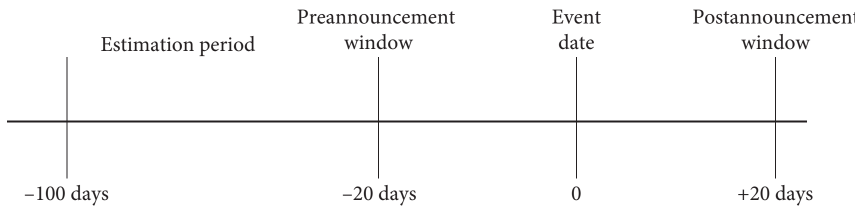

Figure 2: Event study timeline.

sample to investigate the overall reaction of the CDS spread to macro news, while in Section 4.3, we take the average in each region so that we can analyse the differences in the reaction between the three regions) abnormal spread changes (CAASC):

$$\text{CAASC} = \frac{1}{n}\sum_{i=1}^{n} \Delta\text{CASC}_i. \quad (7)$$

Once the CAASC values are determined, we use different test statistics to verify the significance of the changes. Specifically, we test H_0: CAASC = 0 (i.e., the reaction is not significant) against the alternative H_1: CAASC ≠ 0 (i.e., the reaction is significant). Therefore, we investigate whether the CDS prices experience a significant variation due to a precise event against a lack of a substantial reaction in the premiums path.

The vast majority of the literature solely conducts a t-test. However, further enquiries may be employed (the t-test is very straightforward but is subject to cross-sectional correlation and volatility changes, while the Patell test and BMP test are both not influenced by the distribution of ASCs in the event window and account for serial correlation and event-induced volatility but appear to be generally prone to cross-sectional correlation bias. Nonparametric tests do not require any specific distribution of the spread changes and may thus be more powerful than parametric tests. Nevertheless, the literature explains that the generalised sign test accounts for skewness in the return distribution. Therefore, Andres et al. [17] outlined the process steps for a robustness check, based on Barber et al. [22] and Hull et al. [19]. The procedure allows us to correct for the distribution skewness and appears to lead to an improvement in the test efficiency). The adjusted Patell test and Bohemer, Musumeci, and Poulsen (BMP) test are used in our study. These statistics provide better estimates when the variables are normally distributed. In fact, CDS spread changes are positively or negatively skewed and have excess kurtosis. Therefore, to check the validity of the results, we include nonparametric tests. The skewed adjusted test and generalised sign test are components of those test families. A robustness check consisting of the bootstrap methodology completes the result verification. Data-driven nonparametric methods can also avoid the potential problem of heterogeneity across countries.

4. Empirical Results

In light of the research questions, we initially test the CDS prices responses from June 1, 2009, to June 1, 2016, within the main event windows [−20; 20], [−1; 1] and event date [0; 0]. Better/worse-than-expected news indices are assessed separately, which is one of our main contributions. In Tables 4–20, test statistics are reported, while we only consider those significant results that are confirmed by at least three out of six test statistics and at least one parametric and nonparametric test. All the results undergo a robustness check that is performed through a bootstrap process with 1000 resamples, and the bootstrapped p value is reported in the last column of each table.

4.1. Reaction to Contingent News Announcements. Table 4 shows that if we take the whole sample into account, better-than-expected news lowers the CDS spreads. This result is consistent with previous studies such as Greatrex [13], Heinz and Sun [9], and Kim et al. [14]. More specifically, the magnitude of the cumulative average decrease is 236 basis points within a 3-day window around the event date. The statistical insignificance of the abnormal premium changes on the release day makes us suspect that the sovereign CDS market is characterised by information incorporation inefficiencies. Therefore, we extend the analysis to the worse-than-expected news index.

Whereas the impact of good news is fully aligned with the literature, the investigation of bad news effects leads to the most interesting contribution of our research work, as shown in Table 5. Even though the vast majority of the literature point towards the opposite intuition, in the investigated sample that proxies for the CDS market as a whole, we observe that worse-than-expected news lowers CDS spreads. These findings suggest that the risk perception decreases even when the released macroeconomic variables underperform the analysts' forecasts. The effect of the impact is small and not significant within the main event window (−188 bps). However, it is considerable and highly significant on the event date (−228 bps). The last result is consistent with Heinz and Sun [9] who found that CDS spreads tend to react immediately to new information. Indeed, the news component incorporation occurs instantly.

For the 41-day event window, both of the news indices provoke abnormal patterns. The effect is substantial and negative, indicating that the sovereign CDS market fails the efficiency test. The prices' underreaction appears to be a serious challenge to the efficient market hypothesis because a price downward drift means that the market is incapable of translating information into prices. Nevertheless, the reduced effect of the news on CDS prices indicates a new feature of the quotations' behaviour. It is also worth noting that if we look at the frequency of the positive and negative announcements over the reference years, there is an overall predominance of releases that beat the forecast expectations.

Table 4: Impact of better-than-expected news for all countries.

All countries	Better-than-expected news						
Test/event window	Caasc	t-test	Adjusted Patell test	BMP test	Generalized sign test	Skewed-adjusted test	Bootstrap p value
[−20; 20]	−398 bps	−0.87	−0.16	−0.32	5.11***	3.39***	0.00***
[−1; 1]	−236 bps	−1.91*	−0.84	−0.92	−0.88	2.15**	0.046**
[0; 0]	−31 bps	−0.43	−0.15	−0.13	−1.50	2.54**	0.018**

The symbols, ***, **, and * correspond, respectively, to a significance level of 1%, 5%, and 10%.

Table 5: Impact of worse-than-expected news for all countries.

All countries	Worse-than-expected news						
Test/event window	Caasc	t-test	Adjusted Patell test	BMP test	Generalized sign test	Skewed-adjusted test	Bootstrap p value
[−20; 20]	−1053 bps	−2.04**	−0.83	−1.57	4.93**	3.92***	0.00***
[−1; 1]	−188 bps	−1.34	−0.88	−0.96	0.71	1.86*	0.83
[0; 0]	−228 bps	−2.83*	−2.24**	−2.13**	−2.38**	−0.50	0.64

The symbols **, **, and * correspond, respectively, to a significance level of 1%, 5%, and 10%.

Globally, the sample allows ascertaining that the sovereign risk market tends to value new information about macroeconomic fundamentals positively. However, other variables may influence the direction of the drift.

Moreover, a Wilcoxon signed rank test (Wilcoxon [23] shows that the differential (The difference in the effect is computed by subtracting the absolute value of the cumulative abnormal spread changes for worse-than-expected news from the absolute value of the cumulative abnormal spread changes for better-than-expected news.) in the effect of the better- and worse-than-expected news is statistically different from zero (see Table 6). Hence, it is possible to conclude that the market values positive surprises more strongly than negative surprises within the estimated interval.

Table 6: Wilcoxon singed rank test results.

All countries	Wilcoxon signed rank test
Event window [−1; 1]	
CAASCs bad news	188 bps
CAASCs good news	236 bps
Difference in effects	48 bps (0.025)**

The symbol ** corresponds, respectively, to a significance level of 5%.

4.2. Reaction to Individual Fundamental News Announcements. Since the aforementioned results capture new features of the behaviour of sovereign CDS premiums, it appears worthwhile to deepen the knowledge and determine the effects of the individual fundamentals. This approach will help attribute the price patterns to the specific variables. For the sake of the analysing individual variables, we create GDP, CPI, unemployment rate, and consumer sentiment news indices for both good and bad realisation/expectation surprises, and we cross-test them over the entire sample. The numerical test results and discussion are given in the 8 tables from Table 7 to Table 14, for the four macroeconomic indicators, respectively.

4.2.1. Gross Domestic Product. The effect of better-than-expected GDP news does not provoke any abnormal spread reaction on the 18 countries in the sample. The overall change is in line with the literature, as it is found that good news lowers CDS premiums both in the short [−1; 1] and longer [−20; 20] event window.

Similarly, sovereign risk indicators do not appear to instantaneously abnormally react to worse-than-expected GDP news. Additionally, CDS prices show the tendency of not incorporating the national output communications very quickly. In reality, the fact that current GDP announcements are not effective enough to cause a substantial reaction in the main event window should not be surprising. Goldberg and Leonard [20] and Heinz and Sun [9] agree that the major effect on CDS spreads is due to the forward-looking indicators that reflect the future domestic health of the economy. Nevertheless, the anticipation and postdrift effects represent an advance in CDS price behaviour analysis.

4.2.2. Consumer Price Index. CPI is another macroeconomic fundamental that is not conventionally considered to be forward-looking. Interestingly, both good and bad news indices provoke a consistent change in the CDS spreads in the long run, and only better-than-expected information induces an abnormal reaction in the sovereign CDS market. An interesting feature is derived from the event study results. Although very significant, positive surprises cumulatively lower CDS premiums by 875 basis points in the 41-day reference interval and increase them by 324 basis points in the 3-day window. A potential explanation, combined with the stronger impact of more powerful determinants and spillover effects, is the fact that new information regarding inflation is often difficult to interpret. Indeed, an average hike in the price levels can be positively evaluated by deflationary countries and can counteract a plunge in prices. Hence, due to our variable sample, we can impute the increasing effect of CPI news to the specific country-related domestic conditions.

Table 7: Impact of better-than-expected GDP news.

All countries			Better-than-expected GDP news				
Test/event window	Caasc	t-test	Adjusted Patell test	BMP test	Generalized sign test	Skewed-adjusted test	Bootstrap p value
[−20; 20]	−763 bps	−0.68	−0.29	−0.63	1.30	0.33	0.75
[−1; 1]	+73 bps	0.24	0.20	0.20	0.87	1.43	0.18
[0; 0]	+56 bps	0.32	0.46	0.47	−0.19	1.31	0.27

Table 8: Impact of worse-than-expected GDP news.

All countries			Worse-than-expected GDP news				
Test/event window	Caasc	t-test	Adjusted Patell test	BMP test	Generalized sign test	Skewed-adjusted test	Bootstrap p value
[−20; 20]	−1033 bps	−0.75	−0.60	−1.53	2.51**	1.41	0.23
[−1; 1]	+179 bps	0.48	0.94	0.99	0.03	2.09**	0.08*
[0; 0]	−237 bps	−1.10	−0.92	−1.21	−1.77*	−0.55	0.62

The symbols ** and * correspond, respectively, to a significance level of 5% and 10%.

Table 9: Better-than-expected CPI news impact event study results.

All countries			Better-than-expected CPI news				
Test/event window	Caasc	t-test	Adjusted Patell test	BMP test	Generalized sign test	Skewed-adjusted test	Bootstrap p value
[−20; 20]	−857 bps	−1.10	0.02	0.05	3.38***	2.16**	0.04**
[−1; 1]	+324 bps	1.54	2.33**	2.10**	3.94***	4.08***	0.00***
[0; 0]	+20 bps	0.17	0.74	0.55	0.68	1.38	0.19

The symbols *** and ** correspond, respectively, to a significance level of 1% and 5%.

Table 10: Worse-than-expected CPI news impact event study results.

All countries			Worse-than-expected CPI news				
Test/event window	Caasc	t-test	Adjusted Patell test	BMP test	Generalized sign test	Skewed-adjusted test	Bootstrap p value
[−20; 20]	−1448 bps	−1.59	−0.79	−1.65*	2.56**	1.39	0.16
[−1; 1]	+137 bps	0.55	1.28	1.11	2.56**	2.04**	0.04**
[0; 0]	+9 bps	0.06	0.84	0.64	1.58	1.26	0.21

The symbols ** and * correspond, respectively, to a significance level of 5% and 10%.

Table 11: Better-than-expected UR news impact event study results.

All countries			Better-than-expected UR news				
Test/event window	Caasc	t-test	Adjusted Patell test	BMP test	Generalized sign test	Skewed-adjusted test	Bootstrap p value
[−20; 20]	−903 bps	−1.11	−0.43	−0.80	2.20**	1.49	0.16
[−1; 1]	−204 bps	−0.93	−0.49	−0.55	−1.21	0.97	0.38
[0; 0]	+26 bps	0.21	0.57	0.60	0.36	2.03**	0.07*

The symbols ** and * correspond, respectively, to a significance level of 5% and 10%.

Table 12: Worse-than-expected UR news impact event study results.

All countries			Worse-than-expected UR news				
Test/event window	Caasc	t-test	Adjusted Patell test	BMP test	Generalized sign test	Skewed-adjusted test	Bootstrap p value
[−20; 20]	−539 bps	−0.52	0.20	0.38	2.74***	1.46	0.16
[−1; 1]	−133 bps	−0.47	−0.43	−0.51	0.37	1.96**	0.09*
[0; 0]	−55 bps	−0.34	−0.77	−0.90	0.37	1.02	0.42

The symbols ***, **, and * correspond, respectively, to a significance level of 1%, 5%, and 10%.

Table 13: Impact of better-than-expected CS news.

All countries	Better-than-expected CS news						
Test/event window	Caasc	t-test	Adjusted Patell test	BMP test	Generalized sign test	Skewed-adjusted test	Bootstrap p value
[−20; 20]	+446 bps	0.42	0.96	1.80*	3.85***	2.56**	0.01**
[−1; 1]	−193 bps	−0.67	−0.35	−0.49	−2.39**	2.93***	0.01**
[2; 20]	+278 bps	0.38	0.84	1.75*	4.42***	1.71*	0.11
[0; 0]	−34 bps	−0.21	−0.65	−0.96	−2.82***	1.86*	0.31

The symbols ***, **, and * correspond, respectively, to a significance level of 1%, 5%, and 10%.

Table 14: Impact of worse-than-expected CS news.

All countries	Worse-than-expected CS news						
Test/event window	Caasc	t-test	Adjusted Patell test	BMP test	Generalized sign test	Skewed-adjusted test	Bootstrap p value
[−20; 20]	−910 bps	−0.88	−0.25	−0.43	2.38**	1.28	0.21
[−1; 1]	−341 bps	−1.22	−1.56	−2.18**	−0.69	1.48	0.20
[0; 0]	−234 bps	−1.71*	−1.69*	−2.57***	−2.09**	−1.13	0.32

The symbols ** and * correspond, respectively, to a significance level of 5% and 10%.

Table 15: Impact of better-than-expected news on EMEA countries.

EMEA	Better-than-expected news						
Test/event window	Caasc	t-test	Adjusted Patell test	BMP test	Generalized sign test	Skewed-adjusted test	Bootstrap p value
[−20; 20]	−141 bps	−0.20	0.19	0.36	4.57***	2.24**	0.03**
[−1; 1]	−361 bps	−1.86**	−1.47	−1.89*	−1.38	1.54	0.15
[0; 0]	−75 bps	−0.67	−0.92	−1.00	−2.59***	1.80*	0.11

The symbols ***, **, and * correspond, respectively, to a significance level of 1%, 5%, and 10%.

Table 16: Impact of worse-than-expected news on EMEA countries.

EMEA	Worse-than-expected news						
Test/event window	Caasc	t-test	Adjusted Patell test	BMP test	Generalized sign test	Skewed-adjusted test	Bootstrap p value
[−20; 20]	−191 bps	−0.26	0.15	0.29	4.44***	2.21**	0.03**
[−1; 1]	−352 bps	−1.80*	−1.43	−1.84*	−1.31	1.67*	0.12
[0; 0]	−74 bps	−0.65	0.87	−0.94	−2.61***	1.84*	0.09*

The symbols ***, **, and * correspond, respectively, to a significance level of 1%, 5%, and 10%.

Table 17: Impact of better-than-expected news on American countries.

Americas	Better-than-expected news						
Test/event window	Caasc	t-test	Adjusted Patell test	BMP test	Generalized sign test	Skewed-adjusted test	Bootstrap p value
[−20; 20]	+70 bps	0.54	2.64***	1.74*	−1.10	1.91*	0.09*
[−1; 1]	+54 bps	1.52	1.91*	1.55	0.12	1.80*	0.07*
[0; 0]	+26 bps	1.27	1.35	1.00	−0.29	1.08	0.30

The symbols *** and * correspond, respectively, to a significance level of 1% and 10%.

4.2.3. Unemployment Rate. Sovereign CDS quotations do not react very strongly to positive unemployment rate news. The effect is not statistically significant in both short and long time intervals. Prices' response to positive expectation/realisation surprises is akin to negative news because they both cause a drop in the spread levels. The same pattern can be spotted if the entire sample is taken into account. Moreover, the incorporation of the new information set appears to occur instantaneously with no evidence of price adjustments, as documented by Hull et al. [19]. Since it is unanimously agreed that good surprises lower the risk perception of a country, it is interesting to attribute the same reaction to bad surprises. It is possible to state with a high degree of certainty that the effect is time period-related and

Table 18: Impact of worse-than-expected news on American countries.

Americas	Worse-than-expected news						
Test/event window	Caasc	*t*-test	Adjusted Patell test	BMP test	Generalized sign test	Skewed-adjusted test	Bootstrap *p* value
[−20; 20]	+341 bps	2.49	4.37***	3.39***	2.64***	4.34***	0.00***
[−1; 1]	+33 bps	0.89	1.53	1.36	2.23**	1.00	0.32
[0; 0]	+13 bps	0.63	1.61	1.47	0.98	0.60	0.54

The symbols *** and ** correspond, respectively, to a significance level of 1% and 5%.

Table 19: Impact of better-than-expected news on Asian Pacific countries.

Asia pacific	Better-than-expected news						
Test/event window	Caasc	*t*-test	Adjusted Patell test	BMP test	Generalized sign test	Skewed-adjusted test	Bootstrap *p* value
[−20; 20]	−71 bps	−0.49	1.33	0.92	−0.50	1.10	0.27
[−1; 1]	−28 bps	−0.71	−0.32	−0.28	−0.92	−0.64	0.53
[0; 0]	+20 bps	0.88	1.13	1.11	1.21	0.98	0.36

Table 20: Impact of worse-than-expected news on Asian Pacific countries.

Asia pacific	Worse-than-expected news						
Test/event window	Caasc	*t*-test	Adjusted Patell test	BMP test	Generalized sign test	Skewed-adjusted test	Bootstrap *p* value
[−20; 20]	+458 bps	2.64***	4.71***	3.09***	2.83***	2.11**	0.04**
[−1; 1]	+24 bps	0.50	1.56	1.07	0.51	1.60	0.10*
[0; 0]	+11 bps	0.41	0.58	0.52	2.12	0.98	0.36

The symbols **, **, and * correspond, respectively, to a significance level of 1%, 5%, and 10%.

is mainly caused by other movers' fluctuations that offset our indicator's result. The financial indicators are some of these major movers. Since our study focuses on the period between two financial crises, it is reasonable that monetary policy actions and interest rates news are more valuable for market investors. Furthermore, an increase in the labour market workforce may be perceived as temporary and due to a new injection of money into the economy that is not always considered to be risk-reducing.

4.2.4. Consumer Sentiment. This indicator is based on the consumers' perception of economic health. Amid the indicators that we are taking into account, this is an indicator of better proxies forward-looking factors. Remarkable impacts are observed for good and bad news surprises. Whereas better-than-expected news causes a hike in the CDS prices and the effect only shows up in the [−20; 20] event window, driven by a postannouncement drift, a negative news surprise provokes a plunge in the premiums and is quickly incorporated in the price levels. In this case, the price adjustment is observed to occur immediately. Hence, it is reasonably arguable that a weak form of market efficiency holds as publicly available information is well processed into sovereign CDS prices.

4.3. Reaction in Different Regions. The last research question assesses the responsiveness of the single areas in order to understand which macroregions are more sensitive to macroeconomic fundamentals. For each macro area, we investigate both positive and negative surprises' impacts. The test results and their discussion are given in the following. We can see different patterns of responses in different regions. This can be explained by other factors such as commodity including oil markets' impact on CDS spreads, as pointed out by Bouri et al. [24], Bouri et al. [25], and Bouri et al. [26].

4.3.1. Europe, Middle East, and Africa (EMEA). Tables 15 and 16 report the results on EMEA countries. Consistent with the whole sample results, publicising both good and bad macroeconomic fundamentals lowers CDS spreads. In addition to the statistical significance of the 3-day event window for the news indices, we find that CDS premiums experience an overall decrease over the [−20; 20] reference period. The impact corresponds to 141 basis points for better-than-expected news and 191 for worse-than-expected news. The reason why CDS premiums drop is explained by Conrad et al. [15]. When a financial system experiences a period of distress, all asset prices tend to react more strongly to positive news than to negative information. Therefore, the effect of bad news is offset by the positive impact. Furthermore, in line with the literature, our results show that good news lowers risk perception in the sovereign market.

The EMEA region has recently undergone a period of general instability that was characterised by sovereign indebtedness. Thus, the sample is split into two subsamples in order to isolate the effect of the sovereign debt crisis and examine not only the impact it had on the sovereign CDS market but also if it caused a change in the effectiveness of the macroeconomic fundamentals on asset prices. We extend the first subsample from June 1, 2009, to November 1, 2012. The second subsample is from November 2, 2012, to June 1, 2016.

It is very interesting to note that during the European sovereign debt crisis, none of the indicators in the analysis appear to soar at all because of the abnormal spread changes. The period immediately following the debt crisis is relatively more tranquil, which is confirmed by the fact that the results are entirely different from the previous case. However, better-than-expected news has an increasing effect on the CDS premiums, and this is true for both the event date and the 41-day window.

Overall, we can state with a high degree of certainty that during the debt crisis, CDS quotations were almost unaffected by the four indicators that we take into account, confirming that the risk perception shifted towards more conditioning unconventional indicators such as future growth variables or financial measures. One possible driving force of European CDS premiums may be the unconventional monetary policy (i.e., quantitative easing or QE) implemented by the European central bank, as Kinateder and Wagner [27] found that QE has indeed helped to lower yield spreads for sovereign bonds in the short window.

4.3.2. Americas and Asian Pacific Countries. Central and Latin American (see Tables 17–18) and Asian Pacific countries (see Tables 19–20) are the most affected by the macroeconomic surprises. Since a large part of the sample is composed of developing countries, these results are in line with Hull et al. [19] and Yildirim [28]. The study of the effect of news on emerging markets shows that they tend to react more strongly to macroeconomic fundamentals than to financial indicators. Apart from a lack of better-than-expected news significance on Asian countries, all the other event studies show evidence for both an abnormal cumulative change in the [−1; 1] event window and in a slightly longer term.

5. Conclusion

In this work, we initially conduct an event study to test the significance of the impact of gross domestic product, consumer price index, unemployment rate, and consumer sentiment announcement on sovereign credit default swap premiums. Then, we investigate the pre- and post-announcement drifts in order to check whether a weak form of market efficiency is verified in the sovereign risk market. We employ an event study methodology that allows us to estimate the magnitude of the news effects over several event windows. The dataset comprises the historical credit default swap data for 18 countries representing three macroregions: EMEA, Americas, and Asia Pacific. The news information set is divided into better- and worse-than-expected news based on the differential between the released value and the economic market consensus.

This study extends the analysis on CDS spreads to date and provides another angle to interpret sovereign CDS premium dynamics to investors. Considering that the set of macroeconomic fundamentals is only one determining level from which it is possible to investigate the news impact and is also highly time varying, we examine the effectiveness of four nonconventional fundamentals on the credit derivative's prices. An alternative approach from the literature is used, as the theory only focuses on forward-looking indicators that are found to account for 65% of the premiums' changes. The four indicators only reflect the current economic health that may be considered the basis for forecasting. Focusing on these indicators appears to be worthwhile because it allows to check whether the impact of the financial subprime mortgages crisis has led to a turning point in the effect of news in the sovereign risk market. Moreover, we try to provide the investors that further information concerning the behaviour of sovereign CDS prices over a nonconventional economic period featured by the sovereign debt crisis. To the best of our knowledge, there has been no previous report of an event study about the impact of non-forward-looking macroeconomic fundamentals news on sovereign CDS premiums. Very few studies cover the news reaction in the CDS market, and they mainly focus on the spillover effects using regression techniques that appear to be suitable for testing the CDS determinants but are quite limited in the analysis of market efficiency and pre- and postrelease drifts. Hence, we contribute to the expansion of knowledge of credit default swap prices' behaviour.

Overall, our findings suggest that the macroeconomic announcement reduces the uncertainty of the sovereign CDS market, and the announcements are still quite effective in the generation of abnormal spread changes. Both longer and shorter event windows are helpful for explaining the CDS premiums' reaction because they provide the investors with useful information. In particular, for institutional investors who dominate this market, they need to closely monitor the behavior of CDS prices in their hedging processes and risk dynamics. Our results highlight the fact that the CDS price reaction to bad news should be very carefully interpreted, and their strategy should be time-varying and requires continuous revision.

Many gaps can still be filled concerning this topic. We suggest the extension of the news dataset to include other variables such as current account balance and negative interest rates as well as other variables that we do not include due to the lack of consistent and regular data. Another interesting variable to investigate is the announcement of QE. Based on the results of Kinateder and Wagner [27], QE may lower the CDS in the short window, but its effect in the long run may be ambiguous since on the one hand, it increases the liquidity of market, but on the other hand, it may intensify the anxiety of market if its effect turns out to be limited, as we have observed in the market turbulence in the US in the spring of 2020.

Furthermore, a more accurate selection of the CDS historical prices that may employ further statistical analysis of the countries is recommended. Spillover effects and period-related responses may affect the overall findings.

Therefore, an analysis in which the domestic effects are isolated from international impulses would be more specific. However, the CDS market is dropping in terms of the notional amount of outstanding contracts, and, therefore, we assume that future investigations will be harder due to a lack of large quantities of data.

Data Availability

The data required to reproduce these findings cannot be shared at this time as the data also form part of an ongoing study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

The Interactive Effect of Organizational Identification and Organizational Climate on Employees' Taking Charge Behavior: A Complexity Perspective

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In the view of complexity theory, the emergency behavior of individual is nonlinear and influenced not only by individual variables but also by many other environmental variables. Based on complexity perspective, this article explored why employees' taking charge behavior occurs in organizations from a multilevel approach. Specifically, this study has explored the cross-level interactive effect of organization-level factor (organizational justice climate and psychological safety climate) and individual-level factor (organizational identification) on employees' taking charge behavior. Using a total of 806 valid matching questionnaires from 91 firms in China, this study found that first, organizational identification is positively related with employees' taking charge behavior. Second, distributive justice climate positively moderates the influence of organizational identification on employees' taking charge behavior. Third, psychological safety climate negatively moderates the influence of organizational identification on employees' taking charge behavior. According to our results, organizational policies and practices should be made to foster employees' identification with the organization, to construct a fair environment within the organization, and to convince employees that taking charge behavior will not entail political risks, especially for those employees with low organizational identification.

1. Introduction

Organizations are complex adaptive systems in which organizational culture and climate promote the interactions among individuals, teams, and groups, and in turn the ideas, attitudes, and adaptive behaviors emerge from those interactions of their members [1, 2]. Employees' behaviors usually have their determinants at multiple levels (individual, group, and organization level), while most organizational behavior studies have typically analyzed only at one level [3]. Research conducted at a single level often ignores the fact that organizational dynamics result from multilevel interactions. For example, employees in an organization will not only make judgments based on their rational expectations, employees' behavior choices are highly influenced by local relationships, and the majority state in the organization has a significant effect on individuals [4]. Although single-level approaches have their own advantages, there is a knowledge gap in how multiple levels interact with one another and what implications they bring on organizational behavior. Moreover, in the view of complexity theory, the emergency behavior of individual is nonlinear and influenced not only by individual variables but also by many other environmental variables [5]. However, organizational researchers have seldom used multilevel analysis to achieve a bigger picture of organizational dynamics, which results in an incomplete understanding of multilevel interactions and their consequences [3]. So, this paper will use a multilevel approach to study employees' extra-role behavior.

All along, the importance of employees' extra-role behaviors to the competitiveness of corporations has been generally emphasized by scholars [6]. According to whether behavior is helpful to maintain interpersonal relationship, Van Dyne et al. [7] classified extra-role behaviors into two categories: affiliative behavior and challenging behavior. Affiliative behavior is intimate, cooperative, and noncontroversial and tends to consolidate or maintain interpersonal relationships, such as helping behavior; while challenging behavior is change-oriented, controversial, and emphasizing the reform of the status quo, which may damage the relationship with other people, such as voice behavior.

Morrison and Phelps [8] have proposed another example of challenging extra-role behavior, namely, taking charge, which means individual employees dedicate voluntary and constructive efforts to effect organizationally functional change with respect to how work is executed within the contexts of their jobs, work units, or organizations. Although they are both challenging extra-role behaviors, taking charge behavior is different from voice behavior. Voice behavior focuses on information collection and suggestions around problems in the work situation, while the remarkable characteristic of taking charge behavior is to make efforts to initiate and implement change; that is to say, it is not only to make suggestions [9]. Scholars have discussed a lot about voice behavior (see a review of [10], while taking charge behavior has received little attention.

Since Morrison and Phelps [8] put forward this concept, scholars have made some explorations on the influencing factors of taking charge behavior. These influencing factors can be classified into three levels: individual, leadership, and environmental level. At the individual level, factors, such as self-efficacy and felt responsibility [8], conscientiousness in Big Five [11], psychological contract breach [12], and propensity to trust and exchange ideology [13], have been found to positively predict the taking charge behavior of employees. At the leadership level, factors, such as ethical leadership [14], leader inclusiveness [15], LMX [16], empowering leadership [17, 18], transformational leadership [19, 20], and self-sacrificial leadership [21], have strong impact on employees' taking charge behavior through psychological empowerment, trust in leader, and identification with leader, and other mediating variables. At the environmental level, factors, such as top management openness [8], distributive justice and procedural justice [11], control types [13], idiosyncratic deals [22], job insecurity [23], and perceived organizational support [24], have significant predictive effect on employees' taking charge behavior.

According to the complexity theory, individual behavior in an organization is best understood as the result of an interactive process that happen between contextual factors and personal characteristics. Yet, the researchers above have tended to focus on either personal or situational predictors, respectively, and they rarely explore the interactive effect of both influencers on employees' taking charge behavior. Based on complexity perspective, this article explores why taking charge behavior occurs in organizations from a multilevel approach. Specifically, we explore the cross-level interactive effect of organization-level factor (organizational justice climate and psychological safety climate) and individual-level factor (organizational identification) on employees' taking charge behavior.

The rest of the article is organized as follows: in Section 2, the theoretical framework is proposed and a literature review is conducted to highlight the theoretical contributions of this study. In Section 3, research hypotheses are proposed. Section 4 details the research methodology, followed by the empirical analyses and results in Section 5. In Section 6, managerial implications are discussed, and the suggestions for future research are put forward.

2. Research Framework

In a word, this study is of great significance to the theoretical development of taking charge behavior by exploring the direct effect of organizational identification on employees' taking charge behavior, the cross-level direct effect of distributive justice climate and psychological safety climate on employees' taking charge behavior, and the cross-level moderating effect of distributive justice climate and psychological safety climate between organizational identification and employees' taking charge behavior. Our research model is as follows, see Figure 1.

In Figure 1, organizational identification is an individual-level variable, representing an individual influencing factor which has direct effect on the dependent variable. Distributive justice climate and psychological safety climate belong to organizational-level variables, representing environmental factors which have cross-level direct effect on the dependent variable, respectively. At the same time, distributive justice climate and psychological safety climate cross-levelly moderate the impact of organizational identification on the dependent variable, respectively.

Organizational identification refers to the individual perception of oneness with or belongingness to an organization, and it reflects the extent to which an employee defines himself/herself with reference to his/her organizational membership or the extent to which an employee integrating his/her social identity with organizational identity [25]. A variety of organizationally relevant outcomes have been found to be highly correlated with organizational identification, such as innovations, job involvement, in-role performance, and extra-role performance, turnover intentions, etc. [26]. However, few people have tested the impact of organizational identification on employee's taking charge behavior. So, Fuller et al. [27] suggested that, given that organizational identification was found to be positively related to voice behavior, future research should investigate the extent to which it is related to other change-oriented behavior such as taking charge behavior. This study attempts to explore the impact of organizational identification on taking charge behavior, so as to fill the gap. This is the first theoretical contribution of this study.

The literature on organizational justice shows that fair organizational environment can help to induce employees to show extra-role behavior, and unfair organizational environment will reduce employees' desire to engage in them. So, the first environmental factor we considered in our study is organizational justice climate. Organizational justice climate is a collective cognition or a shared perception held by

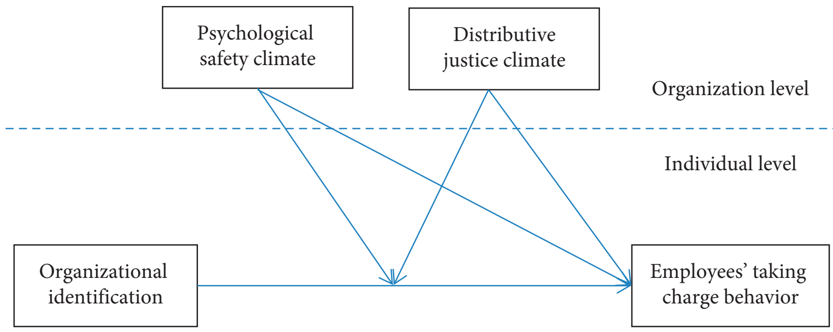

Figure 1: Research framework.

organizational members together about to what extent they are fairly treated by organizational authorities [28]. Organizational justice climate is different from individual justice perceptions. Individual justice perceptions are personal assessments of fair treatment by the organization they work for, while organizational justice climate refers to consensual collective cognitions, often represented by aggregated justice judgments of employees in the organizations [29]. Some scholars suggest that the collective evaluation of fair treatment by an organization may account for unique variance in important outcomes [30]. For example, a few cross-level studies demonstrate that justice climate has incremental validity in predicting individual-level attitudes and behavior beyond individual-level justice perceptions [28, 31]. However, these studies focus more on the impact of organizational justice on affiliative extra-role behaviors, and few studies explore whether employees who are treated fairly have the motivation to perform challenging extra-role behaviors [11]. Therefore, this study will fill in this gap by exploring the cross-level impact of organizational justice climate on taking charge behavior. This is the second theoretical contribution of this study.

On the other hand, it is generally believed that organizational justice consists of three distinct but related components: distributive, procedural justice, and interactive justice [32]. Distributive justice refers to the perceived fairness of outcome distributions or allocations; procedural justice refers to the perceived fairness of the decision-making procedures used to determine the distribution of the outcome; interactive justice refers to the interpersonal treatment of organizational members in the process of implementation of organizational procedures. Because interactive fairness usually occurs between leaders and members, it is rarely concerned by scholars in organizational studies. Although scholars generally focused on the impact of procedural justice on employees' attitudes and behaviors, Lind and Tyler [33] argued that distributive justice judgments are likely to be more influential than procedural justice judgments in determining overall fairness judgments. Consistent with this argument, Conlon [34] found that distributive justice explained more variance in grievant evaluations of authorities (an appeal board) than did procedural justice. Tremblay et al. [35] also reported that the relationships with pay satisfaction and organizational satisfaction were stronger for distributive justice than procedural justice. Moreover, in the countries with collectivism culture, the decision-making process itself is not very transparent, so employees do not have high expectations for procedural fairness, and they tend to pay more attention to the fairness of distribution [36]. Therefore, we will not choose procedural justice climate but distributive justice climate as an environmental factor in this study.

Another environmental factor we considered in our study is psychological safety climate. Psychological safety climate was first studied at team level. Edmondson [37] put forward the concept of team psychological safety climate which is defined as shared perceptions that the team is safe for interpersonal risk taking. Later, Baer and Frese [38] defined the psychological safety climate at the organizational level, which refers to the shared perception of organizational members on "organizational policies or procedures that encourage open and trusted interpersonal interaction in the working environment." No matter at what level the concept is defined, psychological safety climate describes an organizational work environment in which employees can express their opinions boldly without fear of rejection or punishment. Psychological safety climate as an antecedent has been shown to correlate with firm performance [38], learning behaviors [37, 39], team member performance [40], and so on, but few scholars have studied the influence of psychological safety climate on employees' taking charge behavior. Chiaburu and Baker [13] pointed out that organizational culture, team atmosphere, and other predictive variables at the organizational or team level may also affect employees' taking charge behavior, which should be paid more attention. In order to fill the gap, this study will examine the cross-level direct effect of psychological safety climate on employees' taking charge behavior. This is the third theoretical contribution of this study.

3. Hypotheses

3.1. The Direct Effect of Organizational Identification. Based on social identity theory [41] and self-categorization theory [42], organizational identification has been defined as the employees' perception of oneness or belongingness to the organization where they work [25]. Although some scholars argued that there are two forms of organizational identification: situated identification (triggered by situational cues and thus is more temporary and unstable) and deep identification (a more fundamental connection between individual and collective and thus is stable and last), e.g., [43], Ashforth et al. [44] still insisted that organizational identification should be regarded as a more or less stable quality that transcends specific situations, and as a root or deep or stable construct. According to Ashforth and Mael [25], organizational identification is not an attitude concept (such as organizational commitment and job satisfaction), but a perceptual cognitive concept. To identify with an organization, there is no need to show any specific behavior or emotional state towards the organization, and an employee need only perceives himself or herself as psychologically intertwined with the fate of the organization.

According to social identity theory, part of the reason why individuals identify with an organization is to enhance self-esteem [45, 46]. A desire for self-enhancement motivates people to identify with the organization that excel other organizations [47]. By identifying with an organization, a person integrates his or her personal identity with organizational identity, the identity boundary between individual and organization becomes blurred, and then the salient attributes of that organization can be used to define him or herself, so as to gain a sense of self-esteem. Therefore, the strongly organizational identifiers usually hope the organization they identify with has a higher status and attractiveness than those compared organizations [48]. They also hope that the organizations they identify with continue to improve and have a greater competitive advantage in front of their competitors [49]. For strong identifiers, voluntarily helping the organization achieve its goal is important because the organization's goal is theirs as well. Therefore, it is a quite nature and common thing for them to dedicate voluntary and constructive efforts to effect organizationally functional change. The preceding discussion leads to the following hypotheses:

> H1: organizational identification is positively related with employees' taking charge behavior.

3.2. The Cross-Level Direct Effect and Cross-Level Moderating Effect of Distributive Justice Climate. A variety of employee attitudes and behaviors have been widely found to be influenced by perceptions of justice or fairness in the workplace [50]. As an old form of fairness, distributive justice refers to the perceived fairness of decision outcomes and has its roots in research on equity theory [51]. When an individual believes that the outcomes such as rewards or promotions he or she gets from the organization is fair, it is a signal that an individual's abilities and contribution are valued by the organization. According to the principle of reciprocity, when one is perceived as a valued member of an organization, he or she is more likely to demonstrate behaviors to help the organization thrive, as a form of social exchange [11]. Distributive justice has been shown to be significantly related to employee work-related attitudes and behaviors such as outcome satisfaction, system and agent-referenced evaluation of authorities, job satisfaction, organizational commitment, trust, and OCB [52]. So, we believe that fair rewards and recognition of their contributions will encourage individuals to engage in behaviors aimed at triggering positive changes in the organization. Moreover, the existing cross-level justice studies demonstrate that justice climate has incremental validity in predicting individual-level attitudes and behavior beyond individual-level justice perceptions [28]. Therefore, we have reason to believe that distributive justice climate has a positive predictive effect on employees' taking charge behavior. The following assumptions are proposed:

> H2a: distributive justice climate is positively related with employees' taking charge behavior.

According to the group engagement model [53], there are at least two different status evaluations about the groups can be made by employees to shape identification with that group: the group's status in the eyes of those outside the group and his or her own status in the eyes of others within the group. The group's status in the eyes of those outside the group has been indicated as "pride," and the perception of one's relative status within the group has been indicated as "respect." That is, people will be more highly motivated to merge their identity with a group when the group has high status (pride), when they feel that they have status in the group (respect), or both [53]. In the group engagement model, procedural justice judgments, distributive justice judgments, and outcome favorability have all been perceived as antecedents of employees' identity assessments, which implies that a sense of distributive justice helps to enhance employees' organizational identification. The group engagement model also suggests that "pride" will be particularly linked to mandatory-required behavior, whereas "respect" will be linked especially strongly to discretionary-voluntary behavior [53].

On the basis of the group engagement model, Fuller et al. [27] further demonstrated that the status of the organization (pride or prestige) and the individual's status within it (respect) have different antecedents. They specially pointed out that high commitment management (HCM) practices, such as recognition by top management, opportunities for extensive training/development, participation in decision-making and problem solving, and pay for performance, are likely to be viewed by an employee as a signal or cue indicating that he or she is valued and respected within the organization, and should make independent contributions to an individual's overall evaluation of his or her status within the organization (i.e., respect). In a sense, all these HCM practices constitute a fair organizational environment, which is conducive to the formation of employees' perception of distribution fairness. This means that a perception of distributive fairness is beneficial to employees' judgment about "respect," thus enhancing his or her organizational identification.

From the above discussion, we can draw a conclusion that those highly identifiers exposing under a context with high distributive justice climate will engender a positive judgment of one's relative status within the group, thus further enhancing their identification with the organization, and therefore perform more cooperative behavior and engagement in organization. In another word, under a high distributive justice climate, the effect of organizational identification on employees' taking charge behavior will be strengthened. So, the following hypothesis is proposed:

> H2b: distributive justice climate will positively moderate the influence of organizational identification on employees' taking charge behavior. In another word, the positive effect of organizational identification on employees' taking charge behavior will increase with the increase of distributive justice climate in an organization.

3.3. The Cross-Level Direct Effect and Cross-Level Moderating Effect of Psychological Safety Climate. Morrison and Phelps [8] argued that employees will weigh anticipated risks against anticipated benefits when deciding whether to engage in taking charge behavior. Taking charge behavior has potential risks, such as a damaged reputation if the initiative fails or disapproval if it is seen as inappropriate or threatening. According to this, employees will be less likely to engage in taking charge behavior if they fear that doing so will harm their images or bring them other losses. Therefore, employees' psychological safety is very important to improve their motivation to engage in taking charge behavior.

Psychological safety is the perception of employees that their self-image, status, and career will not suffer negative consequences when they employ and show themselves in work context [54]. Psychological safety affects employees' internal motivation to shape individual roles, and when employees experience more psychological safety, they will make higher work engagement [37]. Empirical studies also found that psychological safety helps to explain why employees speak up with suggestions for organizational improvements [55], and take initiative to engage process innovation [38].

Kahn [54] further pointed out that psychological safety was associated with elements of social systems that created more or less nonthreatening, predictable, and consistent social situations in which to engage. It implies that it is necessary to build a supportive organizational environment conducive to employees' psychological safety. Many studies proved that psychological safety climate is just such an organizational environment. For example, employees under high-level psychologically safe organizational climate feel easy and relaxed in taking interpersonal risks and are encouraged to propose new ideas, openly discuss problems, and proactively approach work [38]. Psychologically safe team climates mitigate team members' fears of social rejection or disapproval when speaking up, helping, or engaging in other social interactions in which there is the potential to be judged or humiliated by other team members [37].

Based on the above analysis, we believe that psychological safety climate can help employees gain a sense of psychological safety, so they are more willing to engage in taking charge behavior. Then, the following assumptions are put forward:

> H3a: psychological safety climate is positively related with employees' taking charge behavior.

Yet, what does psychological safety climate mean to those strong organizational identifiers?

Ashforth and Mael [25] argued that the concept of identification is characterized by the following attributes: (1) identification describes only the cognition of oneness, not the behaviors and affect that may serve as antecedents or consequences of the cognition; (2) identification tend to occur even in the absence of strong leadership or member interdependency, interaction, or cohesion; (3) identification can persist tenaciously even when group affiliation is personally painful, other members are personally disliked, and group failure is likely; (4) identification maintains even if in situations involving great loss or suffering, missed potential benefits, task failure, and expected failure; (5) an organizationally identified employee, as a "microcosm of the organization" is likely to have attitudes and take actions that benefit the whole organization rather than benefitting individual self-interest.

The above characteristics of identification implied that there is no need for those strong organizational identifiers to rely on psychological safety to engage in taking charge behavior. Often, the strong organizational identifier wants to be a prototypical member of a particular organization, and his or her basic motivation to identify is the reputation and status of the organization and the self-esteem that derived from interorganizational comparisons [25]. So, the main purpose of engaging in taking charge behavior for them is to improve the reputation, status, and competitiveness of the organization they belong to. Usually, for those strong organizational identifiers, acting on behalf of the organization is tantamount to acting on behalf of themselves [56]. That is to say, although a better psychological safety climate in organization helps to improve the enthusiasm of ordinary people to engage in taking charge behavior, it has little influence on the enthusiasm of strong identifiers to engage in such behavior, because their intention to challenge the status quo is not affected by psychological safety.

However, when the psychological safety climate in the organization is relatively low, it is a different scene. Under a poor psychological safety climate, owing to fear and worry, the ordinary people in organization are often hesitant to engage taking charge. In this case, the strong organizational identifier will feel more obliged and responsible to optimize business operation to help the organization move forward. Because their fate is intertwined with the fate of the organization, the success or failure of an organization is equal to their success or failure. In another word, the poorer the psychological safety climate in an organization is, the more likely the strong organizational identifiers are to engage in taking charge behavior. Accordingly, we propose the following assumptions:

> H3b: psychological safety climate will negatively moderate the influence of organizational identification on employees' taking charge behavior. In another word, the positive effect of organizational identification on employees' taking charge behavior will increase with the decrease of psychological safety climate in an organization.

4. Method

4.1. Samples. Because this study needs to conduct a cross-level analysis between the organizational level and the individual level, it needs to investigate a large number of firms, so the investigation task is very difficult. For this reason, we asked the on-the-job undergraduate students of a distance education university in Shanghai to help us and asked them to collect questionnaires in the corporations where they work. These on-the-job students are located in most provinces and cities in China. They are from different corporations and have rich working experience. After our persuasion, 91 on-the-job students are willing to serve as investigators of this study. These students come from 91 different firms distributed in most industries and cities in China. The questionnaire consists of two separate documents, A and B. The content of document A includes control variables (such as gender, age, tenure, and position), organizational identification, perception of distributive justice, and psychological safety; the content of document B includes employees' taking charge behavior.

The investigation process is as follows: first, we train those on-the-job undergraduate students (as investigators) online. The training content includes questionnaire structure, how to send out and collect questionnaires, and the matters needing attention in the process of the survey. Secondly, we ask each investigator randomly selects some of his or her colleagues as the respondents. Thirdly, questionnaire A with a cover letter indicating the purpose of the investigation was sent to all the selected respondents through various methods such as emails and physical mails. At the same time, the investigators filled in questionnaire B according to the respondents' daily behavior. Lastly, once the questionnaire A returned from one respondent, corresponding questionnaire B will be merged with it to form a matched questionnaire.

This arrangement can prevent common method variance biases because the data of control variables, independent variables, and moderating variables are from the investigator's colleagues (respondents), while the data of result variables are from the investigators themselves. At last, a total of 806 valid matching questionnaires were collected from 91 firms. The number of respondents in each firm ranges from 4 to 13. The distribution of demographic characteristics of the sample is as follows: of the final sample, 39.0% are under 25 years old, 4.5% are over 41 years old, and 56.5% are 26–40 years old; most of them are well educated, 11.8% have high-school education, 85.4% have college or bachelor degree, and 2.8% have graduate degree or above; among the respondents, 4.3% have tenure of 1 year below, 95.7% have tenure of more than 2 years, 73.4% of the respondents are ordinary employees, 26.6% are supervisors or department managers, 41.5% of the respondents are male, and 58.5% are female.

4.2. Measurement

4.2.1. Control Variables. In the empirical studies on taking charge behavior, scholars are used to take demographic characteristics of employees as control variables. For example, Moon et al. [11] used gender and job tenure (measured in years) as control variables in their study. Morrison and Phelps [8] used position level, job tenure, gender, and age as control variables in their study. Demographic characteristics such as job type, age, gender, education, and organizational tenure were used as control variables in the study of Burnett et al. [24]. Therefore, this study takes age, education, tenure (organizational tenure), and rank (position level) as control variables. The coding of control variables is shown in Table 1. For example, age is set as a 5-value variable, below 25 years old is coded as 1, between 26 and 30 years old is coded as 2, and so on, and over 40 years old is coded as 5.

In the above control variables, except for the variable of rank including 3 grades, the other variables include 5 grades. For the latent variables in this study, all scales utilized a five-point response format ranging from strongly disagree (1) to strongly agree (5). Because the survey was conducted in China, so we need to translate the English scales into Chinese. Using the procedures established by Brislin [57], all the English scales were translated and back-translated to ensure the Chinese translation was consistent with the English meaning.

4.2.2. Organizational Identification. Based on the Mael and Ashforth [58] six-item scale (e.g., when I talk about this organization, I usually say "we" rather than "they"), we used "back translation" to form the Chinese version of the organizational identification scale. We used the 806 data to test the reliability, and Cronbach's alpha for this scale was 0.9032, which shows that the organizational identification scale has good measurement reliability.

4.2.3. Distributive Justice Climate. Distributive justice climate is an organization-level variable, and its measurement value is obtained through the integration of the distributive justice perception of individual employees. Ramamoorthy and flood [59] developed a 5-item scale to measure employees' perception of distributive justice (e.g., I am fairly rewarded for the responsibilities I take on). Based on this scale, a Chinese version was formed through "back translation." We used the 806 data to test the reliability, and Cronbach's alpha for this scale was 0.9089, which shows that the distributive justice perception scale has good measurement reliability.

4.2.4. Psychological Safety Climate. Psychological safety climate is an organization-level variable, and its measurement value is obtained through the integration of the psychological safety of individual employees. Edmondson [37] developed a 7-item scale to measure employees' psychological safety. A sample item is "In our company, one is free to take risks." We used "back translation" to turn the scale into a Chinese version. We used the 806 data to test the reliability, Cronbach's alpha for this scale was 0.8804, which shows that the psychological safety perception scale has good measurement reliability.

Table 1: The coding of control variables.

Variable/code	1	2	3	4	5
Age	Under 25 years old	26–30 years old	31–35 years old	36–40 years old	Over 40 years old
Education	Junior high school	High school	Junior college	Undergraduate	Postgraduate
Tenure	Less than 1 years	1-2 years	2–5 years	5–10 years	More than 10 years
Rank	Front-line staff	Supervisor	Manager		

4.2.5. Taking Charge Behavior. Taking charge behavior is an individual-level variable. We used the 10-item scale developed by Morrison and Phelps [8] to assess employees' taking charge behaviors as reported by their colleagues. A sample item is "This person often tries to adopt improved procedures for doing his or her job." Based on this scale, a Chinese version was formed through "back translation." We used the 806 data to test the reliability, Cronbach's alpha for this scale was 0.8979, which shows that the taking charge behavior scale has good measurement reliability.

Then, we construct a first-order 1-factor confirmatory factor analysis model for each latent variable and use 806 data to fit the hypothetical factor model. The fitting indexes of all models are shown in Table 2. Each model fits the data well, which shows that the scale of research variable has good structural validity.

5. Results

In multilevel data analysis, scholars usually use the within-group inter-rater reliability (Rwg) and reliability of score within group (ICC(1)) or reliability of mean group score (ICC(2)) to judge whether individual ratings can be aggregated into collective-level variables. Generally speaking, when Rwg is greater than 0.7 [60], ICC (1) is greater than 0.05 and F test is significant, and ICC (2) is greater than 0.5 [61], researchers can aggregate individual perceptions into collective climate.

In this study, 105 firms were investigated. Firstly, the Rwg coefficient for distributive justice and psychological safety of the respondents in the same firm were computed by SPSS 12.0 software. According to the principle that the Rwg value is greater than 0.7, the data of 91 firms are valid. Among the 91 firms, the mean of Rwg value for distributive justice was 0.8416, ICC (1) value was 0.2196 (F test was significant), and ICC (2) value was 0.7137; the mean of Rwg value for psychological safety was 0.8983, ICC (1) value was 0.3197 (F test was significant), and ICC (2) value was 0.8063. The results show that the scores of distributive justice and psychological safety can be aggregated into the scores of the distributive justice climate and psychological safety climate. All items were answered on a five-point scale, and the descriptive statistics of latent variables are shown in Table 3.

5.1. HLM. Step 1: null model.

Because our model assumes that employees' taking charge behavior is predicted by individual-level and organization-level variables together, so it must be confirmed that taking charge behavior has variance both at individual level and at organizational level. Therefore, the first step is to use ANOVA to divide the variance of employees' taking charge behavior into intragroup and intergroup variance. The results of ANOVA showed that the intergroup variance (τ_{00}) is 0.06413 ($\chi 2 = 201.79877$, $P < 0.001$), indicating that the variance of taking charge behavior between groups was significant. In addition, the within-group variance (σ^2) is 0.46210, and the ICC $(1) = \tau_{00}/(\sigma^2 + \tau_{00}) = 0.122$, indicating that 12.2% of the variance of employees' taking charge behavior comes from the variance between groups, while 88% comes from the variance within the group. Because the dependent variable has significant intergroup variance, then we can test our hypotheses. The hypothesis test is completed in the following three steps, and the test results are shown in Table 4.

Step 2: testing the main effect of organizational identification.

First, we regressed taking charge behavior (dependent variable) on the individual-level independent variables (organizational identification) with control variables (age, education, tenure, and rank). In model 1, γ_{50} represents the influence coefficient of organizational identification on employees' taking charge behavior, which is used to test hypothesis 1. The results of model 1 show that $\gamma_{50} = 0.1783$ ($P < 0.001$, $t = 5.996$). So, hypothesis 1 is supported, and organizational identification is positively related with employees' taking charge behavior. R^2 of model 1 is 0.397, which means 39.7% of intragroup variance can be explained by control variables and organizational identification. In addition, after control variables and organizational identification were entered into model 1, intergroup variance(τ_{00}) is 0.0853 ($\chi 2 = 330.432$ and $P < 0.001$), and it indicates that there may be group-level factors in level-2, so we will go to Step 3 next.

Step 3: testing the direct effect of distributive justice climate and psychological safety climate.

Hypothesis 2a and hypothesis 3a argue that both distributive justice climate and psychological safety climate have a positive impact on employees' taking charge behavior.

In order to test hypothesis 2a and hypothesis 3a, we add distributive justice climate and psychological safety climate to level-2 and estimate the model with intercept as the result variable. In model 2, γ_{01} and γ_{02} represent the estimates of the effect of distributive justice climate and psychological safety climate on employees' taking charge behavior, respectively, after controlling age, education, tenure, rank, and organizational

Table 2: Fitting index of confirmatory factor analysis of measurement tools.

Model	X^2/df	RMSEA	SRMR	NNFI	CFI	GFI
Model 1: organizational identification	4.18	0.075	0.031	0.97	0.98	0.96
Model 2: distributional justice perception	3.423	0.075	0.047	0.96	0.97	0.98
Model 3: psychological safety perception	4.32	0.082	0.052	0.92	0.95	0.91
Model 4: taking charge behavior	4.2	0.085	0.067	0.91	0.93	0.86

Table 3: The descriptive statistics of latent variables.

Variable	Number of samples	Minimum	Maximum	Mean	Standard deviation
Level-1					
Organizational identification	806	1.00	5.00	3.64	0.84
Employees' taking charge behavior	806	1.30	5.00	3.70	0.72
Level-2					
Distributive justice climate	91	1.80	4.82	3.41	0.52
Psychological safety climate	91	2.19	4.76	3.51	0.52

Table 4: HLM analysis with taking charge behavior as dependent variable.

Variable	Model 1	Model 2	Model 3
Level-1			
Intercept (γ_{00})	3.6959***	2.5783***	2.5783***
Age (γ_{10})	0.0335	0.0323	0.0332
Education (γ_{20})	0.1019**	0.1022**	0.1004**
Tenure (γ_{30})	0.0539*	0.0566*	0.0554*
Rank (γ_{40})	0.2027***	0.2017***	0.1991***
Organizational identification (γ_{50})	0.1783***	0.1786***	0.2494**
Level-2			
Cross-level main effects			
Distributive justice climate (γ_{01})		0.1366*	0.1368*
Psychological safety climate (γ_{02})		0.1854*	0.1852*
Cross-level interaction effects			
Distributive justice climate * organizational identification (γ_{51})			0.2177*
Psychological safety climate * organizational identification (γ_{52})			−0.2286**

identification in level-1. T-test of γ_{01} can be used to test hypothesis 2a, and T-test of γ_{02} can be used to test hypothesis 3a.

The results of model 2 show that $\gamma_{01} = 0.1366$, $t = 2.543$, and $P < 0.05$, So, hypothesis 2a is supported. $\gamma_{02} = 0.1854$, $t = 2.075$, $P < 0.05$, and hypothesis 3a is supported. R^2 of model 2 is 0.232, which means 23.2% of intergroup variance of dependent variable can be explained by distributive justice climate psychological safety climate. In addition, $\chi^2(88) = 270.404$ and $P < 0.001$, indicating that the relationship between level-1 predictors and taking charge behavior was significantly different among different groups. Therefore, the next step is to test the moderating effect of distributive justice climate and psychological safety climate.

Step 4: testing the moderating effect of distributive justice climate and psychological safety climate.

Hypothesis 2b argues that distributive justice climate will positively moderate the influence of organizational identification on employees' taking charge behavior, while hypothesis 3b argues that psychological safety climate will negatively moderate the influence of organizational identification on employees' taking charge behavior.

In order to test the above interaction effect, we can use distributive justice climate and psychological safety climate as predictors of the β coefficient of organizational identification, so as to know whether distributive justice climate and psychological safety climate can explain the variance of the β coefficient of organizational identification. In model 3, γ_{51} represents the estimate of the interaction effect between distributive justice climate and organizational identification. T-test of γ_{51} can be used to test hypothesis 2b. In model 3, γ_{52} represents the estimate of the interaction effect between psychological safety climate and organizational identification. T-test of γ_{52} can be used to test hypothesis 3b.

The results of model 3 show that $\gamma_{51} = 0.2177$, $t = 2.444$, and $P < 0.05$, indicating the interaction effect of distributive justice climate and organizational identification on the dependent variable is significant. So, hypothesis 2b is supported. The results of model 3 show that $\gamma_{52} = -0.2286$, $t = -2.653$, and $P < 0.01$, indicating the interaction effect of psychological safety climate and organizational identification on the dependent variable is significant. So, hypothesis 3b is supported.

The interaction effect of organizational identification and distributive justice climate on employees' taking charge behavior is shown in Figure 2. In Figure 2, the black solid line represents the effect of organizational identification on employees' taking charge behavior under the high level of distributive justice climate, and the black dotted line represents the effect of organizational identification on employees' taking charge behavior under the low level of distributive justice climate.

According to Figure 2, the slope of black solid line is positive and steep, indicating that when the level of distributive justice climate is high, organizational identification has a positive impact on employees' impact behavior, and the effect is significant. The slope of black dotted line is negative and gentle, indicating that when the level of distributive justice climate is low, organizational identification negatively affects employees' taking charge behavior, but the effect is not significant. In general, distributive justice climate positively moderates the effect of organizational identification on employees' taking charge behavior.

The interaction effect of organizational identification and psychological safety climate on employees' taking charge behavior is shown in Figure 3. In Figure 3, the black solid line represents the effect of organizational identification on employees' taking charge behavior under the high level of psychological safety climate, and the black dotted line represents the effect of organizational identification on employees' taking charge behavior under the low level of psychological safety climate.

According to Figure 3, the slope of black solid line is negative and gentle, indicating that when the level of psychological security climate is high, organizational identification negatively affects employees' taking charge behavior, but the effect is not significant. The slope of black dotted line is positive and steep, which shows that when the level of psychological safety climate is low, organizational identification has a positive impact on employees' taking charge behavior, and the effect is significant. Generally speaking, the psychological safety climate negatively moderates the influence of organizational identification on employees' taking charge behavior.

6. Discussion

6.1. Theoretical Implications. In practical terms, taking charge behaviors consist of adopting improved procedures for the job, changing how the job is executed in order to be more effective, or correcting a faulty procedure or practice [13]. Such behaviors are consistent with the more recent business imperatives of "getting off the treadmill" and are conducive to the self-improvement and development of corporations. In the past, few scholars have explored the antecedents of employees' taking charge behavior from the perspective of organizational identification. Our study has confirmed the positive effect of organizational identification on employees' taking charge behavior, thus filled this gap. Once identified with the organization, an employee usually shares the common fate with the organization, so he or she intrinsically performs taking charge behaviors to improve the organization's function. It is just the identity integration between them and the organizations (namely, identification) that make them voluntarily engage in taking charge behaviors. Our conclusion also confirms what the group engagement model [53] said, "Cooperation is driven, in other words, by the motivation to create and maintain a favorable identity."

In addition, our study has discussed the boundary conditions of the relationship between organizational identification and employees' taking charge behavior.

Firstly, our study found that organizational distributive justice climate positively moderate the relationship between organizational identification and taking charge behavior. This means that organizational justice climate acts as an environmental catalyst, amplifying the impact of organizational identification on employees' taking charge behavior. In other words, once an organizational identifier works in a fair environment, his organizational identification will be further enhanced, therefore more taking charge behavior will appear. This finding can be explained as follows. The literature proposed that not only the organization's status in society (such as attractiveness, distinctiveness, prestige, construed external image, etc.) but also the individual's status in organization (such as respect etc.) have been considered as the important antecedents of employees' organizational identification, because these factors help to enhance employees' self-esteem and self-image [62].The literature also proposed that organizational justice can enhance employees' organizational identification, because for employees, being treated fairly by the organization's authority equals being respected and valued [62]. Therefore, a fair organizational environment can make those organizational identifiers (those who have identified with the organization for other reasons) experience the feeling of being respected and valued, which further enhances their organizational identification. Our study has found the amplifying effect of distributive justice climate between organizational identification and taking charge behavior, which provided empirical support for the above proposition.

Secondly, our study found that psychological safety climate negatively moderates the relationship between organizational identification and taking charge behavior. Owing to the challenging and risky nature of taking charge behavior, it is generally believed that in an environment that can provide psychological safety, people are more likely to engage in taking charge behavior. That is also what Morrison and Phelps [8] proposed. Generally speaking, this statement is correct, because, when employees decide whether to engage in taking charge, they will trade off the expected cost and expected benefit of that behavior. Our research results showed that psychological safety climate has a positive direct impact on employees' taking charge behavior, which also provides support for the above conclusion. However, for a person who is highly identified with the organization, the positive effect of psychological safety climate on taking charge behavior will weaken or even disappear. The reasons can be explained as follows. According to the literature, an organizationally identified person will not consider personal interests when engaging in taking charge behavior, because

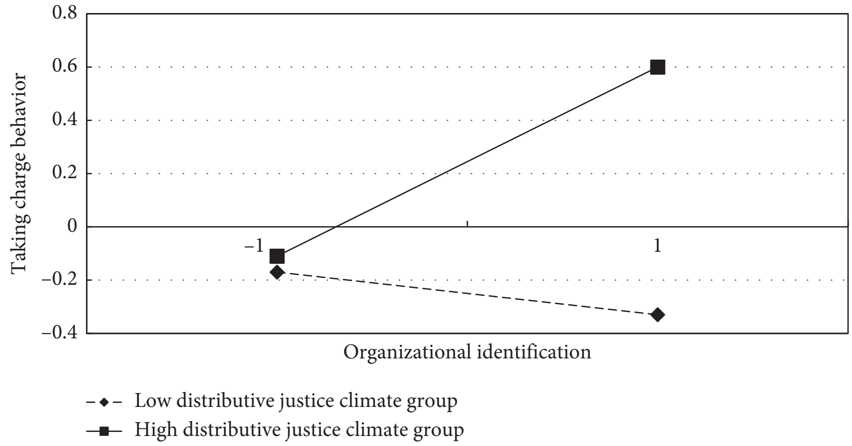

Figure 2: The interaction effect of organizational identification and distributive justice climate on employees' taking charge behavior.

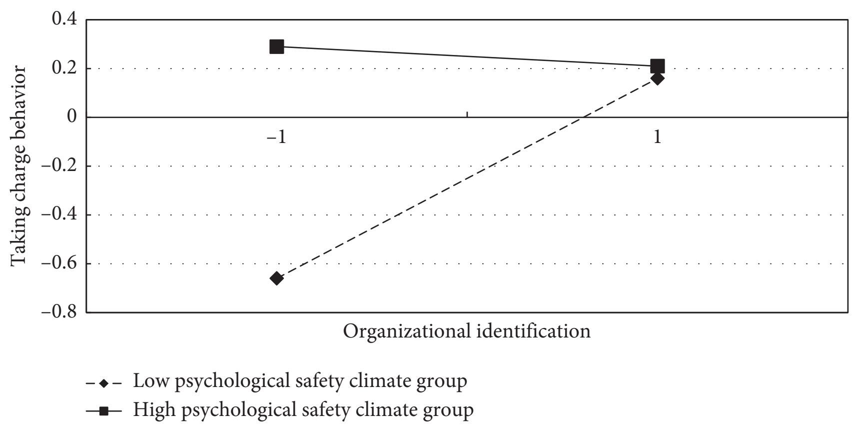

Figure 3: The interaction effect of organizational identification and psychological safety climate on employees' taking charge behavior.

identification maintains even if in situations involving great loss or suffering, missed potential benefits, task failure, and expected failure, and an organizationally identified employee, as a "microcosm of the organization" is likely to have attitudes and take actions that benefit the whole organization rather than benefitting individual self-interest [25]. That is to say, psychological safety is not a necessary condition for organizational identifiers to engage in taking charge behavior. They instinctively engage in such behaviors to change the functions of the organization, so as to increase the reputation and competitiveness of the organization, thus enhancing their own self-esteem and status. In particular, the worse the psychological safety climate, the more responsibility they feel to engage in taking charge. They perceive it as their mission to increase the reputation and competitiveness of an organization through taking charge, especially when no one else dares to challenge the status quo. In short, psychological safety may be a key environmental condition for a person with low organizational identification to engage taking charge behavior. However, for a person with high organizational identification, the lower the psychological safety perception, the more likely he or she is to engage in taking charge behavior, because she or he has the mission and original deep motive to change the bad environment. Our study has found buffering effect of psychological safety climate between organizational identification and taking charge behavior, which has a significant contribution to taking charge behavior research field.

6.2. Practical Implications. As no organization can foresee all environmental changes and potential accidents, the organizations are increasingly relying on employees to engage in proactive behavior to challenge the status quo, promote innovation, and initiate strategic change [63]. Staw and Boettger [64] also strengthened the importance of employees taking actions to correct wrong tasks or work roles. They believe that if the current role definition, procedures, or policies are inappropriate or ineffective, the most important thing for employees is to shift their extra-role efforts to change rather than maintain the status quo. So, it is very important for managers to take strategies to improve the enthusiasm of employees to engage in taking charge behavior.

According to our findings, employees with high organizational identification are more likely to engage in taking charge behavior. Therefore, organizational policies and practices should be made with the intent to foster employees' identification with the organization. The literature shows that the attractiveness, distinctiveness, prestige, construed external image that organizations get from society, and the status and respect that employees get in the company are key determinants of employees' organizational identification. Some human resource management practices, such as participation in decision-making, positive recognition by top management, performance-based reward system, and opportunities for extensive training, can be used to influence employees' perceptions of status and respect within the organization [27]. For example, managers can reduce the uncertainty of the reward system through multiple management strategies (such as improving the transparency of reward system), which will help enhance the organizational identification of employees.

Moreover, in order to improve the company's reputation, some public relation strategies should be used to communicate the company's achievements to internal employees and external stakeholders. Additionally, recruiting, socialization and training programs can incorporate information about the accomplishments of the organization [27]. From the perspective of complexity, feedback loops are the one of key factors that helps self-organizing systems operate effectively [65]. This means that communication is more effective in a complex adaptive system, and managers need to listen carefully to the voice of employees and avoid implanting control or pulling rank behavior during communication [66].

According to our findings, high level of distributive justice climate is conducive to improve the motivation of employees to engage in taking charge behavior. Distributive justice climate refers to the aggregated individual justice perceptions of organizational events and practices related with distribution results. Our results showed that organizational justice climate is the accelerator of organizational identification. People evaluate their identity and status in a particular group by the level of the respect that they are receiving from that group, the more they feel fair, the more they feel being respected, and the more they identify with the organization. Therefore, corporate policy and process should construct a fair environment within the organization. For example, one implication of complexity theory for organization procedure design is that firms should consider the elements of environmental setting and perceived fairness in penalty and reward system design [5].

According to our findings, as far as the motivation of taking charge behavior is concerned, although psychological safety climate has little influence on people with high organizational identification, it has significant influence on people with low organizational identification. High level of psychological safety climate is conducive to improve the motivation of employees with low organizational identification to engage in taking charge behavior. So, the company should construct an environment to convince employees that taking charge behavior will not be met with resistance or entail high political risks. When employees perceive that organizational policies support constructive efforts to bring about improvement, they may be more confident that taking charge will be effective and less concerned about potential costs [8]. Taking charge can only be achieved if strong climates for psychological safety exist in the organization, and for people to feel comfortable engaging in taking charge without fear of ridicule or punishment, managers must work to create a climate of psychological safety. For instance, the complexity lens implies that error-free systems are too rigid to coevolve with the environment [67]. Hence, managers should be deeply aware of the role of failure in organizational learning and adaptation and enhance psychological safety by building a corporate culture that embraces failure.

6.3. Limitations and Future Directions. Firstly, our study could be criticized for the small sample size. So, a lot of companies should be investigated as samples in future study. A second limitation of the research is that all the data were collected at roughly the same time. Thus, we are unable to make definitive causal conclusions based on our findings. Lastly, we use different sources to gather the data for the research variables, so the effect of common method bias on results can be alleviated. In this study, we use coworker's evaluation to measure outcome variable, and supervisor's evaluation can be used to measure outcome variables in future studies, to verify our results.

Future research can explore the influence of proactive personality on taking charge behavior. Proactive personality refers to the tendency of an individual to take initiative to change his external environment without the restriction of situational resistance [68]. Crant and Bateman [69] believe that individuals with proactive personalities prefer to challenge the status quo rather than passively accept their roles. They are good at finding and seizing opportunities, taking initiative actions, and persevere until their actions produce the expected results. They actively change the organization's goals and find and solve problems; they rely on themselves rather than others to influence the world around them. According to the definition of taking charge behavior, we may reasonably conclude that proactive personality has a positive impact on employees' taking charge behavior. However, we are not sure whether and how the influence of proactive personality on taking charge behavior is moderated by organizational justice climate and psychological safety climate. Therefore, this problem deserves the attention of future scholars.

Cooper and Thatcher [47] discussed self-concept orientations on employees' organizational identification. Self-concept orientations are the general tendency to think of the self in terms of individual characteristics, role relationships, or group memberships [47]. Three self-concept orientations were defined, individualist orientation, relationist orientation, and collectivist orientation. Cooper and Thatcher [47] argued that collectivist orientation, which means the tendency of individuals to value groups and view themselves in terms of group memberships, increases the likelihood of work group and organizational identification. Therefore, the future research can take collectivist orientation as an independent variable to explore the impact of self-concept orientation on taking charge behavior.

Another important construct associated with organizational climate is climate strength. Schneider et al. [70] defined climate strength as the intragroup variance of climate perception. Research on climate strength suggests that individuals who operate in strong climates hold convergent expectations about how others will interact and behave, resulting in compliance and uniform behavior [40]. Therefore, climate strength may enhance the influence of climate on outcomes, because group consensus creates a strong situation, which makes it difficult for group members to deviate from consistent practices [70]. For instance, Schneider et al. [70] found that service climate was positively related to customer service quality in strong climates, but unrelated in weak climates. Therefore, the future research should explore the moderating effect of climate strength between psychological safety climate, organizational justice climate, and employees' taking charge behavior.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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Research Article

Modeling and Simulating Online Panic in an Epidemic Complexity System: An Agent-Based Approach

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Following the outbreak of a disease, panic often spreads on online forums, which seriously affects normal economic operations as well as epidemic prevention procedures. Online panic is often manifested earlier than in the real world, leading to an aggravated social response from citizens. This paper conducts sentiment analysis on more than 80,000 comments about COVID-19 obtained from the Chinese Internet and identifies patterns within them. Based on this analysis, we propose an agent-based model consisting of two parts—a revised SEIR model to simulate an offline epidemic and a scale-free network to simulate the Internet community. This model is then used to analyze the effects of the social distancing policy. Assuming the existence of such a policy, online panic is simulated corresponding to different informatization levels. The results indicate that increased social informatization levels lead to substantial online panic during disease outbreaks. To reduce the economic impact of epidemics, we discuss different strategies for releasing information on the epidemic. Our conclusions indicate that announcing the number of daily new cases or the number of asymptomatic people following the peak of symptomatic infections could help to reduce the intensity of online panic and delay the peak of panic. In turn, this can be expected to keep social production more orderly and reduce the impact of social responses on the economy.

1. Introduction

Complexity science is a field of nonlinear science research, e.g., the theory of chaotic dynamics, which contends that simple behavior on an individual level may lead to uncertain complex behavior in aggregate. With advancements in computing power over time, the functions of cellular automata have been empowered, pushing such research into a broader range of fields. In the field of management and social research, Schelling (1971) concluded that simple rules can simulate complex changes and explained the segregation phenomenon using certain move strategies and two types of agents [1]. In such models, the cell is regarded as an agent, and the model in its entirety is called an agent-based model (ABM). The visibility of an ABM model is enhanced by the standardized description of the mapping relationship between each agent's real behavior and abstract mathematical rules [2]. In recent years, a significant amount of data has been generated from unstructured textual data, which is of considerable informational value. Rapid development in natural language processing technology and computing power has enabled us to obtain useful information from them. Khatua, Khatua, and Cambria (2019) used PubMed abstracts in a pretraining model and constructed high-quality quantifier vectors in specific fields, which improved the accuracy of epidemic monitoring based on social media texts [3]. Sentiment analysis, also known as opinion mining, is another important natural language processing technique. It is a data-based method used to analyze emotional tendencies. For example, emotion analysis technology can be used to analyze the impact of terrorist attacks on people's psychology [4]; to predict, monitor, and analyze public opinion on political issues by the government [5]; and to estimate user satisfaction with certain products or services by enterprises [6]. Textual sentiment analysis is beneficial even to researchers, helping the design of more reasonable models and more realistic investigation of the complexity of phenomena.

The objective of the current study is to investigate patterns in the transmission of online panic and to minimize its adverse effects. Panic refers to a special form of collective behavior that occurs when a group subjectively believes that resources are scarce, and it is usually accompanied by maladaptive behavior [7]. In particular, people experiencing panic during an epidemic are liable to act irrationally [8]. In academics, this phenomenon is called a social response. Considerable research has been conducted on epidemiological prediction based on social media data [9] or social responses caused by epidemics [10]. Social responses to epidemic outbreaks range from mental stress and economic downturn to flight from the outbreak site and distrust of official announcements [11]. Fraud, theft, robbery, and other disruptions of social order are known to become common and epidemic prevention orders are often ignored [12, 13]. In the financial market, investor sentiment significantly influences the stock market [14]. The social response to an epidemic affects the stock market, the retail sector, and individual incomes and eventually induces an economic recession. Following the COVID-19 outbreak, the imposition of social distancing policies and international travel restrictions severely affected global economic activity [15]. The International Monetary Fund estimated that the average economic growth rate in advanced economies is −4.9% in 2020 due to the impact of COVID-19. The epidemic has also affected developing economies. The average growth rate in these countries was −2.4% in 2020 [16].

Online panic is characterized by its rapid transmission and is not geographically constrained. These escalate its impact, causing severe economic losses. On April 23, 2013, fake news reports claiming that Barrack Obama was injured in twin explosions in the White House were spread on Twitter, inducing a loss of $ 136.5 billion in the stock market [17]. Online panic can also lead to health problems—people in Iran were misled to believe that drinking alcohol can prevent and treat novel coronavirus, leading to the deaths of hundreds of people in several provinces of Iran [18]. Nicomedes and Avila found levels of anxiety regarding health to be consistent irrespective of the location of individuals or their exposure to COVID-19 patients [19]. Rumor is an important source and vector of online panic, and several researchers have attempted to explain its mechanism [20, 21]. Following the COVID-19 outbreak, the relationship between information and online panic, leading to what is known as an "infodemic," has been studied [22]—the flow of information leads to anxiety and caution, while misinfodemics cause panic, distrust, and confusion [23]. Ahmad and Murad investigated the relationship between social media and the transmission of panic regarding COVID-19 on the basis of questionnaires and identified fake news about COVID-19 and the dissemination of the number of infections to be the two primary contributors [24]. Panic buying (PB) is another important topic of research—online panic often leads to impulsive and obsessive buying, whose negative aspects have been extensively portrayed in the media [25, 26].

Existing studies reveal that sudden outbreaks of diseases often lead to panic, resulting in severe consequences. Recently, online panic following the COVID-19 outbreak has been investigated. Online networks have a special network structure characteristic—that of scale-free networks. This implies that the transmission of panic on the Internet is different from that in real-world environments. As epidemic information plays an essential role in the spread of online panic—transparency on this topic is a double-edged sword. In turn, this increases public distrust of the government. It also triggers panic on the Internet and affects the normal functioning of society and the economy. In this paper, we consider the differences between the transmission of panic in the information age compared to those in earlier times and explore reasonable steps of information disclosure to control panic effectively. Existing studies have used empirical or modeling-based methods to study the damage caused by the transmission of diseases. Fast et al. used an agent-based model to analyze the differences in social responses caused by several epidemics [27]. However, their model assumed the degree distribution of the relationship network to be uniform and did not consider the role of the Internet. Other studies have used questionnaires and regression methods to analyze the reason or impact of online panic without exploring its mechanism. The transmission of diseases and that of online panic should be investigated in an integrated fashion to guide information release policies. The model proposed in this paper is based on this outlook.

2. Materials and Methods

In this study, a dual network model, accounting for offline disease transmission and online emotional transmission, is proposed. This model is applied to investigate the relationships between public disclosure of health information, dissemination of information to mass media, and public perception of the risk of disease. Further, the impact of variations in the parameters on the evolution of online panic is measured.

2.1. Social Media Sentiment Analysis. SnowNLP is a simplified Chinese text processing toolkit that can be used to assign emotional intensity scores, ranging between 0 and 1, to Chinese texts. It employs word segmentation and trains a naive Bayesian model to perform emotional analysis on new texts.

$$P(c_i|w_1,\ldots,w_n) = \frac{P(w_1,\ldots,w_n|c_1)\cdot P(c_1)}{P(w_1,\ldots,w_n)}, \tag{1}$$

$$P(w\_1,\ldots,w\_n) = P(w\_1,\ldots,w\_n|c\_1)\cdot P(c\_1) + P(w\_1,\ldots,w\_n \mid c\_2)\cdot P(c\_2). \tag{2}$$

c_1 and c_2 in (1) denote two separate categories, and $w_1, \ldots, w_n$ denote the features. The model was trained using a training dataset and topical data about COVID-19 collected from blogs and comments published on posts on Weibo (a Chinese social media platform, similar to Twitter) between January 20, 2020, and April 1, 2020. The total text volume was 80,235. Inspired by Xiong et al. (2020), negative comments were defined to be those with an emotional score below 0.1, while positive comments were defined to be those with an emotional score above 0.9 [28].

Tables 1 and 2 record the average emotion scores and the proportion of negative comments. The average emotion scores were observed to lie within the range between 0.368 and 0.684, and negative comments accounted for a maximum of 29.15% of the total number of comments. As the number of confirmed cases reported increased, negative comments were observed to increase in proportion, rising by a factor of 1.97 between January 21 and February 4. This indicates that an increase in the number of reported cases per day sours the mood of online discussions, while a decrease in the number of reported daily cases improves the mood of online discussions. Before the 36 new cases on March 31, the daily number of newly reported cases was less than 10. The sudden spike in the number of reported cases on that day led to a rapid increase in the proportion of negative comments on the Internet.

Figure 1 depicts the emotional distribution of the topics recorded in Tables 1 and 2. The emotional distribution exhibited the trend of a bipolar distribution, and neutral views were observed to not hold much sway. This can be attributed to the young demographic of the Weibo user base and the degree of anonymity that users enjoy on the platform. In addition, whenever the number of reported cases was higher than that of the previous day, the proportion of positive comments (emotion score > 0.9) was observed to decrease significantly, while that of negative comments (emotion score < 0.1) increased significantly, even when there was no significant difference in the number of new cases over a longer period, the total number of cases, the number of asymptomatic infected persons, and other forms of reporting. Thus, it is clear that netizens primarily focus on the comparison between the number of reported cases each day and the corresponding previous day but do not consider the statistical caliber used. This analysis helped us to establish the following rules for the proposed model.

2.2. Attributes Based on Epidemiological Dynamics. Several studies have been conducted on epidemics. Kermack and McKendrick (1927) proposed the SIR model, which divides the population into three categories—susceptible, diseased, and recovered [29]. It is important to note that the SIR model assumes that once infected, patients cannot be infected again—thus, infected patients will either recover or die from the disease. Subsequently, Anderson and May (1992) proposed the SEIR model based on the SIR model [30]. In this model, people are categorized into four classes—susceptible, exposed, infectious, and recovered. Consideration of the scenarios in which patients infected with epidemic diseases do not develop immunity after recovery led to the proposal of the SIS model. Further, diseases may exhibit rapid mutation, leading to short-term immunity of infected and recovered patients but renewed susceptibility over longer terms. The SIRS model was proposed to account for this scenario.

COVID-19 patients exhibited weak infectious ability during their incubation periods [31]. Thus, based on the SEIR model and existing studies, we propose a modified SEIR model with the following parameters: X_i denotes the health status at time t and $X_i(t)\in\{S, E, I, R\}$, where S, E, I, and R denote classes of susceptible, exposed, infected, and recovered individuals, respectively. People travel between the four states over time. Most epidemics are transmitted primarily through close contact between people. Let us suppose that each person comes into close contact with r people at each time step. Let the probability of infection by contact with an exposed person, which includes patients in the incubation period, be β_1, and let the probability of infection by contact with an infected person be β_2. Further, let the probability of recovery for an exposed or infected person be γ. It is to be noted that this includes patients who die of the disease. All recovered persons are considered to be no longer infected. Finally, let the probability of an exposed person becoming susceptible be α. This accounts for the case in which an asymptomatic person turns into a patient with definite symptoms. Given these parameters, the epidemiological dynamics equations are as follows:

Susceptible:

$$\frac{dI}{dt} = -\frac{r\beta_1 ES}{N} - \frac{r\beta_2 IS}{N}. \tag{3}$$

Exposed:

$$\frac{dE}{dt} = \frac{r\beta_1 ES}{N} + \frac{r\beta_2 IS}{N} - \alpha E - \gamma E. \tag{4}$$

Infected:

$$\frac{dI}{dt} = \alpha E - \gamma I. \tag{5}$$

Recovered:

$$\frac{dR}{dt} = \gamma I + \gamma E. \tag{6}$$

The correlation between health status and online social relationships is depicted in Figure 2.

Table 1: The emotional score distribution of comments corresponding to different stages of increasing transmission of COVID-19.

Date	Topic	Average emotion	Negative proportion (%)
1/21	440 confirmed cases of COVID-19	0.630	14.76
1/22	571 confirmed cases of COVID-19	0.538	15.74
1/23	830 confirmed cases of COVID-19	0.482	19.14
1/26	2,744 confirmed cases and 80 deaths	0.430	18.10
1/27	The total number of confirmed cases nationwide has increased to 4515	0.396	23.01
1/28	The number of confirmed cases of COVID-19 exceeds that of SARS	0.368	25.62
1/29	1737 new confirmed cases of COVID-19 nationwide and total 11791 cases	0.405	17.18
1/31	2102 new confirmed cases of COVID-19 nationwide	0.426	22.02
2/4	3887 new confirmed cases of COVID-19 nationwide	0.369	29.15

Table 2: The emotional score distribution of comments corresponding to different stages of decreasing transmission of COVID-19.

Date	Topic	Average emotion	Negative proportion (%)
2/5	3694 new confirmed cases of COVID-19 nationwide	0.511	25.05
2/7	3399 new confirmed cases of COVID-19 nationwide	0.564	13.32
2/8	2656 new confirmed cases of COVID-19 nationwide	0.538	14.48
2/14	2641 new confirmed cases of COVID-19 nationwide	0.620	11.24
2/15	2009 new confirmed cases of COVID-19 nationwide	0.646	6.96
2/16	2048 new confirmed cases of COVID-19 nationwide	0.538	15.74
2/17	1886 new confirmed cases of COVID-19 nationwide	0.596	10.90
2/18	1749 new confirmed cases of COVID-19 nationwide	0.654	8.73
2/20	889 new confirmed cases of COVID-19 nationwide	0.580	7.64
2/21	397 new confirmed cases of COVID-19 nationwide	0.534	8.13
2/22	648 new confirmed cases of COVID-19 nationwide	0.530	15.87
2/23	409 new confirmed cases of COVID-19 nationwide	0.537	9.78
2/24	508 new confirmed cases of COVID-19 nationwide	0.527	18.12
2/25	406 new confirmed cases of COVID-19 nationwide	0.576	13.49
2/26	433 new confirmed cases of COVID-19 nationwide	0.460	21.26
2/27	327 new confirmed cases of COVID-19 nationwide	0.630	15.99
2/29	427 new confirmed cases of COVID-19 nationwide	0.538	19.16
3/31	Thirty-one provinces have confirmed 36 new cases	0.482	24.99
4/1	There were 55 new cases of asymptomatic infections	0.530	19.32

2.3. Netizen Attributes. Netizens are assigned health attributes, $X_i(t)$, and online panic attributes, $Y_i(t)$. $Y_i(t)$ is used to denote the intensity of the online panic of an agent at time t. Y_i is a continuous variable, $Y_i \in [0, 1]$, where 0 represents the absence of all panic and 1 represents the most severe level of online panic. $Y_i \in [0, 0.1]$ in the initial state.

Firstly, when the public is in a rational state of mind, they are willing to listen to public health sector guidance and trust officially released information. Popular judgment of dangers, fears, and proportionate responses are determined to a large extent by their trust in the public health sector. Secondly, on the Internet, panic is not geographically constrained and its communities are prone to cross-regional transmission. Thus, the following three rules are adopted to adapt the rules of transmission while modeling online panic:

(1) When communicating with neighbors, individuals are more susceptible to the emotions of the most fearful neighbors

(2) Whenever the media reports disease-related information, popular panic increases with a certain probability, increasing the values of Y_i

(3) When a node is infected, panic increases rapidly, $Y_i = k$. k is a constant that depends on the severity of the disease, e.g., the number of deaths from the disease and the existence of a sequela of the disease

Psychological studies have established psychological trauma as well as information anxiety decrease over time with a fixed coefficient of $\alpha = 0.95$. At the end of each round of network evolution, each individual's panic is attenuated, and the reduced panic emotion is taken as the initial value of the next round. The following formula is used for this purpose:

$$Y_i(t+1) = \alpha * Y_i(t). \tag{7}$$

Internet users tend to be convinced by users with radical views and empathize with users with strong emotions, as confirmed by research on the transmission of word-of-mouth on the Internet. Mudambi and Schuff (2010) found that users considered extreme emotional comments to be more useful than more moderate comments [32]. Inspired by the DeGroot model and cognitive psychology [33, 34], we contend that individual panic can influence neighbors in a biased manner. In particular, the online panic of each node in the network is a weighted average that is influenced by its neighboring nodes. Agents exhibiting higher panic are assigned higher weights, as follows:

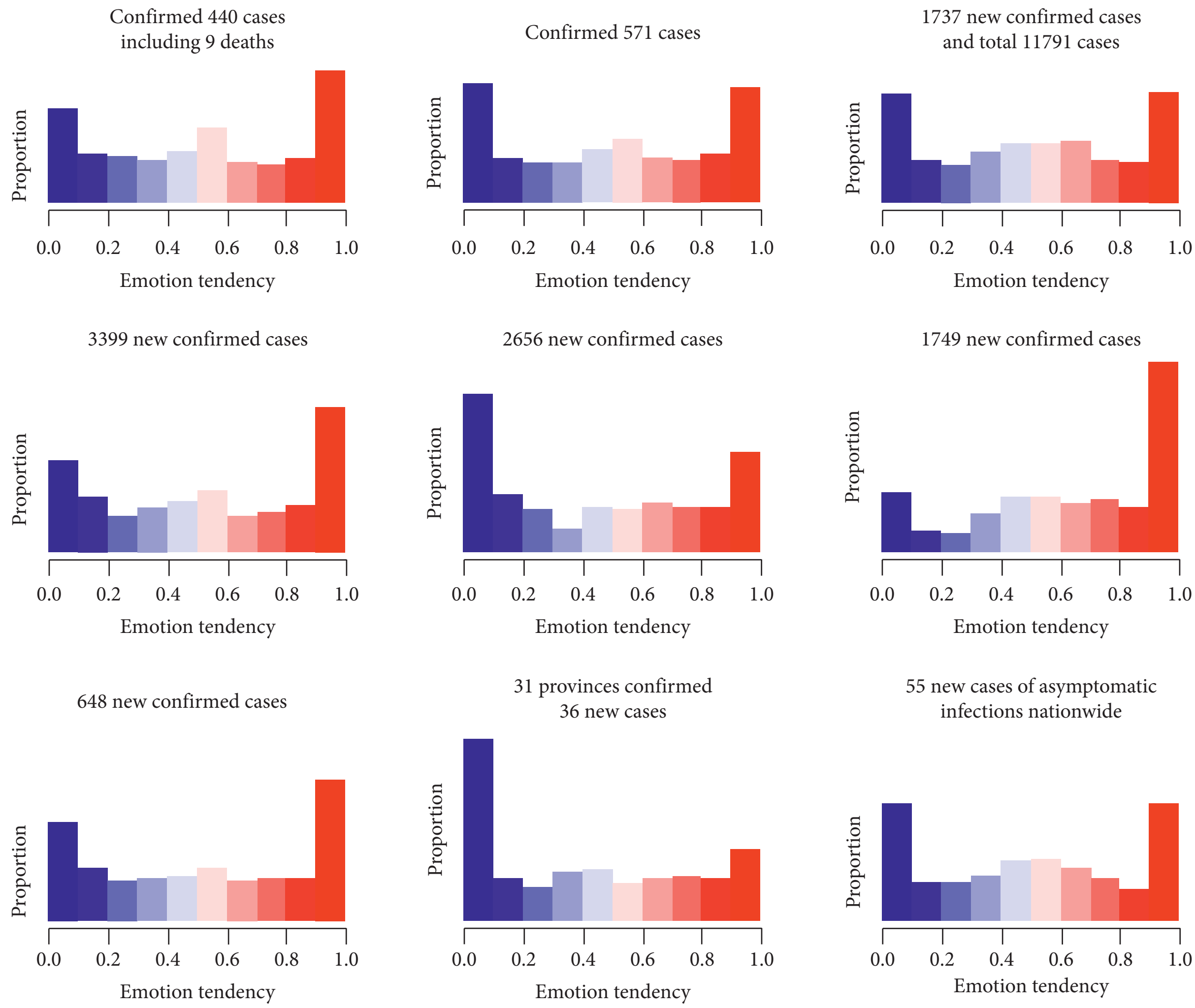

Figure 1: Emotional distribution corresponding to nine different transmission stages. Smaller numbers on the horizontal axis correspond to more negative emotions.

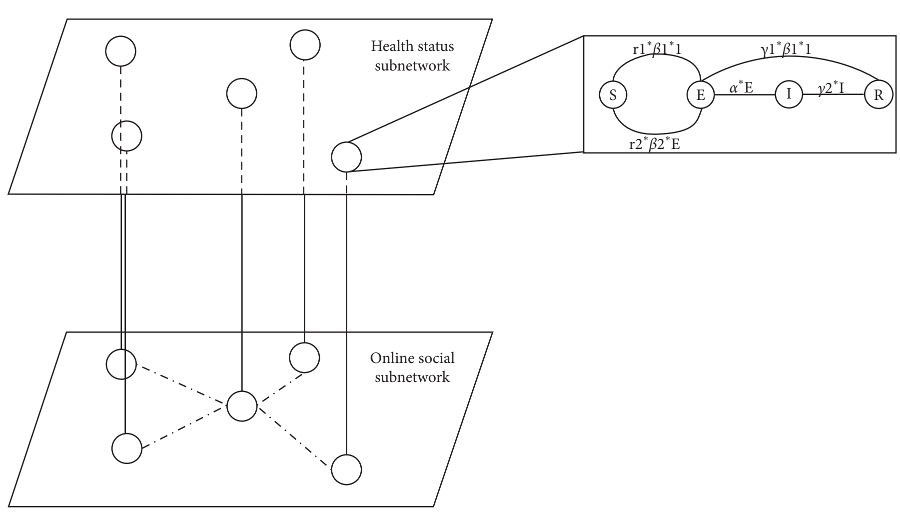

Figure 2: The health status subnet and the online social subnet. At each time step, the health status changes with a certain probability and moves to the next state, while panic-ridden emotion is transmitted through the online social subnetwork that functions as a scale-free network.

$$w_i(t) = \begin{cases} 10, & \text{if } Y_i(t) \geq 0.5, \\ 1, & \text{otherwise,} \end{cases} \quad (8)$$

where $w_i(t)$ denotes the influence weight of the i^{th} node on all neighboring agents at time t and $Y(t)$ denotes the intensity of the online panic of agent i at time t.

In addition, we define the following rules of influence of online panic among individuals as follows, where I_{ij} denotes the existence or absence of a connection between node i and node j—$I_{ij} = 1$ implies the existence of a connection between the two nodes:

$$Y_i(t_0) = \frac{1}{\sum_j I_{ij} W_{ij}} * \sum_j I_{ij} W_{ij} Y_j(t). \quad (9)$$

2.4. Network Attributes. A scale-free network is a type of complex network. Such networks utilize two assumptions for the formation of scale-free networks—the growth hypothesis and the preference connection hypothesis. This means that new nodes continually appear in the network and the new nodes are more inclined to connect with existing nodes with higher degrees. The degree distribution of such a network follows the power distribution, $P(k) \sim A\hat{K}$, where k lies between 2 and 3 [35]. Li et al. (2015) identified the invariant characteristic that the followers' count of users obeys a power-law distribution with an exponent almost equal to 2 by empirically studying 10 million user profiles on the largest Chinese microblog, Sina Weibo, and 41.7 million profiles on Twitter [36]. Moreover, rumors are known to spread faster in scale-free networks, which are also called BA networks, than in small-world networks [37].

In this study, the NetLogo software is used to construct the model and perform the simulation. Individuals are taken to be the agents. Connections between agents are determined by the online connection between the two corresponding people, which is mutual and reflected in the network as an undirected connection between the two points. As depicted in Figure 3, according to these rules, a scale-free network containing 30,000 nodes is constructed in this study, and its degree distribution is observed to follow a power-law distribution with an exponent of 2.

2.5. Attributes Related to the Disclosure of Public Health Information and the Media. Information conveyed by the media to the public has an essential impact on public sentiment. For example, public fear of being in a plane crash is much higher than the probability of developing heart disease, even though, in reality, flight safety is much higher than immunity from heart disease. Young et al. (2013) concluded that diseases that are reported more frequently in the media attract significantly more public attention irrespective of their severity [38]. Disclosure of information by the government also affects the judgment of the media. The government can choose to publish the number of new cases recorded on the previous day and the total number of cases on the previous day or not to declare the number of asymptomatic infected persons. When published data

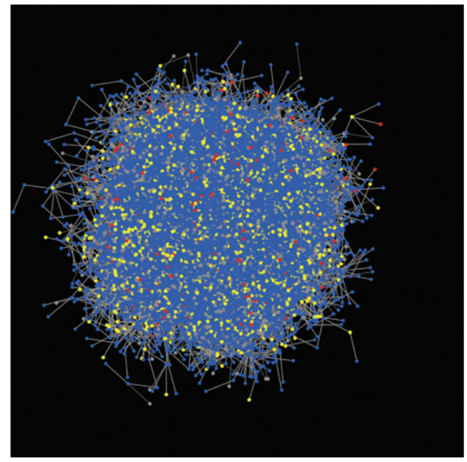

Figure 3: The network diagram in operation shows the network's topology, with nodes of different colors representing different individuals with different health states.

exceed half of the all-time high number of infections, disease-related news frequently appears on social media [8]. In our model, we set the initial intensity of social media (M) to be 0 and update it according to the following rule:

$$M(t) = \begin{cases} \frac{k}{2}, & \text{if } N(t) > N(t_0), \\ 0, & \text{otherwise,} \end{cases} \quad (10)$$

where k denotes a constant that depends on the severity of the disease, $N(t)$ denotes the number of cases declared by the government at time t, t_0 denotes an instant before time t, and $M(t)$ denotes the intensity of M at time t.

An online individual, I, perceives the severity of the epidemic reported by social media with probability, pi, which is determined by the penetration rate of public media:

$$M_i(t) = \begin{cases} M(t), & \text{with probability pi}, \\ 0, & \text{with probability } 1 - \text{pi}. \end{cases} \quad (11)$$

3. Results and Discussion

In this study, He's (2018) method is adopted to summarize agent-related variables used in the model, as recorded in Table 3 [39]. The configuration of certain variables is based on Fast et al. (2015) [8]. At the onset of the COVID-19 outbreak, many countries and regions adopted social distancing policies, including stay-at-home orders and the closure of restaurants. We first examine the use of social distancing policies and assess the agreement between the model and reality. Figure 4 depicts the changes in the health status of individuals during the transmission of the disease without the implementation of any social distancing policy. Initially, the number of exposed individuals increased quickly as the infection infects susceptible portions of the population and reached a peak incubation period at day 28. As the number of exposed individuals increased, so did the number of infected people, with a peak at day 35. Following

Table 3: Agent-related variables used in the model.

Class	Variable	Type	Remark	First equation
Epidemic	r	XV	The number of close contacts of each person per time step, set to 20	(1)
	β_1	XV	The probability of infection by contact with an exposed person, set to 0.02	(1)
	β_2	XV	The probability of infection by contact with an infected person, set to 0.06	(1)
	α	XV	The probability of an exposed person turning into a susceptible person, set to 0.13	(2)
	γ	XV	The probability of recovery of an exposed or infected person, set to 0.2	(2)
Agent	$X_i(t)$	NV	Health statues, $X_i(t) \in \{S, E, I, R\}$	—
	$Y_i(t)$	NV	Intensity of the online panic	(5)
Media	$w_i(t)$	XV	The influence weight on all neighbor agents at time t	(6)
	$M(t)$	NV	The intensity of social media at time t	(8)
	pi	XV	The probability of individual i being influenced by the news	(9)

NV: endogenous variable; XV: exogenous variable. The values of NVs are updated at each time step, t, while those of the XVs remain constant after initialization. Exogenous variables that the regulator can affect directly or indirectly.

the peak, as indicated by the figures, the number of exposed and infected individuals decreased slowly over time, presenting a smoother curve. Throughout the period of transmission, the number of infected people increased, eventually infecting almost everyone. In the second simulation, we added a policy of social distancing on day 22, when the number of confirmed cases rapidly increased, to reduce contact between individuals. The implementation of the social distancing policy was observed to reduce the total number of patients and preserve public health.

At this point, the government's social distancing policy exerts a controlling effect on the epidemic, including slowing the rate of transmission of the disease, reducing the number of cases at the peak, and preventing the occurrence of medical runs. Figure 2 depicts that the total number of cases decreased significantly after the implementation of the social distancing policy by the government.

Then, we obtained the average search volume for facemasks, medical alcohol, and N95 masks between January 20, 2020, and March 10, 2020, based on the Baidu Index (Baidu is a widely used search engine in China and the Baidu Index is similar to Google Trends), and fitted the average values with the extent of online panic after the implementation of the social distancing policy. $R\hat{2} = 0.83$ was obtained, which suggested a proper fitting. This indicated that the simulation method has practical significance and can be used as an effective guide for the government information disclosure policy. Given the success of the social distancing policy and its widespread adoption in reality, in the subsequent simulation, we explored the impact of different information disclosure policies based on the social distancing policy already adopted.

3.1. The Impact of Social Informatization. Based on the social distancing policy during the outbreak of a disease, we now attempt to examine the influence of social informatization on the extent of online panic. Two levels of social informatization were used for comparative analysis.

The evolution of online panic in two communities with similar structure experiencing the same epidemic with different coverage rates of public media is depicted in Figure 5. The community with a lower coverage rate exhibited a lower level of cyber panic, and the corresponding growth rate and peak value of online panic were lower. However, Fast et al. (2018) identified a significant positive correlation between the intensity of media coverage and the decline of epidemics—when media coverage increased tenfold, the epidemic trend decreased by 33.5%, and communities with a high acceptance rate of public media coverage were conducive to preventing the spread of the epidemic [27]. At present, the level of social informatization is relatively high. This could explain the higher psychological harm caused by epidemic diseases in modern times than in the past. For example, COVID-19 induced online panic to a higher degree than SARS.

Transparency and full disclosure of information are necessary to combat epidemics. However, Figure 5 reveals that online panic was very high corresponding to a high level of social informatization. Therefore, the influence of the mode of disclosure of information on online panic should be investigated to determine the most conducive mode of disclosure.

3.2. The Impact of Data Disclosure Patterns. In this section, we explore the impact of two distinct governmental disclosure policies for epidemic information on cyber panic. Figures 5 and 6 depict the changes in the overall average level of panic over time in each scenario over 50 repeated runs of the model. Two statistics can be used to disclose information about an epidemic—the total number of existing cases and the number of daily new cases. As is evident from Figure 6, adoption of the latter statistic effectively reduces the peak of online panic and delays it compared to the other case, giving policymakers more time to respond to the disease. It follows that reporting the number of daily new cases is a more effective policy.

The disclosure of the number of asymptomatic infections is another decision to be made by policymakers. Asymptomatic infected persons do not exhibit any symptoms of infection but can be detected by tests and the detection rate increases over time. The number of asymptomatic infected cases is usually disclosed in aggregate. It is difficult to estimate this figure during the early stages of an outbreak because a high rate of testing is required, which is usually achieved later. Asymptomatic infected persons do not require specialized medical treatment, and most of them heal

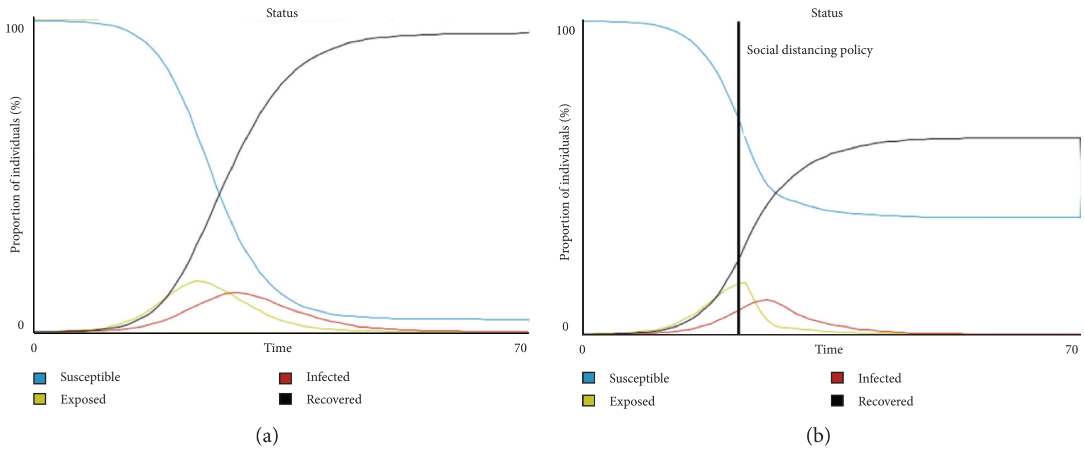

Figure 4: (a) The period of transmission of the disease; (b) the influence of the social distancing policy. The following categories are used—susceptible, i.e., healthy people who have never been infected; exposed, i.e., infected persons going through the incubation period of the disease; infected, i.e., asymptomatic infected persons or infected individuals exhibiting significant symptoms; and recovered, i.e., those recovered from infection who cannot become infected again.

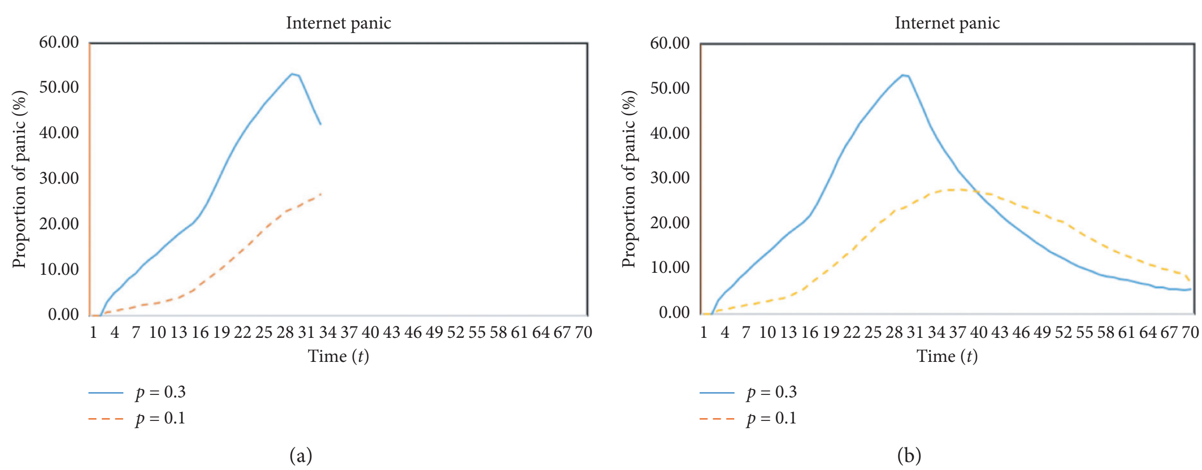

Figure 5: The degree of online panic under different media penetration rates. p: media penetration rates. (a) The total number of cases reported each day when the panic intensity gradually increased. (b) The whole process of panic intensity changes.

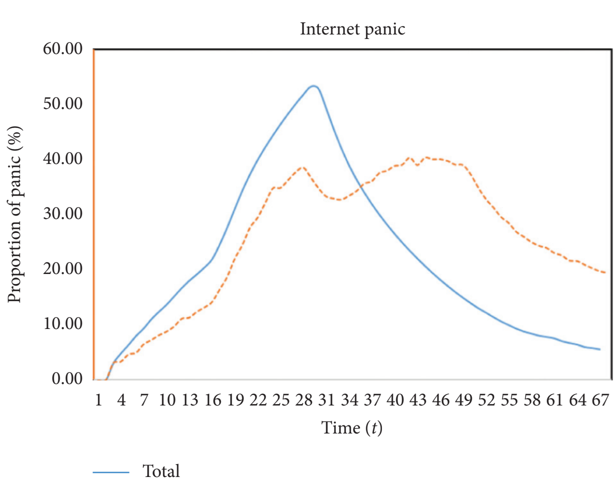

Figure 6: The impact of different disclosure policies for epidemic data on online panic—total cases versus daily new cases.

on their own. Therefore, in our simulation, we selected four key points in time—the first day, the 15th day, the 30th day, and the 45th day—to correspond to the beginning, inflation, peak, and recession phases of the epidemic, respectively.

As indicated by the data presented in Figure 7, disclosing the number of asymptomatic infected patients yields better public informetrics once the number of new infections per day has significantly reduced during the recession phase, exhibiting the lowest peak of online panic. Generally, the faster the public health sector releases information, the higher its transparency and credibility are. It also makes it more likely to calm rumors and foster the steady evolution of public opinion. However, the increase in the number of asymptomatic infected patients cannot be attributed solely to the escalation of the epidemic. It is also significantly influenced by the increase in the detection rate, which, in turn, increases with time. Thus, by disclosing the number of asymptomatic infected people during the recession phase of

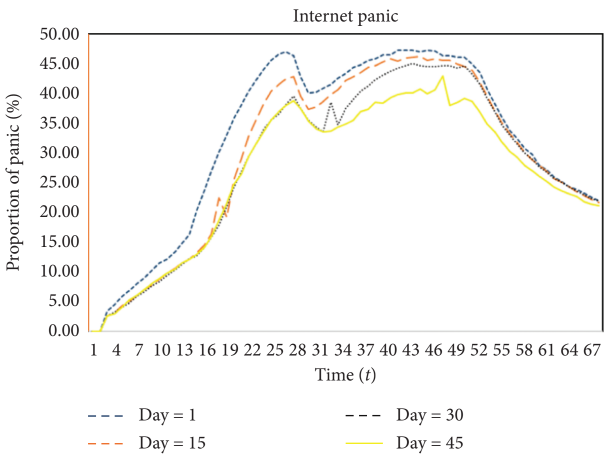

Figure 7: The impact of releasing the number of asymptomatic infections at different phases of the epidemic. The horizontal axis represents the number of days after the data are published in each case.

the epidemic, policymakers can positively impact public opinion, thereby reducing the peak of online panic.

4. Conclusions

In this study, an agent-based simulation was used to consider the effects of both online and offline factors on online panic. During the offline analysis, an improved epidemic dynamics model based on the SEIR epidemic dynamics model is proposed to simulate offline epidemic transmission. In the online component, online community networks are analyzed to propose a scale-free Internet community relationship network, which is used to simulate the transmission of online panic. COVID-19 was selected as a case study to simulate the spread of online panic and the Baidu search index was used to fit the data to the extent of online panic to validate the model. The effectiveness of different information disclosure strategies (such as the type of cases disclosed and the disclosure of asymptomatic infected persons) in response to online panic during disease outbreaks was also assessed. By collecting short essays from Chinese social media for sentiment analysis, the study divided the transmission of the disease into increasing and declining stages with respect to the time and stage of its development. We analyzed the variations in emotions of netizens with respect to the published epidemic data during the two periods. Then, we explored the impact of media penetration on social panic. The study found that high media penetration rates lead to high social panic responses. In the past, when the media penetration rate was low, pandemic-induced online panic rose slowly and soon began to wane. This research is expected to help mitigate the economic impact of epidemics by optimizing information dissemination policies, increasing public trust, and reducing panic.

This study concluded that social distancing policies are effective—in the presence of such policies, simulation results indicated that increased social informatization levels induce more substantial online panic during the outbreak. To reduce the economic impact of epidemics, we suggest that the government should disclose the number of daily new infections rather than the total number of infected cases and withhold the announcement of the number of asymptomatic infections till the peak of symptomatic infections is attained. According to our simulations, this should reduce the intensity of online panic and delay its peak, which would also reduce the adverse impact of social response on the economy.

Finally, this study also contributes to economic development. In 2020, several countries adopted stimulus policies, such as proactive fiscal or loose monetary policies, to help enterprises tide over difficulties and stimulate consumer spending. The conclusions of the study demonstrate clear methods to control and reduce online panic, which, in turn, will help boost public confidence and stimulate consumer spending. This would empower the government's stimulus policies. Moreover, this model can be extended to the field of businesses to help corporate and commercial organizations make better decisions. For example, this model can be adapted to predict the proportion of people who want to attend sales promotional activities during an epidemic, which can inform the decision to hold such an event.

This study suffers from certain shortcomings. Only two categories are used based on NLP sentiment analysis, thus supporting the agent-based model's hypothesis. However, in the real world, emotions may fall into multiple categories. Therefore, we intend to pretrain the model in future works using deep learning-based methods to complete model training and sentiment analysis, e.g., the word embedding model, and further refine the model.

Data Availability

Textual data and program code can be obtained from https://github.com/downw/SocialMediaText.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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Research Article

Unintended Consequences of Agricultural Participation in Voluntary Carbon Markets: Their Nature and Avoidance

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Greenhouse gas (GHG) trading markets have been widely discussed for climate change mitigation. However in implementation coverage has not been universal. Agriculture, despite being the source of nearly 25% of net emissions, has not commonly been capped. But it has been mentioned as voluntary source of net emission offsets. Such offsets could arise from action reducing GHG emissions, enhancing sequestration, or producing feedstocks for low emitting bioenergy replacements for fossil based energy. This could be harnessed by setting up voluntary carbon markets that producers could join at their discretion. However, such a scheme could have unintended consequences. We conduct theoretical and empirical analyses of a voluntary "carbon" market examining both intended and unintended effects. We find certain participation rules can stimulate rebound effects from emitters and suppress participation from sequestration and bioenergy producing entities. To overcome this we develop and simulate offset participation limitations that could preclude unintended consequences.

1. Introduction

Emission trading markets have been advanced as a mechanism reducing emissions in many settings including greenhouse gas (GHG) ones [1]. The Kyoto Protocol (KP) advocated trading markets and since then they have been prominently discussed in the climate change mitigation dialogue with a number of implementations. Such markets conceptually cap the emissions of an entity and then facilitate trading between expensive and cheaper net emissions reducers [1]. Typically capped entities include electricity generators, petroleum refiners, and cement manufacturers all of which generally face high costs to achieve large emission reductions. Sectors such as agriculture and forestry have typically not been capped. However, a number of markets and market designs include provisions where capped entities can buy offsets from uncapped sectors. One way of allowing such sales involves setting up a voluntary carbon offset market in which uncapped producers could make offers to sell. The project-based clean development mechanism (CDM) provides an example of this and allows capped producers in industrialized countries to buy certified emission reduction credits from developing countries. Allowing sales through offsets complements cap and trade programs and can reduce abatement costs relative to a program without access to offsets in uncapped sectors [2].

Agriculture, forestry, and other land use activities have been estimated to have a 23% share of total global emissions in recent times and as such are a potential source of emissions reductions [3]. However, the agricultural sector has generally not been capped in GHG trading schemes but rather is often identified as an offset supplying sector [4]. Such offsets could be developed by adoption of agricultural actions that reduce GHG emissions, enhance carbon sequestration, or provide feedstocks for bioenergy that replace higher emitting fossil based energy [5]. Emission reducing possibilities include actions to lessen emissions from enteric fermentation, manure management, rice cultivation, fertilization, soil management, field burning, machinery operations, and avoided deforestation [5, 6]. Sequestration can be enhanced through deintensification of tillage, residue management, use of soil carbon enhancing crop rotations, cropland conversion to grasslands, improved grassland management, afforestation, reforestation, and restoration of degraded soils [6, 7]. Emissions also can be offset by replacing fossil fuels used in energy production with agriculturally produced feedstocks [8]. Sequestration strategies can also be price-competitive at low carbon prices as they are often complementary to current agricultural soil management practices but at higher carbon prices practices like bioenergy production and forestry can be more desirable as they yield larger net GHG emission reductions [9].

Thus there are three basic situations where a farmer might be able to sell offsets. These are as follows:

(1) A cap and trade system allows covered individuals to purchase offsets from outside of the program or enrolled region. For example, the California Rice Protocol allows use of rice methane emission reducing practices in or out of California to satisfy needed emission reductions by capped parties [10].

(2) A program places emission limits on certain entities (like power plants) but they are allowed to satisfy the limits by purchasing offsets from others. For example, this might have happened under the proposed Clean Power Plan (CPP) that may be revisited in the near term.

(3) An organization offers a program where producers can sign up to sell offsets based on shifts in practices. For example, the Verified Carbon Standard (VCS) functions outside of compliance markets and facilitates purchases by firms that want to be demonstrably "greener" [11]. In recent years, more and more private companies such as Indigo Carbon and Noris Marketplace are getting involved by aggregating carbon offsets and then selling them to interested parties in a voluntary marketplace setting. Voluntary programs require less implementation cost but conceptually lead to lower levels of offsets than do mandatory programs [12].

However, voluntary carbon markets suffer from substantial criticism regarding a large number of nonadditional offsets as a result of adverse selection. That problem stems from the fact that business as usual (BAU) emissions cannot be fully observed by regulators. To address this problem, baseline selection and manipulation have been extensively discussed regarding actions in the transportation [13], commercial building [14, 15], and forestry sectors [16]. In general there is a tradeoff between additionality and participation including payments to "good actors.". In such cases a generous baseline can lead to credits to preexisting practices generating nonadditional offsets and implicitly relaxes the emission cap in compliance markets while a stringent baseline would eliminate many nonadditional offsets but also suppress the incentive to opt in and perhaps cause preexisting users of mitigation practices to reverse such practices stimulating emissions and then join the program [17, 18]. Carbon leakage is also a concern since most of current programs are regional and can displace traditional commodity production stimulating emission increase outside of the programs scope [19].

Participation by those in agriculture also raises challenges. Lichtenfeld [20] indicated that land managers were reluctant to enter the carbon market for three main reasons: high transactions and management costs, imperfect information, and a lack of institutional support. Also farmers have concern over the long term effectiveness of weed control methods that are key to use of limited tillage strategies [21]. On the other hand, emission reductions have measurement issues in cases due to potentially high measurement cost, need for sophisticated equipment, their nonpoint source nature, and variable levels across time, locations, and climate conditions. Because of these factors and eligibility restrictions, the actual level of GHG mitigation is far below what many expected at the time of formation of the Kyoto Protocol [22].

This investigates voluntary market design in an effort to evolve designs that better stimulate program participation and generate net emission reductions. Specifically, we conduct theoretical analysis and empirical simulations of the consequences of alternative voluntary market designs examining effects on net GHG emissions and possible market reactions that lead to unintended consequences.

The significance of this study is fourfold. First, we integrate agricultural emission control activities, sequestration, bioenergy production, and voluntary carbon market participation into a single framework for study. Second, our study explores use of performance baselines, which utilize predefined emissions thresholds for a class of activities, and it differs from many prior studies that focused on setting costly, adverse selection, nonadditional prone project-based baselines [23]. Also, the performance baseline under limited private cost information and an uncertain market environment has been found to reduce leakage [15, 24]. Third, we use a baseline method in per unit participating, rate-based form instead of lump sum form which [25] argues is more realistic and responsive to external conditions. Fourth, since the credits are proportional to the output level, this may lead to unintended effects such as output expansion and emission increase [25, 26], but we introduce fairly simple constraints to limit unintended effects.

This study is organized as follows. Section 2 sets out a basic analytical model of participation and abatement decisions for a profit maximizing entity. Then analytical results are derived and they provide a basis for our empirical study. Section 3 describes an empirical test of our posed constraint effectiveness using an agricultural sector model. Section 4 discusses the simulation results. Section 5 concludes the paper.

2. Theoretical Analysis

In this section, a theoretical analysis will be conducted to investigate the effect of voluntary carbon crediting programs on net GHG emission reductions by examining cases for both emission reducers and sequestration enhancers. We evaluate the circumstances when net emission reductions are achieved and when unintended effects arise. This analytical model is elaborated in [27].

2.1. A No-Trading Base Scenario. A base scenario is set up to portray the situation in the absence of carbon payments. There we assume a producer can access two technologies producing a commodity but with different emissions consequences and costs (i.e., low and high emissions rice). The possibilities are the commonly used baseline strategy, x_1, and a more costly "net emission reducing" alternative, x_2. The producer maximizes profits by solving the following optimization problem where one of the two technologies are chosen:

$$\text{Max}\,\pi = (px_1 + px_2) - x_1C_1(x_1) - x_2C_2(x_2), \quad (1)$$

$$\text{s.t. } x_1x_2 = 0, \quad (2)$$

$$x_1, x_2 \geq 0. \quad (3)$$

p is the output price and $C_i(x_i)$ is the cost function for producing x_i. We assume either x_1 or x_2 is adopted but not both of them by imposing constraints (2) and (3). Additionally, we assume $C_i(x_i)$ is a linear increasing cost function of producing the quantity x_i:

$$C_i(x_i) = c_i + \text{d}x_i, \quad (4)$$

where via this function x_1 production is cheaper than x_2 production since x_2 required one-time investment for technology upgrades. For simplicity we structure this so both alternatives costs increase at the positive rate d as volume is expanded and both alternatives are initially profitable in the market ($c_2 > c_1 > 0$, $p - c_i > 0$; and $d > 0$).

If we use calculus to solve the choice problem we arrive at the base solution that only x_1 will be produced since x_1 is more cost-effective.

$$x_1^* = \frac{p - c_1}{2\,d}, \qquad x_2^* = 0. \quad (5)$$

On the emissions side, we suppose net emissions rates e_i for producing x_i and $e_1 > e_2$ so x_2 is net emissions reducing relative to x_1. We also will assume e_1 and e_2 are of the same sign so they are both either positive or negative. The total net emissions in the absence of a carbon market are

$$EB^* = e_1x_1^* + e_2x_2^* = \frac{e_1(p - c_1)}{2\,d}, \quad (6)$$

EB^* is the total BAU net emissions, and e_1 is the per unit baseline performance standard that the market must do better than under the voluntary market. Note that EB^* could be negative if e_1 is negative.

2.2. Adding in a Voluntary Carbon Market. Now we add carbon price into the model so that producers have an incentive to choose x_2 and reduce emissions (a choice we call opt in). In setting the model up we add a baseline standard per unit produced for the net emission level, e^b, to calculate the reduction of net emissions rate relative to the standard. We also assume payments are paid for the difference in net emissions. The resultant model is

$$\text{Max}\,\pi = (px_1 + px_2) - x_1C_1(x_1) - x_2C_2(x_2) - M\left[x_1\left(e_1 - e^b\right) + x_2\left(e_2 - e^b\right)\right], \quad (7)$$

$$\text{s.t. } x_1x_2 = 0, \quad (8)$$

$$x_1, x_2 \geq 0, \quad (9)$$

where M is the carbon price. We set $e^b = e_1$ since x_1 is adopted in the BAU without a carbon market and equation (7) becomes

$$\text{Max}\,\pi = (px_1 + px_2) - x_1C_1(x_1) - x_2C_2(x_2) - M[x_2(e_2 - e_1)]. \quad (10)$$

From the equation, we see continuing to use x_1 yields no carbon market payments, while using x_2 results in a payment equaling $Mx_2(e_1 - e_2)$ but also a higher production cost. The optimal choice of x in the voluntary market is x_1 for the carbon price below a threshold:

$$x_{1,v}^* = \frac{p - c_1}{2\,d}, \qquad x_{2,v}^* = 0, \quad \text{when } M < \frac{c_2 - c_1}{e_1 - e_2}, \quad (11)$$

and the choice shifts to x_2 when the carbon price is above that threshold with the production level being

$$x_{2,v}^* = \frac{p - c_2 - M(e_2 - e_1)}{2\,d}, \qquad x_{1,v}^* = 0, \quad \text{when } M > \frac{c_2 - c_1}{e_1 - e_2}, \quad (12)$$

and when x_2 is the choice the level of total net emissions is

$$E_v^* = e_1x_{1,v}^* + e_2x_{2,v}^* = \frac{e_2[p - c_2 - M(e_2 - e_1)]}{2\,d}. \quad (13)$$

Then comparing with total BAU net emissions we get

$$E_v^* - EB^* = e_2x_{2,v}^* - e_1x_1^* = \frac{e_2[p - c_2 - M(e_2 - e_1)]}{2\,d} - \frac{e_1(p - c_1)}{2\,d}. \quad (14)$$

In order to simplify the emission difference expression, we substitute $c_2 = c_1 + \Delta c$ and $e_1 = e_2 + \Delta e$. Note that $\Delta c > 0$ and $\Delta e > 0$.

$$E_v^* - EB^* = e_2x_{2,v}^* - (e_2 + \Delta e)x_1^* = \frac{e_2(p - c_1 - \Delta c + \Delta eM)}{2\,d} - \frac{(e_2 + \Delta e)(p - c_1)}{2\,d}, \quad (15)$$

and by simplifying we get

$$E_v^* - EB^* = e_2\left(x_{2,v}^* - x_1^*\right) - \Delta e x_1^* = \frac{\Delta e\left(p - c_1\right) - e_2\Delta c + \Delta e M e_2}{2\,d}. \quad (16)$$

Note that all the items in equation (16) are positive except e_2 which can be positive (when we are paying for reducing emissions) or negative (when we are paying for enhancing sequestration). Now, let us explore whether the program may cause increased net emissions. To do this, we consider two cases where (1) net emissions are positive and are being reduced ($e_1, e_2 > 0$, and $e_1 > e_2$ so $\Delta e > 0$) and (2) net emissions are negative implying sequestration or biofuel offsets that are becoming more negative when x_2 is used ($e_1, e_2 < 0$, and as above $e_1 > e_2$ so $\Delta e > 0$).

In the case of positive emitting strategies, note the last term $+\Delta e M e_2$ has all positive components and can cause an emissions increase that grows as the carbon price (M) does while the other terms ($\Delta e(p - c_1) - e_2\Delta c$) are independent of the carbon price. Now, we solve for the size of M when alternative net emissions exceed the BAU net emissions. We find

$$E_v^* - EB^* > 0, \quad \text{when } M > \frac{c_2 - c_1}{e_1 - e_2} + \frac{p - c_1}{e_2}. \quad (17)$$

Here we find a rebound effect [28] where the carbon price stimulates more x_2 production than in the baseline offsetting the gain from lower per unit emissions. An illustration of such an effect is that if per acre rice emission reductions were possible, the incentive may cause the acreage of "low emitting" rice ($x_{2,v}^*$) to expand substantially over the base levels (x_1^*) and the raw emission from rice expansion ($e_2(x_{2,v}^* - x_1^*)$) overcomes the emissions savings ($\Delta e x_1^*$) from growing lower emitting rice relative to the standard. This finding is consistent with that in Fischer [25] and Strand and Rosendahl [26].

In the case of negative emitting strategies the unintended consequence is that the incentive may be pretty ineffective. Under the assumption that we just want to get an increase in current sequestration or bioenergy activity ($x_2 > x_1$) where the technology is the same (Δc and Δe are both zero), the emission difference in equation (16) reduces to zero. In such case, the carbon price fails to provide any incentive to increase current sequestration or bioenergy production activity.

Thus, for both positive and negative emitting strategies, the voluntary program can potentially give rise to unintended effects with it incurring the rebound effect or failing to provide an incentive to expand negative emission items.

2.3. Altering Payment Eligibility. Now we consider ways to alter the voluntary program to avoid the rebound effect for positive emitting strategies and encourage additional adoption of negative emitting strategies. As suggested by Strand and Rosendahl [26], production increase from positive emitting strategies should be restricted. To do this we add a new variable x_3 that equals the amount of voluntary enrollment beyond the BAU amount that is paid but is not offset by the baseline rate e_1 as follows:

$$\begin{aligned} \text{Max}\,\pi &= p(x_1 + x_2 + x_3) - x_1C_1(x_1) - (x_2 + x_3)C_2(x_2 + x_3) - M\left[x_2(e_2 - e_1) + x_3e_2\right] \\ \text{s.t.}\quad & x_2 \le x_1^*, \quad \text{for } e_2 > 0, \\ & x_1 + x_2 \ge x_1^*, \quad \text{for } e_2 < 0, \\ & x_1x_2 = 0, \\ & x_1, x_2, x_3 \ge 0. \end{aligned} \quad (18)$$

Here, both x_2 and x_3 are net-emissions-reducing practices receiving carbon payments with x_2 being paid on net emission difference ($e_2 - e_1$) and x_3 receiving the full net emissions amount (e_2). Economically x_3 will only enter the solution for negative cases (sequestration and bioenergy offsets) given higher or possibly equal costs for x_3 in comparison with x_1.

The first constraint for positive emitters limits the amount that is paid for x_2 to the BAU level of x_1^*, avoiding the rebound effect caused by x_2 being much greater than x_1. In practice this means only preprogram rice producing acreage could receive payments not any new acreage.

The second constraint for negative emitters requires that the production below the BAU level be either unpaid or paid by the net emission difference ($e_2 - e_1$). Then production expansion x_3 can be paid for full credit (e_2) but this means additional new land or production must come in.

We solve the new objective function and get the solution for positive emitting strategies:

$$\begin{aligned} x_{1,s}^* &= x_1^*, \\ x_{2,s}^* &= 0, \\ x_{3,s}^* &= 0, \quad \text{when } M < \frac{c_2 - c_1}{e_1 - e_2}, \\ x_{1,s}^* &= 0, \\ x_{2,s}^* &= x_1^*, \\ x_{3,s}^* &= 0, \quad \text{when } M > \frac{c_2 - c_1}{e_1 - e_2}. \end{aligned} \quad (19)$$

x_2 no longer increases with the carbon price and remains constant at its upper bound of x_1^*. In this way, we are managed to restrict the total net emissions at

$$E_{v,s}^* = \frac{e_2 (p - c_1)}{2d}, \quad \text{when } M > \frac{c_2 - c_1}{e_1 - e_2},$$
$$E_{v,s}^* - EB^* = \frac{(e_2 - e_1)(p - c_1)}{2d} < 0, \quad \text{when } M > \frac{c_2 - c_1}{e_1 - e_2}. \tag{20}$$

Comparing with the BAU net emissions, the voluntary program with the special payment design always yields lower total net emissions when the carbon price is above the critical value.

The solutions for negative emitting strategies are:

$$\begin{aligned} x_{1,s}^* &= x_1^*, \\ x_{2,s}^* &= 0, \\ x_{3,s}^* &= 0, \quad \text{when } M < A, \\ x_{1,s}^* &= 0, \\ x_{2,s}^* &= x_1^*, \\ x_{3,s}^* &= \frac{c_1 - c_2 - Me_2}{2d}, \quad \text{when } M > A, \end{aligned} \tag{21}$$

where A is the critical value of carbon price above which net-emissions-reducing alternatives will be adopted. We do not present the closed-form expression for A due to its complexity but note that A is smaller than the previously solved critical value $((c_2 - c_1)/(e_1 - e_2))$, because the payment for additional negative offsets is larger for alternative strategies. The total net emission level becomes

$$\begin{aligned} E_{v,s}^* &= \frac{e_2 (p - c_2 - Me_2)}{2d}, \quad \text{when } M > A, \\ E_{v,s}^* - E_v^* &= -\frac{Me_1 e_2}{2d} < 0, \quad \text{when } M > A. \end{aligned} \tag{22}$$

We can see the voluntary program with the special payment design always yields greater net emission reductions than that without alteration.

Through our theoretical analysis, we find the modified payment limits the production of positive emitting strategies at or below the baseline amount and incentivizes producers to expand their production of strategies with negative emissions precluding the unintended consequences.

3. Empirical Study and Methods

Now, we do an empirical based study using a sector model to see if any of these unintended cases occur in an ideal modeling world. Here, we simulate a voluntary carbon offset crediting program, and we test whether we could avoid unintended consequences by adding constraints above. We also compare results to a mandatory program under alternative program designs to gain insight on net emissions reduction effectiveness.

3.1. Simplified Overview of the Sector Model. For the study we use the agricultural component of the Forest and Agriculture Sector Optimization Model-Greenhouse Gas version (FASOMGHG) [29–31]. That model will be set up to simulate farmers' decisions under alternative forms of voluntary and mandatory carbon offset crediting programs.

Elaborating, the agricultural part of FASOMGHG [9, 29, 31–33] is a dynamic, nonlinear, price endogenous programming model that maximizes the net present value of the sum of producer and consumers' surplus across the US agricultural sector over time by optimizing consumption, trade, land/water/labor allocation, processing, and production. Mathematically, the objective function is represented by the area under the product demand curves being less than the area under the factor supply curves as described in McCarl and Spreen [34].

Operationally, the model structure simulates multiperiod, multifactor, multicommodity market equilibria under perfect competition with the constraints of crop and livestock mix, resource limit for land, water, and labor, supply, and demand balances for primary and secondary commodities, trade balances for the US and the rest of world, and GHG balances. The model incorporates agricultural activities for over 100 commodity types across the conterminous US broken into 11 market regions and 28 foreign regions over up to 100 years on a 5-year time step basis. FASOMGHG has already been widely employed to evaluate both economic and environmental impacts of a variety of mitigation strategies and policies. Our contribution to the model is that we incorporate the opt in features into the model and construct different baselines for voluntary market settings.

Equations (23) to (27) are a simplified representation of the model objective and constraints. We only include carbon payments structured for whether producers opt in or not in this brief mathematical exposition.

$$\begin{aligned} \text{Max} \int P_d(Q)\mathrm{d}Q - \sum_o [c_o(X_o) * X_o] \\ - \sum_{o,g} \left(P_c * \text{Pay}_o * \text{GWP}_g * \text{GHG}_{o,g}\right), \end{aligned} \tag{23}$$

$$\text{s.t. } Q - \sum_o f_o(X_o) \le 0, \tag{24}$$

$$\sum_o a_o(X_o) \le b, \tag{25}$$

$$e_{o,g}(X_o) * X_o - \text{GHG}_{o,g} = 0, \quad \text{for all } o, g, \tag{26}$$

$$Q, X_o \ge 0, \tag{27}$$

where

g is a set of GHG accounts

o is an opt in set defining whether producers opt in or not to the program (base, yes_opt in)

Q is a variable giving quantity of commodity consumption

$P_d(Q)$ is an inverse demand function giving price of commodities consumed

X_o is a variable giving production activity level under opt in choice o

$c_o(X_o)$ is cost function varying with the choice of opting in

P_c is the exogenous carbon price

Pay_o is a 0/1 indicator for whether to pay carbon payments under opt in choice o

$\text{GHG}_{o,g}$ is a variable giving net GHG emissions of type g under opt in choice o

$f_o(X_o)$ is the yield of commodities produced by production under opt in choice o

$a_o(X_o)$ is the resource usage function of production activities under opt in choice o

b is a vector of resource endowments

$e_{o,g}(X_o)$ is the amount of net emissions reduction relative to the standard of GHG g when producing X under opt in choice o

GWP_g is the global warming potential of GHG type g

Here, equation (23) is the objective function that is maximized where the maximand is the net present value of welfare including carbon payments and the costs of practices adopted including the cost of altering practices when opting in.

Equation (24) is the supply-demand balance constraint by time period for commodities and reflects production balanced with sales including any alterations in production when opting in.

Equation (25) is a resource endowment and reflects normal resource use under existing practices plus differences in resource use when opting in.

Equation (26) is the balance of total net GHG emissions including sequestration and biofuel offsets by opt in choice. The GHG accounting adds net effects across all the full production domain separately by whether producers opt in or not. The accounting can result in either positive or negative net effects. Various forms of this constraint will be used depending on the structure of the program.

More on the model is in Appendix A.

3.2. Scenarios to Run. In our empirical analysis, we setup a number of scenarios to look at different market setups. These span from no market to a mandatory to a couple of forms of a voluntary market. Details are as follows:

(i) Base (BAU) scenario—a base scenario is set up to simulate how farmers would behave in the absence of a carbon market. We set the carbon price equal to zero. The production level in the base scenario is denoted as X^b.

(ii) Mandatory carbon program—the agricultural sector is treated as if it was capped with the carbon price applied to all changes in net emissions relative to a baseline level. We force all to participate and set the parameter Pay to 1. This scenario is set up for comparison purposes only as we assume the agricultural sector will not be capped.

(iii) Voluntary carbon program—here, producers can opt in. We set a nonzero carbon price ($P_c > 0$), for participants, those opting in ($\text{Pay}_{\text{yes\_optin}} = 1$), and no payments for nonparticipants ($\text{Pay}_{\text{base}} = 0$) making only opting in producers eligible to receive carbon payments. Such a choice needs a baseline that encourages producers to voluntarily enroll and generate additional offsets. Two baseline specifications will be used.

- Per unit baseline: here we setup a per unit baseline level by practice corresponding to Section 2.2. We establish a standard calculated from the base scenario that opting in producers must do better than on a per unit of the practice undertaken basis. Details on practices and the GHG account setup are in Appendix B. Under this per unit baseline, opting in producers get paid upon the difference in emissions per unit for the activity they choose less than the standard baseline rate and enrolled activity levels.
- Per unit baseline plus participation constraints: here, we impose constraints and add variables equivalent to x3 above as developed in the theory section. In that case activity in excess of base scenario receives full payments when the net emission nature of the activity is negative (generally sequestration or bioenergy fossil fuel offsets) or pays full cost when the net emission nature of the activity is positive (for those that on net emit GHGs).

4. Empirical Results

Now, we report on the results by major category and scenario. We examine the net cost of the carbon payment program as well as the effect on net GHG emissions plus other market effects including changes in agricultural commodity production and prices, land usage and value, bioenergy production, and welfare. Additionality and leakage implications will also be addressed.

4.1. GHG Mitigation. Figure 1 presents annualized net GHG emissions by those opting in and not opting in under each alternative carbon market scenario under a CO_2e price of \$30/ton. Net offsets, as an indication of the truly additional ones after accounting for leakage and the rebound effect, are calculated as the difference in net GHG emissions between the base scenario and those occurring under each alternative scenario.

In the results the net emission consequences are usually not equal to the gains paid to participants. This difference arises because of two factors. First, in most cases those not

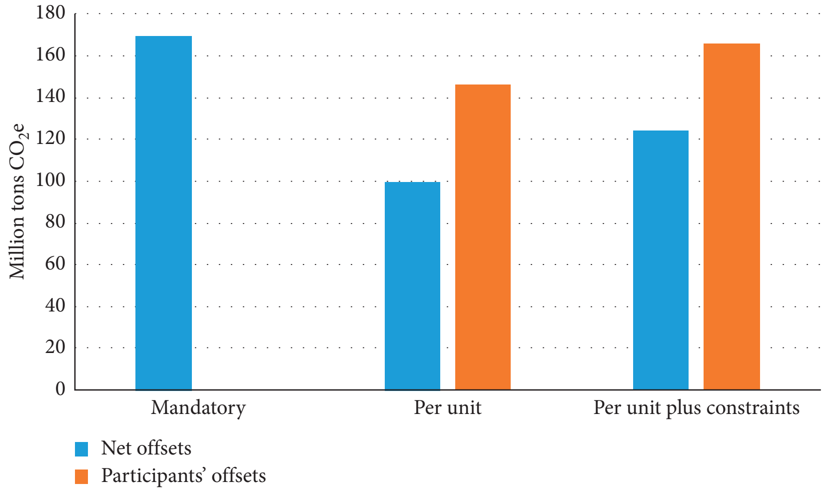

Figure 1: Annualized GHG offsets by scenario at \$30/tCO_2e.

covered by the program choose to increase their net emissions or reduce sequestration relative to the baseline (a leakage effect) when responding to the market alterations caused by the actions of participants. Second, the per unit baseline may cause participants to expand qualifying "emission reductions" to levels beyond that in the base scenario (where $X_o > X^b$ for positive emitters as discussed above).

The mandatory participation scenario generates the most offsets as expected since it imposes the carbon price on all producers and does not pay for nonadditional production and penalizes for any within region leakage. This stimulates the greatest net emission reduction and penalizes for any and all emissions increase or sequestration/bioenergy offsets decrease while rewarding the opposite.

Once we bring in the payment and constraint design, we find that both net offsets and participants' offsets increase significantly. Also, we note this may be a second best solution as it is still less effective than the mandatory but likely hard to implement scenario.

Figure 2 shows more detailed GHG emission mitigation contributions by major strategy under the per unit and per unit plus constraints baselines across CO_2 prices. Agricultural soil sequestration and bioenergy production are two primary categories of negative emission strategies. At low carbon prices, agricultural soil sequestration increases significantly compared to the base scenario and becomes the predominant strategy. That is because most of the agricultural soil sequestration practices are complementary with existing crop production and thus require relatively low costs as in [9]. When the carbon price gets higher, the share of agricultural soil sequestration declines due to the substantial increase in GHG offsets from bioelectricity production. Note that bioelectricity is not produced under the base scenario and at low carbon prices due to its high implementation costs but it has lifecycle GHG offset rates as high as 99%. Such high offset rates combined with higher carbon prices induce producers to shift land and other resources out of traditional crop production to bioelectricity feedstock production. In addition, the per unit plus constraints scenario achieves more GHG offsets from bioenergy production than the per unit baseline because of additional incentives for bioenergy production.

4.2. Program Costs. We now turn to the average program cost per ton of mitigation. This is computed as annualized total carbon payments under the program divided by annualized tons of net CO_2e offsets after considering both nonparticipants and participants net emissions. Although carbon credits are paid to participants only, we evaluate the effectiveness of carbon programs in mitigating GHG emissions considering possible leakage and nonadditionality. To accomplish this we use the total change in net CO_2e offsets across all parties as the denominator instead of just participants' offsets. The average program cost for each program setup is listed in Table 1.

The mandatory scenario has the lowest average program cost which also equals the CO_2e price. Any emission change relative to the base case is rewarded or penalized according to the CO_2e price so there is no leakage within the region associated with the mandatory program.

On the other hand, the average cost of voluntary carbon crediting programs is not equal to the CO_2e price as nonparticipants' emissions are not restricted but are used in the calculation and leakage occurs. The per unit baseline also exhibits high average cost per effective ton CO_2e net emissions reduction cost. In addition to the nonparticipants leakage, the rebound effect is playing a part. As noted above, the per unit baseline is paid upon the difference in emissions per unit and as long as producers could reduce their emission rate, they are rewarded. The rebound effects occur and for some subcategories lead to a total emission increase and higher program costs. For example, we saw increased annualized corn production relative to the base case yielding CO_2e net emissions increases under the per unit baseline but declined production under the per unit plus constraints baseline.

The per unit plus constraints case eliminates the rebound effects and provides more incentives toward expanding sequestration and bioenergy offsets. As previously shown,

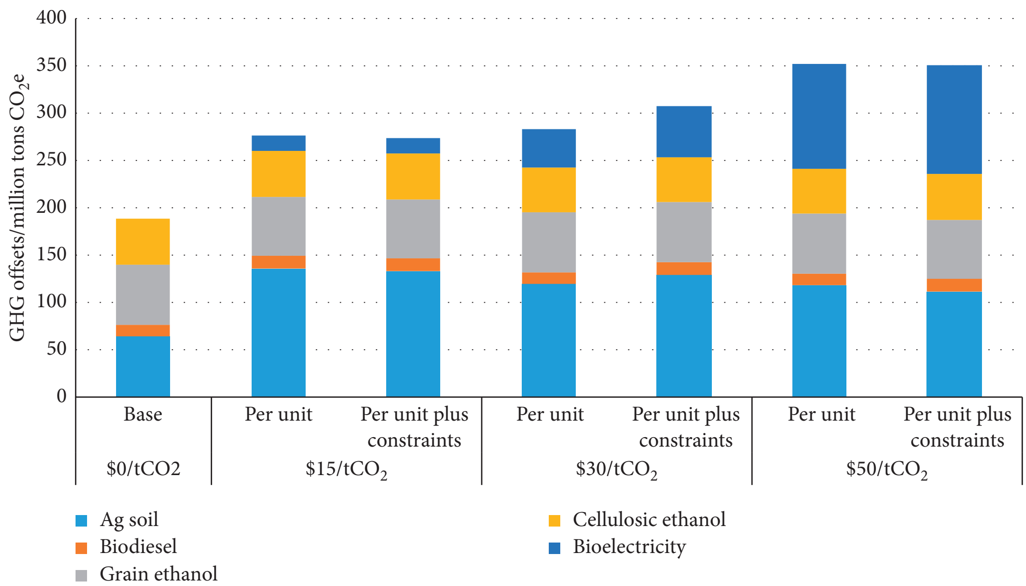

Figure 2: GHG mitigation strategies used under per unit and per unit plus constraints baselines across CO_2 prices.

Table 1: Total and average program costs at \$30/tCO_2e.

	Mandatory	Per unit	Per unit plus constraints
Net offsets (in million tons CO_2e)	169.39	99.85	124.33
Participants' offsets (in million tons CO_2e)	—	146.33	165.79
Total program costs (in million \$)	5,081.68	6,266.10	6,555.77
Average program costs (in \$/ton CO_2e)	30.00	62.75	52.73

the per unit plus constraints baseline induces 8% more GHG net offset from ag soil sequestration and bioenergy at a \$30 price. This results in achieving a lower average program cost than the per unit baseline. However, the existence of non-participants leakage still pushes up the average cost above the CO_2 price.

4.3. Cropped Acres. Figure 3 illustrates the effects on annualized national crop acres in million acres under per unit and per unit plus constraints baselines for alternative CO_2e prices. As that price increases, the percentage of opt in acres increases, indicating the obvious result that higher carbon prices lead to higher participation rates. However, as the carbon price increases from \$30/tCO_2e to \$50/tCO_2e, the opt in acre percentage only increases slightly, showing that voluntary carbon programs are not able to encourage all producers to participate even at high carbon prices. In addition, agricultural soil sequestration practices are predominant mitigation strategies at low carbon prices. But as higher carbon prices, the agricultural soil sequestration no longer increases and bioenergy production begins to dominate as discussed in McCarl and Schneider [9]. In other words, energy crop production comes into play and competes for cropland. That is why we do not see use of less cropland even though we have less traditional crops produced. As shown in Figure 4, producers do not start producing more switchgrass based biopower at \$15/tCO_2e. As the carbon price gets higher, biopower production grows significantly, almost all of which comes from opt in producers. At each carbon price, the per unit plus constraints case exhibits a higher level of switchgrass based biopower production than the per unit case.

4.4. Bioenergy Production. We mainly explore biodiesel and biopower production here because ethanol does not increase after 2020 due to the RFS assumptions in the model settings and the relatively lower CO_2e offset rates. Figure 5 shows growth in the volume of biodiesel produced relative to production at the carbon price of \$30/tCO_2e by scenario.

We see the results that producers start to expand biodiesel production after 2025 because producers need time to react and construct biodiesel processing facilities. The per unit plus constraints baseline stimulates the largest amount of additional biodiesel production, indicating the per unit plus constraints setup provides effective incentives for biodiesel production. The mandatory scenario produces very large amounts of additional biodiesel in 2040 and 2045 and moderate amounts afterward. We also find that the per unit case has essentially the same level of biodiesel production as exhibited in the no carbon price because of the incentive lack as discussed in the theory section.

The change in feedstock usage for biodiesel production relative to the base scenario at alternative carbon prices under the per unit and per unit plus cases baselines

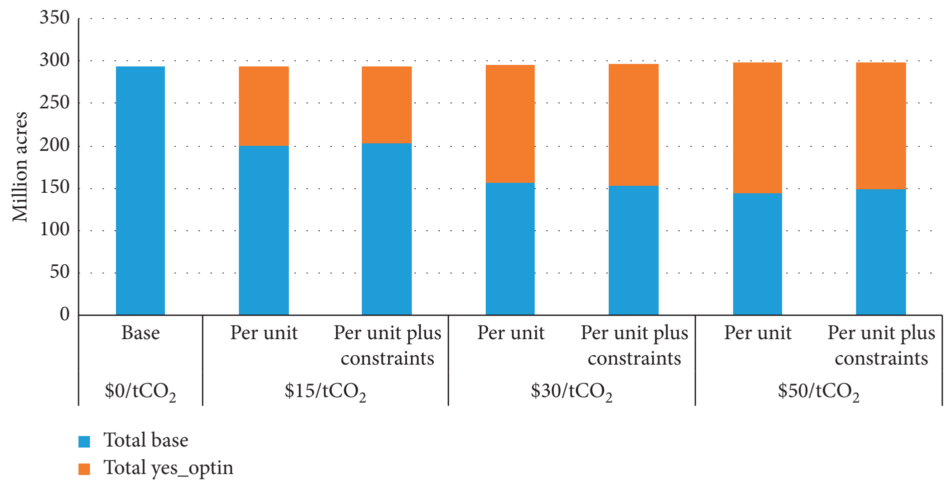

FIGURE 3: Annualized national crop acres under per unit and per unit plus constraints scenarios across carbon prices.

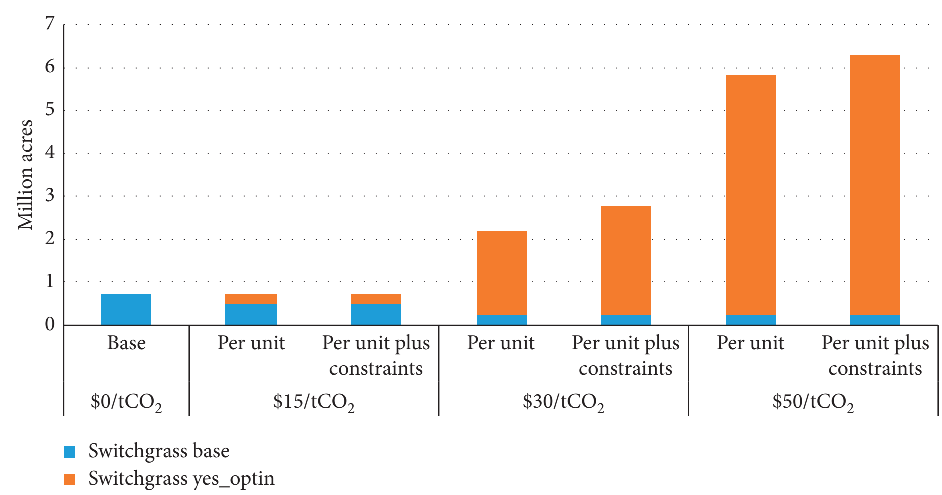

FIGURE 4: Annualized national switchgrass acres under per unit and per unit plus constraints scenarios across carbon prices.

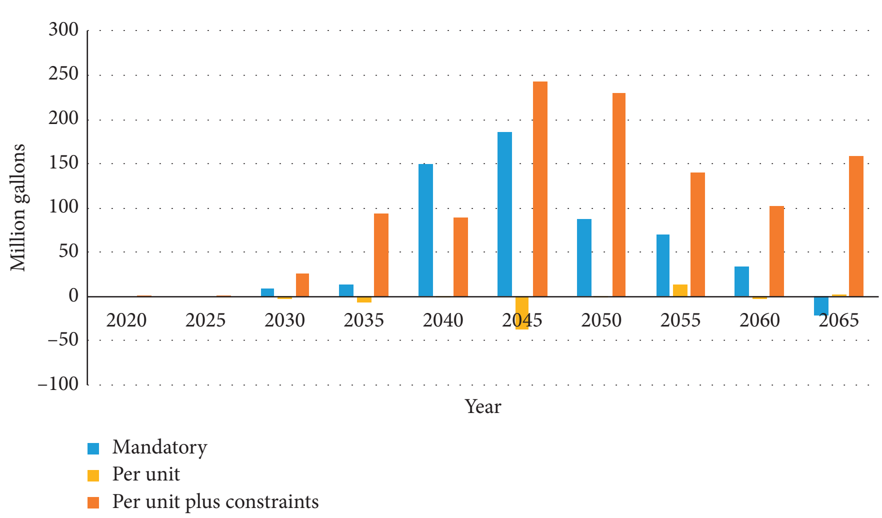

FIGURE 5: Biodiesel production additional to base at $\$30/tCO_2e$.

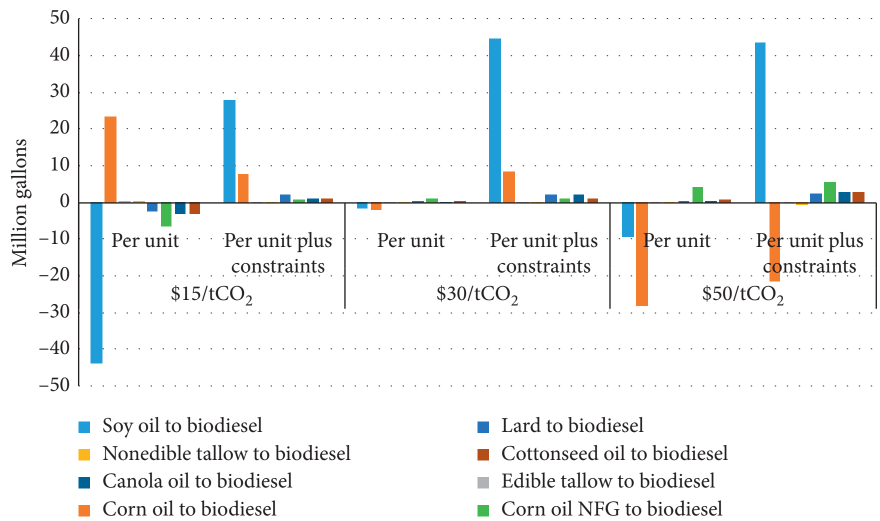

Figure 6: Additional biodiesel production composition from base across carbon prices.

is shown in Figure 6. At each carbon price, the per unit plus constraints baseline yields more production of biodiesel mainly from soybean oil. This result demonstrates that the per unit plus constraints case more effectively stimulates biodiesel production. In addition, we find biodiesel production increases with carbon prices at low prices. However, when the carbon price increases from \$30/tCO_2e to \$50/tCO_2e, biodiesel production no longer expands mainly because of the less use of corn oil under both per unit and per unit plus constraints cases.

Figure 7 presents bioelectricity production over time under all alternative scenarios at \$30/tCO_2e. The mandatory scenario consistently achieves a high level of bioelectricity production. The per unit plus constraints baseline exhibits high levels peaking its bioelectricity production from 2035 to 2055 but then later having it fall.

We now look deeper into the breakdown of feedstock use for bioelectricity. For simplicity, we have combined processes with and without cofiring for each biofeedstock used. Bioelectricity production expands significantly with increased carbon prices. At the carbon price of \$15/tCO_2e, bioelectricity is primarily processed from manure (Table 2). As the carbon price increases to \$30/tCO_2e, we observe increasing use of switchgrass and crop residues especially wheat residues. When the carbon price is \$50/tCO2e, switchgrass expands and is the predominant biofeedstock. We also see the use of corn residues increases substantially and willow comes into play. Note that biodiesel production stops expanding with less use of corn oil at high carbon prices. We observe a trend of shifting resources from biodiesel to bioelectricity due to the higher GHG reduction of bioelectricity.

4.5. Market Effects. Table 3 presents annualized national index numbers for commodity prices and quantities under all market design scenarios at \$30/tCO_2e. The results show that the introduction of voluntary carbon crediting programs leads to less conventional farm production and higher commodity prices with higher land values. This is because agricultural producers shift land use from agricultural production to bioenergy production to receive more carbon payments as in Schneider and McCarl [35]. In turn production falls and commodity prices generally increase with cropland becoming more valuable [8].

We illustrate the national index number changes across carbon prices under the per unit plus constraints scenario in Figure 8. When the carbon price is low, impacts on price and trade indexes are quite minimal. When the carbon price is high, we do see higher commodity prices, fewer exports, and more imports due to less agricultural product supply.

Welfare is also a concern. Table 4 displays percentage changes from the base producers' and consumers' surplus for all the program setup scenarios. Note that the surplus discussed here does not cover: (1) the social cost and benefits of altered GHG emission reductions, erosion, or other environmentally related changes and (2) the government costs of raising the money for program payments and administration. The most noticeable change is the gain in domestic producers' surplus. Despite less agricultural production, the domestic producers' surplus increases under all scenarios since carbon payments provide an additional source of income for program participants and prices are somewhat higher. The mandatory scenario generates the largest increase in the domestic producers' surplus which is directly related to the largest amount of carbon net emissions reductions and resulting payment applied to all producers in the agricultural sector. The per unit plus constraints scenario generates a higher domestic producers' surplus than the per unit scenario does since it pays more for higher sequestration and bioenergy production in spite of actually having a lower average payment for net emission offsets. Changes in domestic and overseas consumers' surpluses are negligible because the commodity price impact is quite small. Overseas producers gain as a result of fewer US exports. Overall, we achieve a net gain in world welfare under all scenarios.

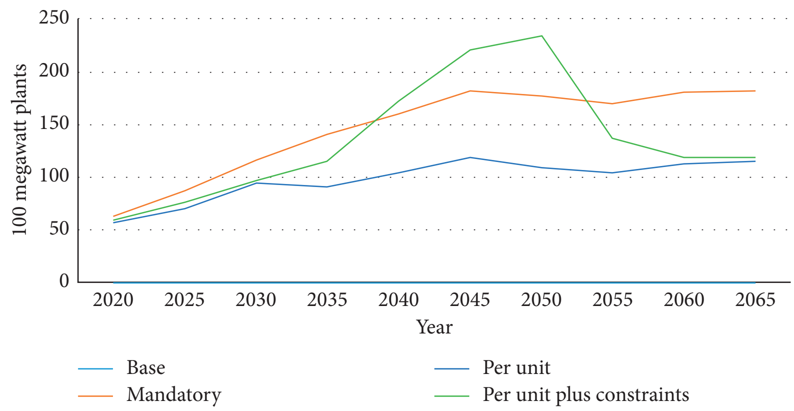

FIGURE 7: Bioelectricity production over time at $30/t$CO_2$e.

TABLE 2: Annualized electricity production breakdown in number of 100 megawatt plants.

Biofeedstock used	$15/t$CO_2$		$30/t$CO_2$		$50/t$CO_2$	
	Per unit	Per unit plus constraints	Per unit	Per unit plus constraints	Per unit	Per unit plus constraints
Corn residue			0.31	4.84	48.19	52.85
Sorghum residue			2.45	4.76	12.77	6.85
Wheat residue	0.01	0.02	9.02	14.80	17.16	18.07
Barley residue	0.35	0.41	5.15	5.87	6.46	6.57
Oats residue			0.32	0.48	0.45	0.49
Bagasse			0.01	0.02	0.82	0.67
Switchgrass	0.11	0.12	24.90	34.41	76.19	81.30
Willow					0.10	0.36
Lignin			6.44	6.70	5.40	5.24
Manure	16.73	16.25	16.37	16.18	17.13	16.54
Beef manure	0.59	3.01	0.67	3.18	2.62	2.91
Dairy manure	7.30	5.36	7.58	5.26	4.88	5.17

TABLE 3: Annualized national index numbers at $30/t$CO_2$e.

Agtype	Item	Base	Mandatory	Per unit	Per unit plus constraints
AllFarmProd	Production	100.00	99.77	96.37	96.34
AllFarmProd	Price	100.00	99.36	100.32	100.05
AllFarmProd	Exports	100.00	99.63	100.16	99.53
AllFarmProd	Imports	100.00	99.86	100.06	100.05
Cropland	Price	100.00	99.37	103.89	104.54

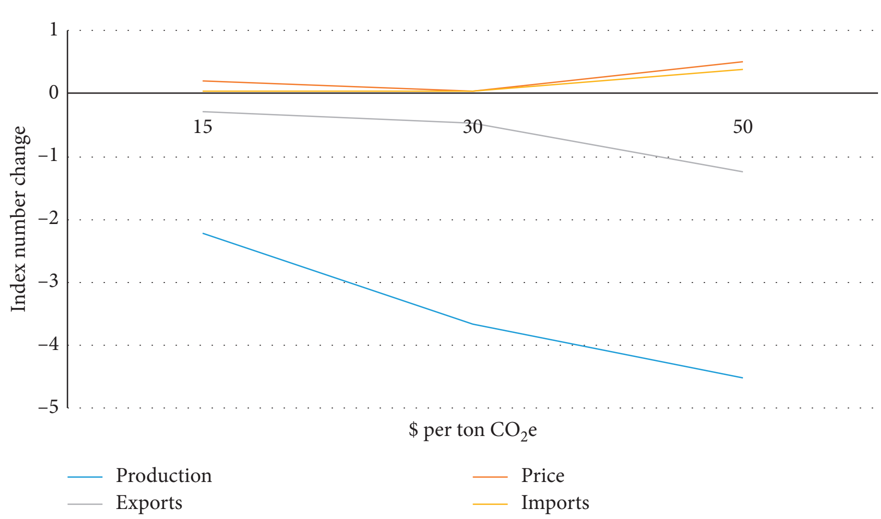

FIGURE 8: Annualized national index number changes under per unit plus constraints scenario across carbon prices.

Table 4: Percentage change from base in welfare at $30/tCO$_2$e.

	Mandatory (%)	Per unit (%)	Per unit plus constraints (%)
Domestic consumers' surplus	−0.05	0.00	−0.01
Domestic producers' surplus	3.50	2.01	2.63
Overseas consumers' surplus	−0.01	0.00	−0.01
Overseas producers' surplus	0.29	−0.05	0.40
Total	0.04	0.04	0.04

5. Conclusion and Policy Implications

As an often noncapped sector in GHG trading markets, agriculture can provide offsets by reducing GHG emissions, enhancing sequestration, or producing feedstocks for bioenergy that replaces higher emitting fossil based energy forms but needs incentives to do so. Voluntary carbon markets can provide such incentives and allow producers to join at their discretion. We set up a baseline condition where participants have to do better at reducing emissions relative to a per unit standard or produce more sequestration or bioenergy feedstocks again relative to a standard. Herein, we analyze market designs under such a situation.

In terms of market design, we first examine the case where a producer is paid the difference between emissions under an improved practice and the emissions under currently used practice (i.e., if current rice cultivation generates x tons of emissions per hectare and an improved practice yields y we will pay for the x-y savings times the land area enrolled). In that case, we find there is an incentive to expand the participating land area beyond preexisting area, thus generating a rebound effect. We subsequently suggest imposition of a maximum participating land area constraint set at the preexisting area which could likely be established using remote sensing.

Subsequently we turned to the sequestration/bioenergy offset case finding that payments relative to a standard discouraged participation. There we suggest only paying relative to the standard on the preexisting area then dropping the standard to zero paying for the full amount for additional participation. Therefore, adding proper constraints to per unit baseline could effectively reduce unintended effects. We also find as carbon prices increase, strategies switch from low-cost such as agricultural soil sequestration to higher-cost but greater per unit land emission offset strategies such as bioenergy production. This is consistent with Forest Trends' Ecosystem Marketplace [36] observation that in 2019 over-the-counter transaction voluntary offset volumes for renewable energy surged by 78 percent while agriculture, forestry, and other land use (AFOLU) volumes dropped by 28 percent.

Our empirical work basically shows imposing such constraints eliminates the rebound effect for emitters and the participation disincentives for those selling sequestration or bioenergy offsets. From a policy standpoint we believe imposing the constraints can help generate cheap, additional actions and feel that imposing the constraints can be done via a requirement that participants prove the amount of preexisting use of the emitting, sequestering, and bioenergy feedstock activities much as done in the US farm and insurance programs. This allows effective ways to harness sectoral potential to reduce emissions relative to current conditions and increase sequestration and bioenergy feedstock production well beyond current levels.

Although our analysis focuses on agricultural sector, the policy design may also be applicable to other voluntary market settings for sectors such as forestry and wetland management. For example, expansions in reforestation may yield substantial carbon benefits but proper incentives or subsidies need to be provided to cause the expansion and reach the optimal harvest cycle with a reward to all of the extra carbon not a measure relative to gains under small implementations of such practices. Such incentives would also likely gain cobenefits in the form of environmental services [37]. Note however caution would be needed to not get carried away with the cobenefits when they make an alternative look better but if one looks at all alternatives there may be other cases where cobenefits are even greater [38]. As for wetland restoration, four project-specific carbon offsets methodologies are approved but no transactions have been made yet because of high cost and lack of proper incentives [39]. We believe that with our baseline design their attractiveness would increase.

There are several limitations to our current study. Since FASOMGHG is used in the empirical phase of our study, our results and discussion depend heavily on its embodied assumptions, data, and model structure including projections of future crop and livestock yields along with ethanol mandates. Also, the uncertainty and permanence issues involved with mitigation are not fully considered in this analysis. Incorporating an uncertainty or permanence discount may alter our results.

Appendix

A. Additional Details on FASOM

The major categories of GHG mitigation strategies included in FASOMGHG are listed in Table 5, as well as the types of GHGs affected by each strategy. Emissions can be reduced through altering tillage, crop management, manure and livestock management, and land use. Tillage and land use change lead to sequestration as do some crop-related actions. Carbon saturation of soils is modeled for the sequestration alternatives (see discussion in [29, 30, 40, 41] for notes on the model implementation approach). GHG emissions from energy use can be reduced by using biomass to replace fossil fuels in electricity generation, replace gasoline with biomass produced ethanol and production, or replace diesel with biodiesel. Bioenergy production can possibly play a major role in mitigating GHG emissions as energy use GHG emissions [31] are large (with an

Table 5: GHG mitigation strategies in agricultural part of FASOMGHG.

Source/sink	Mitigation strategy	GHG affected CO_2	CH_4	N_2O
Manure management	Emission		X	X
Crop mix alteration	Emission, sequestration	X		X
Crop fertilization alteration	Emission, sequestration	X		X
Crop input alteration	Emission	X		X
Crop tillage alteration	Emission, sequestration	X		X
Grassland conversion	Sequestration	X		
Irrigated/dry land conversion	Emission	X		X
Rice acreage	Emission	X	X	X
Enteric fermentation	Emission		X	
Livestock system change	Emission		X	X
Livestock herd size	Emission		X	X
Bioenergy				
Conventional ethanol	Fossil fuel substitution	X	X	X
Cellulosic ethanol	Fossil fuel substitution	X	X	X
Biodiesel	Fossil fuel substitution	X	X	X
Bioelectricity	Fossil fuel substitution	X	X	X

*Source: [29].

over 80% share in the US). Moreover, bioenergy production does not have issues of saturation or reversibility like soil sequestration [31]. In addition, there exists interdependence between different mitigation strategies. The modeling framework considers all GHG mitigation alternatives simultaneously to capture tradeoffs and resource competition. For example, if cropland is converted to switchgrass, it is no longer available to convert to grasslands or to have crop residues harvested [5].

Bioenergy types covered in FASOMGHG include crop ethanol, cellulosic ethanol, biodiesel, and bioelectricity. Each form of bioenergy can be processed using a variety of selected agricultural and forestry commodities within the model [31]. In brief, the possibilities and means of production are as follows:

(i) Biodiesel production can be achieved through conversion of canola oil, corn oil, lard, poultry fat, soybean oil, tallow, or yellow grease into biodiesel, which replaces petroleum-based diesel fuel.

(ii) Bioelectricity production can be achieved through usage of bagasse, crop residues, energy sorghum, per unit plus constraints poplar, lignin, manure, miscanthus, sweet sorghum pulp, switchgrass, willow, wood chips, logging residues, or milling residues as inputs to electric generating power plants in place of coal (through either cofiring or dedicated biomass plants).

(iii) Cellulosic ethanol production can be achieved through usage of bagasse, crop residues, energy sorghum, per unit plus constraints poplar, miscanthus, sweet sorghum pulp, switchgrass, willow, wood chips, logging residues, or milling residues as feedstocks to produce cellulosic ethanol, which replaces gasoline.

(iv) Starch or sugar-based ethanol production can be achieved through usage of barley, corn, oats, rice, sorghum, sugar, sweet sorghum, or wheat in a process that converts these commodities to ethanol that in turn is a replacement for gasoline.

The GHG reduction provided by bioenergy production is equal to the GHGs emitted from burning and producing the fossil fuel replaced less the GHG emissions of producing, transporting, and processing the bioenergy feedstocks. Listed in Table 6 is a lifecycle accounting of emission reduction rates of various bioenergy production possibilities drawn from McCarl [8]. The accounting shows that the target bioenergy type and utilized biofeedstock greatly influence emission reduction rates. Overall bioelectricity with cofiring has the highest GHG emission reduction while crop ethanol replacement of gasoline yields the lowest. Biodiesel processed with soybean oil has a much higher offset rate than that processed with corn oil. We will see how the focus of bioenergy production changes as we increase our carbon prices and switch opt in baselines.

FASOMGHG also incorporates several features regarding bioenergy production to better mimic the real situation. Biofuel mandates such as RFS2 are introduced along with the costs of crossing the blend wall and collectively these limit the attractiveness of ethanol production. Asset fixity is specified in the model [42] requiring that refining and electrical generating facilities once built are immobile and typically can handle only one class of feedstock. FASOMGHG assumes all bioenergy plants to have a lifespan of 30 years. The application of asset fixity prevents sudden regional and feedstock discontinuity in bioenergy production but also sets capacity limits for newly introduced or high-cost bioenergy like bioelectricity due to substantial upfront capital investment costs [42].

B. Additional Details on Model Scenario Setups

B.1. Base Scenario. The base scenario is set up with no carbon market pricing. It simulates how farmers would behave in the absence of a carbon market. We get the base solution by eliminating the choice allowing nonparticipation only and

Table 6: Percentage offset in carbon dioxide equivalent emissions from the usage of a biofeedstock.

Commodity	Liquid fuels			Cofired electricity				Electricity
	Crop ethanol	Cellulosic ethanol	Biodiesel	5%	10%	15%	20%	Fire 100%
Corn	17.2							
Hard red winter wheat	16.1							
Sorghum	27.8							
Sugarcane	64.9							
Soybean oil			95.0					
Corn oil			39.1					
Switchgrass		56.7		86.3	86.5	86.2	86.0	75.1
Poplar		52.6		84.1	84.4	84.1	83.8	71.3
Willow		62.8		90.9	91.0	90.8	90.7	83.4
Softwood log residue		79.3		99.2	99.1	99.1	99.0	97.3
Hardwood log residue		79.4		99.0	98.9	98.8	98.8	96.3
Corn cropping residue		69.8		89.2	89.4	89.2	89.0	80.1
Wheat cropping residue		56.4		93.3	93.4	93.2	93.1	87.2
Manure				99.5	99.4	99.2	99.1	96.4
Bagasse		95.7		98.1	98.1	98.1	98.0	96.5
Lignin				91.3	91.5	91.3	91.2	85.8
Lignin hardwood				91.4	91.5	91.4	91.2	85.7
Lignin softwood				96.2	96.3	96.2	96.2	94.1

*Source: [8].

setting the carbon price equal to zero. Consequently the whole carbon payment part has no effect. We denote the baseline net GHG emissions as GHG_g^b and production activity level as X^b.

B.2. Mandatory Carbon Program. Under the mandatory carbon program scenario, the agricultural sector is treated as if it was capped with the carbon price applied to all changes in net emissions relative to a baseline level with emission reductions rewarded and increases penalized. We drop the opt in choice (o) of not participating only model mandatory participation and set the parameter Pay to 1.

B.3. Voluntary Carbon Programs. A voluntary carbon crediting program is modeled where producers can opt in to contribute to net emission reductions. Such a choice needs a baseline that encourages producers to voluntarily enroll generating offsets at low costs. Producers who opt in would get paid for their reductions in net emissions for the greenhouse gas account relative to a baseline amount. They would also be liable for any increase in net emissions in any account. Producers who do not opt in have no direct financial implications arising from changes in their net emissions. In this case, issues of additionality can occur if producers enroll to do things they would have done anyhow and issues of leakage when nonparticipants and people in other regions respond to market signals and increase net emissions. In addition, the baseline needs to be defined to be applicable only to those opt in as payments need to be made are dependent only when certain producers choose whether or not to opt in a particular activity.

Two baseline specifications will be used as follows:

(i) *Per unit baseline:*
Here, we setup a baseline level by practice establishing a standard that opting in producers must do better than on per unit of the practice undertaken basis. To do this we construct a per unit baseline where, for example, for crop production the net emissions will be judged relative to a standard level as observed in the baseline. Specifically, we define a set bg of GHG types with a per unit baseline as follows:

Baseline_agtill: baseline net emissions from ag tillage
Baseline_crop: baseline net emissions from crop production
Baseline_bioenergy: baseline net emissions from bioenergy
Baseline_enteric: baseline net emissions from enteric fermentation
Baseline_manure: baseline net emissions from manure
Baseline_bioenergypen: baseline net emissions from bioenergy penetration
Baseline_idlepasture: baseline net emissions from idle pasture
Baseline_pasturelandusechange: baseline net emissions from pasture land use
Baseline_grazinguse: baseline net emissions from grazing land use

To calculate the baseline, we need a per unit net emissions estimate applicable to each of the accounts above that would arise in the absence of a carbon market. To get this, we solve the model without any carbon payments and compute the related GHG net emissions per unit for each of the above activity types in each region. To do this, we compute total emissions and divide by the activity level (acres under each tillage practice, acres of a crop, head of an animal type, or tons of biomass feedstock used, etc.). The total GHG emissions are computed on a CO_2 equivalent basis by activity category above (bg) and then divided by the number of units produced under that activity to get a baseline level of per unit net GHG emissions. The formula for this is

$$br_{bg} = \frac{\sum_{g\in bg} \mathrm{GWP}_g * \mathrm{GHG}_g^b}{X_{bg}^b}. \tag{B.1}$$

For example, suppose we wish to calculate the baseline emission rate on a per acre basis for a particular crop; to do this, we add the per acre emissions generated in the baseline, zero carbon price, and no opt in runs across all the GHG emission categories that fall into the crop emissions component of the bg set across all acres of that crop grown in a region and then divide by total acres of that crop in that region. This would involve adding carbon dioxide emissions from direct use of fossil fuel, grain drying, fertilizer usage, pesticide usage, and water pumping, and then adding in the nitrous oxide GWP times the amount of nitrous oxide emissions from crop residue retention, fertilizer usage, agricultural burning plus the methane GWP times the methane emissions from agricultural residue burning, and, if on rice, rice cultivation. We do not include tillage effects under crop production as that is treated in another account but the model requires opted in tillage when treating opted in crop production.

To avoid double counting, the bioenergy baseline calculation only involves offsets and emissions emerged from biofeedstocks processing and transportation but not the production of those biofeedstocks. However we do require that opted in bioenergy activities must use biofeedstocks produced from opted in crops that in turn use opted in tillage. Adding this requirement on the bioenergy makes sure we take into account the full lifecycle including associated crop production, fertilization, and tillage emissions.

The resultant net emissions per unit can be either positive or negative depending on the nature of the particular activity and the contained GHG accounts. A positive emission rate indicates the standard an opted in activity must achieve is one that exhibits a net reduction in emissions relative to baseline levels. Similarly, a negative standard means that the sequestration or bioenergy offset under the opted in activity must exhibit a larger level of offset than the level realized per acre or unit of energy than the one realized under baseline activity.

Under this per unit baseline, opting in producers get paid upon the difference in emissions per unit for the activity they choose less than the standard baseline amount per acre, head, or unit of bioenergy. In turn this will be multiplied by enrolled activity levels. This means they get paid if they either reduce emissions or increase sequestration/bioenergy offsets relative to the baseline practice. Nonparticipants are not paid or penalized. Thus, the objective function and constraints of GHG accounts are modified to become

$$\begin{aligned} \max & \int P_d(Q)\mathrm{d}Q - \sum_o \left(c_o(X_o) * X_o\right) - P_c \\ & * \left(\sum_g \mathrm{GWP}_g * \mathrm{GHG}_{\mathrm{yes\_optin},g} - \sum_{bg} br_{bg} * X_{\mathrm{yes\_optin}}\right) \\ \text{s.t.} \quad & e_{o,g}(X_o) * X_o = \mathrm{GHG}_{o,g}, \quad \text{for all } o, g. \end{aligned} \tag{B.2}$$

The net result is that the objective function contains only the difference in GHG emissions per unit achieved by participants.

(ii) *Per unit plus constraint case:*
Here, we do the per unit case plus adding the constraints developed in the theory section above.

First, we place any restriction on increases in X beyond baseline levels for each account
Second, we restrict the amount not paid plus that paid on improvement relative to the baseline to be greater than or equal to the baseline amount
Third, we add a second opt in option that operates relative to a zero standard

The model is set up as follows:

$$\begin{aligned} \max & \int P_d(Q)\mathrm{d}Q - c_{\mathrm{base}}(X_{\mathrm{base}}) * X_{\mathrm{base}} - c_{\mathrm{yes\_optin}}\left(X_{\mathrm{yes\_optin}} + Y_{\mathrm{yes\_optin}}\right) * \left(X_{\mathrm{yes\_optin}} + Y_{\mathrm{yes\_optin}}\right) \\ & - P_c * \left(\sum_g \mathrm{GWP}_g * \mathrm{GHG}_{\mathrm{yes\_optin},g} - \sum_{bg} br_{bg} * X_{\mathrm{yes\_optin}}\right), \end{aligned} \tag{B.3}$$

$$\text{s.t. } Q - f_{\mathrm{base}}(X_{\mathrm{base}}) - f_{\mathrm{yes\_optin}}\left(X_{\mathrm{yes\_optin}} + Y_{\mathrm{yes\_optin}}\right) \le 0, \tag{B.4}$$

$$a_{\mathrm{base}}(X_{\mathrm{base}}) + a_{\mathrm{yes\_optin}}\left(X_{\mathrm{yes\_optin}} + Y_{\mathrm{yes\_optin}}\right) \le b, \tag{B.5}$$

$$e_{\mathrm{yes\_optin}}\left(X_{\mathrm{yes\_optin}} + Y_{\mathrm{yes\_optin}}\right) = \mathrm{GHG}_{\mathrm{yes\_optin},g}, \quad \text{for all } g, \tag{B.6}$$

$$e_{base,g}(X_{base}) * X_{base} = GHG_{base,g}, \quad \text{for all } g, \tag{B.7}$$

$$X_{base} + X_{yes\_optin} \geq X^b, \quad \text{for net emission reduction activities,} \tag{B.8}$$

$$X_{yes\_optin} \leq X^b, \quad \text{for net emitting activities.} \tag{B.9}$$

The variable Y_{yes_optin} appears in all equations and is the one depicting opt in operation against a zero baseline while X_{yes_optin} is the one depicting operation against the nonzero standard baseline. It represents activity in excess of baseline levels and is constrained for positive net emissions but not for negative cases.

More specifically for cases where the baseline is generating negative net emissions (sequestration or offsets) equation (B.8) requires the amount of activity not receiving payments (X_{base}) plus those eligible to receive payments but at a level offset by the per unit standard (X_{yes_optin}) must be greater than or equal to the level of production baseline. That deals with the nonadditional production (i.e., that which would have existed in the absence of a program). In that case activity in excess of baseline levels falls into the variable Y and receives full payments when the net emission nature of the activity is negative (generally sequestration or bioenergy fossil fuel offsets) or pays full cost when the net emission nature of the activity is positive (for those that on net emit GHGs).

On the negative emission side constraint (B.8) makes sure baseline negative net emissions producers get payments only if they improve relative to what was being done in the baseline (the standard) while new entrants receive full payments from a base of zero. Such a payment design encourages additional producers to expand their sequestration and bioenergy production to receive full credits from the production above baseline.

For entities with positive baseline emissions equation (B.9) limits the activity paid to that occurring in the baseline, without carbon payment case. Beyond that the per unit baseline is zero and payments only arise if the activity can be turned from a net emitter to a net sequestration or a bioenergy offsetter.

The two constraints together deal with both nonadditional and additional cases and prevent the rebound effect from positive emitters while encouraging new negative emitters to expand production.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Additional Points

Highlights. (i) As a noncapped sector, agriculture can voluntarily participate into carbon markets by providing emission offsets, enhancing sequestration, or providing feedstocks for low emitting bioenergy but to do this there is a need for incentives. (ii) Unintended emission effects could be avoided by providing a preprogram baseline on the replacement of high emitting activities with lower ones. (iii) Unintended disincentives for sequestration and bioenergy feedstock production could be reduced by paying the full amount for activity above current levels and only paying for improvements on existing production. (iv) The simulation shows these provisions preclude rebound effects and incentivize greater levels of sequestration/bioenergy with bioenergy production becoming dominant at high carbon prices.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Simulating the Principal-Agent Relationship between Enterprise Owners and Professional Managers Using Evolutionary Game Theory and System Dynamics

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The separation of ownership and management is a common operation mode in modern enterprises, which establishes the principal-agent relationship between modern enterprise owners and professional managers. Due to the information asymmetry and interest conflicts between the principal and agent, the principal-agent problem will occur and affect the efficiency of enterprise operations. Therefore, it is necessary to propose measures to improve the principal-agent relationship. This paper analyzed the principal-agent problem between enterprise owners and professional managers based on system dynamics, evolutionary game, and principal-agent theory and built a principal-agent evolutionary game model to analyze the rule of strategic choices and predict the equilibrium outcomes of different scenarios. In addition, the influence of different factors on strategic choices was simulated by the system dynamics model. The results depicted that the basic benefits and costs of cooperation are the key factors of the strategic choices, and the gap between the expected payoffs of different strategies also affects the probability of choosing those cooperative strategies. Proper supervision, standardization of the managerial labor market, and establishment of long-term incentives are crucial to cooperation between enterprise owners and professional managers.

1. Introduction

In the modern economic market, the sustained, stable, and healthy development of enterprises is closely related to the national economy and people's livelihood. In order to adapt to the increasingly complex market environment, the enterprise owners introduce professional managers and use their mature management experience to provide support for the enterprise's operation [1, 2]. However, the quality of professional managers varies greatly in the managerial labor market, cases of failure in the employment of professional managers by enterprises occur constantly, and agency problems cause the development of enterprises to fall into deadlocks [3, 4]. Due to the different interest demands and asymmetric information, professional managers may take speculative behavior against the intention of the principal, causing the agency problem of moral hazard [5]. Hence, it is a major theoretical and practical issue facing the sustainable development of modern enterprises to improve the principal-agent relationship of enterprises and realize a win-win cooperation between both parties. To solve the agency problem, many scholars researched it mainly based on the principal-agent model, experimental simulation, and game model where these studies have important reference significance for the research of the principal-agent relationship.

First, since the principal-agent theory has developed into a mature theoretical system, using its theoretical model can intuitively reflect the respective utility functions of both parties and find the optimal solution to maximize the utility. Many scholars constructed and applied different principal-agent models to solve the problem of information asymmetry in the principal-agent relationship. There are three basic models applied to the principal-agent problem [6]: The first one is the state-space formulation method, which is proposed by Wilson [7] and further improved by Spence and Zeckhauser [8] and Ross [9]. The second one is the parameterized distribution formulation method originally constructed by Mirrless [10] and developed by Holmstrom [11], which is widely used and has become a standardized approach [12]. The third one is the general distribution formulation method proposed by Gilboa and Schmeidler [13], which clearly describes the model without a complex explanation of the agent's actions and costs. With the continuous development of information economics, the principal-agent model has gradually been developed. Rasul and Sonderegger [14] introduced external transaction factors, combined with the principal-agent model to analyze the agent's external transaction selections. Silvers [15] and Helm and Wirl [16] established a principal-agent model with moral hazard and discussed the contractual issues in the principal-agent problem of asymmetric and public information. Bichler and Paulsen [17] and Uğurlu [18] explored the incentive problem through the development of a model with the assumption that the principal and agent are risk-averse. Chaney [19] examined the principal-agent cooperative relationship and proposed how to establish effective incentive contracts from the perspective of principal-agent theory. Schosser [20], Sun et al. [21], and Chang [22] found that designing the optimal incentive contract is the key to resolve the conflicts of interest between principal and agent. Wang et al. [23] proposed to introduce the time preference into the principal-agent model which provided useful references for solving the agency problem.

Second, the experimental simulation method can adjust the procedures according to the performance characteristics of the participants, thereby obtaining a more precise and concise result [24]. Many scholars have used experimental simulations to examine the factors motivating managers to work conscientiously and explore the optimal contract for principal-agent. Keser [25] studied behaviors in a principal-agent situation with moral hazard and evaluated the effect of principal-agent theory on the relationship. Leopold-Wildburger and Mietek [26] discussed the impact of information asymmetry on compensation and explored the relationship between salary incentives and the degree of effort of the agent. Corgnet et al. [27] constructed a principal-agent model with reference-related utility and proved that the labor contract with weak monetary incentives and wage-independent goals is necessary to solve the principal-agent problem. Flannery and Roberts [28] found that non-monotonic contracts with incentives are more conducive to resolving the principal-agent problem. Rubin and Sheremeta [29] and Rud et al. [30] discussed the influence of competition on the moral hazard in the principal-agent relationship and pointed out the role of managerial labor market on personal incentives and equilibrium results.

Third, since the principal and agent are rational decision-makers, both parties will make beneficial strategic choices to maximize their payoffs and balance the interests of other stakeholders. Game theory can explore the characteristics and rules of the behavior selection of stakeholders [31].Therefore, it is widely used to analyze principal-agent problems. Gong et al. [32] and Azar and Micali [33] constructed the principal-agent game model under the conditions of symmetric and asymmetric information and clarified the design principles of the incentive mechanism through the analysis of the optimal solution. Kellner [34] introduced the ambiguity aversion into the principal-agent model and studied the effective incentives of managers, which provided references for enterprises to design the incentive mechanism. Páez-Pérez and Sánchez-Silva [35] and Kadan et al. [36] studied the mechanism of manager's speculative behaviors based on the game model and suggested that owners should improve the efficiency of supervision to restrain improper behavior. Ni et al. [37] used the game model to analyze the influence of incentives on principal-agent contracts and game equilibrium.

Most of these past studies focused on analyzing the causes of principal-agent problem, the role of transaction cost and risk preference, and proposing to establish an incentive mechanism to restrain the behavior of both parties. However, the root cause of the principal-agent problem is the contradiction between the principal and agent due to the difference of interest preference under asymmetric information; the following characteristics and factors need to be considered when studying the principal-agent relationship. In the cooperation and competition of modern enterprises, the two parties involved in the principal-agent relationship are different groups and play different roles in the operation of companies. There are obvious differences in the interests of the two parties in many aspects such as ownership of property rights and responsibilities where both parties involved making strategic choices based on the principle of maximizing their benefits leading to conflicts [38]. Furthermore, the asymmetric information and the limited rationality of participants caused by the complexity of the principal-agent relationship are obvious as both parties involved in the game are bounded rational stakeholders and cannot collect complete information [39]. The two parties involved in the game will adjust their strategic choices, which is a process of dynamic and constant change. Therefore, it is necessary to analyze the trend and rule of strategic choices of both parties during the decision-making process, and evolutionary games as a natural study approach could apply to analyze the behavior change of the principals and agents involved over time.

Moreover, it is very important to analyze the dynamic evolution process of principal-agent relationship from the quantitative perspective to improve the management efficiency. System dynamics is a computer simulation method for studying information feedback loops of complex systems. Not only can it properly describe the complicated issue of the principal-agent relationship, but it also can provide a comprehensive structure to simulate the strategy choices among different stakeholders. Therefore, it can be applied to understand principal-agent relationship and provide a comprehensive structure to simulate the interesting conflicts between enterprise owners and professional managers.

Therefore, based on the assumption of bounded rationality and asymmetric information, the authors take the conflicts of interests between the two parties of the game as the focus, introduce the principal-agent payoff into the game analysis process, and construct an asymmetric 2×2 dynamic evolutionary game model to find out the behavior evolution path of enterprise owners and professional managers. Through the dynamic evolutionary game analysis of the principal-agent relationship, the authors describe the behavioral decision-making and reaction strategies, analyze the rules of mutual restriction and interaction of both parties, and simulate the process of strategy choice based on a system dynamics model, which will increase the prediction accuracy better than traditional game models.

2. Modeling

There are two game stakeholders: enterprise owners and professional managers. In order to study their dynamic evolutionary game process and evolutionary stability strategies, the following assumptions are made:

(1) Bounded rationality: both enterprise owners and professional managers are economic individuals with bounded rationality, which means that they cannot make the optimal decision at the beginning. It requires constant trial and error and learning to find the optimal strategy. The principle for both parties to choose the optimal strategy is to maximize their respective interests according to their needs and circumstances.

(2) Asymmetric game: the enterprise owners and professional managers have different roles with different payoffs. There are two possible strategies for the enterprise owners: they can strengthen supervision to reduce the speculative behaviors of professional managers or let them run the company freely without any supervision. The strategy set can be described as {M, NM} (M: Monitoring; NM: No monitoring). In response, professional managers also have two choices: make a great effort to manage the company or not to make a great effort to manage the company. The strategy set for enterprise owners can be described as {E, NE} (E: Effort; NE: No effort). The strategy of enterprise owners and professional managers is shown in Table 1.

(3) The payoffs of the two parties in the game are directly related to the operation of the enterprise. For example, when professional managers choose the E strategy, regardless of whether the enterprise owners choose supervision or lack thereof, enterprise owners can obtain extra profit for the company's sound operation. On the contrary, when the professional managers choose the NE strategy and the enterprise owners choose the NM strategy, the owners will suffer losses for the speculative behavior of managers.

(4) Reputation effect of professional managers: when enterprise owners choose the M strategy, if professional managers choose the E strategy, they will gain reputation benefits in the managerial labor market. On the contrary, if professional managers choose the NE strategy, they will suffer a loss of reputation [40].

Based on these assumptions, the payoff matrix of enterprise owners and professional managers is shown in Table 2.

3. Evolutionary Game Analysis

3.1. Evolutionary Stability Strategy. When the enterprise owners and professional managers dynamically adjust their strategies during the game according to the payoffs of different strategies, it is necessary to construct an incomplete information evolutionary game model. If the possibility of the enterprise owners choosing the M strategy is $x\,(0 < x < 1)$, the possibility of choosing the NM strategy is $(1 - x)$. If the possibility of professional managers choosing the E strategy is $y\,(0 < y < 1)$, the possibility of choosing the NE strategy is $(1 - y)$. Based on the payoff matrix (Table 2), the payoffs from the two strategies for enterprise owners are μ_{1m} and μ_{1u}, and the average payoff is $\overline{\mu_1}$:

$$\mu_{1m} = y\left(R_m - C_m + T\right) + (1 - y)\left(R_m - C_m\right), \quad (1)$$

$$\mu_{1u} = y\left(R_u + T\right) + (1 - y)\left(R_u - S\right), \quad (2)$$

$$\overline{\mu_1} = x\mu_{1m} + (1 - x)\mu_{1u}. \quad (3)$$

The replicated dynamic function $f(x)$ of the enterprise owner choosing the M strategy is obtained by combining equations (1) to (3):

$$f(x) = \frac{dx}{dt} = x\left(\mu_{1m} - \overline{\mu_1}\right) = x(1 - x)\left[y(-S) + R_m - C_m - R_u + S\right]. \quad (4)$$

The first derivative of equation (4) with respect to x is

$$f'(x) = (1 - 2x)\left[y(-S) + R_m - C_m - R_u + S\right]. \quad (5)$$

Let $f(x) = 0$; there are three equilibrium points for the replication dynamic equation when enterprise owners choose the M strategy: $x_1 = 0$, $x_2 = 1$, and $y = y^* = (R_m - C_m - R_u + S)/S$:

(1) If $y = y^* = (R_m - C_m - R_u + S)/S$, $f'(x) = 0$, so if professional managers choose the E strategy at the probability of $(R_m - C_m - R_u + S)/S$, there is no difference between the payoffs of the two strategies for enterprise owners; in other words, all x is a stable state.

(2) If $y > y^* = (R_m - C_m - R_u + S)/S$, $f'(0) < 0$, and $f'(1) > 0$, then $x = 0$ is an evolutionarily stable strategy. If professional managers choose the E strategy at the probability higher than $(R_m - C_m - R_u + S)/S$, enterprise owners will gradually change from the M strategy to the NM strategy, and then the NM strategy is the evolutionary stability strategy for enterprise owners.

Table 1: The strategy of enterprise owners and professional managers.

		Professional managers	
		Effort (E)	No effort (NE)
Enterprise owners	Monitoring (M)	(Monitoring, effort)	(Monitoring, no effort)
	No monitoring (NM)	(No monitoring, effort)	(No monitoring, no effort)

Table 2: Payoff matrix of enterprise owners and professional managers.

		Professional managers	
		Effort (E)	No effort (NE)
Enterprise owners	Monitoring (M)	$(R_m - C_m + T, R_d - C_d + F)$	$(R_m - C_m, R_i - F)$
	No monitoring (NM)	$(R_u + T, R_d - C_d)$	$(R_u - S, R_i)$

R_m is the income of enterprise owners when they choose the M strategy, which refers to the higher income due the supervision to managers and active participation of company governance, $R_m \in (0, +\infty)$; R_u is the income of enterprise owners when they choose the NM strategy, which refers to the lower income due to the lack of supervision to managers and participation of company governance, $R_u \in (0, R_m)C_m$ is the cost of enterprise owners for monitoring the professional managers, $C_m \in (0, R_m)$; T is the income of enterprise owners because the professional managers make a great effort to manage the company, $T \in (0, +\infty)$; R_d is the income of professional managers when they choose the E strategy, which refers to the higher income due to their great efforts to manage the company, $R_d \in (0, +\infty)$; R_i is the income of professional managers when they choose the NE strategy, which refers to the lower income due to their lack of efforts to manage the company, $R_i \in (0, R_d)$; C_d is the cost of professional managers for making a great effort to manage the company, $C_d \in (0, R_d)$; F is the gain of professional managers, which is the reputation gain when the strategy choices are {M, E} and the loss of reputation when the strategy choices are {M, NE}, $F \in (0, +\infty)$; S is the loss of professional managers, which is the profit loss suffered by the enterprise owners when the strategy choices are {NM, NE}, $S \in (0, +\infty)$.

(3) If $y < y^* = (R_m - C_m - R_u + S)/S$, $f'(1) < 0$, and $f'(0) > 0$, then $x = 1$ is an evolutionarily stable strategy. If professional managers choose the E strategy at the probability lower than $(R_m - C_m - R_u + S)/S$, enterprise owners will gradually change from the NM strategy to the M strategy, and then the M strategy is the evolutionary stability strategy for enterprise owners.

The dynamic evolution path of the enterprise owner is shown in Figure 1.

As above, the payoffs from the two strategies for professional managers are μ_{2d} and μ_{2i}, and the average payoff is $\overline{\mu_2}$:

$$\mu_{2d} = x(R_d - C_d + F) + (1 - x)(R_d - C_d), \quad (6)$$

$$\mu_{2i} = x(R_i - F) + (1 - x)R_i, \quad (7)$$

$$\overline{\mu_2} = y\mu_{2d} + (1 - y)\mu_{2i}. \quad (8)$$

The replicated dynamic function $f(y)$ of professional manager choosing the E strategy is obtained by combining equations (6) to (8):

$$f(y) = \frac{dy}{dt} = y(\mu_{2d} - \overline{\mu_2}) = y(1 - y)(2Fx + R_d - C_d - R_i). \quad (9)$$

The first derivative of equation (9) with respect to y is

$$f'(y) = (1 - 2y)(2Fx + R_d - C_d - R_i). \quad (10)$$

Let $f(y) = 0$; there are three equilibrium points for the replication dynamic equation when professional managers choose the E strategy: $y_1 = 0$, $y_2 = 1$, and $x = x^* = -(R_d - C_d - R_i)/2F$.

The same method is used to analyze the stable evolution strategy of professional managers. Under the different scenarios: $x = x^* = -(R_d - C_d - R_i)/2F$, $x < x^* = -(R_d - C_d - R_i)/2F$, and $x > x^* = -(R_d - C_d - R_i)/2F$, the dynamic evolution paths of the professional manager are shown in Figure 2.

In summary, replication of the dynamic relationship between enterprise owners and professional managers is shown in Figure 3.

3.2. System Stability Analysis. The two replicated dynamic functions $f(x)$ and $f(y)$ constitute the dynamic replication system of the principal-agent evolutionary game. There are five partial equilibrium points: A(0, 0), B(0, 1), C(1, 0), D(1, 1), and E $-(R_d - C_d - R_i)/2F$, $(R_m - C_m - R_u + S)/S$. These are the equilibrium states of the evolutionary game, representing the evolutionarily stable strategy for both parties. The points can be obtained by partial equilibrium analysis of the determinant and trace of the Jacobian matrix [41]. The Jacobian matrix of the principal-agent evolutionary game is

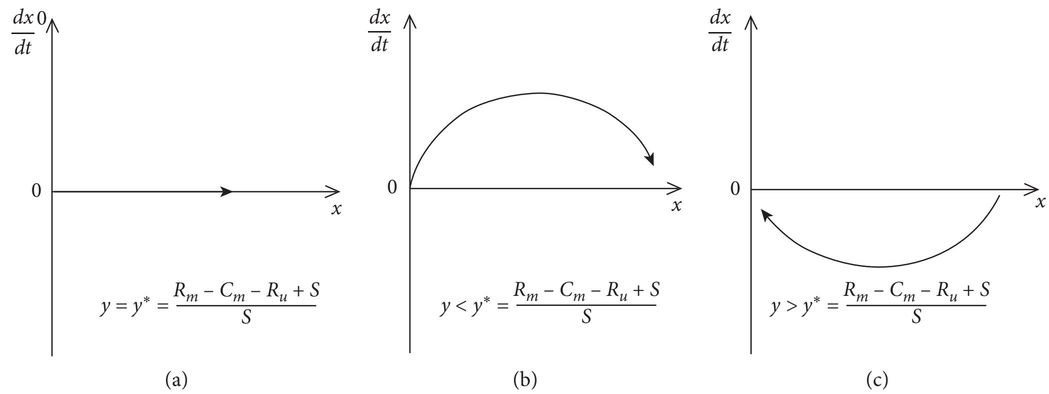

Figure 1: Dynamic evolution path of the enterprise owners.

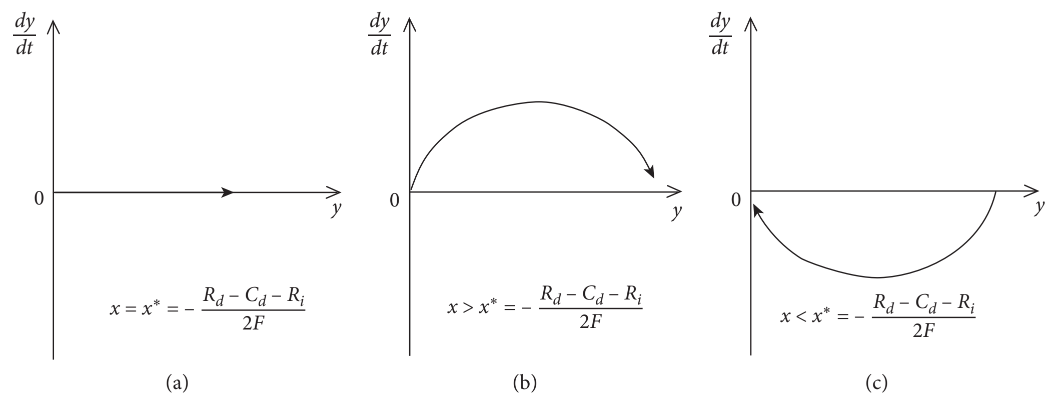

Figure 2: Dynamic evolution path of professional managers.

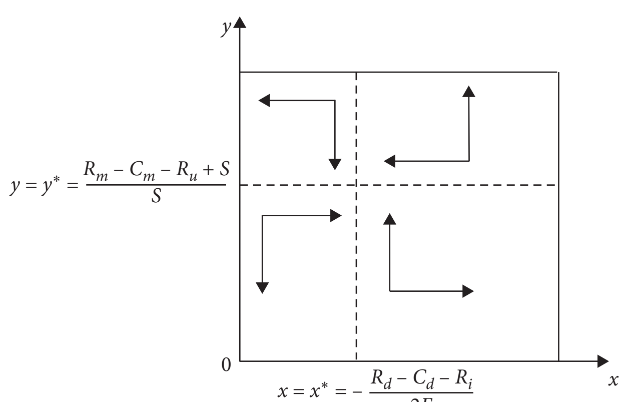

Figure 3: The evolution game of enterprise owners and professional managers.

$$J = \begin{bmatrix} \dfrac{\partial f(x)}{\partial x} & \dfrac{\partial f(x)}{\partial y} \\ \dfrac{\partial f(y)}{\partial x} & \dfrac{\partial f(y)}{\partial y} \end{bmatrix} = \begin{bmatrix} (1-2x)\left[y(-S)+R_m-C_m-R_u+S\right] & x(1-x)(-S) \\ 2Fy(1-y) & (1-2y)\left(2Fx+R_d-C_d-R_i\right) \end{bmatrix}. \quad (11)$$

Thus, the determinant $\mathrm{Det}(J)$ and trace $\mathrm{Tr}(J)$ of Jacobian matrix are

$$\begin{aligned}
\text{Det}(J) &= \frac{\partial f(x)}{\partial x}\frac{\partial f(y)}{\partial y} - \frac{\partial f(x)}{\partial y}\frac{\partial f(y)}{\partial x},\\
\text{Tr}(J) &= \frac{\partial f(x)}{\partial x} + \frac{\partial f(y)}{\partial y},\\
\text{Det}(J) &= (1-2x)(1-2y)\left[y(-S) + R_m - C_m - R_u + S\right]\left(2Fx + R_d - C_d - R_i\right) - 2F(-S)xy(1-x)(1-y),\\
\text{Tr}(J) &= (1-2x)\left[y(-S) + R_m - C_m - R_u + S\right] + (1-2y)\left(2Fx + R_d - C_d - R_i\right).
\end{aligned} \tag{12}$$

If $\text{Det}(J) > 0$ and $\text{Tr}(J) < 0$, the equilibrium points represent the evolutionarily stable strategy for both parties [42–44], and the determinant and trace of the five equilibrium points A, B, C, D, and E are as given in Table 3.

In order to simplify the parameter discussion process, assume that $V_1 = R_m - C_m - R_u$, which means the difference between the net income of the M strategy $(R_m - C_m)$ and the income of the NM strategy R_u for enterprise owners. $V_2 = R_m - C_m - R_u + S$, which means if the goal of professional managers is inconsistent with the goal of the company, then considering the loss S suffered, the difference between the net income of the M strategy $(R_m - C_m)$ and the income of the NM strategy R_u for enterprise owners, thus $V_2 = V_1 + S$. $V_3 = R_d - C_d - R_i$, which means the difference between the net income of the E strategy $(R_d - C_d)$ and the income of the NE strategy R_i for professional managers. $V_4 = 2F + R_d - C_d - R_i$, which is under the promise of the sound managerial labor market; then considering the effect of gain and loss of reputation, the difference between the net income of the E strategy $(R_d - C_d)$ and the income of the NE strategy R_i for professional managers, thus $V_4 = V_3 + 2F$. The Jacobian matrix could be abbreviated as Table 4.

According to Table 4, the variables of V_1, V_2, V_3, V_4 are the key determining parameters of the evolutionary stability strategies; there are 18 different scenarios as given in Table 5.

Under the following scenarios: (1) $V_1 > 0, V_2 > 0, V_3 > 0, V_4 > 0$ and (2) $V_1 > 0, V_2 > 0, V_3 < 0, V_4 > 0$, the evolutionary stability point is D (1, 1) and the evolutionary stable strategy is {M, E} as shown in Figure 4. For enterprise owners, the net income of the M strategy $(R_m - C_m)$ is greater than the income of the NM strategy R_u. For professional managers, the net income of the E strategy $(R_d - C_d)$ is greater than the income of the NE strategy R_i. As a rational stakeholder, they will continue to choose the M strategy and the E strategy as their dominant strategies. The stable states of partial equilibrium points for scenarios (1) and (2) are shown in Supplementary Materials Table A1.

Under the following scenarios: (6) $V_1 < 0, V_2 > 0, V_3 > 0, V_4 > 0, V_1 > V_4$, (7) $V_1 < 0, V_2 > 0, V_3 > 0, V_4 > 0, V_1 < V_4$, (12) $V_1 < 0, V_2 < 0, V_3 > 0, V_4 > 0, V_2 > V_4, V_1 > V_4$, and (13) $V_1 < 0, V_2 < 0, V_3 > 0, V_4 > 0, V_2 > V_4, V_1 < V_4$, the evolutionary stable point is point B (0, 1) and the evolutionary stable strategy is {NM, E} as shown in Figure 5. Take scenario (6) as an example: for enterprise owners, as the net income of the M strategy $(R_m - C_m)$ is less than the income of the NM strategy R_u, they tend to choose the NM strategy even though they may suffer profit loss S. For professional managers, as the net income of the E strategy $(R_d - C_d)$ is greater than the income of the NE strategy R_i, they will also choose the E strategy even if the owners choose the NM strategy. The stable states of partial equilibrium points for scenario (6), (7), (12), and (13) are shown in Supplementary Materials Table A2.

Under the following scenarios: (3) $V_1 > 0, V_2 > 0, V_3 < 0, V_4 < 0, V_2 > V_4, V_1 > V_4$, (4) $V_1 > 0, V_2 > 0, V_3 < 0, V_4 < 0, V_2 > V_4, V_1 < V_4$, and (10) $V_1 < 0, V_2 > 0, V_3 < 0, V_4 < 0, V_2 > V_4$, the stable point is point C (1, 0) and the evolutionary stable strategy is {M, NE} as shown in Figure 6. Take scenario (3) as an example: for enterprise owners, as the net income of the M strategy $(R_m - C_m)$ is greater than the income of the NM strategy R_u, they tend to choose the M strategy in order to maximize their income and avoid loss S. For professional managers, as the net income of the E strategy $(R_d - C_d)$ is greater than the income of the NE strategy R_i and the reputation gain of the E strategy F is less than the income of the E strategy R_i, professional managers tend to choose the NE strategy to maximize the income even at the risk of losing the reputation F. The stable states of partial equilibrium points for scenarios (3) and (4) are shown in Supplementary Materials Table A3.

Under the scenario (18) $V_1 < 0, V_2 < 0, V_3 < 0, V_4 < 0$, the stable point is A (0, 0) and the evolutionary stable strategy is {NM, NE} as shown in Figure 7. For enterprise owners, the net income of the M strategy $(R_m - C_m)$ is less than the income of the NM strategy R_u and the profit loss S of the M strategy does not exceed the acceptable range of the owner, so enterprise owners will take the NM strategy as the dominant strategy. For professional managers, the net income of the E strategy $(R_d - C_d)$ is less than the income of the NE strategy R_i, and the reputation gain F is less than the income of the E strategy R_i. The incentive policy of enterprises is invalid, and professional managers as rational stakeholders will be more inclined to choose the NE strategy. The stable states of partial equilibrium points for scenario (18) are shown in Supplementary Materials Table A4.

Under the scenario (14) $V_1 < 0, V_2 < 0, V_3 > 0, V_4 > 0, V_2 < V_4, V_1 < V_4$, there are two stable points: B (0, 1) and C (1, 0). The evolutionary stable strategies are {NM, E} and {M, NE} as shown in Figure 8. For enterprise owners, as the net income of the M strategy $(R_m - C_m)$ is less than the income of the NM strategy R_u, they will take the NM strategy as their dominant strategy. For professional managers, the net income of the E strategy $(R_d - C_d)$ and the reputation gain F are higher than the income of the NE

Table 3: Determinant and trace of partial equilibrium points.

	Det(J)	Tr(J)
A (0, 0)	$(R_m - C_m - R_u + S)(R_d - C_d - R_i)$	$(R_m - C_m - R_u + S) + (R_d - C_d - R_i)$
B (0, 1)	$-(R_m - C_m - R_u)(R_d - C_d - R_i)$	$(R_m - C_m - R_u) - (R_d - C_d - R_i)$
C (1, 0)	$-(R_m - C_m - R_u + S)(2F + R_d - C_d - R_i)$	$-(R_m - C_m - R_u + S) - (2F + R_d - C_d - R_i)$
D (1, 1)	$(R_m - C_m - R_u)(2F + R_d - C_d - R_i)$	$-(R_m - C_m - R_u) - (2F + R_d - C_d - R_i)$
$E(x^*, y^*)$	$((R_m - C_m - R_u)(R_m - C_m - R_u + S)(2F + R_d - C_d - R_i)(R_d - C_d - R_i)/2FS)$	0

Table 4: The simplified determinant and trace of partial equilibrium points.

	Det (J)	Tr (J)
A (0, 0)	V_2V_3	$V_2 + V_3$
B (0, 1)	$-V_1V_3$	$V_1 - V_3$
C (1, 0)	$-V_2V_4$	$-V_2 - V_4$
D (1, 1)	V_1V_4	$-V_1 - V_4$
E (x^*, y^*)	$V_1V_2V_3V_4/2FS$	0

Table 5: Summary of different scenarios.

(1) $V_1 > 0, V_2 > 0, V_3 > 0, V_4 > 0$
(2) $V_1 > 0, V_2 > 0, V_3 < 0, V_4 > 0$
(3) $V_1 > 0, V_2 > 0, V_3 < 0, V_4 < 0, V_2 > V_4, V_1 > V_4$
(4) $V_1 > 0, V_2 > 0, V_3 < 0, V_4 < 0, V_2 > V_4, V_1 < V_4$
(5) $V_1 > 0, V_2 > 0, V_3 < 0, V_4 < 0, V_2 < V_4, V_1 < V_4$
(6) $V_1 < 0, V_2 > 0, V_3 > 0, V_4 > 0, V_1 > V_4$
(7) $V_1 < 0, V_2 > 0, V_3 > 0, V_4 > 0, V_1 < V_4$
(8) $V_1 < 0, V_2 > 0, V_3 < 0, V_4 > 0, V_1 > V_4$
(9) $V_1 < 0, V_2 > 0, V_3 < 0, V_4 < 0, V_2 < V_4$
(10) $V_1 < 0, V_2 > 0, V_3 < 0, V_4 < 0, V_2 > V_4$
(11) $V_1 < 0, V_2 > 0, V_3 < 0, V_4 < 0, V_2 < V_4$
(12) $V_1 < 0, V_2 < 0, V_3 > 0, V_4 > 0, V_2 > V_4, V_1 > V_4$
(13) $V_1 < 0, V_2 < 0, V_3 > 0, V_4 > 0, V_2 > V_4, V_1 < V_4$
(14) $V_1 < 0, V_2 < 0, V_3 > 0, V_4 > 0, V_2 < V_4, V_1 < V_4$
(15) $V_1 < 0, V_2 < 0, V_3 < 0, V_4 > 0, V_2 > V_4, V_1 > V_4$
(16) $V_1 < 0, V_2 < 0, V_3 < 0, V_4 > 0, V_2 > V_4, V_1 < V_4$
(17) $V_1 < 0, V_2 < 0, V_3 < 0, V_4 > 0, V_2 < V_4, V_1 < V_4$
(18) $V_1 < 0, V_2 < 0, V_3 < 0, V_4 < 0$

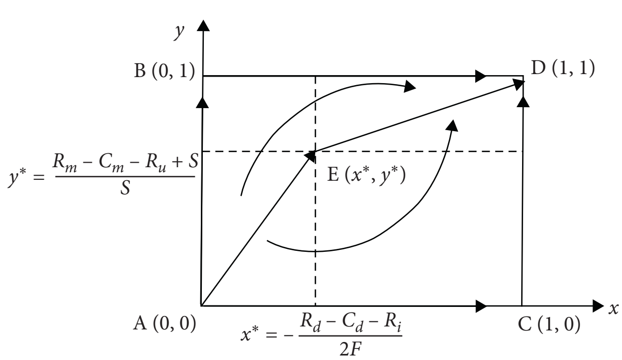

Figure 4: The replication dynamic phase map for scenarios (1) and (2).

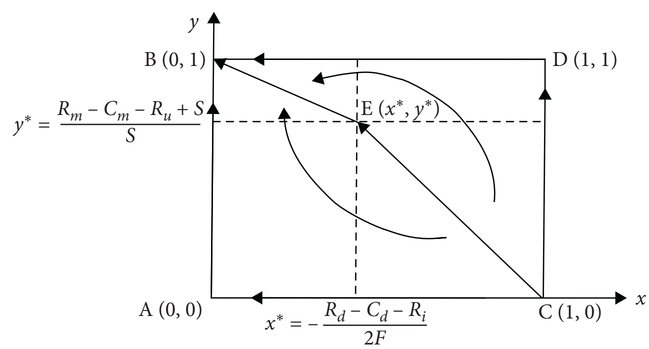

Figure 5: The replication dynamic phase map for scenarios (6), (7), (12), and (13).

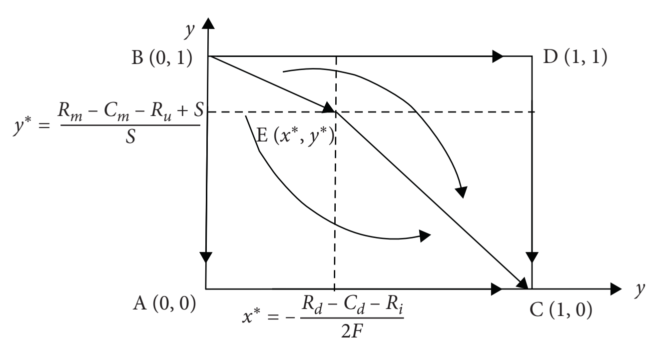

Figure 6: The replication dynamic phase map for scenarios (3) and (4).

strategy R_i; therefore professional managers choose the E strategy. However, with the increase of the possibility of professional managers choosing the E strategy, enterprise owners may turn to the NM strategy in order to avoid costs of supervising C_m and obtain extra profit T. At this time, due to the owner's nonsupervised behavior, the decrease of reputation gain F and the increase of effort cost C_d cause professional managers to change their strategies. The possibility of professional managers choosing the E strategy is closer from 1 to 0. Finally, the two sides achieve evolutionary stability at points B (0, 1) and C (1, 0). The stable states of partial equilibrium points for scenario (14) are shown in Supplementary Material Table A5.

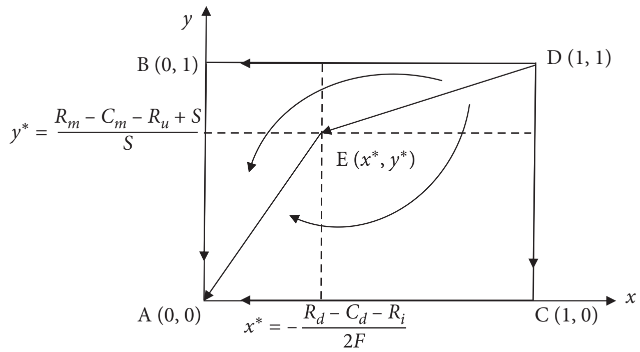

Figure 7: The replication dynamic phase map for scenario (18).

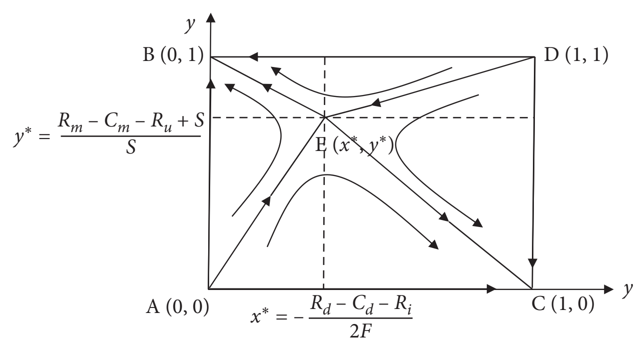

Figure 8: The replication dynamic phase map for scenario (14).

Under the scenario (17) $V_1 < 0, V_2 < 0, V_3 < 0, V_4 > 0, V_2 < V_4, V_1 < V_4$, there are also two stable points: A (0, 0) and C (1, 0) and the evolutionary stable strategies are {NM, NE} and {M, NE} as shown in Figure 9. For professional managers, the net income of the E strategy $(R_d - C_d)$ is less than the income of the NE strategy R_i, so professional managers are more inclined to choose the NE strategy. For the enterprise owners, as the net income of the M strategy $(R_m - C_m)$ is less than the income of the NM strategy R_u, the enterprise owners will choose the NM strategy at the beginning. However, with the increasing probability that professional managers choose the NE strategy, enterprise owners may turn to the M strategy to avoid profit loss S. Since the net income of the NE strategy $(R_d - C_d)$ is always higher than that of the E strategy R_i, the strategy change of enterprise owners will not change the professional managers' strategic choices. Finally, both parties achieve evolutionary stability at points A (0, 0) and C (1, 0). The stable states of partial equilibrium points for scenario (17) are shown in Supplementary Material Table A6.

Under the following scenarios: (5) $V_1 > 0, V_2 > 0, V_3 < 0, V_4 < 0, V_2 > V_4, V_1 < V_4$, (8) $V_1 < 0, V_2 > 0, V_3 < 0, V_4 > 0, V_1 > V_4$, (9) $V_1 < 0, V_2 > 0, V_3 < 0, V_4 < 0, V_2 < V_4$, (11) $V_1 < 0, V_2 > 0, V_3 < 0, V_4 < 0, V_2 < V_4$, (15) $V_1 < 0, V_2 < 0, V_3 < 0, V_4 > 0, V_2 > V_4, V_1 > V_4$, and (16) $V_1 < 0, V_2 < 0, V_3 < 0, V_4 > 0, V_2 > V_4, V_1 < V_4$, there is no evolutionary stable strategy. The long-term evolution of the principal-agent cannot find the evolution equilibrium point, and at this time the strategies of both sides of the game are constantly changing. For enterprise owners and professional

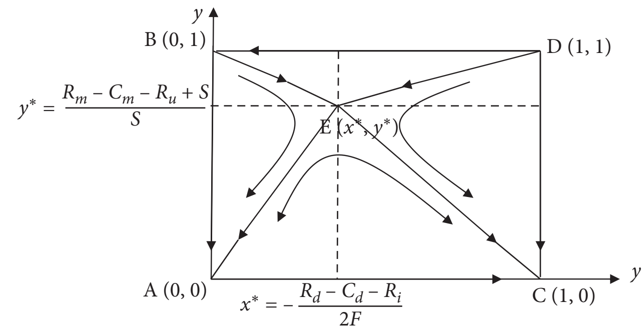

Figure 9: The replication dynamic phase map for scenario (17).

managers, the net income of choosing the M strategy or the E strategy is greater than that of the NM strategy or the NE strategy. However, due to the existence of reputation gain and loss F and profit loss S, both parties are not convinced their strategy is the optimal strategy and therefore expect to make adjustments according to the other party's possible strategy as shown in Figure 10. The stable states of partial equilibrium points for scenarios (5), (8), (9), (11), (15), and (16) are shown in Supplementary Material Table A7.

In summary, the evolutionary stable strategies of 18 different scenarios are as given in Table 6.

3.3. Simulation Results. The evolution path of the game is determined by different utility parameters, so it is necessary to verify the results of the game model through dynamic evolutionary simulation [45]. To assess the impact of different factors on the evolution of the strategic choices of the enterprise owners and professional managers, a system dynamics model for the principal-agent was constructed in Vensim PLS. The simulation model is comprised of two main subsystems capable of simulating the strategy choice of enterprise owners and professional managers based on the evolutionary stability strategy analysis. The model consists of 4 level variables, 2 flow variables, 9 external variables, and 16 intermediate variables as shown in Figure 11. The 4 level variables represent the probability that enterprise owners choose the M strategy or NM strategy and the probability that professional managers choose the E or NE strategy. The 2 flow variables represent the change rate of enterprise owners choosing M strategy to NM strategy and the change rate of professional managers choosing NE strategy to E strategy. The 9 external variables correspond to the variables in the payoff matrix as shown in Table 1. The 16 intermediate variables are the payoff and expected payoff of enterprise owners and professional managers choosing different strategies and the difference in the expected payoff. The arrow represents the relationship between different variables.

The time limit of the model is set as follows: INITIAL TIME = 0, FINAL TIME = 20, TIME STEP = 1. Due to it is hard to find a real case for system dynamics simulation, it is better to analyze the system evolution characteristics of the evolutionary game through simulation. Firstly, determine the size relationship between the data according to the

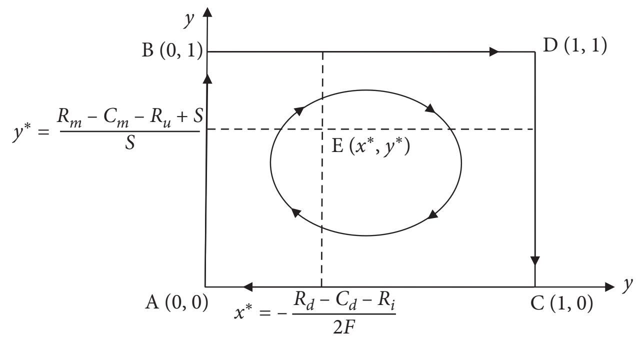

Figure 10: The replication dynamic phase map for scenarios (5), (8), (9), (11), (15), and (16).

Table 6: Summary of the evolutionary stable strategies of 18 scenarios.

Scenarios	Evolutionary stable strategies
(1) (2)	{M, E}
(3) (4) (10)	{M, NE}
(6) (7) (12) (13)	{NM, E}
(18)	{NM, NE}
(14)	{NM, E}, {M, NE}
(17)	{NM, NE}, {M, NE}
(5) (8) (9) (11) (15) (16)	No ESS

assumptions. Secondly, in order to ensure the logic of the parameters and the simplicity of analysis, the value range of the data is determined. Finally, the value is randomly assigned within the value range. The meanings and initial values of each external variable are shown in Table 7.

It was assumed that only one variable changes while the others remain constant in the simulation. The simulation results are as follows.

(1) The impact of R_m on the evolutionary results:

When R_m is increasing and the probability of the enterprise owner choosing the M strategy is increasing, the difference between the expected payoffs of professional managers choosing the E strategy and NE strategy $(\mu_{2d} - \mu_{2i})$ was reduced, resulting in professional managers' hesitation in the process of strategic choices and the probability of choosing the E strategy is decreasing. However, because the expected payoff of the E strategy is still greater than that of the NE strategy, professional managers will eventually choose the E strategy.

When R_m gradually decreases from the initial value 1.5 to 1.2, the difference between the expected payoffs of choosing the M strategy and NM strategy $(\mu_{1m} - \mu_{1u})$ decreases, so the probability of the enterprise owners choosing the M strategy decreases as shown in Figure 12. When R_m decreases to 1.2, the probability of the enterprise owners choosing the M strategy decreases, and owners will choose the NM strategy; then the evolutionary equilibrium point is {NM, E}. When R_m gradually increases from the initial value of 1.5 to 1.8, the probability of enterprise owners choosing the M strategy will continue to increase and the evolutionary equilibrium point is {M, E}.

(2) The impact of R_u on the evolutionary results:

When R_u increases and the probability of the enterprise owner choosing the M strategy decreases gradually, the difference between the expected payoffs of choosing the E and NE strategy increases; then the probability of professional managers choosing the E strategy will increase unceasingly and finally they will choose the E strategy as shown in Figure 13. When R_u gradually reduced from the initial value of 1.0 to 0.7, the probability of the owner choosing the M strategy is increasing, and eventually they choose the M strategy and the evolutionary equilibrium point is {M, E}. When R_u gradually increases to 1.3 and the probability of enterprise owners choosing the M strategy decreases, they finally choose the NM strategy, so the evolutionary equilibrium point is {NM, E}.

(3) The impact of C_m on the evolutionary results:

When C_m is increasing and the probability of enterprise owners choosing M is decreasing, which increases the difference between the expected payoffs of the E strategy and NE strategy, the probability of professional managers choosing the E strategy increases with the number of times of simulation as shown in Figure 14.

When C_m gradually decreases from the initial value of 0.4 to 0.1, the probability of enterprise owners choosing the M strategy is increasing and eventually they choose the M strategy. Then the evolutionary equilibrium point is {M, E}. When C_m increases gradually to 0.7, the probability of enterprise owners choosing the M strategy decreases and finally they choose the NM strategy. The evolutionary equilibrium point is {NM, E}.

(4) The impact of T on the evolutionary results:

If the professional manager chooses the E strategy, the T will not affect the expected payoffs of the enterprise owners of choosing the M strategy and NM strategy in the simulation model as shown in Figure 15. If the professional manager chooses the E strategy, regardless of the enterprise owners choosing either the M strategy or NM strategy, the enterprise owners can obtain extra profit due to the increase in value. On the contrary, enterprise owners cannot obtain extra profit T if the professional managers choose the NE strategy, so the strategic choices of enterprise owners remain unchanged and the evolutionary equilibrium point is {M, E}.

(5) The impact of S on the evolutionary results:

With S increasing, then the enterprise owners are more inclined to choose the M strategy to avoid profit loss. Professional managers will choose the E strategy if expected enterprise owners choose the M

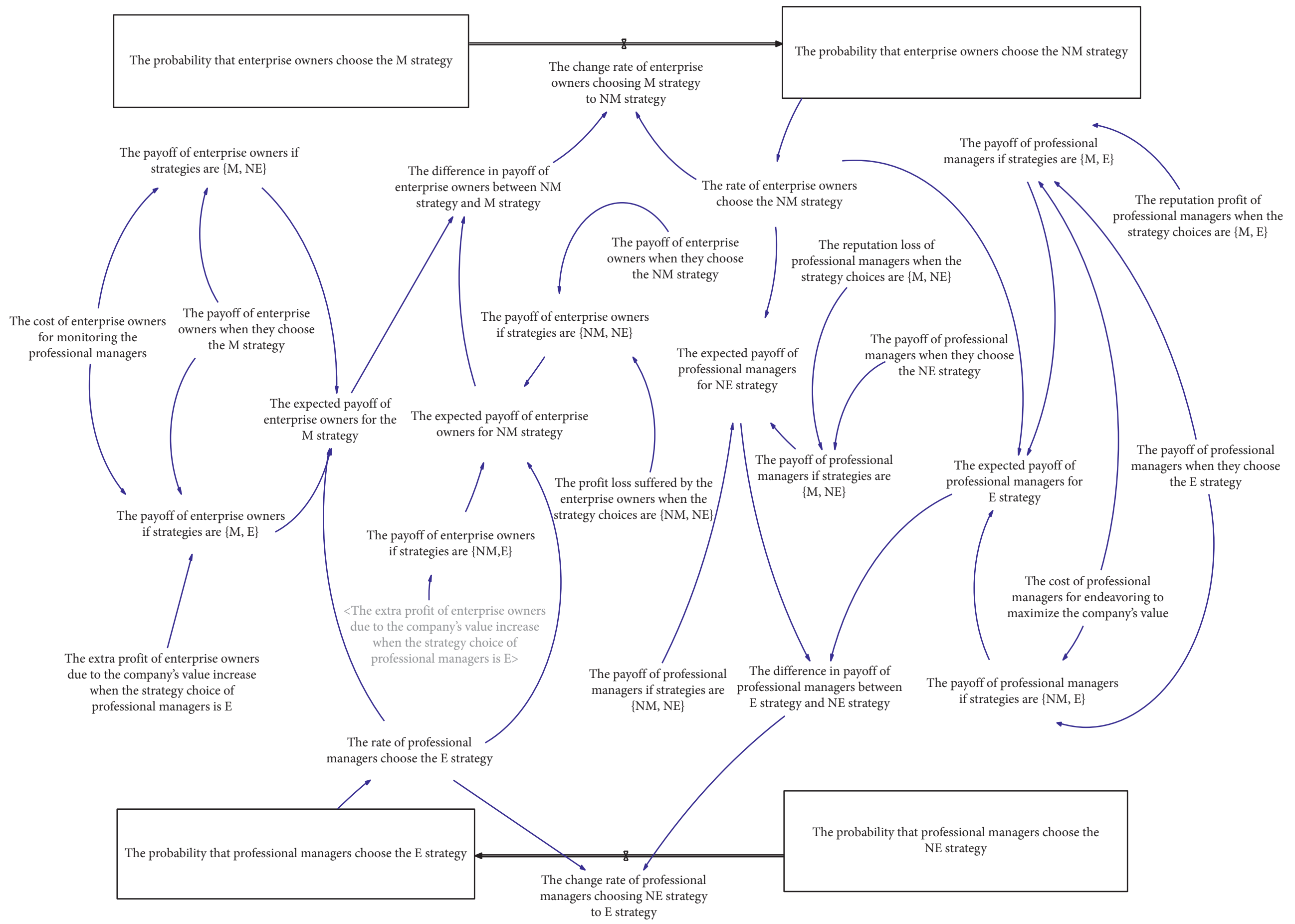

Figure 11: System dynamics model of principal-agent problem.

Table 7: The external variables and initial values of the system dynamics model.

Variables	Definitions	Initial value
R_m	The income of the enterprise owner when choosing the M strategy	1.5
R_u	The income of the enterprise owners when choosing the NM strategy	1.0
C_m	The cost of enterprise owners for monitoring the professional managers	0.4
T	The income of enterprise owners when professional managers make a great effort to manage the company when the strategy choices are {M, E} or {NM, E}	0.3
S	The loss of enterprise owners when the strategy choices are {NM, NE}	0.2
R_d	The income of professional managers when choosing the E strategy	0.7
R_i	The income of professional managers when choosing the NE strategy	0.1
C_d	The cost of professional managers for making a great effort to manage the company	0.4
F	The gain of professional managers which is the reputation gain when the strategy choices are {M, E} and the loss when the strategy choices are {M, NE}	0.05

strategy, so the evolutionary equilibrium point is {M, E} as shown in Figure 16.

(6) The impact of R_d on the evolutionary results:

When R_d is increasing, the difference between the expected payoffs of owners choosing the M strategy and NM strategy gradually increases, resulting in enterprise owners' hesitation in the process of strategy choices and the probability of choosing the M strategy gradually decreases as shown in Figure 17. However, because the expected payoff of choosing the M strategy is still greater than that of the NM strategy, the enterprise owners will eventually choose the M strategy. When R_d gradually decreases from 0.7 to 0.4, the probability of professional managers choosing the E strategy gradually decreases and eventually they choose the NE strategy; thus the evolutionary equilibrium point is {M, NE}. When R_d gradually increases to 1.0 and the probability of professional managers choosing the E strategy

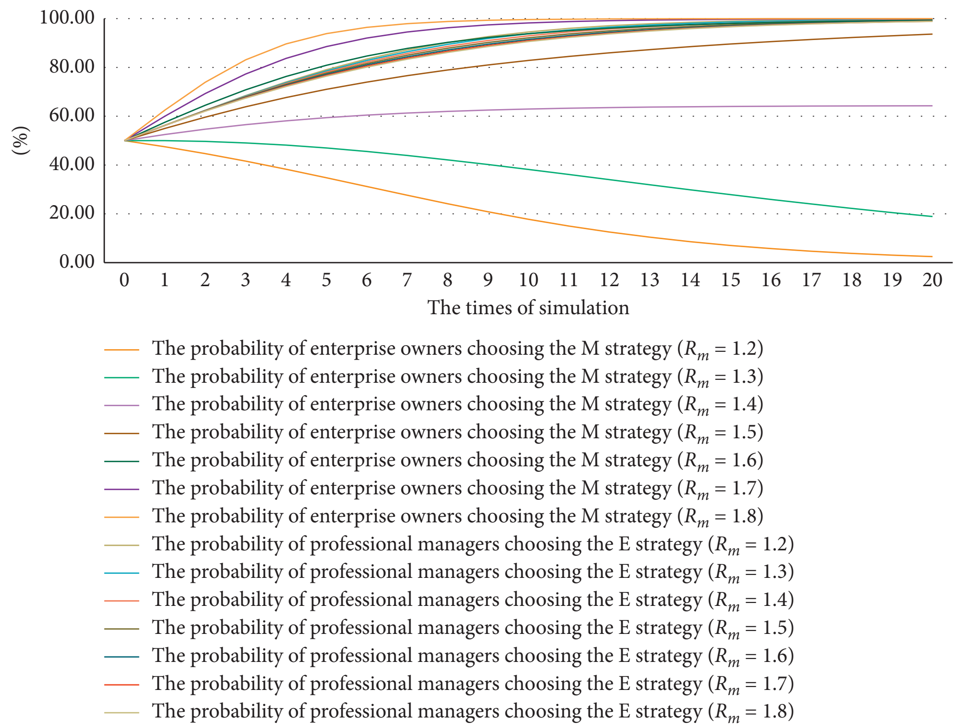

Figure 12: The impact of R_m on the evolutionary results.

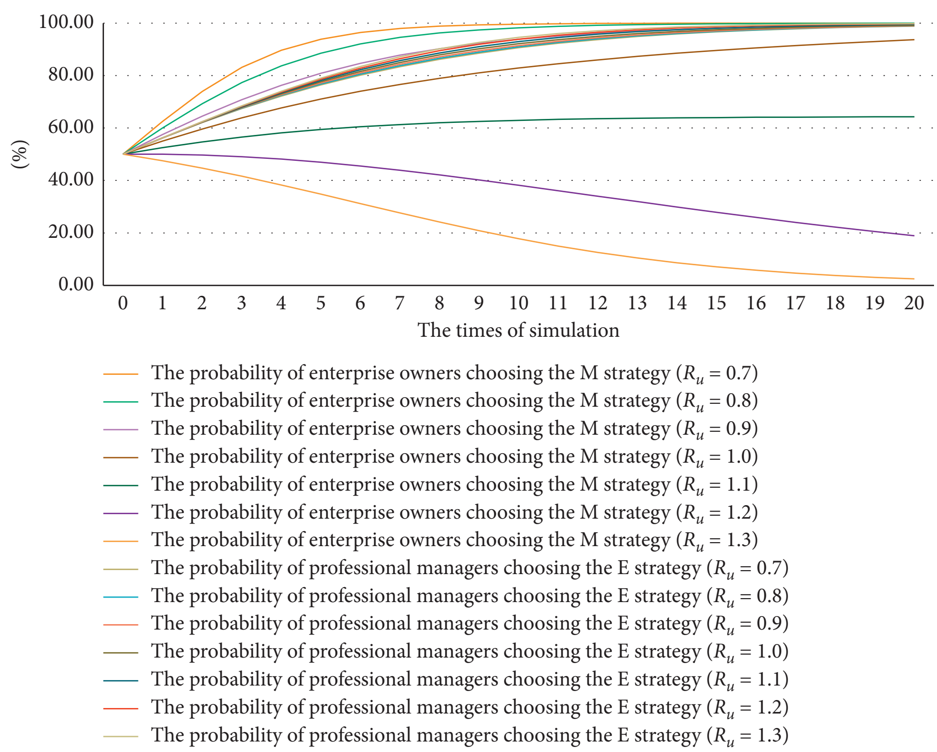

Figure 13: The impact of R_u on the evolutionary results.

increases, then professional managers will choose the E strategy and the evolutionary equilibrium point is {M, E}.

(7) The impact of R_i on the evolutionary results:

When R_i is increasing, the difference between the expected payoffs of the E strategy and NE strategy continues to decrease.Therefore the probability of professional managers choosing the E strategy

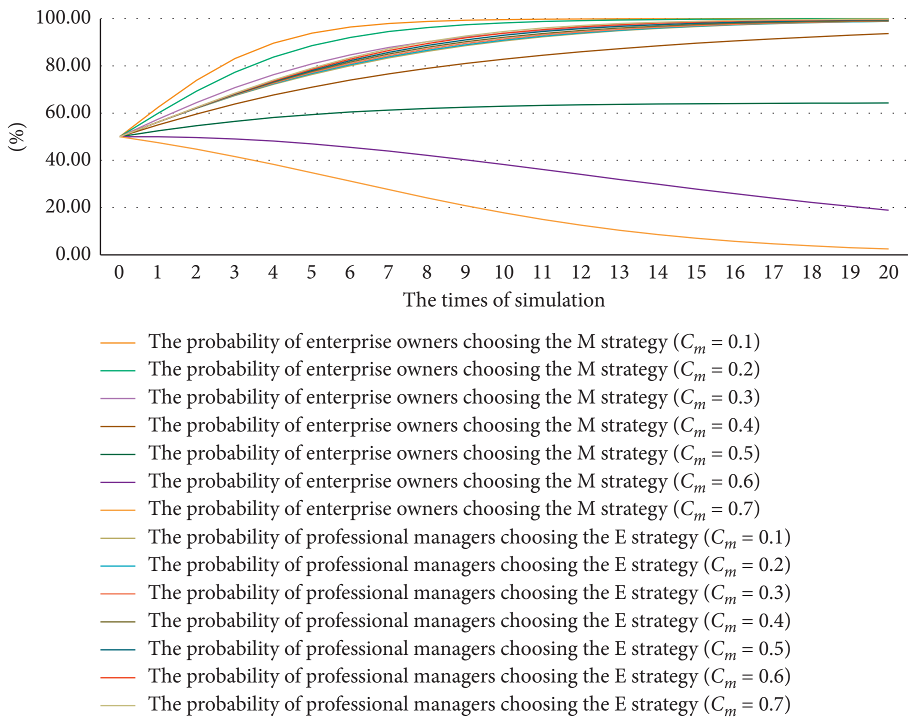

FIGURE 14: The impact of C_m on the evolutionary results.

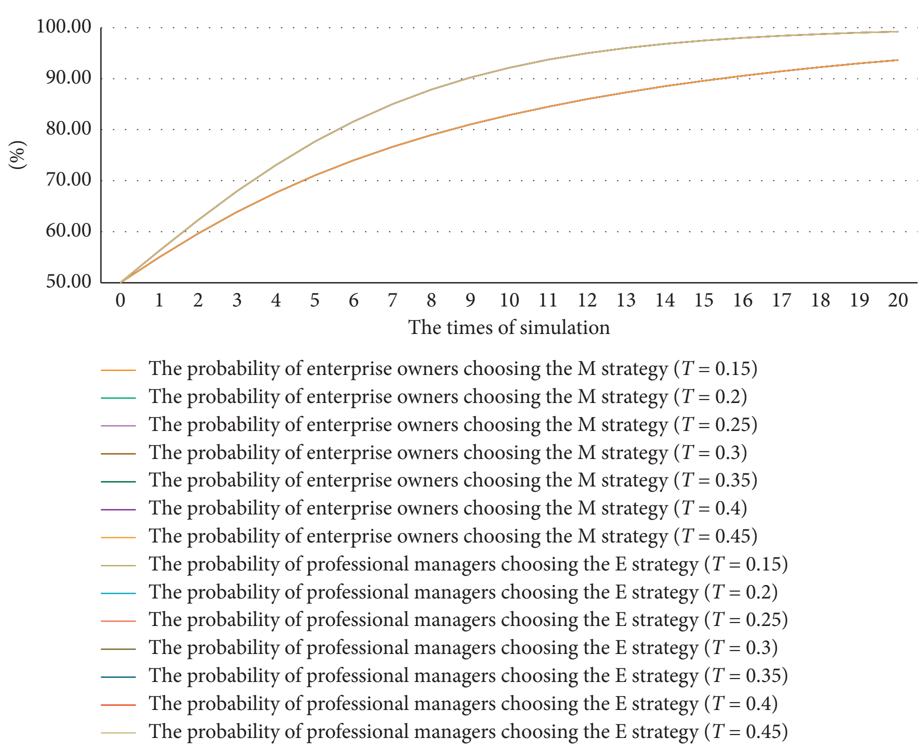

FIGURE 15: The impact of T on the evolutionary results.

decreases as shown in Figure 18. However, since the expected payoff of professional managers choosing the E strategy is greater than the expected payoff of choosing the NE strategy, professional managers will still choose the E strategy. In order to avoid the professional managers choosing the NE strategy, enterprise owners will gradually increase the probability of choosing the M strategy and the evolutionary equilibrium point is {M, E}.

(8) The impact of C_d on the evolutionary results:

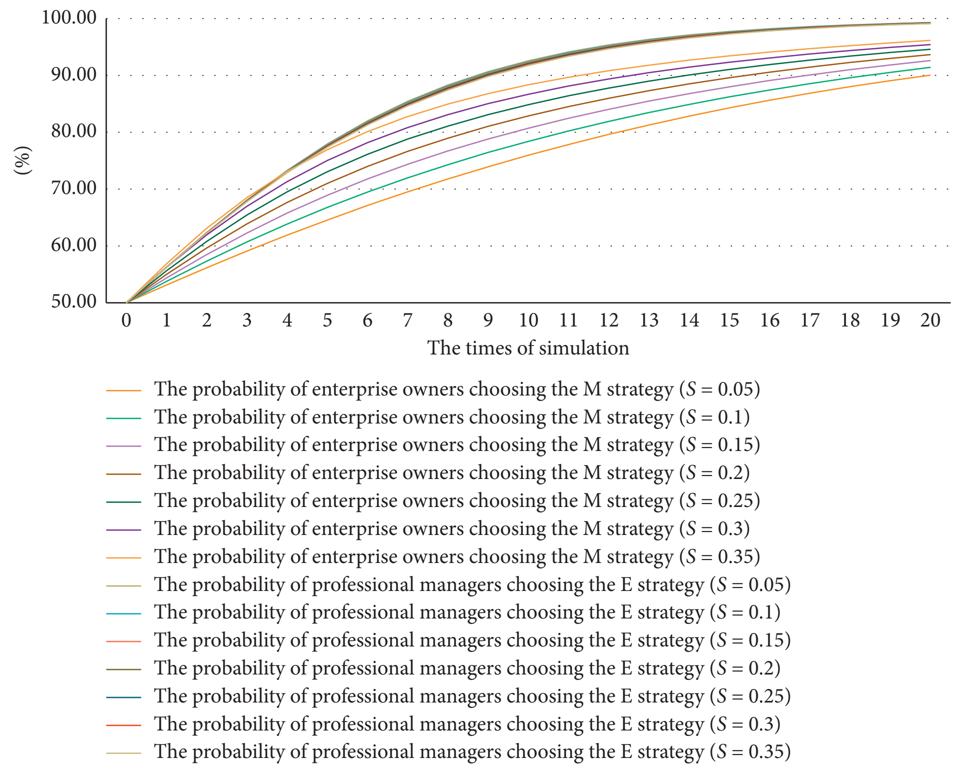

Figure 16: The impact of (S) on the evolutionary results.

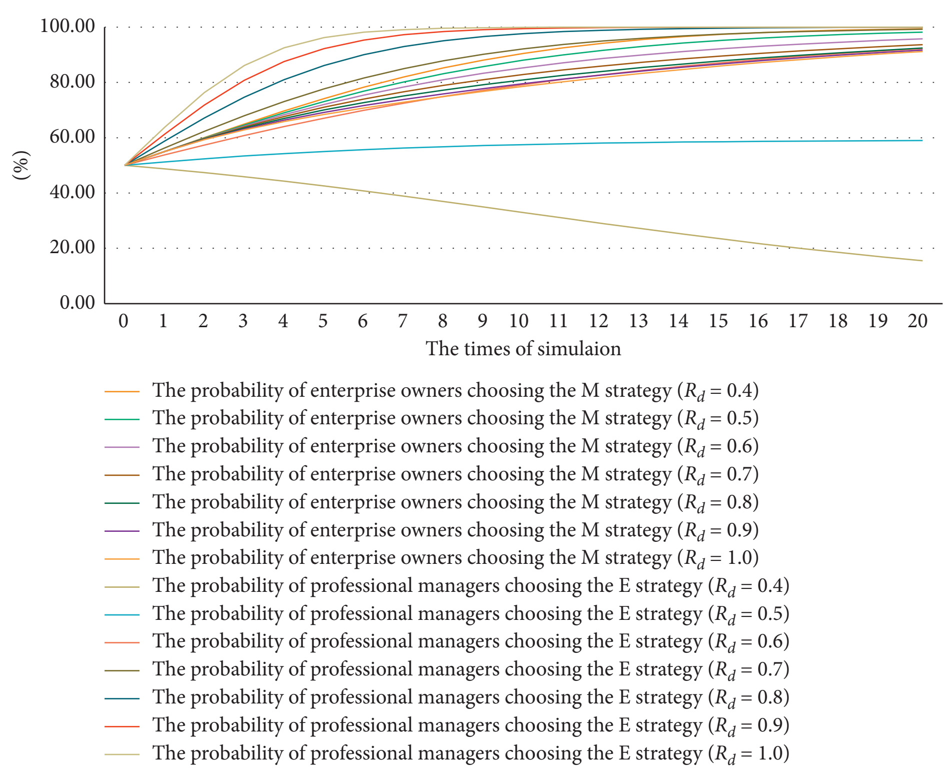

Figure 17: The impact of R_d on the evolutionary results.

When C_d is increasing, the payoff of choosing the M strategy is greater than that of the NM strategy for enterprise owners, and in order to avoid the professional managers choosing the NE strategy, they will gradually increase the probability of the M strategy and eventually choose the M strategy as shown in Figure 19. When C_d decreases from 0.4 to 0.1, the probability of professional managers choosing the E strategy increases continuously and finally they choose the E strategy, and the evolutionary equilibrium point is {M, E}. When C_d gradually rises to 0.7, the probability of professional managers choosing the NE strategy gradually increases and finally they choose the NE strategy, and the evolutionary equilibrium point is {M, NE}.

(9) The impact of F on the evolutionary results:

When F is increasing, professional managers will be more inclined to choose the E strategy. As the difference between the expected payoffs of enterprise owners choosing the M strategy and NM strategy decreases gradually, resulting in the hesitation of enterprise owners in the process of strategy choices, the probability of choosing the M strategy is gradually decreasing in each simulation as shown in Figure 20. However, because the expected payoff of choosing the M strategy is still greater than that of the NM strategy, the enterprise owners will eventually choose the M strategy, and the evolutionary equilibrium point is {M, E}.

In summary, the impact of evolutionary variables on the strategy choices of enterprise owners and professional managers is shown in Table 8.

4. Discussion

Based on the perspective of dynamic evolutionary game theory, the authors constructed a dynamic evolutionary game model of strategy choice between enterprise owners and professional managers, explored the strategic choice behavior and evolutionary path of enterprise owners and professional managers in 18 situations, discussed the strategic choices and evolution path of different scenarios, and simulated the sensitivity of evolutionary parameters. The paper shows that, as a bounded rational stakeholder, the main decisive factor of making choices for both the principal (enterprise owners) and the agent (professional managers) under the asymmetric information scenario is their expected payoffs.

The dynamic simulation analysis shows that the strategic choices of enterprise owners and professional managers have the following characteristics: The probability of strategy choice set {M, E} will increase with the profit of M and E strategy and decrease with that of the NM and NE strategy. An increase in cooperation costs will improve the probability of strategy choice set {NM, NE}, but the change of extra profit T of enterprise owners does not affect the evolutionary results. In addition, high reputation gain or loss F will increase the probability of professional managers choosing the E strategy.

Therefore, the key to improving the relationship of principal and agent is perfecting the incentive-compatibility mechanism, such as increasing the payoff if both parties choose to cooperate, changing the preferences of individuals during the decision-making process [46]. In addition, information asymmetry will lead to adverse selection by both parties. Therefore, it is necessary to further improve the managerial labor market for reduced information asymmetry and promote long-term effective cooperation between the two parties.

Firstly, there is obvious asymmetric information between the professional managers and the enterprise owners, which is the root cause of the principal-agent problem [47]. The factor endowment and information channel of professional managers are better than those of enterprise owners [48], so they have obvious information advantages. Due to limited access to information, the principal cannot collect all the information about efforts of their agents and design an effective incentive contract. Therefore, enterprises need to create an effective information transmission mechanism to improve transmission ability and solve the information asymmetry problem.

Secondly, improve the income of cooperation and reduce that of speculation. The simulation analysis shows that the probability of both sides choosing a strategy is positively related to the payoff of the strategy. Therefore, the enterprise should introduce the performance commission reward which is related to the manager's long-term benefit of the enterprise and establish an incentive mechanism through stocks to bind the interests of both parties [49]. In addition, the income of speculation can be reduced by strengthening corporate governance, improving internal control system, and establishing strict supervision and whistle-blowing mechanisms.

Thirdly, reduce the cost of cooperation. The probability of both sides choosing cooperation is inversely proportional to the costs of monitoring or making an effort [50]. Therefore, enterprises should ensure the legitimate and transparency operation to reduce the costs of professional managers. In addition, owners should trust professional managers and create an environment to help them work conscientiously to maximize the value of the company [51].

Fourthly, standardize the managerial labor market and expand the impact of reputation gains and losses. The reputation gain with a nonmonetary incentive is beneficial to promote professional managers to work conscientiously. In addition, the increase of reputation loss can increase the speculative risk and restrain the speculative behavior of professional managers [52]. The managerial labor market should be constantly standardized by establishing and improving integrity policies, increasing punishment for breach of faith, and maintaining the punishment of speculation.

Fifthly, improve principal-agent cooperation by the principal's appropriate supervision. On the one hand, the strategy choices of the professional managers depend on the probability of the enterprise owners' choices. On the other hand, professional managers will suffer the loss of reputation if the owners choose to supervise, which will increase their

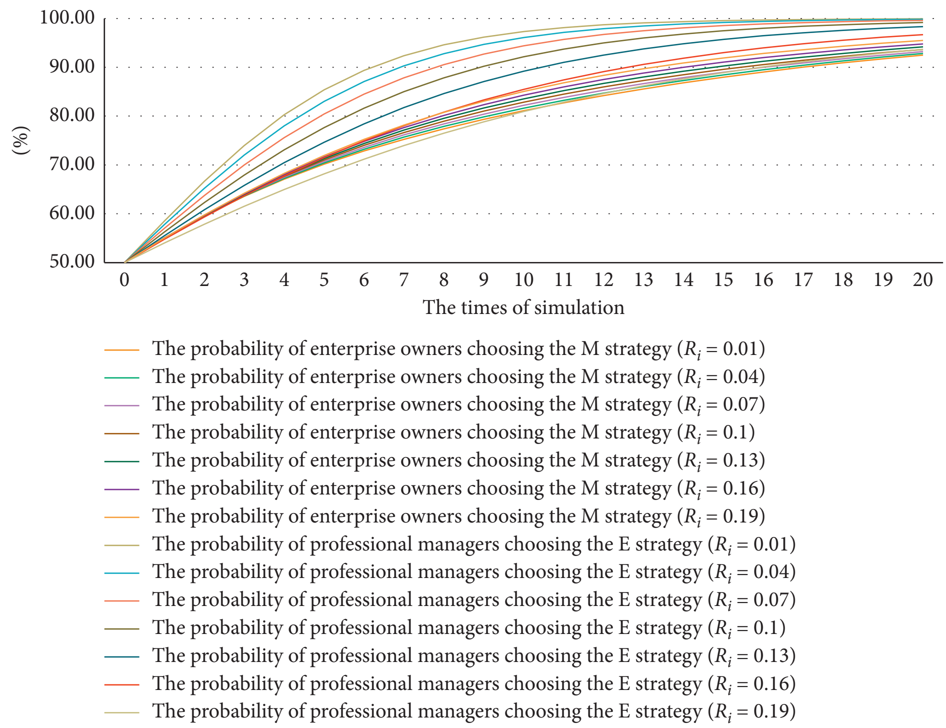

Figure 18: The impact of R_i on the evolutionary results.

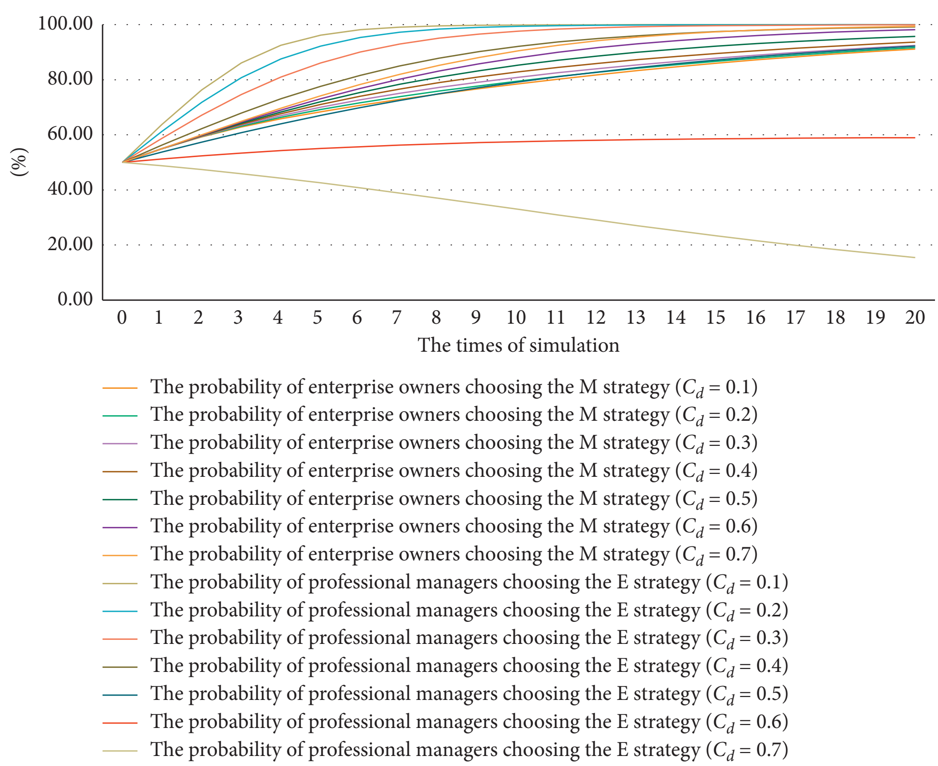

Figure 19: The impact of C_d on the evolutionary results.

speculative costs and prevent speculative behaviors [53]. The higher the supervision cost the owners pay, the greater the possibility of professional managers choosing to work conscientiously. Therefore, enterprise owners should improve supervision input and implement effective supervision measures to prompt professional managers to work

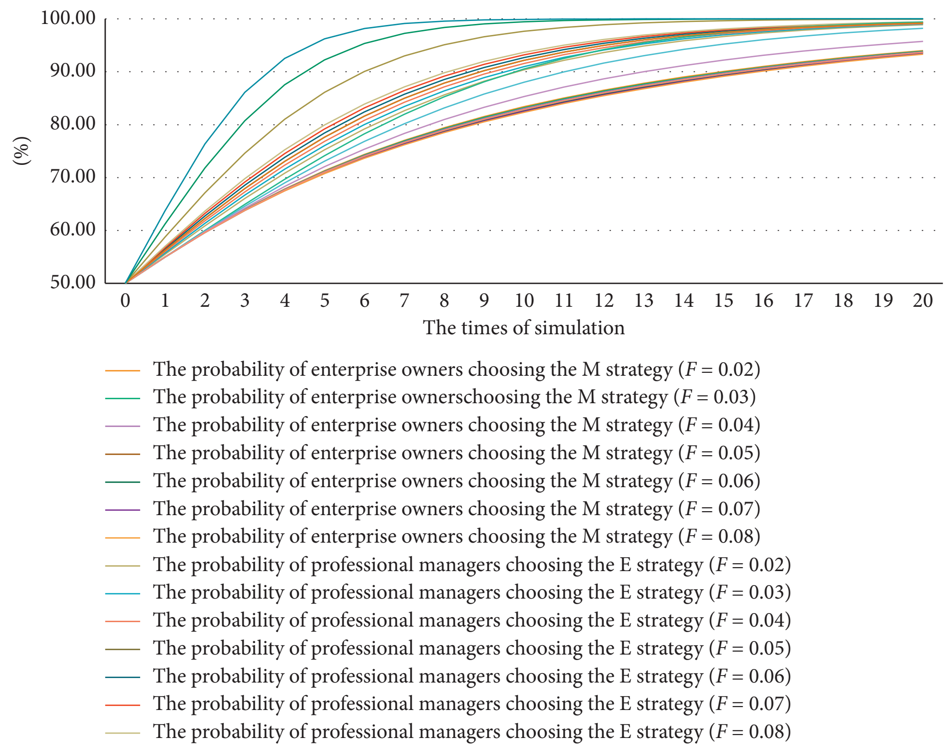

Figure 20: The impact of (F) on the evolutionary results.

Table 8: The influence of variables on the strategy choices.

Variables	The probability of enterprise owners choosing the M strategy	The probability of professional managers choosing the E strategy
R_m	Positive correlation	Partial negative correlation
R_u	Negative correlation	Partial positive correlation
C_m	Negative correlation	Partial negative correlation
T	No effect	No effect
S	Positive correlation	No effect
R_d	Partial negative correlation	Positive correlation
R_i	Partial positive correlation	Negative correlation
C_d	Partial positive correlation	Negative correlation
F	Partial negative correlation	Positive correlation

conscientiously. However, enterprise owners should adopt appropriate supervision regularly, since the supervision does not always have a positive effect on the results of cooperation.

In summary, the principal-agent cooperation of enterprises needs proper supervision and guidance with incentive for the company to maximize its value [54]. The key is to design an incentive and restraint mechanism which can not only induce various stakeholders to choose correct choices but also effectively standardize the behavior of professional managers. In addition to the conventional incentive methods such as equity incentive and performance remuneration, the establishment of agent reputation and promotion mechanisms is also an effective way to improve the principal-agent relationship [55]. Furthermore, standardization of the managerial labor market and increasing the impact of reputation gains and losses are necessary to promote cooperation and achieve win-win results.

5. Conclusion

In this paper, the authors focused on the characteristics of the decision-making behaviors between enterprise owners and professional managers, analyzed the principal-agent problem between enterprise owners and professional managers using system dynamics, evolutionary game and principal-agent theory, discussed the evolution of both parties' strategic behaviors under 18 different scenarios, simulated the impacts of different factors on strategy selection and behavioral evolution, and provided a theoretical basis for resolving the principal-agent problem.

The keys to solving the principal-agent problem and improving the corporate governance are changing the expected payoffs of different strategy choices and the asymmetric status. The targeted suggestions for the principal-agent problem can conclude as follows: Firstly, improve internal information channels and design transmission mechanisms to eliminate the influence of information asymmetry between the principal and agent, which is a precondition for improving the principal-agent relationship. Secondly, increase profit and reduce the cost to increase the profit of cooperation through compliance and mutual trust. Thirdly, standardize the managerial labor market and expand the impact of reputation gains and losses to encourage professional managers to work conscientiously. Fourthly, use monetary and nonmonetary incentives and increase the intensity of punishment to promote the consistency of the goals of principal and agent. Fifthly, adopt appropriate supervision of enterprise owners to improve the outcome of principal-agent cooperation, which should consider the impact of differences in expected payoffs of different strategies.

The results of this paper are important for the ongoing efforts to improve the principal-agent relationship. However, as we mainly focus on the conflict of interests and the characteristics of strategic choices between the principal and agent, the company's profit is not connected with the payoff function of the individuals. Therefore, further studies are necessary to associate the payoff of the stakeholders with company's profit for more accurate modeling and consider additional scenarios in the simulation analysis.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

Liang Yuan and Xiaorui Tao contributed equally to this work.

Acknowledgments

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Supplementary Materials

The stable states of partial equilibrium points for (1)–(18) scenarios are given. (*Supplementary Materials*)

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Review Article

Can Smart City Policy Facilitate the Low-Carbon Economy in China? A Quasi-Natural Experiment Based on Pilot City

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This paper studies the impact of the implementation of smart city policy (SCP) on the development of low-carbon economy (LCE) in China. For this purpose, we developed a nonconvex meta-frontier data envelopment analysis (DEA) approach to measure LCE and used the differences-in-difference (DID) analysis method in the econometric model to empirically analyze the impact of SCP on LCE, using the dataset of 230 cities from 2005 to 2018. The results show that the implementation of SCP can significantly improve the LCE of cities, and the dynamic effect test presents that the promotion of smart cities to low-carbon economy increases with time. In addition, SCP promotes the development of LCE by optimizing government functions and improving the efficiency of governance and the degree of implementation openness. But there is heterogeneity between different cities as follows: the implementation of SCP has a more significant effect on the promotion of LCE in central and western regions in China and large-scale cities and cities without strict environmental protection planning. Finally, the robustness test verifies the reliability of the experimental data again and puts forward conclusions and policy recommendations.

1. Introduction

Since human society entered the 21st century, the process of urbanization has developed rapidly. Global population growth is mainly concentrated in urban areas. It is estimated that, by 2050, two thirds of the world's population will live in cities [1]. As the most populous country in the world, China's rapid economic development has promoted the rapid process of urbanization since reform and opening-up. By 2019, China's urbanization rate has reached 60.6%, followed by a series of "urban diseases," such as resource shortage, environmental pollution, and ecological imbalance [2]. It is obvious that, in the process of urbanization, economic development has produced a lot of carbon dioxide emissions and the resulting greenhouse effect and extreme weather. How to solve the above problems and improve the environmental quality of the city and the sustainable development of the economy has been the topic of concern of scholars. In recent years, driven by new technologies such as Internet of Things, big data, block chain, and cloud computing, the concept of smart city emerges as the times require, providing opportunities for the operation of low-carbon economy.

By integrating new technologies into the management and operation of cities, smart cities provide innovative solutions for the sustainable development and low-carbon operation of cities. It promotes the low-carbon economy by optimizing the supply and demand of energy and information sharing between government, enterprises, and citizens [3]. In other words, smart city policy provides a way to solve multiple urban diseases, that is, cities can achieve innovation and sustainable development goals while maintaining economic development, so as to enhance competitiveness, for example, improving energy efficiency, developing new energy, reducing carbon emissions, and improving the quality of life of urban residents [4]. Based on this background, the Chinese government began to implement the pilot policy of smart city in 2012 and vigorously promote the construction of smart city. By the beginning of April 2020, the number of smart city pilot projects announced by the Ministry of Housing and Urban Rural Development of China has reached 290, and with the accelerated penetration of pilot policies, 800 smart pilot cities will be implemented in China in the near future, and China has become the largest smart city construction implementation country in the world. Do so many smart cities improve the quality of urbanization? Has it improved the effectiveness of urban management and the quality of life of citizens? Does it promote the development of low-carbon economy? This leads to a series of questions.

However, although the academic research on smart city shows an increasing trend, the empirical research in the existing literature is relatively scarce. At present, the research on smart city mainly focuses on the interpretation of the concept, construction planning, evaluation index system, strategic planning, and management measures, as well as the application of new science and technology in the construction of smart city [5, 6]. And, some studies have pointed out that the development of smart city can improve energy efficiency [7], as well as promoting sustainable development [8, 9]. There is little research on the impact of smart city policy on urban low-carbon economic development through empirical research.

The purpose of this paper is to evaluate whether the smart city policy improves the low-carbon economic development level of the city. The main contribution of this paper not only enriches the research results in related fields but also has certain reference value for the planning, managers, and decision makers of low-carbon cities and smart cities. The residual structure of this paper is arranged as follows: Section 2 is literature review and mechanism analysis, which systematically reviews the literature related to smart city and low-carbon economy and analyzes the mechanism of the impact of smart city construction on low-carbon economy. Section 3 is the method and data. This paper establishes a DEA low-carbon economy measurement model and constructs an econometric model to analyze the research data. Section 4 is the result and discussion, including the evaluation of low-carbon economy, the impact of smart city on low-carbon economy, heterogeneity analysis, and robustness test. Section 5 is the conclusion and enlightenment. The conclusions and policy implications are summarized. The flowchart of this paper is shown in Figure 1.

2. Literature Review and Theoretical Fracture

At present, scholars have performed a lot of research on the concept, measurement, influencing factors, and economic and social effects of low-carbon economy. Although the expression of low-carbon economy in the existing literature is different, the basic point of view is the same, that is low-carbon economy is based on low energy consumption, low pollutants, and carbon emissions, considering both economic development and sustainable economic growth mode [10]. It emphasizes the efficient use of energy and the development of new energy to achieve green GDP and maximize social output. And, afterwards, research on the measurement and evaluation of low-carbon economy is also quite rich. For instance, in terms of statistical evaluation methods, Yu et al. [11] introduced the fuzzy fractional differential equation in the construction of the statistical evaluation system of low-carbon economy to quantitatively evaluate the low-carbon economy. In [12], a novel economy and CO2 emissions evaluation model based on the slacks-based measure integrating the data envelopment analysis (SBM-DEA) is proposed to analyze and optimize energy structures of some countries and regions in the world. In terms of index evaluation methods, Mohsin et al. [13, 14] developed an aggregated composite index (ACI) of energy security and environmental sustainability for each of the world's highest GHGs and CO2-emitting countries by a comprehensive set of indicators including carbon emission and energy metrics.

Based on the accurate measurement of low-carbon economy, many scholars have studied the influencing factors of low-carbon economy from different perspectives. These factors can be roughly divided into technology level, industrial structure, economic and financial development level, population factor, and government policy. For instance, in terms of technology, many scholars [15–17] used econometric methods to test the impact of technological progress on environmental performance. They found that the increase of research and development investment and the invention of low-carbon patented technology can significantly improve the environmental performance of polluting industrial enterprises. As for the impact of the industrial structure on low-carbon economy, due to the different definitions of the industrial structure, the research conclusions are inconsistent. These conclusions include that the increase of the proportion of the secondary industry will increase carbon emissions [18], industrial growth and energy consumption have a significant positive impact on carbon emissions in the long and short term [19], the U-shaped correlation between industrial structure and carbon emissions [20], and the optimization of the industrial structure has no significant impact on carbon emissions [21]. In addition, economic and financial development has a positive effect on low-carbon economy [22–25]. Some studies have pointed out that population aging, population migration, and population structure have an impact on low-carbon economy [26–28]. In addition, in terms of government policy, some study [29] point out that government regulation and incentive policies will promote the innovation of low-carbon behavior and low-carbon technology of enterprises and then promote the development of low-carbon economy.

According to the current situation of urbanization in China, the sources of urban carbon emissions can be roughly divided into economic sources and policies, such as industrial carbon emissions ($E1$), transportation carbon emissions ($E2$), personal and household consumption carbon emissions ($E3$), building carbon emissions ($E4$), and policy sources such as urban expansion with low density and high energy consumption ($E5$) [30–32]. In terms of

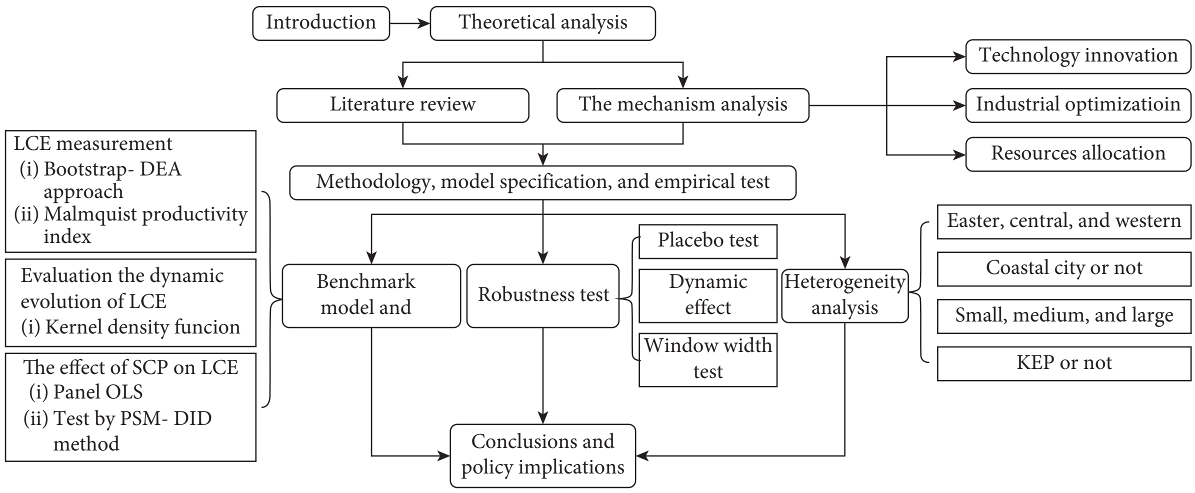

Figure 1: The flowchart of this paper.

industrial production, since 2003, China has accelerated the development of heavy industry, especially energy, raw material industry, and manufacturing industry, resulting in a large amount of carbon emissions. In addition, China's traditional export trade is dominated by processing industries with high energy consumption, which also leads to the increase of energy consumption. In the construction industry, there are a large number of buildings with high energy consumption and repeated urban construction in the process of urbanization, and inefficient use of buildings will lead to waste of building materials and carbon emissions. In terms of transportation, the acceleration of urban logistics circulation and the increase of traffic congestion have led to the rapid increase of transportation energy consumption. In terms of personal and household consumption, the increase of urban population will lead to the increase of residents' energy consumption. Finally, due to the low-density urban sprawl, the local government has pushed up the increase of carbon emissions in the process of urbanization [33, 34]. The population density of 30 major cities in China has declined in the past 30 years, and the urban area has expanded faster than the population has increased. The marginal per capital energy consumption of urban expansion does not decrease but increases. Based on above analysis, the total carbon emissions (TE) in the process of urbanization can be expressed as $\text{TE} = E1 * E2 * E3 * E4 + E5$, which will hinder the sustainable economic growth and is not conducive to the operation of low-carbon economy (shown in Figure 2).

Although some factors, such as technology level and government policy, are related to smart city, there are few studies on the impact of smart city policy on low-carbon economy, especially in China. Referring to [35], this paper argues that smart city policy may affect the operation of low-carbon economy through the following channels (shown in Figure 3).

2.1. To Improve Energy Efficiency through a Series of Technological Innovation. As human society enters the era of Industry 4.0, the concept of smart city and many new technologies are integrated, which realize the information sharing among the government, enterprises, and residents, for example, the use of Hadoop software for energy information management to monitor energy dynamics through the Internet of Things (IoT) and big data to achieve real-time monitoring of energy consumption terminal, so as to optimize energy storage and distribution. In addition, devices in smart cities are embedded with self-sustaining and automated sensors. The integration of physical devices, services, and management can be achieved with the help of network physical systems. Through these technological innovations, to improve energy efficiency and effective distribution of energy and to reduce urban carbon emissions, Babar and Khattak [36] proposed an overall design scheme of smart city energy management based on Internet of Things, ensured the energy efficiency of IOT equipment through data analysis, and constructed a model composed of energy management, data processing, and service management. It is verified that the model can achieve energy-efficient clustering, peak shaving, optimal scheduling, and load balancing optimization. Luo et al. [37] proposed a short-term energy prediction system based on edge computing architecture. The system distributes data acquisition, data processing, and regression prediction on sensor nodes, routing nodes, and central servers, respectively. Semantic and stream processing technologies are used to support efficient data acquisition and processing in the IOT. And, some studies [38–40] have verified that blockchain technology provides an unchangeable account book for security value transactions in the smart city network. This time, grassroots technology can improve the efficiency of various processes in the energy sector. Therefore, blockchain technology promotes the innovation and transformation of the energy market and realizes the point-to-point energy microgrid, thus reducing urban energy consumption. In addition, academic research [41–43] has found that smart cities have more professional applications and spillover effects of technological innovation, thus improving the utilization efficiency and output level of resources, such as clean energy and clean technology. Meanwhile, cities are

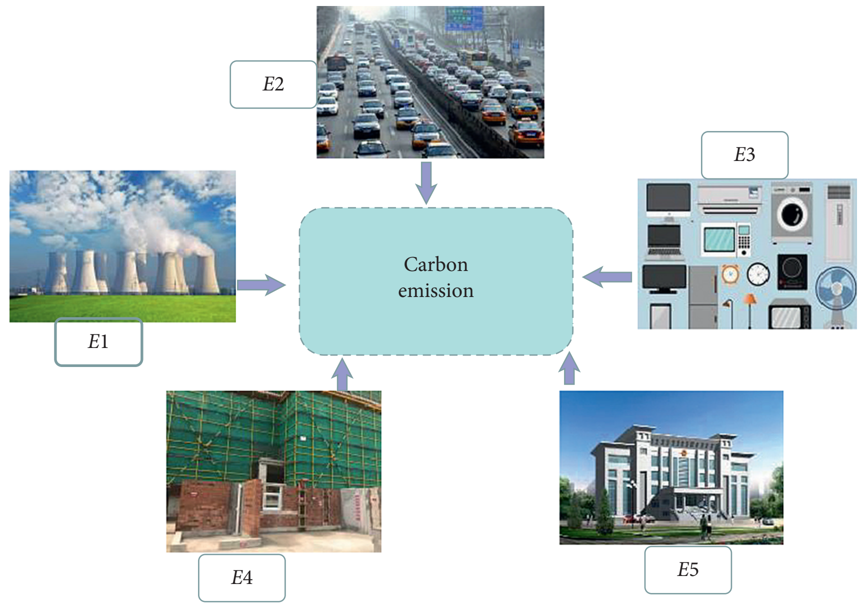

Figure 2: Main sources of carbon emission in the urbanization process.

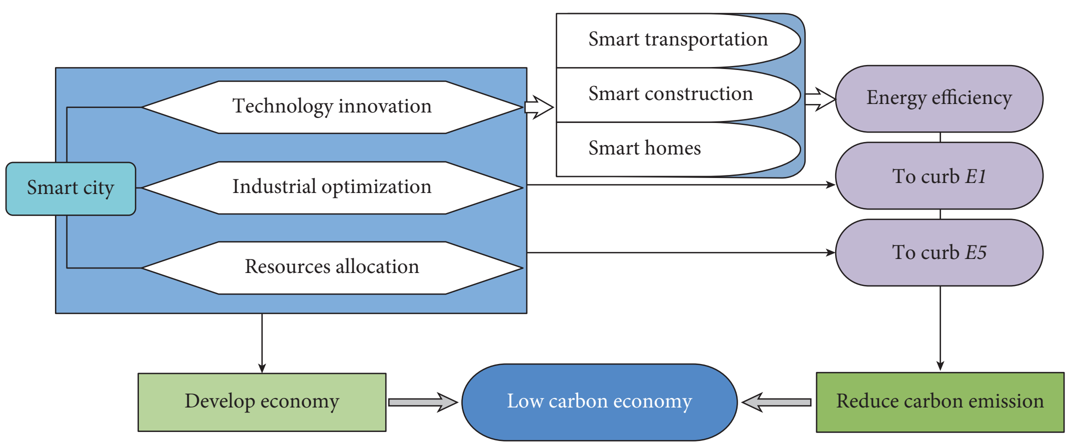

Figure 3: Theoretical framework for the effect of smart city construction on low-carbon economy.

conducive to transforming the mode of urban governance with the latest technologies which make the pollution regulation more efficient [44].

Smart transportation, smart buildings, and smart homes based on smart city technologies can effectively curb the carbon emissions brought by *E*2, *E*4, and *E*3. For *E*2, intelligent transportation uses the traffic data application system to realize data and information sharing among management departments, so as to optimize vehicle scheduling and reduce carbon emissions caused by congestion. In addition, smart cities promote the development of sharing economy and give birth to shared cars, shared logistics, and other formats to reduce urban energy consumption. For *E*4, smart cities realize the integration of urban construction industry, ecology, environmental optimization, and energy saving and consumption reduction through system technologies such as green energy-saving building technology, prefabricated building technology, and big data intelligent management. For *E*3, on the one hand, smart home realizes interconnection, remote control, intelligent analysis, low carbon, and energy saving of various household appliances based on intelligent analysis of big data. On the other hand, the distributed energy system is more convenient for users to use distributed power sources such as solar energy and wind energy, as a supplementary form of household electricity, to shift the peak load and fill the valley and reduce urban carbon emissions.

2.2. To Reduce Carbon Emission through Industrial Structure Optimization. Smart city construction not only promotes the overall economy [42, 45] but also optimizes the industrial structure. First of all, smart city will attract high-quality material capital and investment and human capital to pilot cities, which will become the basis for the transformation and upgrading of the urban industrial structure. And, smart city construction optimizes the industrial results by upgrading the secondary industry and upgrading the high-end service industry in the tertiary industry. In [46, 47], the authors pointed out that smart city will attract investment and talent inflow and provide support for accelerating the optimization of the industrial structure. With the knowledge spillover effect of human capital, it improves the innovation and *R&D* ability of traditional industries and makes the industrial structure more advanced and less energy consuming. Secondly, smart city integrates the development of Internet of Things, big data, new energy, information materials, and other industries [47, 48], which will promote the prosperity of corresponding services, for example, research and development of information technology, software development, and mobile communication operation. Based on these technologies, it will promote the development of knowledge intensive industries with high added value and low energy consumption, thus reducing the carbon emission intensity of cities. Finally, the construction of smart city promotes the development of smart industry and smart consumption, for example, smart transportation, smart health care, smart education, and smart public services. These industries are based on the Internet and belong to technology intensive industries with low dependence on energy. The development of these industries has reduced the carbon emission intensity and environmental pollution caused by *E*1.

2.3. To Allocate Resources for Achieving Low-Carbon Economic Development. Many network physical systems of smart city can solve the coupling problem of resource management by providing resource allocation efficiency [49–51]. For instance, Jing [52] proposed a resource optimization scheduling and allocation for the hierarchical distributed cloud service system in smart city, and the scheduling optimization and utilization efficiency of various resources in the hierarchical distributed cloud service for the smart city effectively reduces the response time of the tenant resource request and optimizes the performance of system resource scheduling on the cloud platform. Similarly, Kunst et al. [53] studied the improving network resources allocation in smart cities video surveillance. Intelligent transportation, intelligent government, intelligent logistics, and functional industrial park based on Internet of Things technology and big data can effectively relieve traffic pressure, greatly improve the operation speed of logistics, people flow, and information flow, reduce the circulation cost of resources, reduce the energy consumption per unit GDP and environmental protection cost, and provide support conditions for urban green development. From the market level, with the help of Internet of Things sensors, cloud computing, and big data analysis, urban enterprises can understand customers' latest demand and preference for products, so as to adjust their production behavior appropriately and promote the balance of resource supply and demand. When more high-quality information resources, knowledge resources, and human resources are gathered in smart cities, the efficiency of government planning and decision-making is improved, thus reducing the carbon emissions brought by *E*5. In summary, smart city can reduce excessive energy consumption and emissions by optimizing resource allocation, so as to improve the development level of low-carbon economy.

3. Methodology and Data

3.1. Bootstrap-DEA Model for Low-Carbon Economy Measurement. By referring to existing studies, we find that most of previous papers use low-carbon total factor productivity, which is calculated by DEA, to measure LCE [54, 55]; this paper estimates the development of LCE by establishing the bootstrap-DEA model and calculating the Malmquist productivity index. The advantage of this method is to simulate the production process with multiple outputs and inputs simultaneously and avoid the error of model setting caused by the parameterized method and the clear assumption that random interference items may not obey normal distribution. And, the low-carbon total factor productivity is measured by MATLAB software in this study. Considering that urban LCE will involve energy consumption, capital input, labor input, economic development, carbon dioxide emission, and afforestation to achieve carbon neutrality, we adopt labor (x_1), capital (x_2), and energy (x_3) as inputs, GDP (x_4) and afforestation area (x_5) as desirable outputs, and carbon emissions (x_6) as undesirable outputs. The function of the low-carbon total factor growth rate is expressed as

$$\mathrm{ML} = F(x_1, x_2, x_3, x_4, x_5, x_6). \tag{1}$$

Among the input indicators, the labor means the number of people employed in the city in each year, and the unit is 10,000 people. And, the energy consumption is expressed by converting the carbon energy consumed by cities into standard coal, and the unit is 10,000 tons. The capital is calculated by the perpetual inventory method, and we take the year 2000 as the base year, deflating the book value of capital by the fixed asset price index, and the unit is 10,000 yuan. In terms of output indicators, we estimate the carbon dioxide emissions of each city in million tons by the method proposed by the Intergovernmental Panel on Climate Change in 2006. And, the GDP of each city is deflated by the price index of the base year 2000; the unit of measurement is 10,000 yuan, which shows the economic development of the city. Finally, the afforestation area mainly represents the artificial afforestation area of each city, and the unit of measurement is ten thousand hectares. The data are mainly from China's Urban Statistical Yearbook, China's Energy Statistical Yearbook, China's Forestry Statistical Yearbook, and the official websites of statistics bureaus of cities.

If there are Q decision-making units (DMU) and, in every period $t\,(t = 1, \ldots, T)$ and in every DMU, there are G kinds of general input $x = (x_{1t}, \ldots, x_{\mathrm{gt}})$, U kinds of unexpected input $z = (z_{1t}, \ldots, z_{\mathrm{ut}})$, P kinds of expected output $y = (y_{1t}, \ldots, y_{\mathrm{pt}})$, and S kinds of unexpected output $b = (b_{1t}, \ldots, b_{\mathrm{st}})$, then the low-carbon economy producing function is

$$T=\left[\left(x_t,z_t,y_t,b_t\right)\sum_{j=1}^{J}\lambda_{js}x_{gjs}\le x_{gt}\forall g;\sum_{j=1}^{J}\lambda_{js}z_{ujs}\ge z_{ut}\forall u;\sum_{j=1}^{J}\lambda_{js}\ge y_{pt}\forall p;\sum_{j=1}^{J}\lambda_{js}b_{ijs}=b_{it}\forall i;\sum_{j=1}^{J}\lambda_{jt}=1;\lambda_{is}\ge 0,j=1,2,\ldots,J\right]. \tag{2}$$

On the basis of the above functions, the distance from each decision-making unit to the optimal production front is calculated by using the directional distance function. According to Fukuyama and Weber [56], the relaxation measure is introduced into the directional distance function, and the SBM model is established. Based on this, the unexpected input and unexpected output are calculated, and the calculation formula is

$$\begin{aligned}
&\overrightarrow{D}^t\left(x_{qt},y_{qt},b_{qt},g\right)=\max\frac{1}{4}\left[\frac{1}{G}\sum_{g=1}^{G}\frac{s_{gt}^x}{g_{gt}^x}+\frac{1}{U}\sum_{p=1}^{P}\frac{s_{ut}^x}{g_{ut}^x}+\frac{1}{P}\sum_{p=1}^{P}\frac{s_{pt}^y}{g_{pt}^y}+\frac{1}{I}\sum_{i=1}^{I}\frac{s_{it}^b}{g_{it}^b}\right],\\
&Z_{rkt}=\sum_{j=1}^{J}\lambda_{js}z_{rjs}-s_{rt}^R,\quad r=1,\ldots,R;\ t=1,\ldots,T,\\
&y_{mkt}=\sum_{j=1}^{J}\lambda_{js}y_{mjs}-s_{mt}^y,\quad m=1,\ldots,M;\ t=1,\ldots,T,\\
&b_{ikt}=\sum_{j=1}^{J}\lambda_{js}b_{ijs}-s_{it}^b,\quad i=1,\ldots,I;\ t=1,\ldots,T,\\
&\forall_{rt}=1,\ldots,T;S_{nt}^x\ge 0\text{ and }\forall n;S_{rt}^x\ge 0\text{ and }\forall r;S_{mt}^y\ge 0\text{ and }\forall m;S_{it}^b\ge 0\text{ and }\forall i,\sum_{j=1}^{J}\lambda_{js}=1;\lambda_{js}\ge 0,\forall j,\text{ and }\forall s,
\end{aligned} \tag{3}$$

where x_0 represents G -dimensional general input, z_0 represents U-dimensional unexpected input, y_0 represents P-dimensional expected output, b_0 represents I-dimensional unexpected output, (g^x,g^z,g^y,g^b) are directional vectors, respectively, indicating the decrease of general input, the increase of unexpected input, the increase of expected output, and the decrease of unexpected output, and (s^x,s^z,s^y,s^b) represents the vectors of general input redundancy, unexpected input shortage, expected output shortage, and unexpected output redundancy. In order to accurately calculate the distance function value, the direction vector is expressed as standardized input and output relaxation variables:

$$\begin{aligned}
g_n^x&=x_n^{\max}-x_n^{\min},\\
g_r^z&=z_r^{\max}-z_r^{\min},\\
g_m^y&=y_m^{\max}-y_m^{\min},\\
g_i^b&=b_i^{\max}-b_i^{\min}.
\end{aligned} \tag{4}$$

In order to avoid the error of calculation result caused by sampling error of DEA in analyzing sample data, bootstrap technology is introduced to measure the urban low-carbon economy situation to improve the accuracy of the results. The basic idea of the bootstrap-DEA model is to apply the resampling technology to the original sample data and calculate a large number of simulated datasets by the DEA model.

Step 1. for each $\mathrm{DMU}_k\,(k=1,\ldots,K)$ in the sample, the original efficiency value θ_k of the DEA model is obtained by solving the linear programming problem of formulas (2) and (3) (the superscript t of time is omitted to avoid the tedious)

Step 2. generating random samples with length K based on smooth bootstrap sampling, which is shown as $\{\theta_i; i=1,2,\ldots,k\}$

Step 3. according to the results of the previous step, a pseudodataset is generated $\{(x_i^*,y_i,b_i^*)\}, i=1,2,\ \ldots,\ k$, $x_i^+=(\theta_k/\theta_i^*)_i^x$, and $u_i^*=(\theta_k/\theta_i^*)u_i$, which constitutes the reference set in the bootstrap-DEA model

Step 4. the estimated value θ_k^* of bootstrap of θ_k is obtained by solving equation (3) from the pseudodataset

Step 5. repeat Step 2 to Step 4 for 2,000 times to obtain a series of estimated values $\{\theta_{kb}^*; b=1,2,\ldots,B\}$ of the original efficiency value $\widehat{\theta}_k$

Bootstrap estimators obtained based on the above iterative process can simulate the distribution of the original efficiency estimators and then correct the bootstrap deviation of the DEA model. The error of L can be calculated by the following formula:

$$\text{Bias}(\theta_k) = \overline{\theta}_k^* - \theta_k, \overline{\theta}_k^* = B^{-1}\sum_{b=1}^{B}\theta_{kb}^*. \quad (5)$$

The estimated low-carbon total factor efficiency of the global DEA model after bootstrap rectification is

$$\widetilde{\theta}_k = \theta_k - \text{Bias}(\theta_k) = 2\theta_k - B^{-1}\sum_{b=1}^{B}\theta_{kb}^*. \quad (6)$$

3.2. Econometric Strategy. The DID method was employed to study the effect of smart city policy on low-carbon economy. This may be described by

$$\text{ML}_{it} = a_0 + a_1(du_{it} * dt_{it}) + a_2 du_{it} + a_3 dt_{it} + \lambda x_{it} + \mu_{it}, \quad (7)$$

where i represents the sample, t means the time, ML_{it} represents the total factor production efficiency of low-carbon economy of city i at time t, du_{it} represents the dummy variables of the experimental group and control group, $\text{du}_{it} = 1$ means that the sample belongs to the experimental group, $\text{du}_{it} = 0$ means that the sample belongs to the control group, dt_{it} represents the time dummy variable, $\text{dt}_{it} = 1$ indicates that the smart city pilot policy has been implemented in t period, $\text{dt}_{it} = 0$ indicates that the smart city pilot policy has not been implemented in t period, x_{it} is the control variable, and μ_{it} is the random disturbance term.

Equation (7) expresses the average impact of implementing smart city policy on low-carbon economy. And, the regression model is shown in the following equation to determine the dynamic effect of smart city on low-carbon economy:

$$\text{ML}_{it} = a_0 + \sum_{t=2013}^{2018} a_1(\text{du}_{it} * \text{dt}_{it}) + a_2\text{du}_{it} + a_3\text{dt}_{it} + \lambda x_{it} + \mu_{it}. \quad (8)$$

Referring to [57, 58], a series of control variables will be considered: technological innovation (Innov) is measured by the number of patents granted by G (computer and automation equipment) and H (semiconductor and communication technology), which belong to ICP classification number and the total number of patents granted by cities. The industrial structure (Indus) is measured by the proportion of the tertiary industry in GDP. Government scale (GScale) is measured by the proportion of government budget expenditure in GDP. The degree of opening up (Open) is measured by the proportion of FDI in GDP. Information technology facilities (Infra) are expressed by the proportion of Internet users in the total urban population. The scale of the city (Size) is measured by the population at the end of the year (unit: 10,000 people), and the financial development level (Fin) is measured by the proportion of the total deposits and loans of financial institutions in GDP at the end of the year. Human capital (Human) is calculated by the proportion of university and college students in the total population. Average economic development (Pgdp) is measured by GDP per unit of capital. Table 1 shows the variable definitions and their measurement.

3.3. Data. Following the principle of representatives and continuity of data, our sample consists of a panel data of prefecture level 230 cities from 2005 to 2018. Our data come from official sources, such as China Statistical Yearbook, China Urban Statistical Yearbook, China Regional Economic Statistical Yearbook, China Urban Construction Statistical Yearbook, China Fixed Assets Investment Yearbook, China Forestry Statistical Yearbook, China Environment Statistical Yearbook, and China Energy Statistical Yearbook. It should be noted that we have processed the sample as follows: (1) due to the lack of data, the data from Tibet, Hong Kong, Macao, and Taiwan are not included. (2) The sample cities with only one county or district as the pilot are excluded from the sample. Table 2 shows the descriptive statistics of the results.

4. Results and Discussion

4.1. Estimated Low-Carbon Total Factor Productivity. In order to understand the dynamic evolution of China's low-carbon economy from 2005 to 2018, the kernel density function analysis technology is introduced for evaluation, which depicts the dynamic evolution of low-carbon economy in different periods, as shown in Figures 4(a)–4(c). We can see that, firstly, during the observation period, the center of the kernel density function of all cities moves to the right, and the peak value and curve shape of the function also change to some extent. In addition, the polarization phenomenon has also experienced different changes, indicating that the low-carbon total factor productivity increases with the passage of time, and the regional difference is not short. The right tail of the low-carbon economy kernel density function curve of all cities gradually disappeared, indicating that the implementation of SCP has promoted the development of low-carbon economy in pilot cities. The multi-peak shape of the urban kernel density curve in the eastern region is more and more obvious, indicating that there is a weak multilevel differentiation in the region. The height of the main peak of urban kernel density curve in Central and Western China increased significantly at first and then decreased gradually, while the change range of kernel density center was weak, indicating that the low-carbon efficiency had little change, and the difference between provinces was obvious.

4.2. Effects of SCP on Low-Carbon Economy. The calculation results of OLS formula (6) are shown in Table 3. The first column is the result without control variables, and the second to tenth columns are the calculation results with control variables. From the regression results, we can see that whether the control variables are considered or not; $\text{du} \times \text{dt}$ has a positive impact on the development of China's low-carbon economy. This is an attribute to the advancement of smart city construction that promotes the gradual development of new technologies and industries, the

Table 1: Variable definitions and measurement.

Variable	Definition	Measurement
MLit	Low-carbon total factor productivity	Calculated by bootstrap-DEA model; input: capital, labor, and energy; desired output: real GDP and afforestation area; undesired output: carbon emissions
Innov	Technology innovation	Calculated by the proportion of patents granted by G and H in the total city patents to acquire technology innovation level
Indus	The industrial structure	Measured by the proportion of the tertiary industry in GDP
GScale	The government scale	Measured by the proportion of government budget expenditure in GDP
Open	The level of opening-up	Measured by the proportion of FDI in GDP
Infra	Information infrastructure	Measured by the proportion of internet users in the total urban population
Size	Urban scale	Measured by the population at the end of the year (unit:10,000)
Fin	Financial development	Measured by the proportion of the total deposits and loans of financial institutions in GDP at the end of the year
Human	Human capital	Calculated by the proportion of university and college students in the total population
Pgdp	The level of economy development	Measured by GDP per unit of capital

Table 2: Descriptive statistics of the various variables for the different groups.

Variable	Total sample			Control group (du = 0)			Treatment group (du = 1)		
	Obs.	Mean	Std. dev.	Obs.	Mean	Std. dev.	Obs.	Mean	Std. dev.
MLit	3220	1.0263	0.5032	2100	0.9653	0.2103	1120	1.3359	0.2055
Innov	3220	0.0897	0.1289	2100	0.0680	0.0412	1120	0.1387	0.5263
Indus	3220	0.4331	0.2252	2100	0.4130	0.1109	1120	0.4934	0.0786
GScale	3220	0.1493	0.0692	2100	0.1822	0.0853	1120	0.1477	0.0692
Open	3220	0.1369	0.1036	2100	0.1232	0.1206	1120	0.1459	0.1341
Infra	3220	0.1231	0.1502	2100	0.1041	0.0558	1120	0.1439	0.0522
Size	3220	2.8564	0.2201	2100	2.8620	0.1102	1120	2.8437	0.2603
Fin	3220	0.3622	0.2256	2100	0.3682	0.2741	1120	0.3598	0.1743
Human	3220	0.0254	0.0631	2100	0.0087	0.0149	1120	0.0034	0.0065
Pgdp	3220	10.3371	0.6570	2100	10.047	0.5203	1120	10.409	0.5012

continuous improvement of information infrastructure, and the popularization of terminal smart application. Undoubtedly, the technological effect, industrial structure upgrading effect, and resource allocation effect induced by smart city construction have been effectively brought into play, so the impact of smart city policy on the low-carbon economy is increasingly strengthened. More specifically, without control variables, the SCP has improved the low-carbon economy by about 5.9% and considering all control variables by around 4.5%.

When considering the nine control variables step by step, only Innov, Indus, human resources, and Pgdp have significant positive effects on low-carbon economy, and their coefficients are all positive. Technological innovation promotes the optimization of the industrial structure, the development of tertiary industry promotes the operation of low-carbon economy, and the development of Pgdp promotes the economic agglomeration effect, thus restraining carbon emissions. The coefficient of government scale, opening degree, and city scale is negative, which shows that the increase of government budget expenditure is not conducive to the development of low-carbon economy. Foreign investment may bring some enterprises with high carbon emissions. The expansion of the city scale is accompanied by the aging of population and the reduction of family size, which are not conducive to the development of low-carbon economy.

4.3. Test Based on PSM-DID Method. Due to the different development level of low-carbon economy between SCP pilot cities and nonpilot cities, this paper uses PSM-DID (propensity score matching-difference in difference) method to test the robustness to reduce the possible deviation of the results of DID. First, we need to test the balance of the model, and the test results are shown in Table 4. After matching, the standardized deviation of all variables is less than 10%, which has a good balance effect. Secondly, from the point of view of the p value, there is no systematic difference between the experimental group and control group. It shows that PSM results are effective, and this robustness test method is more suitable for analyzing the impact of SCP on low-carbon economy.

The empirical results based on the PSM-DID method are summarized in Table 5. The results show that smart city construction significantly improves the urban low-carbon economy by 5.3%. That is to say, there is no significant difference between the estimation results based on the PSM-DID method and the aforementioned DID results, which further supports the robustness of the empirical conclusions in this paper.

4.4. Robustness Test. In order to ensure that the result is robust, we carry out a series of robustness tests, which includes the placebo test, parallel trend hypothesis test, and

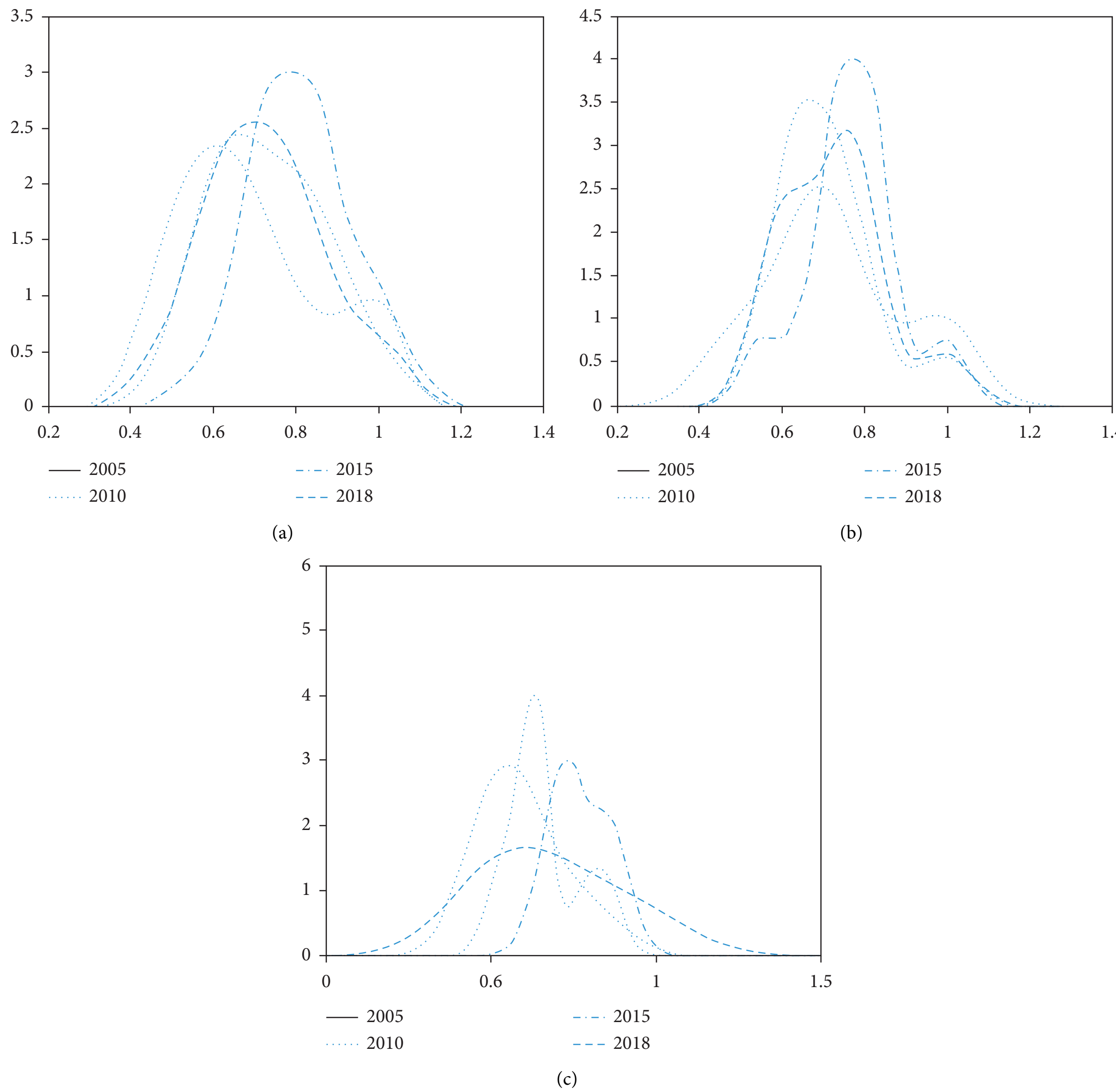

Figure 4: The kernel density curve of the study samples. (a) All. (b) Eastern region. (c) Central and western.

dynamic effect analysis and changing the window width before and after the SCP policy.

4.4.1. Placebo Test. In order to further verify that the conclusion of this paper does not miss a series of other not observable driving factors, referring to the research of Cai et al. [59], we randomly selected cities from the sample to test the main results of this paper with a placebo test. And, 80 cities of the total sample were selected randomly as the artificial treatment group, and the remaining cities as the artificial control group. At the same time, we set a dummy variable du_c^{false} and a placebo cross term $du_c^{false} \times du_t$, which should not have a significant impact on the explained variable and $\beta^{false} = 0$ because the treatment group is artificial. That is to say, if there is no significant missing variable deviation, the regression coefficient of the placebo-treated variables will not deviate significantly from 0. If the estimation coefficient of β^{false} deviates significantly from 0 statistically, it means that there is recognition error in the model setting, that is, other factors that promote the development of low-carbon economy are omitted. Additionally, in order to avoid the interference of other small probability events on the estimation results, we repeated the above process for regression analysis 200 times. Figure 5 reports the estimated coefficient kernel density and corresponding p value distribution of 200 randomly generated processing groups. We can see that the mean value of the regression system is very close to 0, and most p values are greater than 0.1, which proves that the estimation results in this paper are not missing other important variables which may cause serious errors.

Table 3: Estimation results of panel OLS with dependent variable MLit.

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
du × dt	0.0587***	0.0532***	0.0528***	0.0523***	0.0514***	0.0506***	0.0501***	0.0463***	0.0426***	0.0449***
	(3.9685)	(3.8701)	(3.8659)	(3.8612)	(3.8022)	(3.7904)	(3.7885)	(3.6515)	(3.3604)	(3.3517)
Innov		0.0352***	0.0347***	0.0322***	0.0298***	0.0287***	0.0274***	0.0263***	0.0259***	0.0241***
		(3.1453)	(3.1408)	(3.1247)	(3.0052)	(2.9837)	(2.8979)	(2.8928)	(2.8901)	(2.8857)
Indus			0.0209***	0.0207***	0.0204***	0.0199***	0.0187***	0.0182***	0.0176***	0.0175***
			(3.7221)	(3.7044)	(3.6858)	(3.6629)	(3.6436)	(3.5104)	(3.4002)	(3.3917)
GScale				−0.0895**	−0.0916**	−0.0832**	−0.0952**	−0.0809**	−0.0794**	−0.0953**
				(−1.3987)	(−1.4054)	(−1.2541)	(−1.4497)	(−1.3905)	(−1.3842)	(−1.4836)
Open					−0.0925*	−0.0963*	−0.0971*	−0.0903*	−0.0894*	−0.0914*
					(−1.2162)	(−1.1335)	(−1.1347)	(−1.2008)	(−1.1798)	(−1.2185)
Infra						0.0092*	0.0083*	0.0065*	0.0041*	0.0037*
						(0.9966)	(0.9902)	(0.9749)	(0.9682)	(0.9663)
Size							−0.0223*	−0.0207*	−0.0199*	−0.0184*
							(−1.0132)	(−1.004)	(−0.9865)	(−0.9833)
Fin								0.0041*	0.0063*	0.0075*
								(1.2239)	(1.2251)	(1.2260)
Human									0.0105***	0.0103***
									(1.7306)	(1.7299)
Pgdp										0.0196***
										(3.4408)
Constant	0.5239***	0.4887***	0.5031***	0.5540***	0.5306***	0.5412***	0.6203***	0.6395***	0.6802***	0.6703***
	(49.2013)	(47.6791)	(43.2241)	(34.0670)	(29.6502)	(25.9688)	(19.4347)	(16.0203)	(14.0702)	(13.9026)
Observations	3220	3220	3220	3220	3220	3220	3220	3220	3220	3220
R-squared	0.0955	0.1123	0.1137	0.1164	0.1291	0.1330	1.1348	1.1365	1.1397	1.1406

Notes: (1) robust t-statistics in parentheses; (2) $^{***}p < 0.01$, $^{**}p < 0.05$, and $^{*}p < 0.1$.

Table 4: PSM matching effect test: balance test of all variables before and after matching.

Variables	Treatment group mean	Control group mean	Mean bias (%)	p value
MLit	1.1208	1.1146	1.3	≤0.001
Innov	0.1271	0.0959	3.2	≤0.001
Indus	0.4873	0.4607	7.4	≤0.001
GScale	0.1465	0.1488	−1.6	≤0.001
Open	0.1404	0.1353	5.7	≤0.001
Infra	0.1396	0.1375	2.1	≤0.001
Size	2.8401	2.8542	−1.8	≤0.001
Fin	0.3522	0.3611	−1.5	≤0.001
Human	0.0207	0.0260	−1.9	≤0.001
Pgdp	10.382	10.356	3	≤0.001

Notes: (1) ***, **, and *denote significance at the 1%, 5%, and 10% levels, respectively; (2) the null hypothesis is that there is no significant difference between the treatment group and the control group.

Table 5: Smart city construction and low-carbon economy: PSM-DID robustness test.

	MLit		
	Before policy implementation	After policy implementation	DID result
Treatment group	−0.432	−0.475	
Control group	−0.398	−0.494	
Diff (T-C)	−0.034	0.019	0.053
S. err.	0.054	0.051	0.030
T value	−1.320	0.682	1.851
p value	0.1251	0.3976	0.088*

4.4.2. Parallel Trend Hypothesis Test and Dynamic Effect. Considering that economic development is a dynamic process, it is necessary to further study the dynamic marginal effect of smart city pilot policy on China's low-carbon economic development. The premise of this study is that the trend of low-carbon economy development in the treatment group and the control group should be consistent before the smart city pilot policy takes place. With the implement of the pilot policy of smart city, the difference between the treatment group and the control group should begin to increase. Based on the research methods of Liu and Qiu [60], we further investigate the change trend of the treatment

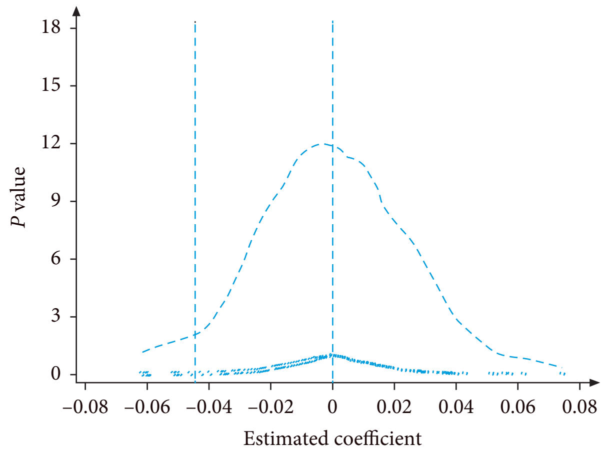

Figure 5: The result of the placebo test.

group and the control group. The empirical equation is set as follows:

$$y_{pt} = \theta_k \sum_{k\geq -5}^{6+} du_p * dt_{2012+k} + X_{pt}\delta + a_p + \partial_t + \gamma_{pt}. \quad (9)$$

Among them, dt is the annual dummy variable, the observation value of the current year is 1, and the observation value of other years is 0. Other variables are consistent with the benchmark model. We tested the trend change from five years before the smart city policy pilot in 2012 to the last year of the sample. Figure 6 reports the results of the analysis. It shows the results of the 90% confidence interval of the regression coefficient of each year, and the dotted line shows the marginal effect of the dual interaction term on the development of China's low-carbon economy. We can see that, before 2012, the coefficient of the double interaction term basically fluctuated around 0 which was not significant, and the trend of the treatment group and control group is consistent. After 2012, the marginal effect line rapidly inclines to the upper right, and the impact effect shows an increasing trend, which indicates that the smart city pilot policy has a significant positive impact on the low-carbon economy, and the impact effect is becoming stronger and stronger.

4.4.3. Changing the Window Width Test. We try to change the window width before and after the SCP to test the different results spanning different periods. At the same time, this method also could help us to know about how the sensitivity of smart city construction to time changes. Specifically, this paper uses the pilot time of SCP in 2012 as the time node and chooses 1 year, 2 years, 3 years, 4 years, and 5 years as window width to carry out logical regression, respectively. The coefficients added to the logic regression have not changed significantly, so the results are robust, and the regression results are shown in Table 6. It can be seen from Table 7 that the system estimated in different time window widths is still significantly positive, indicating that SCP has promoted the development of low-carbon economy. Then, with the increase of the width of the window, the coefficient decreases, indicating that the low-carbon

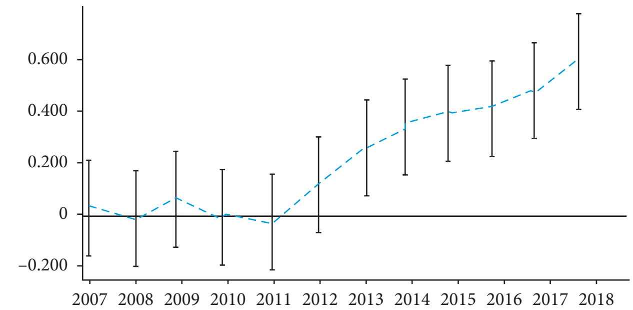

Figure 6: Dynamic effects of SCP on LCE in China.

economic development is not significant before the implementation of SCP.

4.5. Heterogeneity Analysis. In order to measure and understand the heterogeneity of SCP for LCE, we will analyze the heterogeneity of sample data from three aspects. And, these three aspects are the heterogeneity of the geographical location, the heterogeneity of urban population size, and the heterogeneity of environmental regulation.

Firstly, there are great differences in the level of economic development in China, which is reflected in geographical locations, and economic development levels in different regions lead to differences in smart city development strategies. Therefore, this study will separately discuss the impact of SCP in different regions on low-carbon economy, and we divide the sample in different regional categories: (1) cities are classified as the eastern, central, and western regions, while the level of economic development is the best in the eastern region, followed by the central region and the worst in the western region. (2) Cities are divided into coastal cities and noncoastal cities, and the former have better economic development than the latter.

Secondly, we group cities according to the size of cities. According to the notice of the State Council of the People's Republic of China on adjusting the standard of city size classification, we divide the samples into three categories: small-, medium-, and large-scale cities. Finally, they are classified by whether the strict degree of environmental protection regulation and planning are implemented. Referring to the information of China Environmental Yearbook, municipal governments, provincial capitals, core tourist cities, and coastal open cities are the key cities of environmental protection, with strict environmental protection planning (KEP). These cities are the key cities to control and prevent carbon emissions. Other cities are non-KEP.

The estimates are summarized in Tables 6 and 8. The coefficients of du × dt are positively associated with LCE across different groups, indicating that the SCP can also effectively improve LCE by considering regional heterogeneity. From Table 7, we can see that the impact of SCP on LCE is weaker in eastern regions with the better economic development level than in central and western regions with the lower economic development level. Meanwhile, the influence of noncoastal cities is stronger than that of coastal

Table 6: Effect of the SCP on the LCE: geographical heterogeneity.

Variable	(1) Eastern	(2) Central	(3) Western	(4) Coastal	(5) Noncoastal
du × dt	0.0339* (1.3209)	0.0517*** (3.2085)	0.0545*** (1.8869)	0.0393* (1.0062)	0.0484*** (2.0694)
Innov	0.0122* (3.2872)	0.0338** (3.2296)	0.0397*** (2.4017)	0.0115* (1.0205)	0.0351** (1.6914)
Indus	0.0298** (3.4128)	0.0315** (2.8266)	0.0335** (3.7961)	0.0147** (1.0834)	0.0288** (1.5501)
GScale	−0.0688* (−1.3040)	−0.5027* (−1.5834)	−0.0379* (−1.2582)	−0.0307* (−1.3798)	−0.0352* (−1.5021)
Open	−0.0854** (−1.3292)	−0.0912** (−1.8041)	−0.0908** (−1.3377)	−0.0811* (−0.5896)	−0.0917* (−1.2449)
Infra	0.0022* (1.9073)	0.0069* (1.6502)	0.0051* (0.9785)	0.0033* (0.8115)	0.0035* (1.8341)
Size	−0.0202* (−1.2869)	−0.0255* (−1.1967)	−0.0354* (−0.5802)	−0.0229* (−1.9003)	−0.0207* (−1.5417)
Fin	0.0056* (1.3308)	0.0063* (1.8596)	0.0082* (1.5507)	0.0058* (1.3939)	0.0064* (1.2804)
Human	0.0102*** (1.0824)	0.0259*** (1.1037)	0.0398*** (0.8597)	0.0104*** (1.0201)	0.0357*** (1.3970)
Pgdp	0.0122*** (1.3025)	0.0159*** (1.2887)	0.0308*** (1.5697)	0.0128*** (1.1214)	0.0207*** (1.4590)
Constant	0.4697*** (23.332)	0.4855*** (39.578)	0.4704*** (41.056)	0.4983*** (33.978)	0.4782*** (26.308)
Observations	1540	1330	350	1204	2016
R-squared	0.0997	0.0798	0.0115	0.0712	0.0873

Notes: (1) robust t-statistics in parentheses; (2) $^{***}p < 0.01$, $^{**}p < 0.05$, and $^{*}p < 0.1$.

Table 7: Regression results for changing time window width.

Variables	$T1$ 2011–2013	$T2$ 2010–2013	$T3$ 2009–2015	$T4$ 2008–2016	$T5$ 2007–2017
du × dt	0.0607*** (4.1213	0.0598*** (5.0227)	0.0575*** (5.4094)	0.0492*** (5.8730)	0.0446*** (5.0024)
Innov	0.0258*** (4.3671)	0.0249*** (9.3471)	0.0289*** (5.2296)	0.0357*** (4.0024)	0.0387*** (5.3182)
Indus	0.0362*** (3.5174)	0.0058** (6.6502)	0.0044** (5.5735)	0.0019* (2.2064)	0.0013** (2.1730)
GScale	−0.0703** (−1.2409)	−0.0058* (−3.220)	−0.0003* (−15.20)	−0.0001 (−22.36)	−0.0069* (−2.361)
Open	−0.0795* (−1.0226)	−0.0965* (−0.8564)	−0.0897* (−0.3028)	−0.0402* (−0.1514)	−0.0854* (−0.3075)
Infra	0.0013* (1.4534)	0.0009* (2.2208)	0.0022* (5.2094)	0.0008 (10.021)	0.0003 (15.026)
Size	−0.0185* (−1.2230)	−0.0231* (−1.9632)	−0.0556* (−3.0294)	−0.0482* (−2.958)	−0.0703* (−1.1543)
Fin	0.0037* (1.6654)	0.0008 (4.0302)	0.0054* (1.9064)	0.0026 (4.5236)	0.0094* (3.5294)
Human	0.0472*** (1.6053)	0.0563*** (2.0301)	0.0798** (11.025)	0.0013* (3.2093)	0.0634** (5.9210)
Pgdp	0.0096*** (1.9879)	0.0088*** (2.1543)	0.0075*** (3.0225)	0.0049*** (0.0364)	0.0027*** (2.2052)
Constant	0.9665 (11.927)	0.4702*** (9.326)	0.4885*** (8.110)	0.4926*** (14.038)	0.4804*** (15.602)
R-squared	0.9631	0.9867	1.1460	1.5523	1.6942

Notes: (1) robust t-statistics in parentheses; (2) $^{***}p < 0.01$, $^{**}p < 0.05$, and $^{*}p < 0.1$.

Table 8: Effect of the SCP on the low-carbon economy: heterogeneity.

Variable	(3) Small	(4) Medium	(5) Large	(6) KEP	(7) Non-KEP
du × dt	0.0409* (1.9102)	0.0168 (1.0254)	0.0499*** (3.0459)	0.0231 (1.0021)	0.0473*** (3.6004)
Innov	0.0305*** (2.4017)	0.0018** (1.0205)	0.0306*** (3.6914)	0.0258*** (3.0214)	0.0296*** (2.8551)
Indus	0.0801*** (3.7961)	0.0025** (1.0834)	0.0357*** (3.9306)	0.0121*** (3.5023)	0.0163*** (3.9013)
GScale	−0.0250** (−1.0609)	−0.0353** (−1.4170)	−0.0987** (−1.3552)	−0.0550** (−1.1213)	−0.0998** (−2.0231)
Open	−0.0963** (−1.4701)	−0.0823* (−0.9173)	−0.0905* (−1.3860)	−0.0955* (−1.1402)	−0.0983* (−1.1913)
Infra	0.0099* (0.9021)	0.0012* (0.8832)	0.0020* (1.9069)	0.0085* (0.9092)	0.0091* (0.9991)
Size	−0.0322* (−0.9916)	−0.0278* (−1.4470)	−0.0299* (−1.0930)	−0.0210* (−1.1105)	−0.0204* (−1.0497)
Fin	0.0096* (1.2037)	0.0028* (1.5046)	0.0075* (1.7853)	0.0032* (1.4607)	0.0091* (1.7741)
Human	0.0332*** (0.9996)	0.0101*** (1.0286)	0.0366*** (1.4352)	0.0204*** (1.2520)	0.0308*** (1.4931)
Pgdp	0.0235*** (1.5861)	0.0140*** (1.0032)	0.0101*** (1.4970)	0.0123*** (1.5021)	0.0107*** (1.3248)
Constant	0.4921*** (43.597)	0.5384*** (34.112)	0.5209*** (28.225)	0.3705*** (19.402)	0.5541*** (14.086)
Observations	644	1064	1512	1932	1288
R-squared	0.2062	0.1990	0.0923	0.2605	1.0833

Notes: (1) robust t-statistics in parentheses; (2) $^{***}p < 0.01$, $^{**}p < 0.05$, and $^{*}p < 0.1$.

areas. The possible reason for this difference is that, in cities with the high economic development level, the supporting information facilities' hardware and software are already very mature, such as Internet of Things, big data, artificial intelligence, 5G, and other technologies, and the low-carbon economic operation of these cities is in a high position even without SCP, so SCP is just the icing on the cake. For cities with weak economic development, their formalization foundation is weak, but they have the unique advantage of SCP overall planning and promotion. Through the systematic layout of cities, they can promote their economic growth, while reducing carbon emissions, thus improving LCE performance. Therefore, the SCP in the central and western regions and noncoastal cities with scarce resources and underdeveloped economy may obtain higher marginal contribution to LCE.

As shown in Table 8, comparing to cities with KEP, non-KEP cities have better positive impacts. While comparing to small- and medium-size cities, SCP has more significant impact on large-scale cities. The possible reason is that cities with KEP have achieved certain results in low-carbon operation through strict policy control, while SCP may have diminishing marginal effects. However, for those non-KEP cities, the implementation of SCP policy is a new external force, which will stimulate industrial upgrading, structural optimization, and urban innovation in these cities and play an indispensable and significant role in promoting LCE. In addition, the problem of energy efficiency in large cities leads to excessive carbon emissions, which is more prominent. Therefore, the role of SCP in reducing carbon emissions by balancing energy supply and demand may be more significant. Furthermore, the economic agglomeration effect of big cities may make SCP exert better impact.

5. Conclusions and Policy Implications

At present, the academic research on smart city mainly focuses on the concept and theory, and there is little research on the influence of SCP on LCE. Existing literature points out that smart cities can optimize the industrial structure, promote urban innovation, and optimize resource allocation which may facilitate the urban LCE. Based on the sample data of 230 cities in China from 2005 to 2018, this paper empirically tests the influence of SCP on LEC by using the DID method and enhances the credibility of the conclusion through the robustness test. And, the research results are as follows: firstly, SCP can significantly improve the LCE performance of cities. Compared with nonpilot cities, SCP pilot cities can increase the LCE performance of cities by about 4.5–5%. Meanwhile, through the analysis of parallel trend hypothesis test and dynamic effect, we can know that, with the deduction of SCP pilot over time, its positive influence on LCE is more and more obvious, and its effect shows a dynamic increasing trend. Secondly, the influence of SCP on LCE is heterogeneous. In China, the LCE of SCP has increased by about 3.4% in the eastern region, while it has increased by more than 5% in the central and western regions, which shows that its positive effect is more significant in the central and western regions than in the eastern regions. Similarly, the LCE of noncoastal cities has increased by 4.8%, which is 0.91% better than that of coastal cities. In addition, the impact on non-KEP cities is more significant than that of KEP cities, and the impact on large cities is more significant than that of small- and medium-sized cities.

Based on the above conclusions, this paper proposes that the construction of smart cities should be based on the characteristics of different regions and explores strategies to promote local LCE performance according to local conditions. Specific recommendations are as follows: based on the advantages of excellent development foundation, environmental protection policy, and good business environment, cities in eastern and coastal areas can integrate with traditional industries and promote the diffusion of the digital low-carbon sharing business model through the digital infrastructure of smart cities in strategic planning, so as to realize the nonlinear feature of increasing marginal effect of smart cities on local LCE and even high-quality economic development. The cities in the central region are adjacent to the eastern region, which has the geographical advantage of further developing LCE. In order to better play the role of SCP, we should actively attract outstanding talents and promote the upgrading and transformation of traditional industries. At the same time, the government should actively learn from the experience of advanced regions, strengthen the shaping of sustainable business environment, and build a knowledge sharing system. Affected by topography and location, the western region is relatively backward in economic development, and the advantages of natural resources have not been brought into full play. Then, driven by the dual policies of SCP and western development, we should actively conceive how to better develop and utilize local new energy sources, such as solar energy and wind energy, and devote ourselves to cultivating characteristic new energy development centers, attracting more social capital and technical resources, and promoting the development of regional LCE.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

The Overseas Experience of Audit Committee and Audit Fees: Empirical Evidence from China

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The complexity of audit committee experience, including the overseas experience, has an important impact on corporate governance. In this paper, we study the impact of the overseas experiences of the members of audit committee on audit fees. Our empirical analysis and results show that the audit committee overseas experience can significantly increase audit fees. Further, the positive influence of the audit committee overseas experience on audit fees is more pronounced in state-owned enterprises and regions with weak marketization. In addition, we divide the overseas experience into overseas learning experience and overseas working experience. We find that both types of experience present in the audit committee significantly increase the audit fees. Finally, we find that the audit committee overseas experience can significantly improve the quality of accounting information and play a positive role in corporate governance.

1. Introduction

Since the reform and opening-up, China has made remarkable progresses in its economic and social development, which are inseparable from the advanced technologies and management experience from a large number of overseas returnees. The *2018 Statistical Bulletin of Human Resources and Social Security Development* issued by the Ministry of Human Resources and Social Security showed that about 3.65 million Chinese have chosen to return to China to start their careers between 1978 (the year of reform and opening-up) to the end of 2018 [1]. With more and more overseas talents returning to China, the influence of returnees on China's macroeconomy and microenterprise behavior has been studied extensively in the literature [2, 3].

The complex experience of executives affects their values, knowledge structure, management philosophy, and social relations, which influence the decision-making and development of enterprises [4]. Overseas experience is an important type of experience for executives. It is generally believed that returnees who have received more systematic and all-round professional education are more familiar with the latest technologies and have richer management experience, better international vision, and wider relational network [5, 6]. China's governments have been actively developing preferential policies to attract returnees. It has been shown that returned executives can facilitate enterprise innovation [7], improve total factor productivity [8], and improve investment efficiency [9, 10], which reflect the knowledge accumulation effect of their overseas experience. Secondly, having studied and worked abroad for a period of time, returnees may have developed fixed ways of thinking under the influence of the overseas institutional and cultural environment. They possess ideas and perceptions relatively consistent with those in foreign countries after returning to China. For example, the existing literature has indicated that returned executives influenced by the individualism thinking of Western countries show greater awareness in risk taking and supervision [11, 12].

The audit committee plays a vital role in corporate governance. Specifically, it is mainly responsible for supervising financial reporting and internal control, hiring external audit, and bargaining the audit fees. The committee members' characteristics will affect the committee governance. Usually, the returnees have the greater governance and supervision awareness than domestic talents [4]. Will the overseas experience of an audit committee affect the demand of listed firms for the external audit and the audit fees? Currently, whether the audit committee overseas experience affects the committee governance function has not been directly studied in the literature. To address this research gap, in this paper, the governance effect of the audit committee overseas experience is studied from the perspective of audit fees. Theoretically, from the view of audit demand, the audit committee overseas experience indicates stronger awareness of audit supervision and corporate governance and relates to audit demand positively [13]. This can increase the audit fees [14]. This paper verifies the conjecture through an empirical study.

Our empirical analysis and results lead to the following major findings. First, audit committee overseas experience is significantly and positively correlated with the audit fees. Second, compared with the nonstate-owned enterprises, the state-owned ones have more pronounced positive correlation between the audit committee overseas experience and the audit fees. Third, compared with regions with high marketization degree, regions with low marketization degree have more significant positive correlation between the audit committee overseas experience and audit fees. Fourth, if the overseas experience is divided into the overseas learning experience and the overseas working experience, we find that the audit committee overseas learning experience and overseas working experience both can significantly lead to the higher audit fees. Lastly, we find that the audit committee overseas experience can significantly reduce earnings management and improve accounting information transparency.

This paper makes the following two major contributions. Firstly, the existing literature mainly focuses on the influence of the audit committee independence, financial expertise, gender composition, participation degree, and other characteristics on the governance effect of audit committee. There is a lack of research on the influence of audit committee overseas experience on the governance effect of audit committee. This paper fills this research gap. Secondly, existing studies indicate that enterprises with globalizing board and overseas experience of executives are more inclined to choose "Big 4." Different from previous studies, this paper focuses on the audit committee, a subject which can directly affect auditor choice and audit fees. Hence, our research can enrich the literature on the influencing factors of audit fees.

The remainder of this paper is organized as follows. Section 2 reviews related research. Section 3 develops our hypothesis based on theoretical analysis. Section 4 describes the basic research design, including data source, sample description, model design, and variable definition. Section 5 discusses the empirical findings from our empirical analysis and robustness test. Section 6 concludes the study and puts forward the policy insights.

2. Literature Review

2.1. Literature on Audit Committee Governance. The first one is the influence of the audit committee's financial expertise on the governance effect of audit committee. The *Detailed Implementing Rules of the Audit Committee of the Board of Directors* prepared by China Securities Regulatory Commission in 2002 pointed out that the audit committee should include at least one independent director who is an accounting professional to ensure the presence of financial and accounting expertise [15]. It is generally acknowledged that the larger the number of accounting professionals is, the stronger the financial expertise becomes in the audit committee and the better the governance effect of audit committee is. Most studies found that the audit committee's financial expertise can reduce the probability of financial restatement [16, 17], radical earnings management behavior [18], and internal control defects [19]. It can also increase the audit fees [20]. In addition, from the perspective of outside investors, several studies found that the capital market has a positive reaction when the audit committee hires accounting experts [21, 22], and the audit committee's accounting expertise can improve the stock liquidity and turnover [23], while the capital market will face a negative reaction when accounting experts leave the audit committee [24].

The second one is the influence of audit committee independence on the governance effect of audit committee. The *Detailed Implementing Rules of the Audit Committee of the Board of Directors* pointed out that the audit committee shall be formed with 3–7 directors, a majority of whom should be independent directors, so as to keep the audit committee highly independent [15]. In the absence of direct economic and emotional connection between independent directors and management, the weak supervision caused by the intimate relationship will be blocked [25]. Most of the existing studies have found that the audit committee independence can improve its governance effect. For example, in the presence of stronger audit committee independence, there will be higher earning quality [26], lower occurrence of radical earnings management [18], higher internal control quality [19], lower probability of financial restatement [16], lower probability of financial fraud [27], and higher audit fees [28–30]. The influence of the audit committee independence on the governance effect has also been studied in several studies from the view of the remuneration structure of the committee members [31–33] and the "revolving door" of the committee members [34].

The third one is the influence of the audit committee diligence on the governance effect of audit committee. Since independent directors often work in different listed companies and therefore take it as a part-time job, the committee members' diligence will affect the function of supervision. For example, several existing studies have found that the audit committee diligence is positively correlated to the audit fees [35]. And, it can reduce the probability of financial restatement [16], the radical earnings management [18], and the financial fraud [27].

2.2. Positive Effect of Returnees as Executives. The returning of overseas can significantly improve the economic development speed of developing countries [2]. The existing studies mainly focus on the vital function of returnees as executives and CEO in the enterprise development, involved in the knowledge accumulation effect and governance effect of overseas experience. As for the knowledge accumulation effect, the existing studies found that the returned executives can bring the advanced management experience and knowledge [4], which mainly come from the international vision and the management ability of returnees [3]. It facilitates the enterprise innovation input [8, 11] and improves the companies' total factor productivity [10] and the investment efficiency [9]. On the contrary, overseas experience can form a unique overseas social network, which can help returnees obtain more information and capital advantages [36]. In terms of the governance effect, several studies found that the overseas experience of CEO can reduce the listed companies' earnings management [12] and that the overseas experience of executives can improve the awareness of the listed companies to fulfill their social responsibilities [37], promote the internal salary gap [36], enhance the internal control quality [38], improve the corporate governance [4], and intend to choose "Big 4" for audit [39].

2.3. Our Contributions. In conclusion, the existing studies in the literature mainly focus on the influence of the audit committee characteristics on its governance effect. These characteristics include audit committee's financial expertise, audit committee independence, audit committee diligence, committee members' gender, and audit committee scale, while the governance effect includes earnings quality, internal control quality, information disclosure, and auditor choice. However, there is a lack of research on the influence of the overseas experience of an audit committee on its governance effect. Starting from the perspective of overseas experience, this paper further studies the governance effect of audit committee, so as to enrich the literature about audit committee governance. Secondly, the existing literature mainly studies the influence of individual overseas experience on the corporate behavior from the perspective of executives and CEO, while there is little research taking the audit committee as the main body to study the influence of overseas experience on the corporate governance. Therefore, this study can also enrich the literature about the influence of individual overseas experience on the corporate behavior.

3. Theoretical Analysis and Hypothesis

Complexity represents a state in which many factors interact [40]. The complex experiences of executives form their personal characteristics, which affect the development of enterprises. The complex experiences of executives include academic experience, political experience, professional experience, and overseas experience. There are studies on the impact of single experience on corporate governance, enterprise innovation, and enterprise performance. According to complexity theory, complex systems have the characteristics of auto-organization [41]. Executives' single experience can spontaneously form an orderly state to adapt to the environment and promote the development of enterprises. The audit committee is an integral part of the company's management, which plays an active role in supervision and governance. The overseas experience is one aspect of complex experience, which affects the governance effect of audit committee.

This paper takes audit fees as the representative of corporate governance effect. Audit fees reflect the audit supervision demand of management. The higher the demand of management audit supervision is, the higher the audit fees charge is and the better the corporate governance effect is [14]. According to the literature, the factors influencing audit fees consist of the auditee's size, the auditee's business complexity, the financial risk, the business risk, the accounting information transparency, and the corporate governance level [42–46]. According to the *Rules for Governance of Listed Companies, the Detailed Implementing Rules of the Audit Committee of the Board of Directors, and the Basic Specifications for Internal Control of Enterprises* [15, 47, 48], audit committee is responsible for the selection of auditors of listed companies, and audit fees should be determined on the basis of consultation between audit committee and external auditors. Specifically, the audit committee should discuss the audit scope, audit plan, and other contents with external auditors to determine the audit fees. Therefore, the committee members' characteristics will affect the behavior of the audit committee and then the audit fees.

Based on the audit demand view, the returnees in the audit committee have stronger motivation and ability to participate in the governance, so there is higher demand for high-quality audit [13]. It is well known that the legal system in many developed countries and regions is more comprehensive, and the stricter legal system can better constrain individual behaviors, so individuals can better develop a habit of observing laws and disciplines. Secondly, different from China, many developed countries and regions have the capital markets under "strong supervision." In case of financial fraud, the listed companies and accounting firms will suffer from huge compensation and class action [49]. On the contrary, China's weak legal system, defective regulatory environment, and slight punishment may lead to prevailing financial fraud of listed companies. Based on the cognitive imprinting theory [50], returnees are more likely to maintain the ideas and behaviors formed overseas after returning to their homeland, to become more self-disciplined and other-disciplined. Therefore, when joining the audit committee of listed companies, returnees will bring this awareness and concept to the audit committee in addition to maintaining their consistent behavioral criteria and then affect the awareness and behavior of other committee members, so as to consolidate the supervision function of the whole committee [12]. Meanwhile, having received the systematic and cutting-edge accounting and audit knowledge education abroad, these returnees will have the greater supervision ability [4]. Based on the above analysis, with higher demand for high-quality audit, audit committee is inclined to hire high-quality auditors and require external auditors to invest more time and energy, resulting in higher audit fees. From the analysis mentioned above, this article puts forward the following research hypothesis to be tested:

Hypothesis 1. The audit committee overseas experience is positively correlated to the audit fees.

According to the theory of property right, the property right state is an important factor influencing the corporate governance. The state-owned enterprises' property rights are ultimately attributable to all Chinese citizens. As an agent, SASAC is responsible for supervising managers of state-owned enterprises, and the unclear property rights often cause the owners' supervision absence, the stronger opportunistic motives of managers, and more serious agency problem in the state-owned enterprises [51]. The returned executives are more likely to choose the international "Big 4" firms for audit in case of relatively serious agency problem, which means that the listed companies have higher demand for high-quality audit [13]. In addition, low-quality auditors may easily compromise with state-owned enterprises. The returnees have a strong sense of the legal system and are less likely to conspire with auditors [52]. In that way, in the state-owned enterprises, in the absence of the owners' supervision, it can be reasonably expected that the audit committee overseas experience has the higher demand for high-quality audit, and this committee will require auditors to put more time and energy in work so that the audit fees are higher. Based on this, this paper puts forward the following research hypothesis to be tested.

Hypothesis 2. Compared with nonstate-owned enterprises, the audit committee overseas experience of state-owned enterprises has more significant influence on the increase of audit fees.

China is a vast country with different levels of regional economic development and institutional environment. The regions with high marketization often have more developed economy, better business climate, less government intervention, more equal judicial system, and stricter regulatory environment than those with low marketization. In the regions with higher marketization, the financial fraud of listed companies can be found and exposed more easily. Once the fraud is exposed, the management and governance layer of the listed companies will be more easily punished by the regulators [53]. Based on the cognitive imprinting theory [50], the returnees' ideas and cognition formed abroad are often entrenched and stable for a long time. Therefore, the returnees in the audit committee are less affected by the external environment of the marketization process in China. With higher demand for high-quality audit, these returnees of the audit committee will pay high attention to the corporate governance and supervision regardless of the external marketization process. Conversely, if all the members of the audit committee are domestic talents, they will be affected by the external regulatory environment easily. They actively participate in the corporate governance in the regions with higher marketization process, while they have lower motivation to participate in corporate governance in the regions with the weak marketization process. Based on the above analysis, this paper puts forward the following research hypothesis to be tested.

Hypothesis 3. Compared with the regions with the high marketization process, the positive correlation between the audit committee overseas experience and the audit fees is more significant in the regions with the weak marketization process.

4. Study Design

4.1. Sample Selection and Data Sources. Our sample comprises *A*-share companies listed on the Shanghai and Shenzhen Stock Exchanges from 2007 to 2018 in China. Consistent with the literature, we remove any samples with missing value. Additionally, we winsorize any quantiles with continuous variables above and below 1%. As a result, 17,241 samples are obtained. The data of audit committee members come from CSMAR (CSMAR is the abbreviation of China Stock Market Accounting Research.). In order to include more samples in the empirical analysis (since several studies are based on the information of audit committee members disclosed in their resumption reports, the number of samples is reduced significantly. To minimize the sample selection problem, the information of audit committee members of the companies in the year are sorted out manually and determined based on the time of assumption of duty and the time of leaving the post of executives in CSMAR), we use the information about the appointment and departure time of audit committee members from CSMAR to judge the names of audit committee members. These names are matched with the individual characteristic data of executives in CSMAR, and the variable of audit committee overseas experience (OVERSEA) is obtained. The variable of accounting firm change (CHANGE) is obtained manually after excluding merges and renaming. The other financial indexes in this study are from CSMAR.

4.2. Model Design and Variable Definition

4.2.1. Model Design. To test the influence of audit committee overseas experience on audit fees, this paper sets the following model:

$$\begin{aligned}\text{FEES} = {} & \beta_0 + \beta_1\text{OVERSEA}\,(\text{OVERSEA\_ratio}) + \beta_2\text{SIZE} + \beta_3\text{LEV} + \beta_4\text{ROA} + \beta_5\text{REC} + \beta_6\text{INV} \\ & + \beta_7\text{SHARE1} + \beta_8\text{INDEP} + \beta_9\text{SEGMENT} + \beta_{10}\text{STATE} + \beta_{11}\text{BIG4} + \beta_{12}\text{CHANGE} + \beta_{13}\text{OPINION} + \text{YEAR} + \text{IND} + \varepsilon. \end{aligned} \tag{1}$$

In order to test Hypothesis 2, two interaction terms have been designed in this paper. One is the interaction term (STATE × OVERSEA) between the property right state (STATE) and the audit committee overseas experience (OVERSEA), and the other is the interaction term (STATE × OVERSEA_ratio) between the property right state (STATE) and the audit committee overseas experience ratio (OVERSEA_ratio). The specific model is as follows:

$$\begin{aligned}\text{FEES} = {} & \beta_0 + \beta_1\text{OVERSEA}\,(\text{OVERSEA\_ratio}) + \beta_2\text{STATE} \times \text{OVERSEA}\,(\text{STATE} \times \text{OVERSEA\_ratio}) + \beta_3\text{SIZE} + \beta_4\text{LEV} + \beta_5\text{ROA} \\ & + \beta_6\text{REC} + \beta_7\text{INV} + \beta_8\text{SHARE1} + \beta_9\text{INDEP} + \beta_{10}\text{SEGMENT} + \beta_{11}\text{STATE} + \beta_{12}\text{BIG4} + \beta_{13}\text{CHANGE} + \beta_{14}\text{OPINION} \\ & + \text{YEAR} + \text{IND} + \varepsilon. \end{aligned} \tag{2}$$

In order to test Hypothesis 3, two interaction terms have been designed in the study. One is the interaction term (MAR × OVERSEA) between the marketization process (MAR) and the audit committee overseas experience (OVERSEA), and the other is the interaction term (MAR × OVERSEA_ratio) between the marketization process (MAR) and the audit committee overseas experience ratio (OVERSEA_ratio). Based on the interaction terms, this paper constructs the following model:

$$\begin{aligned}\text{FEES} = {} & \beta_0 + \beta_1\text{OVERSEA}\,(\text{OVERSEA\_ratio}) + \beta_2\text{MAR} \times \text{OVERSEA}\,(\text{MAR} \times \text{OVERSEA\_ratio}) + \beta_3\text{MAR} \\ & + \beta_4\text{SIZE} + \beta_5\text{LEV} + \beta_6\text{ROA} + \beta_7\text{REC} + \beta_8\text{INV} + \beta_9\text{SHARE1} + \beta_{10}\text{INDEP} + \beta_{11}\text{SEGMENT} + \beta_{12}\text{STATE} \\ & + \beta_{13}\text{BIG4} + \beta_{14}\text{CHANGE} + \beta_{15}\text{OPINION} + \text{YEAR} + \text{IND} + \varepsilon. \end{aligned} \tag{3}$$

4.2.2. Variable Definition. The specific definitions of the variables in the models are as follows.

(1) Explained Variable. In this paper, the explained variable is the audit fees (FEES). FEES is expressed by the natural logarithm of audit fees.

(2) Explaining Variable. In this paper, the dummy and continuous variables are used to measure the audit committee overseas experience characteristic. The first variable is the audit committee overseas experience (OVERSEA). The audit committee of China's listed companies usually consists of three to seven members. If at least one of the members has overseas experience, then OVERSEA = 1; otherwise, OVERSEA = 0. The second variable is the audit committee overseas experience ratio (OVERSEA_ratio). OVERSEA_ratio means the ratio of audit committee members with overseas experience. We also consider the moderate effect of the property right state and marketization process. The property right state (STATE) is a dummy variable. When the enterprise is state-owned, STATE is 1; otherwise, STATE is 0. Wang et al. [54] published the *2017 Marketization Index of China*. We use the index to measure the marketization process.

(3) Control Variable. Following the literature, the control variables in this paper include company size (SIZE), leverage (LEV), return on assets (ROA), receivables ratio (REC), inventory ratio (INV), share ratio of the largest shareholder (SHARE1), the ratio of the independent director (INDEP), the number of segments (SEGMENT), the property right state (STATE), the international big 4 firms or not (BIG4), the accounting firm change (CHANGE), audit opinion type (OPINION), the year (YEAR), and the industry (IND). The definitions of the main variables in this paper are shown in Table 1.

5. Empirical Results and Data Analysis

5.1. Descriptive Statistics. The descriptive statistical results of the variables are presented in Table 2. As shown in the table, the mean of audit committee overseas experience (OVERSEA) is 0.293, which indicates that the number of audit committee members with overseas experience accounts for 29.3% in China's *A*-share listed companies, and it maintains an upward trend year by year, which means that it is becoming more and more common for returnees to join the governance layer of listed companies in China. The mean of audit committee overseas experience ratio (OVERSEA_ratio) is 0.104, and the number of audit committee members with overseas experience accounts for 10.4% in average, which indicates that the audit committee overseas experience ratio is relatively low and there is still space for improvement. The maximum and minimum of the marketization process are 10.62 and 2.88, respectively, which reflect that different enterprises are in different market environments. The mean of STATE is 0.389, which indicates that more than half of the enterprises' ultimate controllers are not state-owned. The descriptive statistical results of other variables are shown in Table 2.

5.2. Univariate Analysis. The univariate analysis results of main variables are presented in Table 3. Based on the criterion on whether the audit committee members have overseas experience, the samples are divided into two groups, and the statistics is made on the mean and median of

Table 1: Main definitions of variables.

Variable	Symbol	Variable description
Audit fees	FEES	Fees paid for audit service
Audit committee overseas experience	OVERSEA	If at least one of the members has overseas experience, OVERSEA is 1; otherwise, OVERSEA is 0
Audit committee overseas experience ratio	OVERSEA_ratio	Audit committee members with overseas experience/total audit committee members
Marketization process	MAR	Marketization index of China
Property right state	STATE	Dummy variable: STATE = 1 for state-owned enterprise; STATE = 0 for nonstate-owned enterprise
Company size	SIZE	Natural logarithm of total assets
Leverage	LEV	Liabilities/total assets
Return on assets	ROA	Net profit/total assets
Receivables ratio	REC	Receivables/total assets
Inventory ratio	INV	Inventory/total assets
Share ratio of the largest Shareholder	SHARE1	Share ratio of the largest shareholder
Ratio of the independent Directors	INDEP	Ratio of independent directors to the total number of directors
Number of segments	SEGMENT	Natural logarithm of the number of segments
Big 4	BIG4	If the listed company is audited by international big 4 firms, BIG4 is 1; otherwise, BIG4 is 0
Auditor change	CHANGE	Dummy variable: in case of auditor change, CHANGE is 1; otherwise, CHANGE is 0
Audit opinion	OPINION	Dummy variable: if the current audit opinion is modified, OPINION is 1; otherwise, OPINION is 0
Year	YEAR	
Industry	IND	

Table 2: Descriptive statistics.

Variable	Sample size	Mean	Standard deviation	Minimum	Median	Maximum
FEES	17241	13.530	0.589	12.430	13.460	15.310
OVERSEA	17241	0.293	0.455	0	0	1
OVERSEA_ratio	17241	0.104	0.177	0	0	0.667
MAR	17241	7.903	1.831	2.880	8.080	10.62
SIZE	17241	22.040	1.220	19.470	21.910	25.630
LEV	17241	0.445	0.212	0.055	0.439	0.943
ROA	17241	0.038	0.056	−0.201	0.035	0.196
REC	17241	0.112	0.102	0	0.087	0.459
INV	17241	0.157	0.150	0	0.117	0.748
SHARE1	17241	0.345	0.150	0.085	0.325	0.749
INDEP	17241	0.372	0.052	0.333	0.333	0.571
SEGMENT	17241	2.301	1.015	0	2.303	4.812
STATE	17241	0.389	0.487	0	0	1
BIG4	17241	0.041	0.198	0	0	1
CHANGE	17241	0.069	0.253	0	0	1
OPINION	17241	0.036	0.187	0	0	1

variables, respectively, for the mean test (T test) and median test (Z test). As shown in Table 3, the mean values of the audit fees in the audit committee overseas experience group (OVERSEA = 1) and the audit committee nonoverseas experience group (OVERSEA = 0) are 13.67 and 13.48, respectively. The results have shown that the audit fees of the listed companies with audit committee overseas experience are significantly higher than those of the listed companies with audit committee nonoverseas experience, which preliminarily supports Hypothesis 1. In addition, the listed companies with audit committee overseas experience tend to have the larger size, the higher share ratio of the largest shareholder, the larger number of segments, the lower probability of state-owned enterprises, the higher probability of employment of international Big 4 firms, and the lower probability of nonstandard audit opinions from auditors.

5.3. Correlation Coefficient Analysis. The correlation coefficient analysis of the main variables is presented in Tables 4 and 5. It indicates that the audit committee overseas experience

Table 3: Univariate analysis.

Variable	OVERSEA = 1		OVERSEA = 0		Mean test	Median test
	Mean	Median	Mean	Median	*T* value	*Z* value
FEES	13.67	13.57	13.48	13.40	−20.07***	−17.39***
OVERSEA	0	1	0	0		
OVERSEA_ratio	0.132	0.333	0	0		
MAR	8.178	8.640	7.790	7.880	−12.71***	−12.55***
SIZE	1.342	23.05	1.157	22.65	−13.23***	−10.95***
LEV	0.208	0.601	0.213	0.605	0.99	0.61
ROA	0.055	0.066	0.056	0.063	−5.38***	−6.18***
REC	0.101	0.168	0.103	0.167	−0.41	−1.03
INV	0.158	0.196	0.146	0.199	−0.91	1.88*
SHARE1	0.154	0.455	0.148	0.444	−2.51**	−1.82*
INDEP	0.052	0.400	0.052	0.429	0.44	0.26
SEGMENT	1.055	3.135	0.991	2.890	−12.46***	−11.86***
STATE	0.480	1	0.490	1	5.15***	5.15***
BIG4	0.271	0	0.154	0	−16.96***	−16.82***
CHANGE	0.258	0	0.251	0	−1.09	−1.09
OPINION	0.171	0	0.193	0	2.77***	2.77***
N (observed value)	5045	12196				

Table 4: Correlation coefficients (1).

	FEES	OVERSEA	OVERSEA_ratio	MAR	SIZE	LEV	ROA	REC
FEES	1							
OVERSEA	0.151***	1						
OVERSEA_ratio	0.158***	0.915***	1					
MAR	0.224***	0.096***	0.113***	1				
SIZE	0.700***	0.100***	0.097***	0.029***	1			
LEV	0.263***	−0.008	−0.014*	−0.158***	0.425***	1		
ROA	0.002	0.041***	0.045***	0.085***	0.018**	−0.366***	1	
REC	−0.042***	0.003	0.015**	0.183***	−0.167***	−0.042***	0.026***	1
INV	0.031***	0.007	0.009	−0.033***	0.114***	0.307***	−0.083***	−0.111***
SHARE1	0.097***	0.019**	0.019**	−0.011	0.206***	0.045***	0.121***	−0.091***
INDEP	0.018**	−0.003	0.008	0.028***	−0.004	−0.019**	−0.034***	0.025***
SEGMENT	0.589***	0.094***	0.105***	0.142***	0.564***	0.277***	0.000	−0.051***
STATE	0.059***	−0.039***	−0.057***	−0.228***	0.289***	0.266***	−0.087***	−0.198***
BIG4	0.332***	0.128***	0.149***	0.049***	0.266***	0.081***	0.049***	−0.064***
CHANGE	−0.011	0.008	0.006	−0.035***	0.009	0.039***	−0.038***	0.013
OPINION	−0.028***	−0.021***	−0.020***	−0.050***	−0.113***	0.180***	−0.264***	−0.028***

Note: ***, **, and * indicate significance at 0.01, 0.05, and 0.10 levels, respectively.

Table 5: Correlation coefficients (2).

	INV	SHARE1	INDEP	SEGMENT	STATE	BIG4	CHANGE	OPINION
INV	1							
SHARE1	0.069***	1						
INDEP	0.006	0.021***	1					
SEGMENT	0.132***	0.006	0.034***	1				
STATE	0.048***	0.214***	−0.081***	0.051***	1			
BIG4	−0.015*	0.124***	0.004	0.110***	0.093***	1		
CHANGE	−0.006	0.002	0.002	−0.007	0.042***	0.040***	1	
OPINION	−0.033***	−0.091***	0.018**	−0.052***	−0.029***	−0.026***	0.060***	1

Note: ***, **, and * indicate significance at 0.01, 0.05, and 0.10 levels, respectively.

(OVERSEA) and the audit committee overseas experience ratio (OVERSEA) are significantly and positively correlated to the audit fees (FEES) at the level of 1%. This means that the audit fees of listed companies with audit committee overseas experience is higher, and the larger the audit committee overseas experience ratio is, the higher the audit fees become.

5.4. Multiple Regression Analysis

5.4.1. Audit Committee Overseas Experience and Audit Fees. The regression results of model (1) are presented in Table 6. It shows that the audit committee overseas experience (OVERSEA) and the audit committee overseas experience ratio (OVERSEA_ratio) are significantly and positively correlated to the audit fees (FEES) at the level of 1%. This indicates that the audit committee overseas experience (OVERSEA) leads to significant increase in the audit fees when other factors are controlled. Further, the larger the audit committee overseas experience ratio (OVERSEA_ratio) is, the higher the audit fees become, which supports Hypothesis 1. As indicated, although the audit committee overseas experience can strengthen the corporate governance and reduce the audit risk faced by external auditors, the audit committee with overseas experience will have the higher demand for high-quality audit. It is more inclined to hire high-quality auditors and require them to put more time and energy in work so that the audit fees are increased. Then, the audit demand dominates. In addition, SIZE and SEGMENT are positively correlated with audit fees at the level of 1%, which indicates that audit cost is an important determinant of audit fees. BIG4 is positively correlated with audit fees at the level of 1%, which indicates that BIG4 charges premium fees. CHANGE is negatively correlated with audit fees at the level of 1%, mainly because of low balling.

Table 6: Audit committee overseas experience and audit fees.

	(1) FEES	(2) FEES
OVERSEA	0.0584***	
	(5.06)	
OVERSEA_ratio		0.1519***
		(5.03)
SIZE	0.2750***	0.2753***
	(35.17)	(35.25)
LEV	0.0179	0.0184
	(0.52)	(0.54)
ROA	−0.2099**	−0.2113**
	(−2.46)	(−2.48)
REC	0.1567**	0.1545**
	(2.42)	(2.39)
INV	−0.0825	−0.0840
	(−1.56)	(−1.59)
SHARE1	−0.0068	−0.0075
	(−0.16)	(−0.17)
INDEP	−0.0835	−0.0878
	(−0.85)	(−0.90)
SEGMENT	0.0066***	0.0066***
	(15.93)	(15.88)
STATE	−0.1068***	−0.1060***
	(−7.00)	(−6.94)
BIG4	0.5085***	0.5051***
	(13.30)	(13.14)
CHANGE	−0.0486***	−0.0483***
	(−4.08)	(−4.06)
OPINION	0.1286***	0.1283***
	(5.44)	(5.41)
YEAR	Control	Control
IND	Control	Control
Cons	7.2711***	7.2676***
	(43.27)	(43.30)
N	17241	17241
R^2 adjusted	0.610	0.610
F	173.2***	172.4***

Note: ***, **, and * indicate significance at 0.01, 0.05, and 0.10 levels, respectively. All t-statistics are adjusted for robust standard errors.

5.4.2. Audit Committee Overseas Experience, Property Right State, and Audit Fees. In this paper, we consider the moderate effect of the property right state. The study results of model (2) are presented in Table 7. As shown in the table, the interaction term (STATE × OVERSEA) and the interaction term (STATE × OVERSEA_ratio) coefficients are significantly positive at the level of 1%, which means that the audit committee overseas experience of state-owned enterprises has more significant influence on the increase of audit fees than that of nonstate-owned enterprises. Hypothesis 2 is supported.

5.4.3. Marketization Process, Audit Committee Overseas Experience, and Audit Fees. In this paper, we also consider the moderate effect of the marketization process. The study results of model (3) are presented in Table 8. As shown in the table, the interaction term (MAR × OVERSEA) and the interaction term (MAR × OVERSEA_ratio) coefficients are significantly negative at the level of 1%, which means that the audit committee overseas experience in the regions with the low marketization process has more significant influence on the increase of audit fees than that in the regions with the high marketization process. The results support Hypothesis 3.

5.5. Further Analysis

5.5.1. Audit Committee Overseas Working Experience vs. Learning Experience. The overseas experience of audit committee members can be divided into the overseas working experience and the overseas learning experience. Liu [36] showed that the overseas learning experience would have larger influence on the individual values and behavior pattern than the overseas working experience. This is mainly because the overseas learning experience brings the longer and deeper western culture experience to individuals than the overseas working experience, and since the individuals in the education stage have not formed the complete values and behavior patterns, the education and culture they are exposed to during this stage can be integrated more easily by their values than those during the working stage.

Therefore, in this paper, the variable of audit committee overseas experience (OVERSEA) has been further subdivided into three variables: the audit committee overseas learning experience (OVERSEA1), the audit committee overseas working experience (OVERSEA2), and the audit committee overseas learning and working experience (OVERSEA3). The audit committee overseas learning experience (OVERSEA1) is a dummy variable, and when the audit committee member only has the overseas learning

Table 7: Audit committee overseas experience, property right state, and audit fees.

	(1) FEES	(2) FEES
OVERSEA	0.0424***	
	(5.62)	
OVERSEA × STATE	0.0444***	
	(3.30)	
OVERSEA_ratio		0.1270***
		(6.76)
OVERSEA_ratio × STATE		0.0748**
		(2.04)
SIZE	0.2742***	0.2748***
	(73.47)	(73.64)
LEV	0.0192	0.0193
	(1.07)	(1.07)
ROA	−0.2096***	−0.2113***
	(−3.72)	(−3.74)
REC	0.1566***	0.1554***
	(4.82)	(4.79)
INV	−0.0854***	−0.0862***
	(−3.27)	(−3.29)
SHARE1	−0.0067	−0.0073
	(−0.33)	(−0.36)
INDEP	−0.0841	−0.0884*
	(−1.59)	(−1.67)
SEGMENT	0.0066***	0.0066***
	(31.44)	(31.24)
STATE	−0.1191***	−0.1131***
	(−15.84)	(−15.37)
BIG4	0.5060***	0.5027***
	(28.00)	(27.53)
CHANGE	−0.0486***	−0.0482***
	(−4.04)	(−4.01)
OPINION	0.1273***	0.1276***
	(7.73)	(7.73)
YEAR	Control	Control
IND	Control	Control
Cons	7.2918***	7.2804***
	(90.58)	(90.47)
N	17241	17241
R^2 adjusted	0.610	0.610
F	540.3	538.2

Note: ***, **, and * indicate significance at 0.01, 0.05, and 0.10 levels, respectively. All t-statistics are adjusted for robust standard errors.

experience, OVERSEA1 is 1; otherwise, OVERSEA1 is 0. The audit committee overseas working experience (OVERSEA2) is a dummy variable, and when the audit committee member only has the overseas working experience, OVERSEA2 is 1; otherwise, OVERSEA2 is 0. The audit committee overseas learning and working experience (OVERSEA3) is a dummy variable, and when the audit committee member both have the overseas learning and working experience, OVERSEA3 is 1; otherwise, OVERSEA3 is 0. The audit committee overseas experience (OVERSEA) in model (1) is replaced with OVERSEA1, OVERSEA2, and OVERSEA3. The regression is made for model (1), and the results are shown in Table 9. The results indicate that the coefficients of three variables of OVERSEA1, OVERSEA2, and OVERSEA3 are significantly positive, which means that the audit committee overseas working experience and the audit committee overseas learning experience both can significantly increase the audit fees. After the T test has been made to study the significant difference in the coefficients of three variables, OVERSEA1, OVERSEA2, and OVERSEA3, it has been found that there is no significant difference between OVERSEA1 and OVERSEA2. That means, in terms of the influence on the audit fees, there is no significant difference between overseas working experience and overseas learning experience, while the coefficient of OVERSEA3 is significantly greater than that of OVERSEA1 and OVERSEA2. It means that the richer the overseas experience of audit committee, the better the governance effect.

5.5.2. Economic Consequence: Earning Quality. The previous empirical studies found that the audit committee overseas experience can improve the audit committee's enthusiasm and ability to participate in corporate governance so that the external audit demand and audit fees are increased. Can the increasing demand for external audit caused by audit committee overseas experience improve the information transparency of listed companies? Based on the agent theory [55], the inconsistent interests between shareholders and management will cause the agency problems, while the shareholders' employment of external independent auditors for financial statement audit can restrain the earnings management for management supervision. As the audit committee overseas experience leads to increasing demand for external audit, the external audit will obviously play a more important role in the supervision to reduce the earnings management and improve the information transparency. On the basis of this, the correlation between the audit committee overseas experience and the earnings management (EM) (the calculation of earnings management (EM) refers to the method adopted in Dechow and Dichev [26]) has been studied in this paper. We construct model (4) for multiple linear regression, and the multiple linear regression results are shown in Table 10. The coefficients of the audit committee overseas experience (OVERSEA) and the audit committee overseas experience ratio (OVERSEA_ratio) are significantly negative at the levels of 1% and 5%. The audit committee overseas experience can reduce the earnings management and improve the information transparency:

$$\begin{aligned}\mathrm{EM} = {} & \alpha_0 + \alpha_1\mathrm{OVERSEA} + \alpha_2\mathrm{SIZE} + \alpha_3\mathrm{LEV} + \alpha_4\mathrm{ROA} + \alpha_5\mathrm{REC} + \alpha_6\mathrm{INV} + \alpha_7\mathrm{GROWTH} \\ & \alpha_8\mathrm{SHARE1} + \alpha_9\mathrm{INDEP} + \alpha_{10}\mathrm{STATE} + \alpha_{11}\mathrm{HOLD} + \frac{\alpha_{12}B}{M} + \alpha_{13}\mathrm{BIG4} + \mathrm{YEAR} + \mathrm{IND} + \varepsilon.\end{aligned} \tag{4}$$

Table 8: Marketization process, audit committee overseas experience, and audit fees.

	(1) FEES	(2) FEES
OVERSEA	0.2046***	
	(7.18)	
MAR × OVERSEA	−0.0187***	
	(−5.45)	
OVERSEA_ratio		0.5413***
		(7.09)
MAR × OVERSEA_ratio		−0.0491***
		(−5.44)
MAR	0.0433***	0.0427***
	(22.56)	(22.66)
SIZE	0.2649***	0.2654***
	(69.66)	(69.87)
LEV	0.0400**	0.0409**
	(2.22)	(2.26)
ROA	−0.2519***	−0.2533***
	(−4.40)	(−4.42)
REC	0.0631**	0.0619*
	(1.98)	(1.94)
INV	−0.1032***	−0.1056***
	(−3.98)	(−4.07)
SHARE1	−0.0175	−0.0182
	(−0.88)	(−0.92)
INDEP	−0.0540	−0.0566
	(−1.03)	(−1.08)
SEGMENT	0.1378***	0.1371***
	(37.85)	(37.65)
STATE	−0.0851***	−0.0846***
	(−12.80)	(−12.72)
BIG4	0.5023***	0.4981***
	(28.61)	(28.27)
CHANGE	−0.0382***	−0.0377***
	(−3.23)	(−3.19)
OPINION	0.1400***	0.1397***
	(8.52)	(8.50)
Cons	6.9426***	6.9393***
	(85.73)	(85.74)
YEAR	Control	Control
IND	Control	Control
N	17241	17241
R^2 adjusted	0.627	0.626
F	601.4	602.0

Note: ***, **, and * indicate significance at 0.01, 0.05, and 0.10 levels, respectively. All t-statistics are adjusted for robust standard errors.

Table 9: Audit committee overseas working experience, learning experience, and audit fees.

	(1) FEES
OVERSEA1	0.0540**
	(2.49)
OVERSEA2	0.0418***
	(2.90)
OVERSEA3	0.0987***
	(5.63)
SIZE	0.2630***
	(32.81)
LEV	0.00360
	(0.11)
ROA	−0.2133**
	(−2.39)
REC	0.1269**
	(2.00)
INV	−0.0838
	(−1.57)
SHARE1	0.0102
	(0.24)
INDEP	−0.0883
	(−0.90)
SEGMENT	0.1444***
	(19.57)
STATE	−0.1036***
	(−6.84)
BIG4	0.5189***
	(14.08)
CHANGE	−0.0461***
	(−3.89)
OPINION	0.1374***
	(5.93)
Cons	7.3029***
	(43.73)
YEAR	Control
IND	Control
N	17241
R^2 adjusted	0.615
F	182.1

Note: ***, **, and * indicate significance at 0.01, 0.05, and 0.10 levels, respectively. All t-statistics are adjusted for robust standard errors.

5.6. Robustness Test

5.6.1. Add Other Characteristic Variables of the Audit Committee. According to the literature, other characteristics of the audit committee might affect the governance ability of audit committee [16, 19, 56, 57]. Therefore, other characteristic variables of audit committee have been added into model (1) in this paper, including audit committee's gender composition (GENDER_ratio), audit committee size (ACSIZE), audit committee independence (INDEP_ratio), and the average age of audit committee members (AGE). The regression results are shown in Table 11. The audit committee overseas experience (OVERSEA) and the audit committee overseas experience ratio (OVERSEA_ratio) are still significantly positive at the level of 1%.

5.6.2. Self-Selection. Intuitively, those listed companies with the larger size and stronger comprehensive power are more likely to attract returnees to join, and as these listed companies have the relatively perfect governance structure and higher demand for external high-quality audit, model (1) may face the self-selection problem in the verification of the correlation between the audit committee overseas experience and the audit fees. For lower influence of self-selection, two methods have been used in this paper. The first one is the propensity score match (PSM). Firstly, the company size (SIZE), the leverage (LEV), the return on

Table 10: Audit committee overseas experience and earnings management.

	(1) EM	(2) EM	(3) EM	(4) EM
OVERSEA	−0.0021***		−0.0020***	
	(−3.15)		(−2.93)	
OVERSEA_ratio		−0.0045**		−0.0041**
		(−2.55)		(−2.31)
FEES			−0.0023***	−0.0023***
			(−2.72)	(−2.75)
SIZE	0.0016***	0.0016***	0.0024***	0.0024***
	(3.20)	(3.14)	(3.96)	(3.93)
LEV	0.0123***	0.0123***	0.0125***	0.0125***
	(4.41)	(4.41)	(4.47)	(4.48)
ROA	0.5835***	0.5835***	0.5825***	0.5825***
	(58.17)	(58.18)	(57.95)	(57.96)
REC	0.0222***	0.0223***	0.0227***	0.0227***
	(5.67)	(5.68)	(5.76)	(5.78)
INV	0.0056	0.0057	0.0055	0.0055
	(1.59)	(1.61)	(1.55)	(1.56)
GROWTH	−0.0006**	−0.0006**	−0.0007**	−0.0007**
	(−2.12)	(−2.12)	(−2.16)	(−2.16)
SHARE1	−0.0014	−0.0014	−0.0016	−0.0016
	(−0.63)	(−0.64)	(−0.69)	(−0.69)
INDEP	−0.0075	−0.0073	−0.0076	−0.0075
	(−1.26)	(−1.23)	(−1.29)	(−1.26)
STATE	−0.0023***	−0.0023***	−0.0026***	−0.0026***
	(−2.92)	(−2.92)	(−3.26)	(−3.26)
HOLD	−0.0038*	−0.0038*	−0.0037*	−0.0037*
	(−1.89)	(−1.87)	(−1.84)	(−1.83)
B/M	0.0086***	0.0087***	0.0081***	0.0082***
	(4.06)	(4.08)	(3.82)	(3.84)
BIG4	−0.0045***	−0.0046***	−0.0034**	−0.0034**
	(−2.83)	(−2.83)	(−2.10)	(−2.10)
Cons	−0.0502***	−0.0499***	−0.0372***	−0.0367***
	(−5.09)	(−5.05)	(−3.56)	(−3.51)
YEAR	Control	Control	Control	Control
IND	Control	Control	Control	Control
N	13433	13433	13433	13433
R^2 adjusted	0.405	0.404	0.405	0.405
F	143.9	143.8	140.6	140.5

Note: ***, **, and * indicate significance at 0.01, 0.05, and 0.10 levels, respectively. All t-statistics are adjusted for robust standard errors.

Table 11: Other characteristic variables of the audit committee.

	(1) FEES	(2) FEES
OVERSEA	0.0639***	
	(5.54)	
OVERSEA_ratio		0.1639***
		(5.51)
SIZE	0.2620***	0.2622***
	(32.37)	(32.44)
LEV	0.0054	0.0055
	(0.16)	(0.16)
ROA	−0.2189**	−0.2199**
	(−2.46)	(−2.46)
REC	0.1268**	0.1256**
	(2.00)	(1.98)
INV	−0.0847	−0.0858
	(−1.60)	(−1.62)
SHARE1	0.0085	0.0086

Table 11: Continued.

	(1) FEES	(2) FEES
	(0.20)	(0.20)
INDEP	−0.0828	−0.0840
	(−0.84)	(−0.85)
SEGMENT	0.1446***	0.1442***
	(19.60)	(19.54)
STATE	−0.1061***	−0.1062***
	(−6.95)	(−6.95)
BIG4	0.5216***	0.5179***
	(14.16)	(13.97)
CHANGE	−0.0461***	−0.0459***
	(−3.90)	(−3.89)
OPINION	0.1390***	0.1388***
	(6.04)	(6.02)
ACSIZE	−0.0065	−0.0026
	(−0.65)	(−0.27)
AGE	0.0027**	0.0027**
	(2.42)	(2.42)
INDEP_ratio	−0.0643	−0.0725
	(−0.86)	(−0.98)
GENDER_ratio	−0.0025	−0.0005
	(−0.10)	(−0.02)
Cons	7.2581***	7.2491***
	(40.93)	(40.91)
YEAR	Control	Control
IND	Control	Control
N	17241	17241
R^2 adjusted	0.615	0.615
F	173.8	173.3

Note: ***, **, and * indicate significance at 0.01, 0.05, and 0.10 levels, respectively. All *t*-statistics are adjusted for robust standard errors.

Table 12: Propensity score match.

	(1) FEES	(2) FEES
OVERSEA	0.0598***	
	(7.17)	
OVERSEA_ratio		0.1528***
		(7.45)
SIZE	0.2807***	0.2810***
	(51.74)	(51.85)
LEV	0.0061	0.0089
	(0.23)	(0.33)
ROA	−0.2833***	−0.2873***
	(−3.24)	(−3.27)
REC	0.0575	0.0534
	(1.27)	(1.18)
INV	−0.0514	−0.0556
	(−1.30)	(−1.40)
SHARE1	−0.0489*	−0.0509*
	(−1.70)	(−1.77)
INDEP	−0.0811	−0.0893
	(−1.04)	(−1.15)
SEGMENT	0.1402***	0.1392***
	(26.19)	(25.98)
STATE	−0.0975***	−0.0954***
	(−9.84)	(−9.62)
BIG4	0.5196***	0.5144***
	(25.54)	(25.10)

Table 12: Continued.

	(1) FEES	(2) FEES
CHANGE	−0.0420**	−0.0416**
	(−2.46)	(−2.44)
OPINION	0.1259***	0.1248***
	(5.07)	(5.01)
Cons	6.9468***	6.9492***
	(61.44)	(61.51)
YEAR	Control	Control
IND	Control	Control
N	8490	8490
R^2 adjusted	0.643	0.643
F	369.8	369.2

Note: ***, **, and * indicate significance at 0.01, 0.05, and 0.10 levels, respectively. All t-statistics are adjusted for robust standard errors.

Table 13: Two-stage procedure.

	(1) The first stage OVERSEA	(2) The second stage FEES
OVERSEA		0.3126*
		(1.85)
SIZE	0.0861***	0.2559***
	(6.52)	(41.40)
LEV	−0.2700***	0.0223
	(−3.97)	(0.97)
ROA	0.290	−0.2390***
	(1.33)	(−4.01)
REC	0.0270	0.1262***
	(0.23)	(3.93)
INV	−0.0881	−0.0754***
	(−0.93)	(−2.86)
SHARE1	0.114	0.00160
	(1.56)	(0.07)
INDEP	−0.329	−0.0584
	(−1.63)	(−1.04)
SEGMENT	0.0740***	0.1386***
	(5.58)	(25.24)
STATE	−0.1500***	−0.0920***
	(−6.18)	(−8.80)
BIG4	0.6366***	0.4631***
	(12.28)	(10.12)
CHANGE	0.0427	−0.0499***
	(1.05)	(−4.09)
OPINION	0.0317	0.1357***
	(0.52)	(8.27)
IMR		−0.150
		(−1.49)
Cons	−2.6031***	7.3970***
	(−9.16)	(71.47)
YEAR	Control	Control
IND	Control	Control
N	17241	17241
R^2 adjusted	0.036	0.615
Wald chi^2/F	703.59	591.2

Note: ***, **, and * indicate significance at 0.01, 0.05, and 0.10 levels, respectively. All t-statistics are adjusted for robust standard errors.

assets (ROA), the property right state (STATE), and the BH share (BHSHARE) are selected as the matching variables for the nearest neighbour matching. Upon the matching, in case of no significant difference between the treatment group and the control group, the parallel hypothesis is met. Secondly, all unmatched samples are removed, and new samples are used for model (1) regression, while the results are shown in Table 12. The audit committee overseas experience (OVERSEA) and the audit committee overseas experience ratio (OVERSEA_ratio) are still significantly positive at the level of 1%. The second one is the Heckman two-stage procedure (2SLS). In the first stage, the audit committee overseas experience (OVERSEA) is used as the dependent variable, and the control variable in model (1) is taken as the independent variable for multiple linear regression. The inverse Mills ratio (IMR) is calculated in the first stage. In the second stage, the inverse Mills ratio (IMR) is placed into model (1) for regression, and the results are shown in Table 13. The coefficient of audit committee overseas experience (OVERSEA) is still significantly positive at the level of 1%.

6. Conclusions and Managerial and Policy Insights

The governance role of audit committee has always been a topic of public concern for academics, practitioners, and regulators. Unlike previous research on committee members' accounting expertise, independence, enthusiasm, and other characteristics, this paper focuses on the influence of the audit committee overseas experience on the audit fees. The major findings of this paper include the following. First, the audit committee overseas experience can significantly increase the audit fees. Second, the audit committee overseas experience can also improve the demand of listed companies for external audit. Third, the audit committee overseas experience has more pronounced positive effect on the audit fees in state-owned enterprises, which indicates that the audit committee members with overseas experience have higher demand for external audit in case of relatively serious agency. Fourth, the audit committee overseas experience has more significant positive effect on the audit fees in the regions with the weak marketization process. It means that the returnees can maintain their consistent cognition and behavior with those in foreign countries in regions with both high and low marketization, which supports the cognitive imprinting theory. Fifth, in this paper, the overseas experience is divided into overseas learning experience and overseas working experience. The results show that both experience types can significantly increase audit fees. Finally, the governance role of the audit committee overseas experience is analyzed from the perspective of accounting information quality in this paper. The results indicate that the audit committee overseas experience can improve earnings quality.

The conclusions obtained through this research lead to the following insights. The audit committee is an important part of the corporate governance mechanism. This research indicates that the corporate governance and information transparency can be strengthened and improved under the audit committee with overseas returnees. The higher the audit committee overseas experience ratio is, the better the governance effect of audit committee becomes. Therefore, the listed companies should attach importance to attract overseas returnees. Especially, those with poor corporate governance and more serious agency problems should focus on hiring this returnee to improve their corporate governance. Finally, our research results can also guide investors in the capital market. The governance of listed companies with overseas returnees can often improve the earnings quality and the information transparency, so the investors should take the corporate governance factors into account during their decision-making [58–61].

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Research Article

Board Financial Expertise and Corporate Cash Holdings: Moderating Role of Multiple Large Shareholders in Emerging Family Firms

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This study contributes to the literature by exploring the relationship between board financial expertise and cash holding policy and further showing how this relation is moderated by multiple large shareholders (MLS). This research is based on agency theory, resource dependence, trade-off, and pecking order theory to confirm how resourceful directors screen cash holding practices. This study selects the 100 listed family firms from the emerging economy of Pakistan for the period of 2006–2017. With the use of static (random and fixed effect estimator) and dynamic (GMM) estimation techniques, this study reveals that the financial expertise of the board members has a significant negative impact on the firms' cash holding level. Further, moderating effect of MLS between board financial expertise and cash holding is significantly positive due to weak corporate governance mechanisms in family firms. Moreover, the research has implications for developing corporate governance mechanism and the management of liquid assets that corporate management might use for their benefits.

1. Introduction

Family-owned businesses are the oldest and quite popular form of business around the globe. Depending on the country of origin, the family-owned business might be from 20% to 70% of the biggest companies globally [1]. Pakistani stock exchange is an emerging market [2] with rich business history and a traditional form of firm ownership based on families. Around 55–70 percent of businesses are still in control and operated by families [3]. Numerous researches suggest that family enterprises underperform [4] due to corporate governance systems [5, 6].

Generally, family firms have a distinct pattern of ownership structure and governance status. Ownership concentration is a severe issue in family-controlled firms in the emerging economy of Pakistan [7], and family ownership is half of the total ownership retained by concentrated owners [8]. This situation may cause resource expropriation along with the minority shareholder's exploitation through large shareholders. The asset expropriation mainly belongs to family firms, which shows the tunneling behavior of family firms. The overall level of country governance is relatively low in Pakistan [9].

Furthermore, the regulatory bodies are struggling to enforce corporate governance mechanism in Pakistan. However, there are many loopholes in its implementation, including concentrated ownership, incapability of directors towards their role, inadequately trained personnel, absence of professional knowledge, training, and operational weakness. According to the Pakistan firm's ordinance (section XL VII, 1984), shareholders with 20 percent shares are qualified to go to court and file a complaint under any misconduct. With at least 10% representation, the shareholders can only file a complaint to Pakistan's security and exchange commission. Still, there is no provision which deals with the shareholders who hold less than 10% shares. Therefore, it is predicted that there is less or no insurance for minority investors within the Pakistani context [10].

Cash holding not only is a subject of increasing interest in political and academic discussions but also is essential for the ordinary investor because of comprehensive media reports regarding several global firm's cash holding practices such as Google, Apple, and Microsoft [11–14]. A recent study by da Cruz et al. [15] finds the upward trend in cash holding around the globe; therefore, corporate cash holding is a vital phenomenon in the corporate setting nowadays. Corporate cash holding—the firm's capital in cash instead of property, bonds, and equities [16]—leaves firm resources to be used by managers, rather than paying back to shareholders [17]. But corporation may face many consequences for the high level of cash holdings. It results in high agency cost when corporate governance mechanism is weak [18], shareholder protection is low [19], law enforcement is weak [20], capital markets are vulnerable [11], managers' interests are not aligned with shareholders' interests [21, 22], and there is a low level of trust [23]. Furthermore, the resource expropriation behavior in family firms through excess cash holding is the primary cause of strife among majority and minority shareholders [24]. Literature also reported that effective corporate governance could be helpful in the reduction of cash holdings [25].

In the existing literature, researchers also find a series of factors contributing to cash holding, including firm-specific factors such as growth opportunities [26], cash flow volatility [27], leverage [28, 29], investment opportunities [30], firms diversification [31], and research and development [32]. Since the corporate governance mechanism offers the dynamics of how credit providers can get a return from their investment, cash holdings can be best explained under the corporate governance mechanism [20]. To mitigate the agency conflict, various governance systems have already been analyzed concerning cash holding, including ownership structure [33], board composition [34], and CEO compensation [35]. Literature is too extensive to study here, but recent studies document that this phenomenon of cash holding may be known and relevant for corporate managers and other policymakers [36, 37]. Therefore, there is still a need to examine the characteristics of the board concerning cash holdings [15] in the equity markets.

The study introduces a new dimension—board financial expertise—to explain the cash holding decision. The study investigates the board financial expertise's impact on corporate cash holding, which is motivated by two reasons. First, comprehensive media reports about several firm's cash holding practices like Google, Apple, and Microsoft [12, 14], along with renowned corporate scandals like HealthSouth, Enron, WorldCom, and Tyco [38, 39], have shifted the attention of regulators and market makers to have financial expertise on board for effective corporate governance mechanisms. Therefore, weakening governance system in family firms in emerging economies like Pakistan requires special attention, which ultimately affects corporate policies, including cash holdings. Second, numerous studies examined the relationship of board financial expertise with specific corporate policies, including earning management [40], dividend policy [38], corruption disclosure [41], firm performance [42], and audit quality [43]. Moreover, financial expertise also improves board efficiency [44] and leads to better corporate governance practices [45]. Therefore, there is a need to extend the debate on the role of board financial expertise towards another corporate policy, that is, cash holdings of family firms, by examining the impact of board member financial expertise on cash holding policy, which is a potential element for mitigating agency conflict and enhancing governance practices in family firms of the emerging economy.

We also introduces for the first time the moderating role of multiple large shareholders (MLS) in the relationship between corporate governance mechanism and cash holding. To the best of our knowledge, this is also the first attempt which analyzes the impact of board financial expertise on cash holding with the moderating role of multiple large shareholders. Further, we follow Luo et al. [46] and develop a conceptual model by studying three distinct features of multiple large shareholder structures, that is, (a) presence of large shareholder, (b) contest for control, and (c) number of the large shareholders. In addition, we also examine the effect of board independence, board gender diversity, and board size on cash holding [18, 47–49] by controlling the firm-specific determinants, that is, firm size, liquidity, leverage, profitability, capital expenditure, dividend payout, cash flow, and investment opportunity. This study employed the static and dynamic panel models, that is, random effect (RE), fixed effect (FE), and two-step generalized method of moment (GMM) [50, 51] on a sample of 100 nonfinancial listed family firms from the emerging economy of Pakistan during 2006–2017. The study result shows that the financial expertise of board members has a significant negative impact on the cash holding policy. These findings recommend that a quality board can send back a controlling family's momentum for unnecessary cash holdings by cutting down the volume of liquid assets. Therefore, results support the monitoring role of financial experts in concentrated ownership context, which stressed the importance of the board of directors towards quality governance. The structure of MLS also moderates the relationship between corporate governance and cash holdings. In addition to these, the finding suggests that profitability, firm size, leverage and dividend payout, investment opportunity, and capital expenditure have a significant association with cash holding practices.

This study extends the existing literature in the following four ways. Firstly, we introduce the board financial expertise as a potential factor for explaining the cash holding policy of family firms; therefore, this study extends the debate on internal corporate governance mechanism and cash holding in financial literature [33, 47, 52–55]. We also examine other governance characteristics such as the role of board gender diversity, the board size, and board independence towards cash holding. Secondly, we analyze the moderating role of MLS (presence, contest, and number) in the relationship between corporate governance and cash holding. Thirdly, we select the emerging equity market of Pakistan. Existing literature on internal governance structure and cash holding is badly inclined towards developed economies [20, 56, 57] which raises a need to analyze board financial expertise and MLS role towards cash holding in emerging economies.

Furthermore, Pakistan does not have any legal requirement about financial expertise on board which left the gap for analysis of board financial expertise role towards cash holding decision. Fourthly, we select the listed family firms due to their distinct ownership structure and governance status. Therefore, it is vital to examine the governance characteristics and their relation with cash holding in family firms.

This paper is organized as follows. The following section describes the theoretical background and hypothesis development; the next section describes data and research methodology, followed by empirical results. Finally, we have a discussion and conclusion section.

2. Theoretical Background and Hypothesis Development

This section discusses the theoretical background and hypothesis of the study. It includes the main theories which provide the foundation for our research in the context of emerging markets.

2.1. Theoretical Background. The theoretical relationship between cash holding and board characteristics is best explained by agency theory [58], resource dependence theory [59], trade-off theory [60, 61], and pecking order [62] theory as these theoretical underpinnings are more appropriate and dominant in the motivation of cash holding. Due to different vital roles performed by a board of directors, such as (a) monitoring and control role, (b) provision of valuable advice, (c) ensuring organization's compliance with statutory law and regulations, and (d) connection of organization with the external environment [63], it is challenging to explore the board characteristics, cash holding nexus with any single theory. de Villiers et al. [64] showed that agency and resource dependence theories gave the critical solution in determining board's monitoring capabilities, while Al-Najjar [26] focused on the trade-off and pecking order theory to determine the firm cash holdings.

Agency theory explains that the interest of shareholders and managers should be aligned [32, 65, 66] and argues that free cash flow leads towards agency problem. Entrenched managers do not distribute excess cash among shareholders [58, 67, 68], instead retained for personal uses due to easily accessible asset [69]. Agency theory explains the principal-agent and principal-principal conflict [70–73]. The predominance of principal-principal conflict in Asian countries is family ownership and control [74]. Therefore, strong governance with a strong board structure is necessary for observing the insiders. Hence, board financial expertise may be a tool that the board can use to enhance the governance mechanism.

Resource dependence theory deals with how users access the resources that depend on the director's access to firm resources [75, 76]. The presence of a capable director on the corporate board as a resource develops strategic policies regarding any particular issue. Board members deliver numerous benefits to the companies, such as advice and recommendations [75, 77], and act as channels for information. Hillman and Dalziel [76] classify board capital into two types, i.e. human capital (advice, knowledge, experience, expertise, and reputation) and relational capital (relationship channel). Existing literature advocates the rigid behavior of any resourceful person towards unethical actions due to their popularity and reputation [78] and their role in reducing information asymmetry among stakeholders. Therefore, resourceful directors such as board financial experts may have a valuable opinion to enhance corporate governance by reducing agency problems of cash among shareholders to improve investor's confidence and raise investment.

The trade-off theory believes that the optimal level of cash is determined through the trade-off among the marginal costs and cash holding [26, 79, 80]. Ferreira and Vilela [30] suggested that cash holding has three advantages: (1) shrink the possibility of financial distress, (2) make investment policy less vulnerable during financial constraints, and (3) reduce external financing cost. According to the Keynes [81] concept, there are two incentives behind cash holding: precautionary and transaction cost incentive. Under transaction cost incentive, firms cladding an insufficiency of internal reserves can seek external funds through incurring of variable and fixed costs, such as assets liquidity, dividends reduction, and issuance of new stock or debt instruments [82], while under precautionary incentive, firms stockpile cash in the pursuance of an unexpected investment opportunity when external source financing is high. In family firms where transaction costs are essential, trade-off theory seems vital in explaining the firm's cash holding policy.

The pecking order theory has been presented by Myers and Majluf [62]. It states that firms first go for internal funds as they are the cheapest source of funding. After that, firms opt for external financing because external funding source is high when firms face asymmetric information problems [69]. This problem of information asymmetry is more in family firms from emerging markets [83]. Therefore, pecking order theory should be considered while explaining the cash holding policy of family firms in emerging markets.

2.2. Hypothesis Development. This section includes the underpinning between board financial expertise with cash holding in family firms. Furthermore, it also discusses the moderating role of multiple large shareholders in the relationship between corporate governance mechanisms and cash holdings.

2.2.1. Board Financial Expertise (BFE) and Cash Holding. As examined by recent literature, the board of directors is an essential component of corporate governance [41, 73], particularly in substantial business enterprises [84]. The internal governance is ordinarily estimated by ownership structure, nonexecutive directors on board, effective audit, and so forth [85, 86]. Research reveals that strong governance decreases the level of cash holdings [55, 86]. Therefore, managers may have some inclination to hold more cash during the absence of strong governance. Consequently, it is expected that the corporate board has a viable role in relieving agency issues due to cash holding.

The vast body of literature on corporate board and firm's governance characterized board obligations into different roles [52, 53, 84, 85]. These roles are not fundamentally distinct, and each one is fortified with an expert financial presence on board. Investors prefer more financial expertise on the board because they have to perform numerous roles, including improvement of financial reporting quality, financial statement's transparency, and prevention of controlling shareholder's internal control [87, 88]. Financial experts on board help monitor the ability and potential of management towards financial decisions and provide experience-based reviews on policies [38, 89]. Furthermore, to reduce the firm's agency conflict, they can work as arbitrators among external and internal auditors [90].

The need for financial experts on the board arises in the 1990s after the accounting crises and economic crisis; for example, according to the USA, Sarbanes–Oxley Act (2002) firm's board has to acquire at least one financial expert. Furthermore, the UK, Australia, Singapore, and the new governance rules of India also interdict about the board's technical and financial expert's inclusion [91]. A study on Singaporean firms revealed the watchdog role of accounting and financial experts on board to foster financial disclosure quality [91]. Furthermore, the study of [92] on UK firms found that the financial experts have a role in promoting corporate social responsibility (CSRP disclosures with their reputation, background, and experience). In addition to this, existing literature found that board financial experts have a positive impact on the board's proficiency [87, 88], firm practices [88, 93], and execution [42, 94, 95] and lead to quality governance. According to Abďioğlu [96], quality governance is linked to decreased cash holding. Studies also suggest that strong governance is related to low cash holding [67, 97]. Therefore, the first hypothesis of this study is as follows:

H1a: board financial expertise has a significant negative impact on the cash holding of listed family firms.

2.2.2. Board Size (BS) and Cash Holding. The quality of the corporate board may also depend on the number of directors on the board. Although the large board size may have various experience and skills, it leads to organizational inefficiencies [47]. A larger board size makes the decision-making process slow which may increase the agency problems. Furthermore, different studies discussed the association of board size with cash holdings [18, 85, 86, 98]. Researchers suggested that a bigger board size will, in general, be inefficient in decision-making and has a higher administrative cost [98, 99], resulting in poor governance and easy to have control of the A chief executive officer (CEO) [100]. The smaller board size leads to minimization of the agency conflicts. Due to more significant agency conflicts, an upward trend in cash holding is expected under the larger board size [47]. Therefore, following the existing literature on board size, we develop the following hypothesis:

H1b: board size has a positive impact on the cash holding of listed family firms.

2.2.3. Board Independence (BI) and Cash Holding. Board independence has been widely discussed as part of the corporate governance mechanism [32, 101]. It is a vital factor in determining the monitoring quality of the corporate board [47, 101]. Furthermore, these directors generally have no financial interest other than fees [102]. Earlier literature discussed the association of board independence with cash holding [103]. In light of the theory of financial hierarchy, board independence has a positive relationship with the holding of cash [61], as agency cost decreases by effective monitoring. The board independence can also protect the rights of minority shareholders. Anyhow, researchers [33, 104] found an insignificant association among these variables. Therefore, board composition is an important matter to discuss the agency problems and associated cost. An increase in the level of cash holdings also increases the risk of expropriation [47]. Therefore, it is expected that level of board independence decreases the cash holding of firms. Following existing literature on the association of board independence and cash holding [18, 47, 48], this study develops the following hypothesis:

H1c: board independence has a negative impact on the cash holding of listed family firms.

2.2.4. Board Diversity (BD) and Cash Holding. The gender differences among the general population are different from those of the professional populations in terms of financial risk preferences [105]. Furthermore, Croson and Gneezy [105] also discussed the findings of Dwyer et al. [106] that the female mutual fund investors are more risk averse than the counterpart. But, Dwyer et al. [106] argued that this difference is attenuated when controlling financial investment knowledge. Therefore, it can be concluded that financial ability may decrease gender differences. It is expected that solid financial understanding is generally low in the family firms of the developing economies. Therefore, gender diversity may be higher in family firms of developing economies.

Companies push more females in the corporate board due to the economic benefit achieved through the unique skills and talent of the female [107]. Furthermore, the rational economic theories such as resource dependence, stakeholder, agency theory, and stewardship theory suggest that females on board have a significant impact on the board independence and monitoring and advisory capacity by having more connection towards the external environment [108, 109]. Furthermore, recently, Zalata et al. [110] strongly argued that female CEOs are more risk averse than females on the corporate board. Therefore, it is concluded that female takes less risky decisions than male board members. Thus, board diversity deals with two main functions, including precautionary and agency cost. From the agency cost point of view, more female directors on board enhance the significance of the board and lead towards greater quality

[111]. Subsequently, board diversity affects board adequacy, which may benefit shareholders [47]. It also decreases the likelihood of seizure of firm assets [112]. As per the precautionary motive, females are risk averse than males [113] and are less confident in decision-making [49, 114]. Therefore, companies with a diversity of gender hold high cash reserves [49, 115]. Consequently, we develop the following hypothesis:

> H1d: board diversity has a positive impact on the cash holding of listed family firms.

2.2.5. Multiple Large Shareholders (MLS) and Cash Holding. Excess cash is the reason for agency conflict among shareholders and managers and principal-principal (P-P) conflict among majority and minority shareholders [58]. P-P conflicts are a vital concern of corporate governance [116, 117]. Governance characteristics are previously premeditated to resolve principal-agent (P-A) conflicts and are proven to be ridiculed in resolving P-P conflicts [118, 119]. Under this context, researchers have claimed that multiple large shareholders can act as a possible governance mechanism that might restrain the expropriation of controlling families and thus feasibly mitigate P-P conflicts. Maury and Pajuste [120] stated about the second-largest stockholders that they increased the profitability of European corporate bodies. Faccio et al. [121] examined the expropriation-reducing role of multiple large shareholders and revealed the increasing expropriation role in Asia because of weak shareholder protection and governance in Asia. Attig et al. [122] showed that uneven appropriated control rights decrease the efficient monitoring of numerous block holders because they could even frame control alliances and offer private advantages expropriation. Therefore, there exists conflicting argument in the existing literature on multiple large shareholders and cash holdings. We develop a conceptual model which refers to the three features of multiple large shareholder structure including (a) presence, (b) competition for control, and (c) sum of large shareholders.

2.2.6. Presence of Multiple Large Shareholders and Cash Holding. Being an emerging economy, Pakistan has a weak external governance structure, low legal investor protection [123], and grievous P-P conflicts [7]. Under these circumstances, an internal governance structure would be more vital [124]. Therefore, multiple large shareholders' mechanisms might be a valuable internal mechanism while dealing with P-P conflicts [117, 125]. Under the monitoring role, other large shareholders cooperate in bartering common interests and restraining expropriation by the controlling families [117, 125]. Under the entrenchment role, other large shareholders make a controlling alliance with controlling families to extract and share personal benefits [122, 126]. By following Liu et al. [16] findings, we theorize that multiple large shareholders would not mitigate agency conflicts in Pakistani family firms and do not perform a vital monitory role towards expropriating behavior of families as observed in the developed world [120, 126]. Therefore, we set the following hypothesis:

> H2a: the presence of MLS structure has a positive impact on the cash holding of listed family firms.

2.2.7. Contest of Multiple Large Shareholders for Control and Cash Holding. The literature discussed the relative dominance among monitoring effect and entrenchment effect [46]. The relative intensity of monitoring and entrenchment role would vary under different levels of the contest for control. When the contest for control is at a low level, then controlling families affect the firm, which then expropriates exclusively by using their rights [16]. When a family firm goes towards collusion, they need to share private advantages, thus allowing them to expose if an attempt to expropriate or a tunnel is made. Therefore, the MLS structure's net governance effect is the monitoring effect [46].

On the other hand, under the high level of the contest for control, the MLS net governance role will become an entrenchment role. The first reason behind it is that dominant families find it difficult to expropriate and must establish coalitions with other major shareholders to extract and distribute private advantages [16, 127, 128]. The above situation happens particularly in emerging economies because of low legal protection for minority shareholders [119]. Secondly, due to the equal distribution of equity among family and other large shareholders, one could not entirely control the firm [129]. Therefore, it is hard for the largest shareholder to form a successful alliance, but numerous large shareholders would engage in different directions separately by using minority shareholders' wealth. Therefore, we predict the dominancy of entrenchment effect when competition for control is high and ultimate, and it has a positive impact on cash holding.

Further, when competition for control is intense, it boosts the entrenchment effect, which permits large shareholders to make winning alliances with a minor equity stake or chase their distinctive targets individually, enhancing the expenses of minority shareholders. Therefore, it may lead to more severe principle-principle (P-P) conflicts and expropriation [122]. Consequently, we expect a positive connection between multiple large shareholder's contests for control and corporate cash holding. Hence, our hypothesis is as follows:

> H2b: the contest for control of MLS structure will positively impact cash holding of listed family firms.

2.2.8. Number of Multiple Large Shareholders and Cash Holding. Literature also pointed out that if a sole large shareholder has the control, it leads to the absence of adequate supervision and equilibrium [117, 119]. On the other hand, having many large shareholders may weaken the dominancy of controlling families, restrict expropriation, and mitigate P-P conflicts [130], affecting corporate cash holdings. Further, it is hard to assume that more large shareholders are the best choice [46]. According to

Bennedsen and Wolfenzon [126], several large shareholders make winning alliances with other large shareholders with small equity stake and facilitate winning coalition for expropriation [131, 132], which leads to more cash holding in firms. Therefore, the literature concludes that a number of large shareholders (LS) structures increase the corporate cash holding, so our next hypothesis is as follows:

H2c: the number of large shareholders has a positive impact on the cash holding of listed family firms.

2.2.9. The Moderating Role of Multiple Large Shareholders on the Relationship between Corporate Governance and Cash Holding. The theoretical literature on corporate governance suggests that strong governance is adequate to mitigate agency conflict. However, multiple large shareholders can monitor well controlling investors (an observing motivation) or might be structure controlling alliances with them to get private advantages (a conspiracy motivator) [25, 104, 122]. Therefore, we analyze the interaction effect of corporate governance and multiple large shareholders with cash holding. Consistent with the study of Liu et al. [16], it is expected that MLS in Pakistan likely interact with controlling shareholders because of poor governance and investor protection because control rights are skewed towards controlling families. Therefore, we develop the following hypothesis:

H3: the interaction of multiple large shareholders and corporate governance proxies positively impacts the cash holding of listed family firms.

3. Data and Research Methodology

The initial sample of the study consists of all Pakistani nonfinancial listed family firms on the Pakistan stock exchange (PSX). Since the financial sector has a distinctive capital structure and other legal requirements, we exclude the financial sector. Further, we sorted family firms from listed firms of the nonfinancial sector. Therefore, all the listed family firms are the initial population of this study. The period of the analysis is 2006 to 2017 on an annual basis. During the data collection of dependent, independent, and other variables, a series of secondary sources were examined, including published corporate governance reports published annual reports of each sample family firm, the company's official websites, and directors' profiles. In addition, firms having missing data sets have been excluded. Therefore, for reduction of outlier's effect, on each variable, we trim our sample at 1% in each tail. Due to the nonavailability of board members profiles for some sample family firms, our final sample consists of 100 firms from 11 nonfinancial industries, including cement, chemical products and pharmaceuticals (CP&P), energy, electrical machinery and apparatus (EEM&A), food products and minerals (FP&M), information, communication and transport services (IC&TTS), manufacturing, motor vehicle and transport (MV&T), paper, paperboard, and products (PPB&P), refined petroleum products (RPP), sugar, and textile. A detailed description of the sample firms has been presented in Table 1.

3.1. Research Methodology. This study employs the following research methodology.

3.1.1. Board Financial Expertise and Cash Holdings. To econometrically investigate the impact of board financial expertise on cash holding in listed family firms of an emerging economy, we estimate the following two equations:

$$\begin{aligned}\text{CCET}_{i,t} &= \beta_o + \beta_1 * \text{Board financial expertise} + \beta_i * \text{Governance mechanism}_{i,t} + \beta_k * \text{Control}_{i,t}\\ &\quad + \beta_l * \text{Industry}_{i,t} + \beta_m * \text{Year}_{i,t} + \mu_{i,t},\\ \text{CCET}_{i,t} &= \beta_o + \beta_1 * \text{BFE}_{i,t} + \beta_2 * \text{BS}_{i,t} + \beta_3 * \text{BI}_{i,t} + \beta_4 * \text{BD}_{i,t} + \beta_5 * \text{FS}_{i,t} + \beta_6 * \text{CF}_{i,t} + \beta_7 * \text{CE}_{i,t}\\ &\quad + \beta_8 * \text{IO}_{i,t} + \beta_9 * \text{ROA}_{i,t} + \beta_{10} * \text{Lev}_{i,t} + \beta_{11} * \text{DP}_{i,t} + \beta_{12} * \text{FL}_{i,t} + \beta_l * \text{Industry}_{i,t} + \beta_m * \text{Year}_{i,t} + \mu_{i,t}.\end{aligned} \tag{1}$$

Here, CCET denotes the cash and cash equivalent (cash holding), BFE represents the board financial expertise, BS denotes the board size, BI denotes the board independence, FS depicts the firm size, CF denotes the cash flow, CE denotes the capital expenditure, IO denotes the investment opportunity, ROA denotes the return on asset, LEV denotes leverage, and DP denotes dividend payout. Finally, FL offers the liquidity of the family firm.

3.1.2. Multiple Large Shareholders and Cash Holdings. We divide multiple large shareholder (MLS) structures into its three attributes—presence, control contest, and number of large shareholders (LS)—to fully explain the governance role of MLS structure towards corporate cash holding. Specifically, we estimate the following set of equations (2)–(8) to analyze the impact of MLS on cash holdings of listed family firms in Pakistan:

Table 1: Sample description.

Description	No of firms
Total listed companies	558
Less: financial listed companies (146)	412
Less: nonfamily listed firms (145)	267
Total listed family firms	267
Less: companies with nonavailability of board members' profile for data of corporate governance characteristics (107)	160
Less: companies with nonavailability of other control variables' data (32)	128
Less: companies with missing data in some of the years (28)	100
A final sample of a study	100

$$\begin{aligned}\mathrm{CCET}_{i,t} = {} & \beta_o + \beta_1 * \mathrm{BFE}_{i,t} + \beta_2 * \mathrm{BS}_{i,t} + \beta_3 * \mathrm{BI}_{i,t} + \beta_4 * \mathrm{BD}_{i,t} + \beta_5 * \text{Block dummy}_{i,t} + \beta_6 * \text{Firm's controls} \\ & + \beta_l * \mathrm{Industry}_{i,t} + \beta_m * \mathrm{Year}_{i,t} + \mu_{i,t},\end{aligned} \tag{2}$$

$$\begin{aligned}\mathrm{CCET}_{i,t} = {} & \beta_o + \beta_1 * \mathrm{BFE}_{i,t} + \beta_2 * \mathrm{BS}_{i,t} + \beta_3 * \mathrm{BI}_{i,t} + \beta_4 * \mathrm{BD}_{i,t} + \beta_5 * \text{Contest } 1_{i,t} + \beta_6 * \text{Firm's controls} \\ & + \beta_l * \mathrm{Industry}_{i,t} + \beta_m * \mathrm{Year}_{i,t} + \mu_{i,t},\end{aligned} \tag{3}$$

$$\begin{aligned}\mathrm{CCET}_{i,t} = {} & \beta_o + \beta_1 * \mathrm{BFE}_{i,t} + \beta_2 * \mathrm{BS}_{i,t} + \beta_3 * \mathrm{BI}_{i,t} + \beta_4 * \mathrm{BD}_{i,t} + \beta_5 * (\text{Contest } 1)^2_{i,t} + \beta_6 * \text{Firm's controls} \\ & + \beta_l * \mathrm{Industry}_{i,t} + \beta_m * \mathrm{Year}_{i,t} + \mu_{i,t},\end{aligned} \tag{4}$$

$$\begin{aligned}\mathrm{CCET}_{i,t} = {} & \beta_o + \beta_1 * \mathrm{BFE}_{i,t} + \beta_2 * \mathrm{BS}_{i,t} + \beta_3 * \mathrm{BI}_{i,t} + \beta_4 * \mathrm{BD}_{i,t} + \beta_5 * (\text{Contest } 2)_{i,t} + \beta_6 * \text{Firm's controls} \\ & + \beta_l * \mathrm{Industry}_{i,t} + \beta_m * \mathrm{Year}_{i,t} + \mu_{i,t},\end{aligned} \tag{5}$$

$$\begin{aligned}\mathrm{CCET}_{i,t} = {} & \beta_o + \beta_1 * \mathrm{BFE}_{i,t} + \beta_2 * \mathrm{BS}_{i,t} + \beta_3 * \mathrm{BI}_{i,t} + \beta_4 * \mathrm{BD}_{i,t} + \beta_5 * (\text{Contest } 2)^2_{i,t} + \beta_6 * \text{Firm's controls} \\ & + \beta_l * \mathrm{Industry}_{i,t} + \beta_m * \mathrm{Year}_{i,t} + \mu_{i,t},\end{aligned} \tag{6}$$

$$\begin{aligned}\mathrm{CCET}_{i,t} = {} & \beta_o + \beta_1 * \mathrm{BFE}_{i,t} + \beta_2 * \mathrm{BS}_{i,t} + \beta_3 * \mathrm{BI}_{i,t} + \beta_4 * \mathrm{BD}_{i,t} + \beta_5 * \text{Block number} + \beta_6 * \text{Firm's controls} \\ & + \beta_l * \mathrm{Industry}_{i,t} + \beta_m * \mathrm{Year}_{i,t} + \mu_{i,t},\end{aligned} \tag{7}$$

$$\begin{aligned}\mathrm{CCET}_{i,t} = {} & \beta_o + \beta_1 * \mathrm{BFE}_{i,t} + \beta_2 * \mathrm{BS}_{i,t} + \beta_3 * \mathrm{BI}_{i,t} + \beta_4 * \mathrm{BD}_{i,t} + \beta_5 * (\text{Block number})^2_{i,t} + \beta_6 * \text{Firm's controls} \\ & + \beta_l * \mathrm{Industry}_{i,t} + \beta_m * \mathrm{Year}_{i,t} + \mu_{i,t}.\end{aligned} \tag{8}$$

3.1.3. The Moderating Role of Multiple Large Shareholders in the Relation between Financial Expertise and Cash Holding. This study estimates the moderating role of block dummy in the relationship between board financial expertise and cash holding by the following equation:

$$\begin{aligned}\mathrm{CCET}_{i,t} = {} & \beta_o + \beta_1 * \mathrm{BFE}_{i,t} + \beta_2 * \mathrm{BS}_{i,t} + \beta_3 * \mathrm{BI}_{i,t} + \beta_4 * \mathrm{BD}_{i,t} + \beta_5 * \text{Board financial expertise} * \text{Block dummy}_{i,t} \\ & + \beta_6 * \text{Firm's controls} + \beta_l * \mathrm{Industry}_{i,t} + \beta_m * \mathrm{Year}_{i,t} + \mu_{i,t}.\end{aligned} \tag{9}$$

Equation (10) estimates the moderating role of block dummy in the relationship between board size and cash holding for Pakistani listed family firms:

$$\begin{aligned}\mathrm{CCET}_{i,t} = {} & \beta_o + \beta_1 * \mathrm{BFE}_{i,t} + \beta_2 * \mathrm{BS}_{i,t} + \beta_3 * \mathrm{BI}_{i,t} + \beta_4 * \mathrm{BD}_{i,t} + \beta_5 * \mathrm{BS} * \text{Block dummy}_{i,t} + \beta_6 * \text{Firm's controls} \\ & + \beta_l * \mathrm{Industry}_{i,t} + \beta_m * \mathrm{Year}_{i,t} + \mu_{i,t}.\end{aligned} \tag{10}$$

We also analyze the moderating role of block dummy in the relationship between board independence and cash holdings by estimating the following equation:

$$\begin{aligned}\text{CCET}_{i,t} = {} & \beta_o + \beta_1 * \text{BFE}_{i,t} + \beta_2 * \text{BS}_{i,t} + \beta_3 * \text{BI}_{i,t} + \beta_4 * \text{BD}_{i,t} + \beta_5 * \text{BI} * \text{Block dummy}_{i,t} + \beta_6 * \text{Firm's controls} \\ & + \beta_l * \text{Industry}_{i,t} + \beta_m * \text{Year}_{i,t} + \mu_{i,t}.\end{aligned} \tag{11}$$

This study investigates equation (12) for examining the moderating role of block dummy in the relationship between board diversity and cash holding in listed family firms:

$$\begin{aligned}\text{CCET}_{i,t} = {} & \beta_o + \beta_1 * \text{BFE}_{i,t} + \beta_2 * \text{BS}_{i,t} + \beta_3 * \text{BI}_{i,t} + \beta_4 * \text{BD}_{i,t} + \beta_5 * \text{BD} * \text{Block dummy}_{i,t} \\ & + \beta_6 * \text{Firm's controls} + \beta_l * \text{Industry}_{i,t} + \beta_m * \text{Year}_{i,t} + \mu_{i,t}.\end{aligned} \tag{12}$$

We estimate the baseline regression with static—fix and random effect model—and dynamic—two-step GMM—panel data estimation techniques for Pakistani family firms. The panel statistics assess the endogeneity by controlling firm, precise effects. Also, we employ the unbalance estimation model to avoid the likely heteroscedasticity in data. We used the Hausman test to analyze whether the fixed or random effect is appropriate. We also view that data is free from cross-sectional correlation among firms due to the clustering as we only consider the nonfinancial sectors. We employ GMM to estimate our model. To acquire the predictable evaluations, the fixed effect will estimate through model first difference by taking lag of independent variables to eliminate the endogeneity problem [50]. GMM consistency relies upon the independent variable's validity and the presumption that the error term does not show the sequential relationship. In this manner, two particular tests, endogenous and Wald test for endogenous variables, are also applied. Our two-step GMM estimation considers the lag of cash holding and other explanatory variables as instruments by analyzing the dynamism in cash holding and controlling the potential problems of autocorrelations, heterogeneity, and endogeneity.

3.2. Measurement of Variables. This section discusses the operationalization of the battery of variables of our study.

3.2.1. Family Firms. Consistent with the study of Bunkanwanicha et al. [133], we consider a family firm in which the founder or family member holds at least 20% of the equity of the firm in the sample period. In line with existing literature, we measure our dependent variable corporate cash holdings (CCET) as cash and cash equivalent to total asset ratio in listed family firms [16, 82, 134].

3.2.2. Corporate Governance Variables. Under the consideration of agency and resource dependence theory, we identified the following variables, which likely affect cash holdings:

(1) Board Financial Expertise. We operationalize the financial expertise as the proportion of financial expertise on corporate board to total board members [38, 88, 135]. Section 202 of the Sarbanes–Oxley act defines a person as a financial expert who has financial and accounting experience or performs financial responsibilities with supervisory expertise. We classify a person as a financial expert if a person has finance, accounting, and economics degree or working experience as auditor accountant, finance manager, chief financial officer, financial analyst, or financial advisor in any financial sector or nonfinancial sector. We divide the financial expertise into five categories: a bachelor in accounting and finance (A&F), master in accounting and finance (A&F), PhD degree, professional certification, and law background.

(2) Board Size (BS). It is defined as the size of the corporate board at the end of the fiscal year [98, 136, 137].

$$\text{BS} = \text{Total number of director in a corporate board}. \tag{13}$$

(3) Board Independence (BI). The study conceptualizes board independence as the proportion of independent directors on board to the entire board of directors [47, 55, 138].

$$\text{BI} = \frac{\text{Total number of independent director}}{\text{Board size}}. \tag{14}$$

(4) Board Diversity (BD). It is defined as a female director on the board [49, 139].

$$\text{BD} = \text{number of female directors in a board}. \tag{15}$$

3.2.3. Multiple Large Shareholders: Moderating Variable. The study incorporates multiple large shareholders (MLS) structure as a moderating variable. It divides the MLS structure into three attributes—presence, control contest, and number of large shareholders (LS)—to examine the governance role of MLS structure towards corporate cash holding. We use a dummy variable to capture the MLS, denoted as block dummy, and assign 1 if the second-largest shareholder owns at least 5% equity rights otherwise “0” [34, 117]. We are expecting the positive impact of this variable on cash holding. To measure control contest, we take the ratio of the summation of the second- to fifth-largest shareholders' equity rights to the first-largest shareholder's equity rights [46, 122], represented as contest 1, and it measures the relative intensity of larger shareholders equity rights to other shareholders' equity right.

Further, we computed the sum of the square of difference among the second- to third-largest shareholder's equity right, third- to fourth-large shareholder's equity right, and fourth to fifth shareholder's equity rights [120, 122] and represented contest 2. Contest 2 specifies the equity right distribution among other LS. Therefore, we used contest 1 and contest 2 to measure the contest for control. If both variables are high, it denotes the higher control contest among shareholders. Further to measure the number of large shareholders (LS), we included second- to fifth-LS holding at least 10% equity rights [46]. By following the pecking order theory, the trade-off theory, and prior empirical studies [38, 53, 115, 140], we incorporated control variables (see Appendix A).

3.2.4. Control Variables. Firm-specific variables might influence the firms' cash holding policy. Following the theoretical predictions of the pecking order theory, the trade-off theory, and prior empirical studies [30, 53, 61, 115, 141], we incorporated the following control variables into our study: dividend, capital expenditure, investment opportunity, firm size, leverage, profitability, liquidity, and cash flows. Capital expenditure (CE) is the ratio of summation change in fixed assets and depreciation to net assets. It may negatively affect cash because the investment decision generally decreases the cash balance of the firms [140]. Firm size (FS) measures through the natural logarithm of net assets. It results in a negative association with cash holding, consistent with trade-off theory because stable, large, and well-diversified firms hold less cash [30, 61].

The investment opportunity (IO) ratio of stock market value plus debt's book value to asset's book value is expected to positively impact corporate cash holdings [141]. Leverage (LEV) is a ratio of total debt to total assets of the firm. More levered firms will accumulate large cash to diminish the risk of financial distress and bankruptcy; therefore, the relationship between leverage and cash holding could be positive according to trade-off theory [142]. Dividend (DIVT) payout is measured through the ratio of dividend per share, and existing literature argued its negative relationship [143, 144]. Profitability (ROA) measures the ratio of companies' profit to net assets in the last year [73, 145–147], and it may directly affect the cash holdings. This is because profitable firms hold more cash for reinvestment purposes [148]. Cash flow (CF) denotes the operating cash flow measured as the cash flow ratio to net assets at the last of the year [141]. The pecking order theory suggests that firms having the capacity to generate more cash are likely to hold it more; therefore, there may be a positive association between cash flow and cash holding [149]. Liquidity (FL) is defined as net working capital less cash divided by net assets. Furthermore, the trade-off theory also suggests that more liquid assets may be considered substitutes and quickly shifted into cash. Hence, firms with more cash may have less liquid assets [82, 150].

4. Empirical Results

We start our empirical results by plotting a graph of board financial expertise across the nonfinancial listed family firms in the Pakistani stock exchange. Figure 1 plots the log of the amount of board financial expertise in Pakistani family firms. It shows that most family firms hire law background professionals in Pakistan, followed by directors having professional certifications. Appendix B include the pie charts of decomposition of financial expertise of our study; Figures 3–7 depict the decomposition of financial expertise based on bachelor in accounting and finance (A&F), master in accounting and finance (A&F), PhD degree, professional certification, and law background, respectively.

The pie chart of Figure 2 further decomposes the board financial expertise into 5 categories. We define a financial expert if the director has any banking experience (Banker) or has experience as a finance officer (CFO), finance expert of nonfinancial firms (FENF) or from academia (professor of finance (PF)), and professional investor (PI). Results show that about 35% of financial experts belong to the category of FENF while 29% are from bankers in Pakistani family firms.

Table 2 presents summary statistics for the entire sample variables. It reports the mean, standard deviation, and maximum and minimum values of each studied variable for 12 years of data span. For example, the mean value of CCET is 0.04 with a 0.07 standard deviation, representing cash holding 4 times of total assets. The average value of BS is 8, which shows that, on average, family firms have 8 members in their corporate board, while the minimum value for BS is 4. The maximum value is 15 with 1.746 standard deviations. The mean value of BD is 1.21 showing that on average female representation in the board of family firms is relatively low. On average, family firms have 1.73 financial experts in their corporate board, while its maximum value in the sample is 10 with a standard deviation of 2.01. Similarly, Table 2 reports the summary statistics of all the other control variables used in this study.

Table 3 uncovers the results of the degree of associations among variables. Correlation shows the strength and direction of association among studied variables. For example, CCET is positively correlated with BS, BD, IO, ROA, and CF, while BI, BFE, DIVT, CE, FS, LEV, and FL have a negative association with corporate cash holding. Furthermore, the maximum association is observed between ROA and CF, that is, 0.59, which may also show no evidence of multicollinearity in the studied variables. We refer to Table 3 for further details of the degree of association among variables.

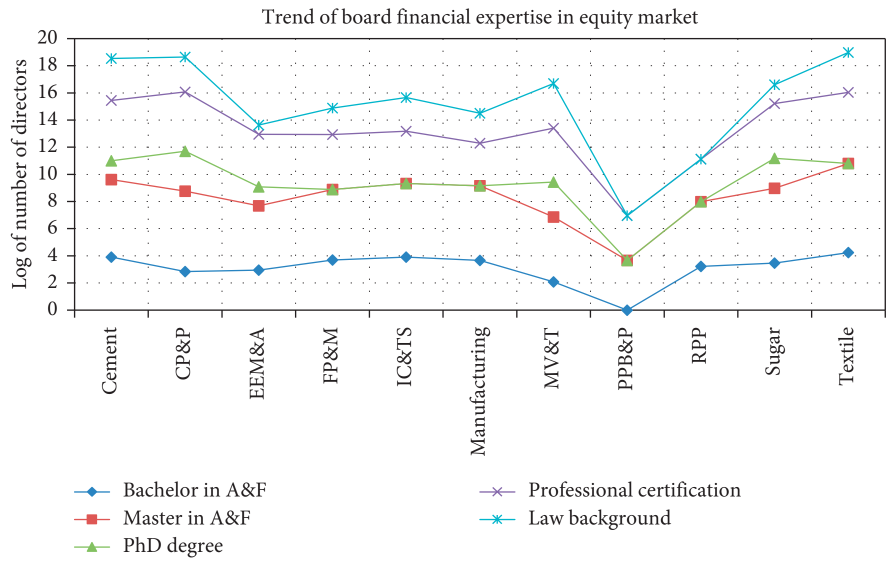

Figure 1: Trend of board financial expertise in Pakistani listed family firms.

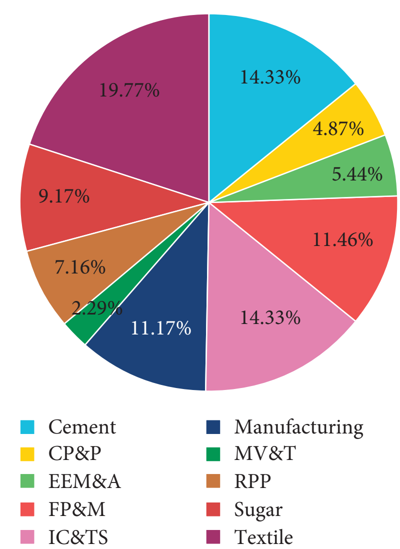

Figure 2: Decomposition of financial expertise in Pakistani listed family firms.

Table 2: Summary statistics.

Variable	Mean	Std. dev	Min	Max
CCET	0.04	0.07	0.0001	0.69
BS	8.08	1.75	5.00	15.00
BD	1.21	1.32	0.00	6.00
BI	0.98	1.69	0.00	8.00
BFE	1.73	2.01	0.00	10.00
DIVT	0.03	0.05	0.00	0.32
CE	0.80	0.31	0.00	2.15
IO	1.38	2.04	−2.27	19.19
FS	8.09	1.71	2.77	12.82
LEV	0.61	0.26	0.03	0.99
ROA	0.11	0.11	−0.45	0.57
FL	1.40	1.34	0.00	11.81
CF	0.10	0.15	−0.51	1.55

Table 3: Correlation matrix.

	CCET	BS	BD	BI	BFE	DIVT	CE	IO	FS	LEV	ROA	FL	CF
CCET	1												
BS	0.2546	1											
BD	0.3175	0.0652	1										
BI	−0.1449	0.0439	0.0658	1									
BFE	−0.2096	0.0648	−0.2017	0.3274	1								
DIVT	−0.1103	−0.071	0.0034	0.0935	0.0626	1							
CE	−0.2269	−0.2445	−0.0531	0.0494	−0.0292	0.0308	1						
IO	0.5308	0.1807	0.0925	−0.1524	−0.0817	−0.0811	−0.2194	1					
FS	−0.1924	0.1913	−0.1928	−0.0417	0.2454	−0.0491	−0.1777	−0.0527	1				
LEV	−0.2315	−0.1567	0.0611	0.0112	−0.0991	0.0793	0.2754	−0.4224	−0.1335	1			
ROA	0.4927	0.1876	0.0758	−0.1423	−0.0948	−0.1192	−0.2896	0.4785	0.04	−0.4356	1		
FL	−0.009	−0.0521	−0.1367	0.0172	0.084	−0.052	−0.1594	0.0663	−0.072	−0.3832	0.0878	1	
CF	0.5216	0.3345	0.1237	−0.1037	−0.0268	−0.0718	−0.2074	0.3782	0.0617	−0.3534	0.5972	0.0251	1

4.1. Examination of Hypothesis 1 (H1a, H1b, H1c, and H1d): Board Financial Expertise and Cash Holding Policy. Table 4 shows regression estimates for the association among board financial expertise, the board size, board independence, and board diversity with cash holding policy. Findings of the fixed and random effect model show a significant negative effect of financial expertise on cash holding. However, the Hausman test depicts that the fixed effect model (FE) is suitable, whereas Wald and endogeneity test show the presence of endogeneity and heteroscedasticity, which makes the FE estimates susceptible.

Board financial expertise has a negative and significant impact on cash holding. These results are consistent with existing [67, 97] studies that strong governance is linked with less cash holding as excess cash can be used for personal shareholder benefits. Board size has a significant positive relationship with cash holding; these results are consistent with the studies of [98, 99, 137]. As studies reveal that a large board appears to be more inefficient, companies with a large board inferred poor corporate governance with a higher managerial cost. Coefficients of board independence are negative with cash holding consistent with the studies of [47, 55, 69] argued as lower information asymmetry is associated with higher BI. Because external finance providers may think that BI is a positive signal for a firm, there is no need to hold more cash in this situation. The relationship between BI and cash holding is negative. Coefficients of board diversity are positive with cash holding, which is consistent with the studies of Loukil and Yousfi [49] and Van Uytbergen and Schoubben [139], who argued that females having risk-averse behavior and less confident nature hold more cash reserves, and firms with gender-diverse boards hold more cash. Investment opportunities have a positive coefficient with cash holding because growth opportunities require high cash holdings [141]. Cash flows have a significant positive effect on cash holdings, which is consistent with the pecking order theory, which proposes that firms are generating more cash flows and are engaged to hold more cash. Firm size has a significant negative association with cash holdings, which is consistent with trade-off theory. Since larger firms can gain profit through economies of scale [151], have constant cash flows, prefer more diversification, and have easy accessibility of financial markets with low borrowing cost [30, 61], capital expenditure also negatively affects cash holding, consistent with Jebran et al. [140]. The relation between dividends and cash holdings proxies is negative and statistically significant, consistent with trade-off theory and existing studies [137, 152]. Liquidity has a negative relationship with cash holding because liquid assets could be considered a substitute for cash when firms face a cash shortage [30]. More levered firms will accumulate large cash to diminish the risk of financial distress and bankruptcy; therefore, the relationship between leverage and cash holding could be positive according to trade-off theory. Profitability has a positive association with cash holdings, consistent with the study of Al-Najjar and Clark [53].

4.2. Examination of Hypothesis 2 (H2a, H2b, and H2c): Multiple Large Shareholders and Cash Holding Policy. Table 5 demonstrates the findings of the impact of MLS—presence, control contest, and number of LS—towards corporate cash holding in listed family firms of the emerging economy. It presents the results of 7 models, comprehensive measures to capture the MLS and its impact on cash holding. Hypothesis H2a is related to MLS structure, and Table 5, model 1, shows that MLS structure directly impacts cash holding ($P < 0.001$). Thus, hypothesis H2a is accepted, which suggests that the presence of MLS is related to more cash reserves. These results are consistent with Liu et al. [16] as MLS does not play a monitoring role in the alleviation of agency conflicts and the reduction of families' expropriation in the emerging economy as they played in developing countries [120, 126].

Hypothesis H2b concerns MLS competition for control, operationalized through two variables, that is, contest 1 and contest 2, expecting a positive impact on cash holding. Table 5, model 2, shows that contest 1 has a positive and significant coefficient ($P < 0.001$), and model 3 shows that contest 1 squared has a positive and significant coefficient ($P < 0.001$). Similarly, model 4 shows that contest 2 has a positive and significant coefficient for the alternative measure, and model 5 shows that contest 2 squared has a positive and significant coefficient. These results are consistent with

Table 4: Board financial expertise impact on cash holding of family firms.

Variables	CCET Random	CCET Fixed	CCET GMM1	CCET GMM2
L.CCET	0.59*** (0.018)	0.208*** (0.023)	0.132*** (0.002)	0.211*** (0.002)
BS	0.002** (0.001)	0.007*** (0.001)	0.009*** (0.0004)	0.007*** (0.003)
BD	0.005*** (0.001)	0.007*** (0.001)	0.011*** (0.001)	0.015*** (0.0004)
BI	−0.001 (0.001)	−0.002** (0.001)	−0.002** (0.001)	−0.003*** (0.0004)
BFE	−0.001* (0.001)	−0.001** (0.001)	−0.001*** (0.002)	−0.002*** (0.0001)
DIVT	−0.033 (0.023)	−0.032 (0.020)	−0.025*** (0.007)	−0.035*** (0.007)
CE	−0.005 (0.004)	−0.013** (0.006)	−0.007** (0.003)	−0.018*** (0.002)
IO	0.007*** (0.006)	0.009*** (0.001)	0.011*** (0.0002)	0.010*** (0.0001)
FS	−0.004*** (0.001)	−0.007*** (0.001)	−0.003*** (0.0004)	−0.003*** (0.0003)
LEV	0.016** (0.005)	0.018** (0.016)	0.017*** (0.002)	0.012*** (0.002)
ROA	0.042** (0.014)	0.062*** (0.015)	0.029*** (0.006)	0.029*** (0.002)
FL	−0.001 (0.010)	−0.002* (0.001)	−0.003*** (0.001)	−0.004*** (0.001)
CF	0.067*** (0.010)	0.05*** (0.009)	0.063*** (0.003)	0.092*** (0.003)
P value			0.000	0.000
R-square	0.3354	0.4532		
Hausman test		0.000		
Heteroscedasticity test		0.000		
Sargan statistics			0.107	0.125

Note. t-statistics are in parentheses. *, **, and *** show the significance level of 99%, 95%, and 90%. The table shows the findings of the influence of financial expertise on cash holdings by considering other governance and firm's specific variables on the sample of listed family firms in Pakistan. It shows the results of fixes, random, and GMM estimation techniques. Furthermore, it also reports the result of the Hausman test, a test of heteroscedasticity, and Sargan statistics.

Luo et al. [46] study when a contest for control raises the monitory role of multiple large shareholder declines, making an alliance with controlling families and holding more cash. Thus, we accept hypothesis H2b. Our hypothesis H2c is related to the number of LS. For hypothesis H2c, we posited that the number of large shareholders blocks in Table 4 with model 6 has a positive relation with cash holding ($P < 0.001$). While the model 7 blocks' number squared is positively and significantly related to corporate cash holding ($P < 0.001$), accepting the hypothesis H2c that blocking the number has a direct impact on the cash holding behavior of family firms.

4.3. Examination of Hypothesis 3: Moderator Role of Multiple Large Shareholders in the Relation between Financial Expertise and Cash Holding. Table 6 presents the moderating role of MLS in the relationship between corporate governance and cash holding of family firms. As model 1 in Table 6 shows, multiple large shareholders have a significant positive impact on board size and cash holding relationship. Similarly, model 2 represents the presence of multiple large shareholders significantly positively impacting the relationship between board diversity and cash holding. Model 3 results indicate that multiple large shareholders significantly moderate the relationship between board independence and cash holding in family firms. Therefore, in the presence of MLS, board independence cannot reduce cash holding. Instead, it leads to having more cash in family firms. Similarly, model 4 results indicate that multiple large shareholders decrease the impact of board financial expertise to improve corporate governance by reducing cash holding since multiple large shareholders family firm hold more cash and board financial expertise cannot mitigate cash holding. Therefore, we accept our hypothesis H3.

5. Discussion

We split this study into three main objectives. We for the first time examine the impact of board financial expertise along with other board attributes on cash holding. Secondly, we develop seven models to analyze the effect of MLS (a proxy of internal governance) structure on cash holding. Thirdly, we develop five novel models to investigate the moderating effect of MLS structure in the relationship between corporate governance characteristics and cash holding in family firms.

The impact of financial experts on cash holding is inverse for Pakistani family firms. It indicates that firms with more financial experts on board reduce the cash holding due to the strong corporate governance, which reflects their financial advice to policymakers regarding the cash reduction policy. We accept hypothesis H1a, and the finding confirms that strong governance leads towards low cash holding [67, 97]. The study also reveals that cash holding in Pakistani family firms is influenced by the increase in board size. Therefore, we accept the hypothesis H1b, which is consistent with the existing studies [98, 99, 137, 138] that bigger board size appears to be idle in decision-making and has more managerial cost and easier for them to control CEO. In addition, board independence is negatively related to cash holding, which leads to the acceptance of hypothesis H1c. These results are consistent with the existing studies [47, 55, 69, 138], lower information asymmetry comes through higher board independence, and firms may be able to finance externally because the provider of external finance is concerned with more increased board independence that reduces the need for excess cash. The impact of board diversity on cash holding is positive; therefore, we accept hypothesis H1d. Our findings are consistent with the existing studies [49, 139]. Females are supposed to have less

Table 5: Multiple large shareholders impact on cash holding.

	Model 1		Model 2		Model 3		Model 4		Model 5		Model 6		Model 7	
	GMM 1	GMM2	GMM 1	GMM2	GMM 1	GMM2	GMM 1	GMM2	GMM 1	GMM2	GMM 1	GMM 2	GMM 1	GMM 2
L.CCET	0.131***	0.202***	0.132***	0.212***	0.132***	0.211***	0.129***	0.201***	0.128***	0.199***	0.096***	0.131***	0.087***	0.115***
	(0.002)	(0.003)	(0.002)	(0.003)	(0.002)	(0.003)	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)	(0.003)	(0.002)
BS	0.009***	0.006***	0.009***	0.007***	0.009***	0.007***	0.009***	0.007***	0.009***	0.006***	0.008***	0.006***	0.008***	0.006***
	(0.0004)	(0.0002)	(0.0004)	(0.0003)	(0.0004)	(0.0003)	(0.0004)	(0.0002)	(0.0004)	(0.0002)	(0.0004)	(0.0002)	(0.0004)	(0.0002)
BD	0.011***	0.014***	0.012***	0.015***	0.012***	0.015***	0.011***	0.015***	0.011***	0.003***	0.010***	0.011***	0.009***	0.010***
	(0.0004)	(0.0003)	(0.0004)	(0.0004)	(0.0004)	(0.0003)	(0.0005)	(0.0003)	(0.0004)	(0.0003)	(0.001)	(0.0003)	(0.0004)	(0.0003)
BI	−0.001*	−0.002***	−0.001*	−0.002***	−0.001**	−0.003***	−0.001**	−0.002***	−0.001*	−0.002***	−0.0001	−0.001**	−0.0001	−0.001
	(0.0001)	(0.0004)	(0.0005)	(0.0004)	(0.0004)	(0.0004)	(0.0004)	(0.0002)	(0.0001)	(0.0004)	(0.0004)	(0.0002)	(0.0001)	(0.0004)
BFE	−0.001***	−0.002***	−0.002***	−0.002***	−0.001***	−0.002***	−0.001***	−0.002***	−0.001***	−0.002***	−0.001***	−0.002***	−0.0003***	−0.001***
	(0.002)	(0.0001)	(0.0002)	(0.0001)	(0.0002)	(0.0001)	(0.0004)	(0.0001)	(0.002)	(0.0001)	(0.0001)	(0.0001)	(0.002)	(0.0001)
Block dummy	0.016***	0.017***												
	(0.001)	(0.001)												
Contest1a			0.004***	0.017***										
			(0.001)	(0.001)										
Contest1asqr					0.001***	0.0004**								
					(0.0002)	(0.0001)								
Contest2a							0.002***	0.002***						
							(0.0001)	(0.0002)						
Contest2asqr									0.0003***	0.0003***				
									(0.001)	(0.001)				
Block number											0.012***	0.014***		
											(0.002)	(0.0002)		
Block numbersqr													0.0003***	0.0005***
													(0.001)	(0.001)
Control variables	*Included*	*Included*	*Included*	*Included*	*Included*	*Included*	*Included*	*Included*	*Included*	*Included*	*Included*	*Included*	*Included*	*Included*
P value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Sargan statistics	0.120	0.101	0.102	0.118	0.104	0.120	0.225	0.252	0.241	0.265	0.200	0.267	0.198	0.268

Table 6: The moderating role of multiple large shareholders on the relationship between board financial expertise and cash holding.

	Model 1		Model 2		Model 3		Model 4		Model 5	
	GMM 1	GMM2	GMM 1	GMM2	GMM 1	GMM2	GMM 1	GMM2	GMM 1	GMM2
L.CCET	0.130*** (0.003)	0.203*** (0.003)	0.132*** (0.003)	0.191*** (0.002)	0.141*** (0.002)	0.210*** (0.002)	0.148*** (0.003)	0.208*** (0.002)	0.145*** (0.003)	0.198*** (0.003)
BS	0.007*** (0.0004)	0.004*** (0.0002)	0.008*** (0.0003)	0.006*** (0.0002)	0.008*** (0.0004)	0.006*** (0.0002)	0.010*** (0.0004)	0.006*** (0.0002)	0.008*** (0.0004)	0.006*** (0.0004)
BD	0.011*** (0.001)	0.014*** (0.0004)	0.004*** (0.001)	0.005*** (0.0003)	0.007*** (0.001)	0.010*** (0.0003)	0.007*** (0.001)	0.010*** (0.0003)	0.003*** (0.0006)	0.004*** (0.0006)
BI	−0.001* (0.0004)	−0.001*** (0.0004)	−0.001** (0.0004)	−0.003*** (0.0003)	−0.003*** (0.0005)	−0.004*** (0.0003)	−0.001** (0.003)	−0.001*** (0.0003)	−0.002*** (0.0003)	−0.002*** (0.0003)
BFE	−0.001*** (0.0002)	−0.002*** (0.0001)	−0.001*** (0.0002)	−0.002*** (0.0001)	−0.002*** (0.0001)	−0.002*** (0.0001)	−0.004*** (0.0003)	−0.004*** (0.0001)	−0.002*** (0.0003)	−0.003*** (0.0003)
BS ∗ BD	0.002*** (0.0001)	0.002*** (0.0001)							0.0005 (0.0001)	0.002 (0.0001)
BDi v ∗ BD			0.011*** (0.001)	0.013*** (0.0004)					0.006*** (0.001)	0.006*** (0.001)
ID ∗ BD					0.010*** (0.0002)	0.010*** (0.0002)			0.004*** (0.0004)	0.004*** (0.0004)
BFE ∗ BD							0.006*** (0.0002)	0.006*** (0.0002)	0.004*** (0.0003)	0.004*** (0.0003)
Control variables	*Included*	*Included*	*Included*	*Included*	*Included*	*Included*	*Included*	*Included*	*Included*	*Included*
P value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Sargan statistics	0.087	0.091	0.249	0.211	0.333	0.302	0.165	0.216	0.301	0.285

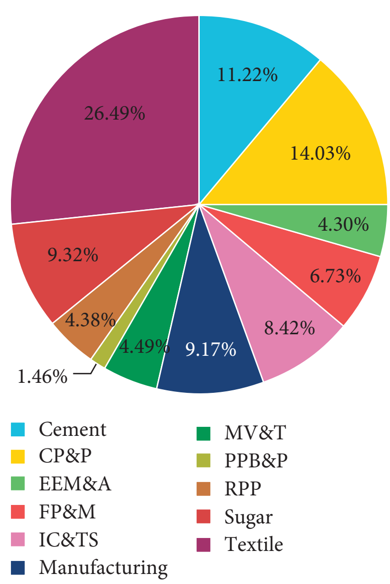

Figure 3: Decomposition of financial expertise (bachelor in A&F) in equity market.

confidence in nature and have a risk-averse attitude; therefore, family firms with more females on board hold more cash in emerging economies.

Our findings show that MLS's presence, contestability for control, and number of measures significantly positively impact cash holding. Therefore, this study accepts the hypotheses H2a, H2b, and H2c. These outcomes represent that, in our sample, investors can notice that MLS are not playing their monitoring role to prevent family firms' expropriation from mitigating agency conflicts as practicing in developed economies [120, 126]. Furthermore, the result reveals that, in the presence of MLS structure, board financial expertise also leads to excess cash holding, which confirms that MLS contributes to weak corporate governance mechanisms in family firms. Hence, we accept our hypothesis H3. It is argued that corporate governance mechanisms work to

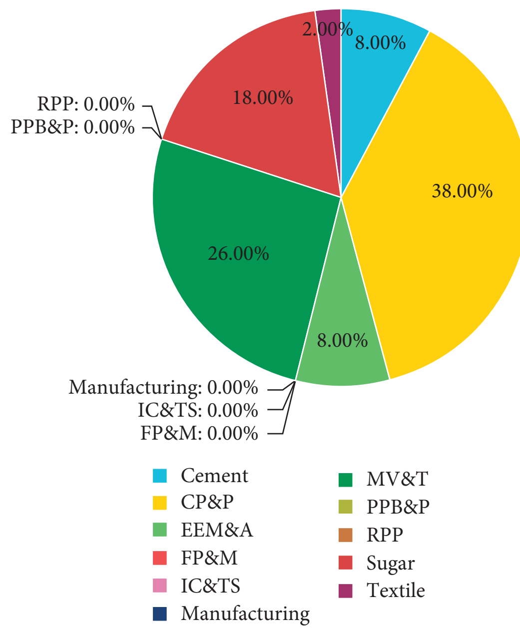

Figure 4: Decomposition of financial expertise (master in A&F) in equity market.

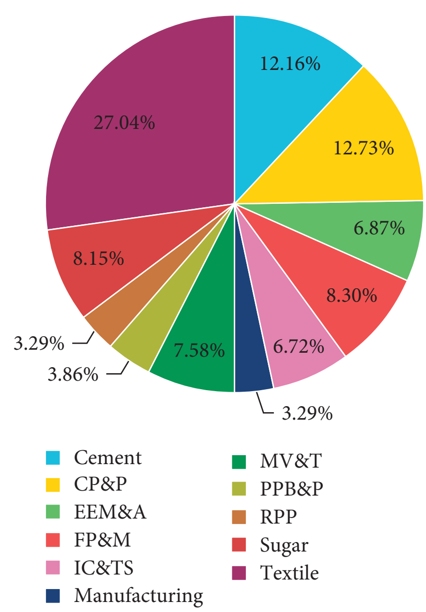

Figure 5: Decomposition of financial expertise (PhD degree) in equity market.

strengthen compliance because firms contribute to a healthy economy [153]. However, Pakistan's economy needs to practice corporate governance in the true sense to establish an influential position. In Pakistan, listed firms practicing with weak governance [154] and regulatory bodies can barely put corporate governance code into practice. Consistent with the literature [155], there are unspecified obstacles that discourage the practice of corporate governance code in Pakistani firms. Furthermore, in most Pakistani firms, independent directors are ineffective, ownership is concentrated, and scarcity of professional's wisdom and inadequacy of professionals in firms are increasing barriers to developing improvements in Pakistan's corporate governance system.

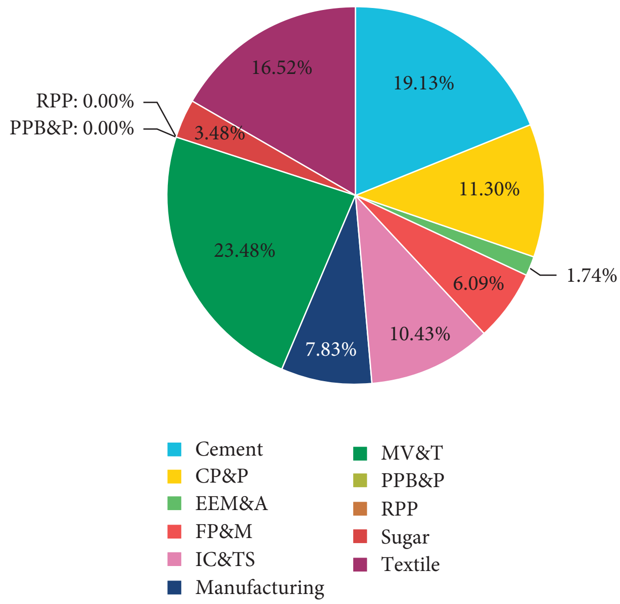

Figure 6: Decomposition of financial expertise (professional certification) in equity market.

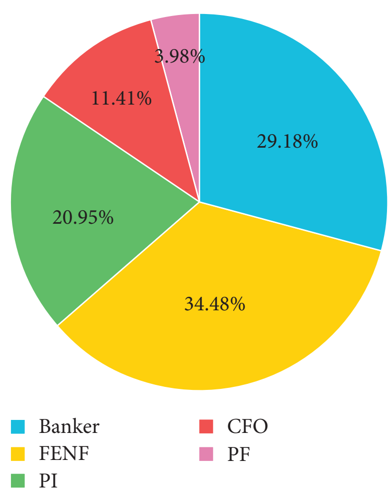

Figure 7: Decomposition of financial expertise (law background) in equity market.

Table 7: List of variables.

Variable types	Variable name	Symbol	Variable explanation
Explained variable	Cash holding	CCET	Cash and cash equivalent to net assets
Governance variable	Board size	BS	Entire size of the corporate board at the last of fiscal year
	Gender diversity	BD	Number of female directors on board
	Independent director	BI	Proportion of independent directors on board to the entire board of directors
	Board financial expertise	BFE	Proportion of financial expertise on corporate board to total board members

Table 7: Continued.

Variable types	Variable name	Symbol	Variable explanation
Moderating variable	Presence of MLS	Block dummy	If the second-largest shareholder has more than 10% equity rights
	Control contest	Contest 1	The summation of the second- to fifth-larger shareholders' equity rights to the first-larger shareholder's equity rights
		Contest 2	Square the summation of the second- to third-largest shareholder's equity right difference, third- to fourth-large shareholder's equity right difference, and fourth- to fifth-large shareholder's equity rights difference
	Number of MLS	Block number	The second- to fifth-large shareholders who own at least 10% equity rights
Control variable	Dividend payout	DivT	Dividend paid per share every year
	Capital expenditure	CE	Summation change in fixed assets and depreciation to net assets
	Investment opportunity	IO	Proportionate of stock market value plus debt's book value to asset's book value
	Firm size	FS	Ln of total asset
	Profitability	ROA	Companies' profit to net assets every year
	Leverage	LEV	Ratio of comparison between total debt to total assets of firm's
	Liquidity	Liq	Net working capital less cash, divided by net assets
	Cash flow	CF	Cash flow to net assets every year

6. Conclusion

We for the first time analyze the impact of board financial expertise on the cash holding policy of family firms. Our other novel contributions are investigating the moderating role of MLS structure in the relationship between corporate governance characteristics and firm cash holding. The current research focused on board financial expertise as a proxy of internal governance and other board attributes to analyze its impact on cash holding. This study is based on data from Pakistani family listed companies from 2006 to 2017. We employ static and dynamic panel estimation techniques for examining the board's financial expertise and cash holding policy.

Findings strongly support our argument and suggest inverse relationships between board financial expertise and corporate cash holding. These findings recommend that a top-quality board can send back a controlling family's momentum for unnecessary cash holdings by cutting down the volume of liquid assets. Overall findings of research support the monitoring role of financial experts in concentrated ownership context, which stressed the importance of the board of directors towards quality governance. Further, we considered the MLS structure as an internal governance proxy to see the relationship with cash holding. Under consideration of monitoring and entrenchment effect of MLS structure, our findings reveal that MLS structure does not always mitigate agency conflicts. Specifically, different proxies of the MLS structure increase cash holding in Pakistani family firms. Additionally, the result shows that MLS structure significantly positively moderating the relationship between corporate governance characteristics and firm cash holdings.

Besides the novel contribution to existing literature, this study also has the following practical policy implications. First, the finding reveals that financial experts significantly shape family firms' cash holdings in emerging economies. Further, policymakers should strengthen corporate governance by having more financial experts on the corporate board. Secondly, investors and policymakers should also consider the MLS structure before any investment. Because finding reveals that companies with sole large shareholders or with MLS structure are not attractive for investments, under inadequate legal protection for investors, MLS might collude with controlling shareholders to tunnel and share private incentives. Thirdly, the Securities and Exchange Commission of Pakistan and other regulatory authorities of the stock exchange could demand a mandatory provision to include financial experts on board. Regulators significantly focus on the supervision of family firms with sole large shareholders or with several large shareholders due to more agency problems within these ownership structures.

Despite contributions in prevailing literature, we recommend the following guidelines for future potential researchers. First, we ignore the financial expert's identity effect, for example, legal, financial expert, and accounting financial expert. However, various financial experts might have different professional skills, resources, and benefits to monitor controlling families. Therefore future research should focus on these aspects of board financial experts. Second, we also ignore the effect of large shareholder's identity through different large shareholders who might contribute with professional knowledge, skills, and resources, which help in the monitoring of the family firm. Therefore, future research could see the aspect of large shareholder identities. Thirdly, our empirical study took the sample of listed family firms only. Therefore, further study is required to explore the nonlisted family firms and nonfamily firms, as agency costs might vary among these firms. Another limitation of this study is generalizability as we only consider one economy. However, Pakistan is an emerging economy, but other emerging economies like China, Russia, or India have different institutional contexts from Pakistan, which may give different results. Therefore, future work should explore our argument's boundary across numerous emerging economies.

Appendix

A

The definition of variables is provided in Table 7.

B

The graphs of board financial expertise across listed family firms are given in Figures 3–7.

Data Availability

The data used to support the findings of the study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no potential conflicts of interest concerning the research, authorship, and/or publication of this article.

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Research Article

Optimal Financing Decision in a Contract Food Supply Chain with Capital Constraint

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To solve the financing problem of the food producers, we consider a two-echelon contract food supply chain composed of a family farm with capital constraints and a food processing enterprise. With no capital constraints as the benchmark model, we analyze optimal decisions of the family farm and the food processing enterprise in the case of bank financing with bank participation only and bank financing with "government, bank, and insurance" coparticipation. Then, we discuss how the risk of yield uncertainty influences the optimal decisions and profits of the family farm and the food processing enterprise under different financing situation. Meanwhile, the reason why the government subsidizes agriculture is explored, and the policy of minimum purchase price of the food is initiated when the market price is too low. Finally, the numerical examples and sensitivity analysis are presented. The results show that the bank financing with "government, bank, and insurance" coparticipation improves the welfare of supply chain members more obviously than the bank financing with bank participation only; when the rice price is too low, the policy of minimum purchase price of food is initiated, which increases the revenue and the growing enthusiasm of the family farm; the profits of the family farm and the food processing enterprise will decrease as the risk of yield uncertainty increases in the case of bank financing, and the risk of yield uncertainty will be reduced for the family farm when bank financing with "government, bank, and insurance" coparticipation.

1. Introduction

As the Chinese saying goes "Hunger breeds discontentment," food security is self-evident to a country and is the foundation of national security. COVID-19 made the global food trade situation extremely severe in 2020, where 18 countries around the world banned food exports, and more than 20 countries increased their food reserves. Countries have paid more attention to food production to ensure their own food security since 2020. According to the National Bureau of Statistics of China, China's total food yield in 2020 was 669.49 million tons, which was 5.65 million tons more than in 2019, and the food yield has remained at more than 500 million tons since 2008. However, the national conditions of limited arable land and large population require us to be mindful of crisis in times of peace and ensure national food security. The embryonic form of moderately scaled agricultural development has emerged in recent years with the development of urbanization in China, and many large-scale operation entities represented by family farms, cooperatives, large specialized growers, and agricultural enterprises have emerged, which are the main force in the production of commodity food. The yield of the agricultural products is uncertain because its production is susceptible to natural conditions. At the same time, agricultural production materials, land transfer cost, labor cost, agricultural social service purchase cost, and purchase and maintenance cost of agricultural machines are all inseparable from financial support. However, there is an urgent need for efficient financing due to the lack of collateral for food growers and the short preparation time for crop production, but banks often hesitate to lend to reduce bad debts.

Supply chain finance refers to two or more organizations and external service providers in a supply chain that work together to create the value of all participating companies by planning, steering, and controlling the flow of financial resources at an interorganizational level [1, 2]. Meanwhile, it is an effective way to solve the financing problem of small- and medium-sized enterprises (SMEs) [3–6], which is widely used in the manufacturing industry. We learn that the characteristics of family farms are similar to those of SMEs, so supply chain finance may be one of the feasible ways to solve their financing problem. However, food is an agricultural product that people must consume every day which has the attributes of a quasi-public product. The annual growing scale of food must be maintained above a certain safety level to ensure food security, and the yield is uncertain, which makes it different from the manufacturing supply chain. Government support is needed in food production and financing process, and many countries have corresponding domestic support policies for agricultural production in practice. In 2009, the agricultural loan mode of "government-bank-insurance" cooperation was firstly explored in Sanshui District, Foshan City, Guangdong Province, China. Up to now, Sanshui District has gone through 12 years of exploration, which has become the "golden key" to solve the problem of farmers' loans. In recent years, the agricultural loan mode of "government-bank-insurance" cooperation has also been promoted in China's Shandong, Hainan, and Fujian provinces and some other regions.

In this study, we discuss the financing decisions of the capital-constrained food supply chain and explore the following issues: is the mechanism of the choice of bank financing by the capital-constrained family farm consistent with the choice of bank financing by manufacturers in the manufacturing industry? Is it possible to simply apply the supply chain financing method which is relatively mature in the manufacturing industry to the contract food supply chain? Why are the food processing enterprises willing to choose contract farming? Why do the food processing enterprises provide guarantee for family farms when they choose bank financing? Why do governments need to intervene and support agricultural production? Why is the bank financing with "government, bank, and insurance" coparticipation an effective way to promote the financing for the family farm?

To answer these questions, we discuss a two-echelon contract food supply chain composed of a family farm with capital constraints and a food processing enterprise, where the food processing enterprise is the dominant and the family farm is the follower, and the family farm grows a single variety of rice. Assuming that the initial capital of the family farm is zero, short-term financing is required to prepare for production. Agricultural production is different from manufacturing production, which is susceptible to natural and climatic factors and has uncertain yield. Therefore, a yield random factor is introduced in this study. At the same time, the situation with no capital constraints is used as a benchmark model.

We analyze the mature supply chain financing model in the manufacturing industry where only banks participate at first. Then, after theoretically discussing why the government should subsidize agricultural production, we discuss the supply chain financing model in the case of "government, bank, and insurance" coparticipation, and the optimal decisions of the supply chain members are obtained. The conclusions show that financing improves the welfare of members of the supply chain, and the improvement is more significant in the case of bank financing with "government, bank, and insurance" coparticipation. However, the welfare of supply chain members fails to reach the welfare level of the benchmark model in either financing situation, which indicates that the cost generated in the financing process cannot be ignored.

The main contributions of this study are as follows: firstly, the yield uncertainty of agricultural supply chain is discussed, and yield random factor is introduced into the model, which is different from Huang & Lin [7]. Agricultural production is greatly affected by natural conditions, so its yield uncertainty cannot be ignored. Secondly, the government participation in agricultural production is theoretically discussed, and the theoretical basis of government support for agricultural production is analyzed. Thirdly, the minimum purchase price policy of rice is considered in the model, which effectively improves the welfare of the family farm, thereby increasing their enthusiasm for growing rice. The bank financing with "government, bank, and insurance" coparticipation can significantly improve the welfare of the supply chain members, which will be an effective way to solve the financing problem of the family farm.

The study is organized as follows: we review the literature review in Section 2 and then present the research model description and hypotheses in Section 3. Section 4 discusses the benchmark model, followed by analysis of decisions of the supply chain members when bank financing with bank participation only and bank financing with "government, bank, and insurance" coparticipation in Section 5. The numerical simulation and sensitivity analysis are presented in Section 6. Finally, the study's conclusions, management implications, and some future research suggestions are summarized.

2. Literature Review

The study focuses on yield uncertainty, contract farming, and supply chain finance and agricultural supply chain finance. Thus, the review of early literature related to the study includes three main research streams: yield uncertainty, contract farming, and supply chain finance and agricultural supply chain finance.

2.1. Yield Uncertainty. He and Zhao [8] analyzed the optimal decisions of the multiechelon supply chain with uncertainty of demand and supply and coordinated the supply chain through the combination of wholesale price contract and return strategy. Ding and Wan [9] discussed bank financing and manufacturer financing in a capital-constrained supply chain and demonstrated that the pay back contract can coordinate the supply chain in these two financing situations, in which the supplier's yield is random. In order to solve the problem of random yield, the downstream members of the supply chain will choose multiple suppliers [10–14]. Because agriculture is greatly affected by natural conditions, the uncertainty of its yield cannot be ignored. At present, some literature on agricultural supply chain discusses the issue on yield uncertainty. Kazaz and Webster [15] investigated the optimal sales price and production quantity in the case of supply uncertainty in the agricultural industry. Huang and Lin [7] analyzed the dynamic game among the government, the bank, the companies, and farmers in the case of uncertain yield and made a case analysis of the new agricultural loan model of "government-bank-insurance" in Sanshui District, Foshan City, Guangdong Province, China, and put forward suggestions for improvement. Peng and Pang [16] discussed the optimal decision of a contract farming supply chain composed of a farmer, a supplier, and a distributor under government subsidy policies, where the farmer's yield is uncertain.

2.2. Contract Farming. Contract farming comes into being in order to cope with the uncertainty of agricultural yield and demand. There are some studies on the coordination of contract farming supply chain under uncertain yield and uncertain demand, where Ye et al. [17] consider a revenue sharing-production cost sharing-guaranteed money mechanism and Liu et al. [18] adopt the revenue-sharing-plus-margin contract. Zhang [19] pointed out that China's contract farming is very different from the experience of other developing countries and conducted a political economic analysis of contract farming in China's agricultural transformation. Wuepper and Sauer [20] argue that self-efficacy and social capital are decisive factors for farmers to successfully integrate into contract farming. Bellemare and Novak [21] explain the role of contract farming in structural transformation. Shi and Cao [22] discuss whether agricultural producers are willing to form an alliance in order to jointly deal with the uncertainty of yield in contract farming, which reveals why agricultural producers should form cooperatives, how they should cooperate, and how to design fair profit distribution policy. Ba et al. [23] show that the healthy development of contract farming will promote the upgrading of the national rice value chain. Zhang [24] explores a blockchain-supported contract farming financing solution, which aims to improve the credit system and information asymmetry, thereby increasing the reliability of transactions and reducing the cost of traditional agricultural order financing. There are also some research studies suggesting that farmers' incomes and other welfare are increased by contract farming [25–33].

2.3. Supply Chain Finance and Agricultural Supply Chain Finance. Supply chain finance is an effective way to solve the financing problems of SMEs [2–6]. It transforms the uncontrollable risks of a single enterprise into the controllable risks of the entire supply chain, effectively constructs a benign industrial ecology for banks, core enterprises, and SMEs, and promotes the interactive development of capital and industry in the real trade situation through the effective control of cash flow, information flow, and logistics. There is a lot of literature on bank financing and upstream and downstream financing within the supply chain [9, 34–37]. However, the supply chain of agricultural products, especially food, is different from that of industrial products, and the government will provide subsidies to guarantee its supply [38, 39]; therefore, agricultural supply chain financing will also involve government subsidies. Van Bergen et al. [40] discuss the supply chain finance arrangement in the procurement of agricultural products and compare the three management strategies of soft tolling, hard tolling, and contract farming, and the supply chain is fully coordinated under the contract farming strategy. Yan et al. [41] investigate the financing strategies of the fresh produce supply chain. Yi et al. [42] analyze a two-echelon agricultural supply chain consisting of an intermediary platform and a farmer with capital constraints, where the intermediary platform directly provides loans for the farmer or provide guarantees for the farmer in bank financing, and shows that the two financing support ways of the intermediary platform improve the welfare of the farmer and increase the total profit of the supply chain.

The above literature is elaborated from the perspectives of yield uncertainty, contract farming, and supply chain finance and agricultural supply chain finance. It can be seen that there is some literature related to yield uncertainty and contract agriculture, contract agriculture and supply chain finance, and yield uncertainty and supply chain finance. However, there is relatively few literature that combines yield uncertainty, contract agriculture, and supply chain finance, and only Huang and Lin [7] try it, which is most relevant to our study. Huang and Lin [7] mainly discuss the government subsidy mechanism in the contract farming supply chain financing in which the yield is uncertain, and the yield uncertainty is measured by the probability of occurrence in bumper years and disaster years in their study. We focus on the optimal decision of supply chain members in the contract food supply chain with capital constraints, and we introduce a random variable to measure the uncertainty of yield which is different from Huang and Lin [7]. At the same time, the food in our study is the bulk agricultural products with different characteristics from the general agricultural products, so we conduct a theoretical analysis of the government's participation in food production.

3. Model Description and Assumptions

A two-echelon food supply chain in a large food-producing county in China is designed, which consists of a family farm with insufficient working capital and a food processing enterprise with sufficient working capital. Among them, the food processing enterprise is the dominant player in the supply chain, and the family farm is the follower. The two parties play a Stackelberg game to determine their optimal decision, as shown in Figure 1. According to the contract, the

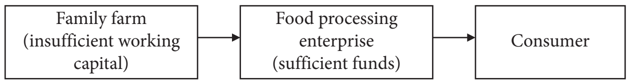

Figure 1: Two-echelon food supply chain structure.

family farm will grow a single variety of rice, which will be purchased by the food processing enterprise after being harvested and dried and then sold to consumers after being processed and further processed.

For simplicity, the initial capital of family farms is set as 0 which refers to Jing and Seidmann [43]. Through interviews with the staff of China Construction Bank, China Minsheng Bank, and other banks, we know that more and more upstream and downstream enterprises in the supply chain take the supply chain as a whole and take the credit of the core enterprises in the supply chain as the guarantee. The specific process is as follows: first, SMEs with capital constraints apply for loans from the bank. Then, the bank checks whether they are in the list according to the white list provided by the core enterprises. In this study, the core enterprise of the supply chain is the food processing enterprise, which dominates the whole supply chain, and the family farm is the follower. Second, the family farm applies for loans from the bank and provides the contract signed with the food processing enterprise. Then, according to a white list of approvals provided by the food processing enterprise, the bank disburses the loan to the food processing enterprise, which in turn disburses the loan to the family farm. Finally, the family farm obtains the loan to prepare for production.

The production of food is greatly affected by natural conditions, so its yield is highly random. At the same time, the property of food is quasi-public; therefore, the government will participate in regulation and control in order to ensure the country's food security. This study focuses on the bank financing decision of the food supply chain, which includes only the bank participation and "government, bank, and insurance" coparticipation.

The planned input of the family farm is q, which is affected by the growing area. X is the random factor of yield and $X \in [\mathrm{d1}, \mathrm{d2}]$ where d1 and d2 are constants. The density function of X is $g(x)$, and its distribution function is $G(x)$, where meet $E(X) = \mu$ and $D(X) = \sigma^2$. Meanwhile, σ^2 is used to measure the risk of yield uncertainty. All the rice harvested from the family farm is purchased by food processing enterprises. Q represents the actual yield of rice and satisfies $Q = qX$. In contrast to manufacturing economies of scale, agricultural production is diseconomies of scale [44], so we let the cost function $C(x) = c_1 q + cq^2$, where c_1 represents the input cost of unit rice production, such as labor, fertilizer, seed, and pesticide, and c represents the cost coefficient of production effort of the family farm. Meanwhile, we assume $c_1 = 0$ for simplicity. As mentioned before, food is a kind of staple agricultural products with the nature of quasi-public goods. When the market price of food is too low, the government entrusts the food processing enterprise with certain qualifications to purchase farmers' food at the minimum purchase price set by the government. p is the market sales price of food, and its demand function is $p = m - \beta Q$, where m represents the market size of rice and β represents the price elasticity coefficient of the rice.

In order to reduce the debt repayment risk of the family farm and prevent the supply chain disruption caused by bankruptcy of the family farm, the core enterprise of the supply chain, namely, the food processing enterprise, will purchase an insurance, and the government will subsidize it. The economic explanation is to encourage social capital to invest in the food industry through financial subsidy. And some other symbols used in this study are summarized in Table 1.

Some assumptions are given as follows:

A1: it is assumed that both sides of the supply chain will abide by the order contract and there will be no breach of contract; that is, there is no moral hazard.

A2: the working capital of the family farm is set at 0, and only the input cost of rice growing and the interest generated by financing are considered.

A3: the family farm, the food processing enterprise, the bank, and the government are risk-neutral and perfectly rational, and no information asymmetry such as Kouvelis and Zhao [35] and Luo et al. [37].

A4: as described in Kouvelis and Zhao [35], the residual value, out-of-stock cost, and holding cost of the product do not change the nature of the problem, and these costs are also ignored in this study, so the cost of the food processing enterprise only considers the purchase cost of rice, and the income of the food processing enterprise only considers rice processing and sale.

It can be seen from the assumptions that the members of the supply chain are risk-neutral, so their utility functions are the expected profit functions. For example, the optimal decision of the family farm is the input that maximizes its expected profit.

4. No Financing: The Benchmark

When the family farm has enough working capital, financing will no longer be needed, and the optimal decisions of the family farm and the food processing enterprise under this condition are obtained as follows.

The optimal decision for the family farm in this case is shown in the following equation:

$$\max \pi_{f0} = w_0 q_0 X - cq_0^2. \tag{1}$$

The optimal decision for the food processing enterprise in this case is shown in the following equation:

$$\max \pi_{m0} = p_0 q_0 X - w_0 q_0 X = (m - \beta q_0 X) q_0 X - w_0 q_0 X$$
$$\text{s.t.} \quad \begin{cases} q_0 = q_0^*, \\ w_0 \geq w. \end{cases} \tag{2}$$

Table 1: Introduction of the symbol.

Symbol	Symbolic meaning
w	The minimum purchase price of rice
q_i	q_0, q_1, and q_2, respectively, represent the planned input of the family farm when there is no financing, when bank financing with bank participation only, and when bank financing with "government, bank, and insurance" coparticipation
Q_i	Q_0, Q_1, and Q_2, respectively, represent the actual yield of the family farm when there is no financing, when bank financing with bank participation only, and when bank financing with "government, bank, and insurance" coparticipation
r_i	r_1 and r_2, respectively, represent the loan interest rate of the bank when bank financing with bank participation only and when bank financing with "government, bank, and insurance" coparticipation
w_i	w_0, w_1, and w_2, respectively, represent the rice purchase price given by the food processing enterprise when there is no financing, when bank financing with bank participation only, and when bank financing with "government, bank, and insurance" coparticipation
p_i	p_0, p_1, and p_2, respectively, represent the market price of rice when there is no financing, when bank financing with bank participation only, and when bank financing with "government, bank, and insurance" coparticipation
R_i	R_1 and R_2, respectively, represent financing amount when bank financing with bank participation only and when bank financing with "government, bank, and insurance" coparticipation, and $R_1 = cq_1^2$, $R_2 = cq_2^2$
Q_{thi}	Q_{th1} and Q_{th2}, respectively, represent the threshold of actual yield of the family farm when bank financing with bank participation only and when bank financing with "government, bank, and insurance" coparticipation, $Q_{th1} = (1+r_1)R_1/w_1$, $Q_{th2} = (1+r_2)R_2/w_2$
r_i	r_1 and r_2, respectively, represent the interest rate from the bank when bank financing with bank participation only and when bank financing with "government, bank, and insurance" coparticipation
r_f	Average return of the capital markets
d_{thi}	d_{th1} and d_{th2}, respectively, represent the threshold of yield random when the supply chain disruptions in the case of bank financing with bank participation only and in the case of bank financing with "government, bank, and insurance" coparticipation, and $d_{th1} = (1+r_1)R_1/q_1w_1$, $d_{th2} = (1+r_2)R_2/q_2w_2$
s	The bank loan subsidy rate given by the government to encourage banks to lend $(0 < s < 1)$
b	The premium rate given by the insurance company $(0 < b < 1)$
j	The insurance subsidy rate given by the government $(0 < j < 1)$
π_{fi}	π_{f0}, π_{f1}, and π_{f2}, respectively, represent the profit of the family farm when there is no financing, when bank financing with bank participation only, and when bank financing with "government, bank, and insurance" coparticipation
π_{mi}	π_{m0}, π_{m1}, and π_{m2}, respectively, represent the profits of the food processing enterprise when there is no financing, when bank financing with bank participation only, and when bank financing with "government, bank, and insurance" coparticipation
$E\pi_{fi}$	$E\pi_{f0}$, $E\pi_{f1}$, and $E\pi_{f2}$, respectively, represent the expected profits of the family farm when there is no financing, when bank financing with bank participation only, and when bank financing with "government, bank, and insurance" coparticipation
$E\pi_{mi}$	$E\pi_{m0}$, $E\pi_{m1}$, and $E\pi_{m2}$, respectively, represent the expected profits of the food processing enterprise when there is no financing, when bank financing with bank participation only, and when bank financing with "government, bank, and insurance" coparticipation

Proposition 1. *When there is no financing in the contract food supply chain, the optimal planned input of the family farm is* $q_0^* = m\mu/[4c - 2p(\sigma^2 + \mu^2)]$, *and the optimal purchase price of the food processing enterprise is* $w_0^* = mc/[2c - p(\sigma^2 + \mu^2)]$, *and the optimal purchase price of the food processing enterprise is* w *when* $w_0^* < w$.

Proposition 1 shows the optimal decisions of the family farm and the food processing enterprise in the case of sufficient working capital in the supply chain. At the same time, because of the quasi-public property of food, the food processing enterprise should purchase rice from the family farm at the minimum purchase price when $w_0 < w$.

Meanwhile, the optimal expected profits of the family farm and the food processing enterprise can be obtained as follows:

$$
\begin{aligned}
E\pi_{f0}^* &= \frac{m^2\mu^2 c}{4\left[2c - \beta\left(\sigma^2 + \mu^2\right)\right]^2},\\
E\pi_{m0}^* &= \frac{m^2\mu^2}{4\left[2c - \beta\left(\sigma^2 + \mu^2\right)\right]}.
\end{aligned}
\tag{3}
$$

We can draw Corollary 1 by analyzing the relationship among the risk of yield uncertainty and the optimal decisions and expected profits of the supply chain members.

Corollary 1. *When there is no financing in the contract food supply chain and the minimum purchase price policy is not considered, with the increase of the risk of yield uncertainty, the family farm will increase the scale of growing and the food processing enterprise will increase the purchase price, and the profits of the family farm and the food processing enterprise will increase accordingly.*

Corollary 1 shows that when there is no financing in the supply chain, the family farm will expand the scale of growing with the increase of the risk of yield uncertainty. As the scale of growing expands, input costs of the family farm continue to increase. Once the risk of random events occurs, the family farm's harvest will be severely damaged, but the price will rise as demand exceeds supply, so the expected profit of the family farm will increase. Similarly, for the food processing enterprise, as the risk of yield uncertainty increases, and the market will be in short supply, so the food processing enterprises will increase the purchase price. Even if the risk random event occurs, the food processing enterprise will not lead to a sharp decline in profits; on the contrary, his profit will increase with the increase of the risk of yield uncertainty. In fact, it is ideal that members of the supply chain have no financial constraints no matter how much investment is increased. Therefore, the situation described in Corollary 1 does not exist in practice and is only for comparison.

5. Bank Financing

With the development of economy and society, the competition among enterprises in the 21st century has transformed into competition among supply chains and it has become a consensus. There are many SMEs in the upstream and downstream of the supply chain. "Difficult to finance" and "expensive financing" are very common for SMEs, while solutions may be provided by supply chain finance. Due to the quasi-public product characteristics of food, this study analyzes two types of supply chain finance. In the first case, the supply chain members and the bank participate, and in the other case, the supply chain members and "government, bank, and insurance" participate together. Financing costs will be incurred, so in these two financing situations, the decision-making of the family farm and the food processing enterprise and how their welfare will change are the focus of our next analysis.

5.1. Bank Financing with Bank Participation Only

5.1.1. Financing Interest Rate When Bank Financing with Bank Participation Only. According to the previous assumption, the working capital of the family farm is 0, and she needs to finance $R_1 = cq_1^2$ from the bank and needs to repay $R_1(1 + r_1)$ at the end of the period. When a random event occurs, the actual yield of the family farm is not enough to repay loans, so there is a risk of supply chain disruption. Q_{th1} and d_{th1}, respectively, represent the threshold of the family farm' actual yield and the threshold of yield random when the supply chain disruptions. The yield of the family farm can repay the loan when $X \geq d_{th1}$.

As a rational decision-maker, the bank considers that the expected return on financing should be at least equal to the average return on the capital market when deciding whether to lend. The interest rate r_1 is designed based on the expected return on financing equal to the average return on the capital market as the following equation:

$$\int_{d_1}^{d_{th1}} w_1 Q_1 g(x)\mathrm{d}x + \int_{d_{th1}}^{d_2} w_1 Q_{th} g(x)\mathrm{d}x = \int_{d_1}^{d_{th1}} w_1 q_1 x g(x)\mathrm{d}x + \int_{d_{th1}}^{d_2} (1 + r_1)R_1 g(x)\mathrm{d}x = R_1\left(1 + r_f\right). \quad (4)$$

Proposition 2. *When there is competition in the capital market, the financing rate r_1 will increase with the increase of the average rate of return r_f in the capital market.*

Proposition 2 shows that the financing rate r_1 will increase with the increase of the average rate of return r_f in the capital market and the problems of "difficult financing" and "expensive financing" will become prominent. Therefore, bank financing of the contract supply chain with bank participation only could not solve the financing problem in the supply chain cause of the quasi-public property of food.

5.1.2. Decisions When Bank Financing with Bank Participation Only. In 1992, Christopher predicted that the competition among enterprises would transform into competition among supply chains in the 21st century. Nowadays, supply chain financing has become the main way to solve the financing problems of SMEs. Family farms have similar characteristics to SMEs, so the study will employ supply chain financing to solve the financial constraints of the family farm. As shown in Figure 2, the process of bank financing with bank participation only is as follows: firstly, the food processing enterprise and the family farm who has capital constrains sign an order contract. Secondly, the family farm applies for loans from the bank and provides the order contract, the bank will make loans to the food processing enterprise after approval, and then it is offered to the family farm by the food processing enterprise. Thirdly, the food processing enterprise repays the loans and purchases all the rice according to the order after the harvest, and the remaining payment is delivered to the family farm by the food processing enterprise after deducting the principal and interest of the loan. If there is a random event of yield, the risk will be borne by the food processing enterprise.

The expected profit of the family farm when bank financing with bank participation only is shown in the following equation:

$$E\pi_{f1} = w_1 q_1 \mu - (1 + r_1)cq_1^2. \quad (5)$$

The profit of the food processing enterprise when bank financing with bank participation only is shown in the following equation:

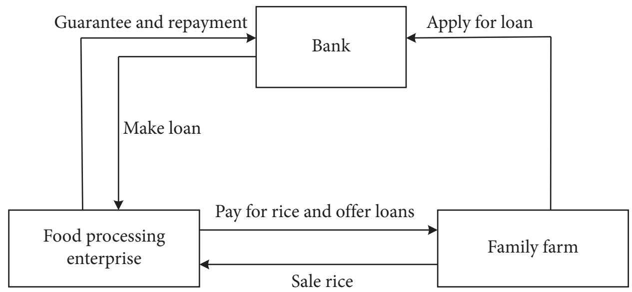

FIGURE 2: Operation diagram for bank financing with bank participation only.

$$\pi_{m1} = p_1 q_1 X - w_1 q_1 X = (m - \beta q_1 X) q_1 X - w_1 q_1 X = m q_1 X - w_1 q_1 X - \beta q_1^2 X^2$$
$$\text{s.t.} \begin{cases} q_1 = q_1^*, \\ w_1 \geq w. \end{cases} \quad (6)$$

The expected profit of the food processing enterprise when bank financing with bank participation only is shown in the following equation:

$$E\pi_{m1} = m q_1 \mu - w_1 q_1 \mu - \beta q_1^2 (\sigma^2 + \mu^2). \quad (7)$$

Proposition 3. *When the family farm has capital constraint, optimal decisions when bank financing with bank participation only are as follows: the optimal planned input of the family farm is $q_1^* = m\mu/\{2[2c(1+r_1) + \beta(\sigma^2+\mu^2)]\}$, and the optimal purchase price of the food processing enterprise is $w_1^* = mc(1+r_1)/[2c(1+r_1) + \beta(\sigma^2+\mu^2)]$, and the optimal purchase price of the food processing enterprise is w when $w_1^* < w$.*

Proposition 3 shows the optimal decisions of the family farm and the food processing enterprise in the case of bank financing with bank participation only. At the same time, because of the quasi-public property of food, the food processing enterprise should purchase rice from the family farm at the minimum purchase price when $w_0 < w$.

We can draw Corollary 2 by analyzing the relationship among yield uncertainty and the optimal decisions and expected profits of the supply chain members.

Meanwhile, the optimal expected profits of the family farm and the food processing enterprise in the case of bank financing with bank participation only can be obtained as follows:

$$E\pi_{f1}^* = \frac{m^2 \mu^2 c(1+r_1)}{4\left[2c(1+r_1) + \beta\left(\sigma^2+\mu^2\right)\right]^2},$$
$$E\pi_{m1}^* = \frac{m^2 \mu^2}{4\left[2c(1+r_1) + \beta\left(\sigma^2+\mu^2\right)\right]}. \quad (8)$$

Corollary 2. *When bank financing with bank participation only and the minimum purchase price policy is not considered, with the increase of the risk of yield uncertainty, the family farm will decrease the scale of growing and the food processing enterprise will decrease the purchase price, and the profits of the family farm and the food processing enterprise are all reduced as a result.*

Corollary 2 shows that in the case of bank financing with bank participation only, the increase of the risk of yield uncertainty will cause the family farm to reduce the scale of growing, and the food processing enterprise will reduce the purchase price, which in turn will decrease the profits of the family farm and the food processing enterprise. Due to financial constraints, when the family farm applies for loans from the bank, the food processing enterprise provides guarantees and assumes joint and several liabilities. Therefore, they will become prosperous. The family farm and the food processing enterprise will make more conservative decisions. As the risk of yield uncertainty increases, the family farm reduces her growing scale and the food processing enterprise reduces his purchase price. In the end, the expectation profits of them will be reduced.

5.2. Bank Financing with "Government, Bank, and Insurance" Coparticipation. The previous section described the situation of bank financing in the food supply chain, in which the food processing enterprise gives guarantees to bear the risk when the family farm fail to repay the loan. Due to the quasi-public property of food, theoretical discussion on government support for agriculture will be arranged, and we will analyze bank financing with "government, bank, and insurance" joint participation in the next.

5.2.1. Theoretical Discussion on Government Support for Agriculture. Assume that the supply and demand curves of industrial goods and agricultural products are linear, and their supply and demand functions are as follows, where p_{ind} and p_{agr} are the prices of industrial products and agricultural products, respectively, Q_{ind} and Q_{agr} are the trading volume of industrial products and agricultural products, respectively, A, B, C, and D are all positive constant, β_{indd} and β_{agrd}

are the demand elasticity coefficients of industrial products and agricultural products, respectively, and β_{inds} and β_{agrs} are the supply elasticity coefficients of industrial products and agricultural products, respectively:

$$p_{\text{agr}} = A - \beta_{\text{agrd}} Q_{\text{agr}}, \tag{9}$$

$$p_{\text{agr}} = B + \beta_{\text{agrs}} Q_{\text{agr}}, \tag{10}$$

$$p_{\text{ind}} = C - \beta_{\text{indd}} Q_{\text{ind}}, \tag{11}$$

$$p_{\text{ind}} = D + \beta_{\text{inds}} Q_{\text{ind}}. \tag{12}$$

The equilibrium price and equilibrium transaction volume of agricultural products can be obtained as follows by combining equation (9) and equation (10):

$$\begin{aligned} p_{\text{agr}} &= \frac{A\beta_{\text{agrs}} + B\beta_{\text{agrd}}}{\beta_{\text{agrs}} + \beta_{\text{agrd}}}, \\ Q_{\text{agr}} &= \frac{A - B}{\beta_{\text{agrs}} + \beta_{\text{agrd}}}. \end{aligned} \tag{13}$$

Similarly, the equilibrium price and equilibrium transaction volume of industrial products can be drawn as follows by combining equation (11) and equation (12):

$$\begin{aligned} p_{\text{ind}} &= \frac{C\beta_{\text{inds}} + D\beta_{\text{indd}}}{\beta_{\text{inds}} + \beta_{\text{indd}}}, \\ Q_{\text{ind}} &= \frac{C - D}{\beta_{\text{inds}} + \beta_{\text{indd}}}, \end{aligned} \tag{14}$$

and then we assume that the supply-demand relationship of the two products remains unchanged, and their supply functions remain the same, while the demand for industrial products increases by J units and the demand for agricultural products increases by H units, so the demand curves for industrial products and agricultural products move to the right by the distance of J and H, respectively. The new equilibrium prices of agricultural products and industrial products are as follows, where p'_{ind} and p'_{arg} are the prices of industrial products and agricultural products, respectively, when the demand increases:

$$p'_{\text{ind}} = \frac{(C + J)\beta_{\text{inds}} + D\beta_{\text{indd}}}{\beta_{\text{inds}} + \beta_{\text{indd}}}, \tag{15}$$

$$p'_{\text{arg}} = \frac{(A + H)\beta_{\text{agrs}} + B\beta_{\text{agrd}}}{\beta_{\text{agrs}} + \beta_{\text{agrd}}}. \tag{16}$$

Δp_{ind} and Δp_{agr}, respectively, indicate the increase in prices of industrial products and agricultural products, which is as follows:

$$\Delta p_{\text{ind}} = \frac{J\beta_{\text{inds}}}{\beta_{\text{inds}} + \beta_{\text{indd}}}, \tag{17}$$

$$\Delta p_{\text{agr}} = \frac{H\beta_{\text{agrs}}}{\beta_{\text{agrs}} + \beta_{\text{agrd}}}. \tag{18}$$

The price increase difference between industrial products and agricultural products is shown in the following equation:

$$\Delta p_{\text{ind}} - \Delta p_{\text{agr}} = \frac{(J - H)\beta_{\text{agrs}}\beta_{\text{inds}} + J\beta_{\text{inds}}\beta_{\text{agrd}} - H\beta_{\text{agrs}}\beta_{\text{indd}}}{\left(\beta_{\text{agrs}} + \beta_{\text{agrd}}\right)\left(\beta_{\text{inds}} + \beta_{\text{indd}}\right)}. \tag{19}$$

Since the price elasticity of demand for agricultural products is less than that of most industrial products (except for salt, etc.), $\beta_{\text{indd}} > \beta_{\text{agrd}}$, the supply price elasticity of industrial products is greater than that of agricultural products, so $\beta_{\text{inds}} > \beta_{\text{agrs}}$, and the growth rate of demand for agricultural products is slower than that of industrial products, that is, $J > H$, so $\Delta p_{\text{ind}} - \Delta p_{\text{agr}} > 0$ can be obtained. The above analysis indicates that the price of agricultural products is rising more slowly than that of industrial products. Therefore, farmers cannot exchange the same amount of agricultural products for the same amount of industrial products, which requires the government to support agricultural products. In fact, many countries currently have domestic support policies for agricultural production.

5.2.2. Financing Interest Rate When Bank Financing with "Government, Bank, and Insurance" Coparticipation. Similar to the case of bank financing with bank participation only, the working capital of the family farm is 0, and she needs to finance $R_2 = cq_2^2$ from the bank and needs to repay $R_2(1 + r_2)$ at the end of the period. In the case of bank financing with "government, bank, and insurance" coparticipation, Q_{th2} and d_{th2}, respectively, represent the threshold of the family farm's actual yield and the threshold of yield random when the supply chain disruptions, the yield of the family farm can repay the loan when $X \geq d_{th2}$, and the interest rate r_2 is designed based on the expected return on financing equal to the average return on the capital market as

$$\int_{d_1}^{d_{th2}} w_2 Q_2 g(x)\mathrm{d}x + \int_{d_{th2}}^{d_2} w_2 Q_{th2} g(x)\mathrm{d}x = \int_{d_1}^{d_{th2}} w_2 q_2 x g(x)\mathrm{d}x + \int_{d_{th2}}^{d_2} (1 + r_2) R_2 g(x)\mathrm{d}x = R_2\left(1 + r_f\right). \tag{20}$$

Just like Proposition 2, the financing rate r_2 will increase with the increase of the average rate of return r_f in the capital market, and the above analysis indicates that the government will support agricultural products, so loan interest discount and insurance subsidy will be provided by the government in this study.

5.2.3. Decisions When Bank Financing with "Government, Bank, and Insurance" Coparticipation. The process of bank financing with "government, bank, and insurance" coparticipation is as follows: firstly, the food processing enterprise and the family farm who has capital constrains sign an order contract. Secondly, the family farm applies for loans from the bank and provides the order contract, the bank will make loans to the food processing enterprise after approval, and then it is offered to the family farm by the food processing enterprise. Thirdly, the food processing enterprise purchases loan guarantee insurance, bank submits interest discount applications to the government, and the insurance company submits premium subsidy applications to the government. Fourthly, the food processing enterprise repays the loans and purchases all the rice according to the order after the harvest, and the remaining payment is delivered to the family farm by the food processing enterprise after deducting the principal and interest of the loan. If there is a random event of yield, claim settlement will be started, and the risk of yield uncertainty will be borne by the government, banks, and insurance together. The specific process shown is in Figure 3.

The expected profit of the family farm when bank financing with "government, bank, and insurance" coparticipation is shown in the following equation:

$$E\pi_{f2} = w_2 q_2 \mu - c q_2^2 - (1-s) r_2 c q_2^2. \tag{21}$$

The profit of the food processing enterprise when bank financing with "government, bank, and insurance" coparticipation is shown in the following equation:

$$\pi_{m2} = p_2 q_2 X - w_2 q_2 X - b(1-j)(1+r_2) c q_2^2$$
$$\text{s.t.} \begin{cases} q_2 = q_2^*, \\ w_2 \geq w. \end{cases} \tag{22}$$

The expected profit of the food processing enterprise when bank financing with "government, bank, and insurance" coparticipation is shown in the following equation:

$$E\pi_{m2} = m q_2 \mu - w_2 q_2 \mu - \beta q_2^2 (\sigma^2 + \mu^2) - b(1-j)(1+r_2) c q_2^2. \tag{23}$$

Proposition 4. *When the family farm has capital constraint, optimal decisions when bank financing with "government, bank, and insurance" coparticipation are as follows: the optimal planned input of the family farm satisfies* $q_2^* = (1/2) m\mu / \{2c[1+(1-s)r_2] + \beta(\sigma^2+\mu^2) + b(1-j)(1+r_2)c\}$, *the optimal purchase price of the food processing enterprise satisfies* $w_2^* = mc[1+(1-s)r_2] / \{2c[1+(1-s)r_2] + \beta(\sigma^2+\mu^2) + b(1-j)(1+r_2)c\}$, *and the optimal purchase price of the food processing enterprise is* w *when* $w_2^* < w$.

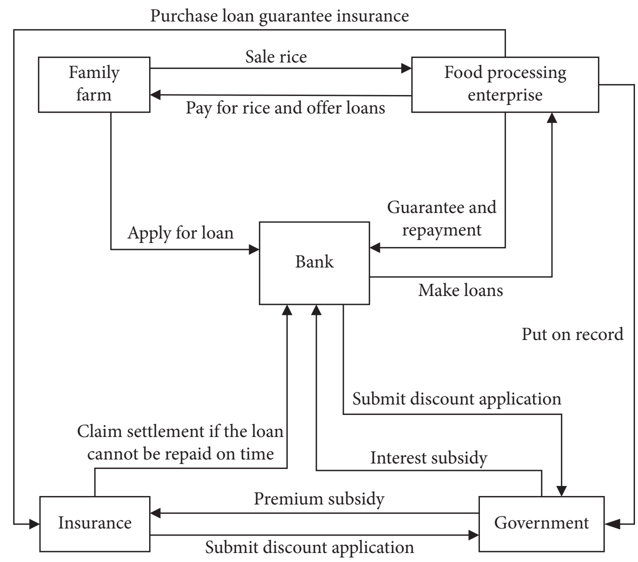

Figure 3: Operation diagram for bank financing with "government, bank, and insurance" coparticipation.

Proposition 4 shows the optimal decisions of the family farm and the food processing enterprise in the case of bank financing with "government, bank, and insurance" coparticipation. At the same time, because of the quasi-public property of food, the food processing enterprise should purchase rice from the family farm at the minimum purchase price when $w_0 < w$.

Meanwhile, the optimal expected profits of the family farm and the food processing enterprise in the case of bank financing with "government, bank and insurance" coparticipation can be obtained as follows:

$$E\pi_{f2}^* = \frac{m^2 c \mu^2 [1+(1-s)r_2]}{4\{2c[1+(1-s)r_2] + \beta(\sigma^2+\mu^2) + b(1-j)(1+r_2)c\}^2},$$
$$E\pi_{m2}^* = \frac{\mu^2 m^2}{4\{2c[1+(1-s)r_2] + \beta(\sigma^2+\mu^2) + b(1-j)(1+r_2)c\}}. \tag{24}$$

Corollary 3 can be drawn by analyzing the relationship among yield uncertainty and the optimal decisions and expected profits of the supply chain members.

Corollary 3. *When bank financing with "government, bank, and insurance" coparticipation and the minimum purchase price policy is not considered, with the increase of the risk of yield uncertainty, the family farm will decrease the scale of growing and the food processing enterprise will decrease the purchase price, and the profits of the family farm and the food processing enterprise are all reduced as a result.*

Corollary 3 shows that in the case of bank financing with "government, bank, and insurance" coparticipation, the increase of the risk of yield uncertainty will cause the family farm to reduce the scale of growing, and the food processing enterprise will reduce the purchase price, which in turn will decrease the profits of the family farm and the food processing enterprise. By comparing Corollary 1–3, it can be seen that when there are financial constraints in the supply chain, the decision of supply chain members to deal with the yield uncertainty is opposite. The possible reason is that financial constraints make the supply chain members more conservative.

6. Numerical Examples and Sensitivity Analysis

The above propositions and corollaries will be further verified by the numerical examples, and the sensitivity analysis is also carried out. As mentioned earlier, the parameters are set as follows: $m = 5000$, $\beta = 0.5$, $c = 100$, $w = 2335.3333$, $d_1 = 5 - a$, $d_2 = 5 + a$, $X \sim U[5 - a, 5 + a]$, $\mu = 5$, $\sigma^2 = a^2/3$, $r_f = 0.0002$, $s = 0.05$, $b = 0.025$, and $j = 0.8$. In Table 2 and 3, Δq_1 represents the planned input difference before and after the launch of the minimum purchase price policy in the case of bank financing with bank participation only and Δq_2 represents the difference of planned investment before and after the launch of the minimum purchase price policy in the case of bank financing with "government, bank, and insurance" coparticipation. The meanings of $\Delta E\pi_{f1}, \Delta E\pi_{f2}, \Delta E\pi_{m1}$ and $\Delta E\pi_{m2}$ are similar and will not be repeated.

6.1. No Financing: The Benchmark. Given the relevant parameters, the optimal decision and optimal expected profit of each member in the contract food supply chain can be obtained easily, which verifies Proposition 1. At the same time, as we can see from Table 2, as the risk of yield uncertainty increases, the family farm will increase the growing scale, and the food processing enterprise will increase the purchase price. Meanwhile, the profits of the family farm and the food processing enterprise will increase as the risk of yield uncertainty increases, which proves Corollary 1.

6.2. Bank Financing with Bank Participation Only. As can be seen from Figure 4, when there is competition in the capital market, the financing rate r_1 will increase with the increase of the average rate of return r_f in the capital market, which verifies Proposition 2. This indicates that, in the case of bank financing with bank participation only, given relevant parameters, there is a single optimal input amount for the family farm to maximize her profit and a single optimal purchase price for the food processing enterprise to maximize his profits. However, the financing rate r_1 will increase with the increase of the average rate of return r_f of the capital market, which will make financing more and more expensive, and the financing problem will be more and more difficult to solve in the case of bank financing with bank participation only. Therefore, it is urgent for the government to participate and offer solutions.

As shown in Table 3, it is easy to obtain the optimal decision and optimal expected profit of each member of the contract food supply chain when given corresponding parameters in the case of bank financing with bank participation only, which verifies Proposition 3.

Table 2: Sensitivity analysis of the risk of yield uncertainty without capital constraints.

a	σ^2	q_0	w_0	$E\pi_{f0}$	$E\pi_{m0}$
0.1	0.0000	63.29	2531.65	432825.59	995527.51
0.5	0.0833	63.29	2531.69	432888.77	996245.41
1	0.3333	63.31	2532.36	433839.72	998795.45
1.5	0.7500	63.38	2535.26	437996.93	1004107.97
2	1.3333	63.58	2543.09	449491.14	1013852.23
2.5	2.0833	63.99	2559.77	475260.00	1030390.09
3	3.0000	64.77	2590.67	528157.11	1056314.22
3.5	4.0833	66.08	2643.22	636713.16	1091786.20
4	5.3333	68.20	2728.10	881843.28	1118961.14
4.5	6.7500	71.54	2861.74	1598258.54	1198933.35
5	8.3333	76.79	3071.67	5981214.56	1360822.31

When $w_1 < w = 2335.33$, the optimal purchase price is w as mentioned before. It can be drawn directly that after the minimum purchase price is implemented from the 7th, 8th, and 9th columns of Table 3, the optimal input amount of the family farm is more than when the minimum purchase price policy is not activated, and the expected profit of the family farm is higher than when the minimum purchase price policy is not activated. Therefore, the welfare of the family farm is improved after the implementation of the minimum purchase price policy, which explains why the minimum purchase price policy is initiated. At the same time, the expected profit of the food processing enterprise after starting the minimum purchase price policy is lower than that without starting the minimum purchase price policy, and when the risk of yield uncertainty is the largest, the expected profit decreases more. This is because the minimum purchase price is higher than the market price, and the profit of the food processing enterprise is bound to decrease.

6.3. Bank Financing with "Government, Bank, and Insurance" Coparticipation. As shown in Table 4, it is easy to obtain the optimal decision and optimal expected profit of each member of the contract chain after the corresponding parameters are given in the case of bank financing with "government, bank, and insurance" coparticipation, which verifies Proposition 4. Proposition 4 shows that, given relevant parameters, there is a single optimal input amount for the family farm to maximize their profits and a single optimal purchase price for the food processing enterprise to maximize their profits in the case of bank financing with "government, bank, and insurance" coparticipation.

The minimum purchase price is implemented when $w_2 < w = 1950$. It can be observed intuitively that after the minimum purchase price is implemented from the 7th, 8th, and 9th columns of Table 4, the optimal input amount of the family farm is greater than when the minimum purchase price policy is not activated. The expected profit of the family farm is much higher than when the minimum purchase price policy is not initiated. Therefore, the implementation of the minimum purchase price policy greatly increases the profit of the family farm in the case of bank financing with "government, bank, and insurance" coparticipation, which

Table 3: Sensitivity analysis of the risk of yield uncertainty in the case of bank financing with bank participation only.

a	σ^2	q_1	w_1	$E\pi_{f1}$	$E\pi_{m1}$	Δq_1	$\Delta E\pi_{f1}$	$\Delta E\pi_{m1}$
0.0	0.0000	59.43	2356.40	341842.30	727923.19	0.00	0.00	0.00
0.5	0.0833	59.03	2355.25	341005.74	727370.26	0.00	0.00	0.00
1.0	0.3333	58.72	2353.78	340644.07	726486.84	0.00	0.00	0.00
1.5	0.7500	58.18	2350.18	339857.66	726302.35	0.00	0.00	0.00
2.0	1.3333	58.12	2346.95	339020.23	725518.91	0.00	0.00	0.00
2.5	2.0833	58.04	2342.82	338922.41	725456.36	0.00	0.00	0.00
3.0	3.0000	57.95	2337.76	338655.53	723118.56	0.00	0.00	0.00
3.5	4.0833	56.84	2331.71	337308.55	721307.07	3.11	914.61	−3267.77
4.0	5.3333	55.69	2325.19	334993.40	719355.91	5.19	3296.55	−7131.37
4.5	6.7500	54.51	2317.76	332590.86	717483.64	8.32	5765.19	−8086.41
5.0	8.3333	53.30	2309.29	330296.79	715146.61	10.56	8026.28	−9348.95

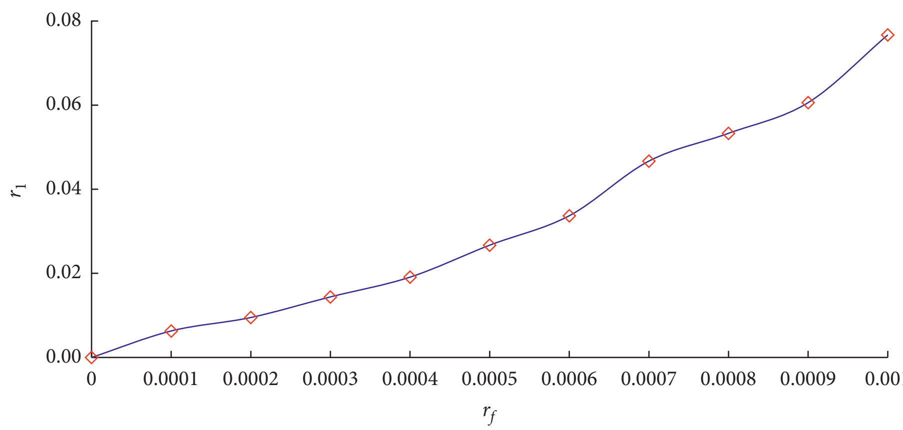

Figure 4: The relationship between r_1 and r_f when $a = 3$.

Table 4: Sensitivity analysis of the risk of yield uncertainty in the case of bank financing with "government, bank, and insurance" coparticipation.

a	σ^2	q_2	w_2	$E\pi_{f2}$	$E\pi_{m2}$	Δq_2	$\Delta E\pi_{f2}$	$\Delta E\pi_{m2}$
0.0	0.0000	70.49	2348.01	359977.62	738357.53	0.00	0.00	0.00
0.5	0.0833	68.03	2347.53	352940.28	734426.84	0.00	0.00	0.00
1.0	0.3333	65.41	2346.13	349615.43	732971.69	0.00	0.00	0.00
1.5	0.7500	63.39	2343.77	347115.03	731838.19	0.00	0.00	0.00
2.0	1.3333	62.82	2340.56	344944.74	730981.93	0.00	0.00	0.00
2.5	2.0833	61.23	2336.44	341113.37	729045.04	0.00	0.00	0.00
3.0	3.0000	59.12	2331.42	338754.31	728798.02	7.10	1138.35	−1052.05
3.5	4.0833	58.01	2325.46	338259.16	727146.11	10.25	2870.92	−3470.08
4.0	5.3333	57.81	2318.82	337152.17	726679.14	13.41	4791.34	−6192.66
4.5	6.7500	57.59	2311.34	335795.99	723919.02	17.60	6944.22	−7057.56
5.0	8.3333	57.37	2302.99	332311.31	721137.16	23.81	9344.26	−8141.48

further explained why to adopt the minimum purchase price policy.

Combining the 7th, 8th, and 9th columns of Tables 3 and 4, we can obtain that after the implementation of the minimum purchase price when the market price is too low, the expected profit reduction of the food processing enterprise in the case of bank financing with "government, bank, and insurance" coparticipation is less than that of bank financing with bank participation only. The reason is that the government and insurance companies share part of the risks for the food processing enterprise in the case of bank financing with "government, bank, and insurance" coparticipation. Meanwhile, the increase in input amount and expected profit of the family farm in the case of bank financing with "government, bank, and insurance" coparticipation are both greater than those of bank financing with bank participation only. The reason is that the yield uncertainty of the family farm is reduced in the case of bank financing with "government, bank, and insurance" coparticipation.

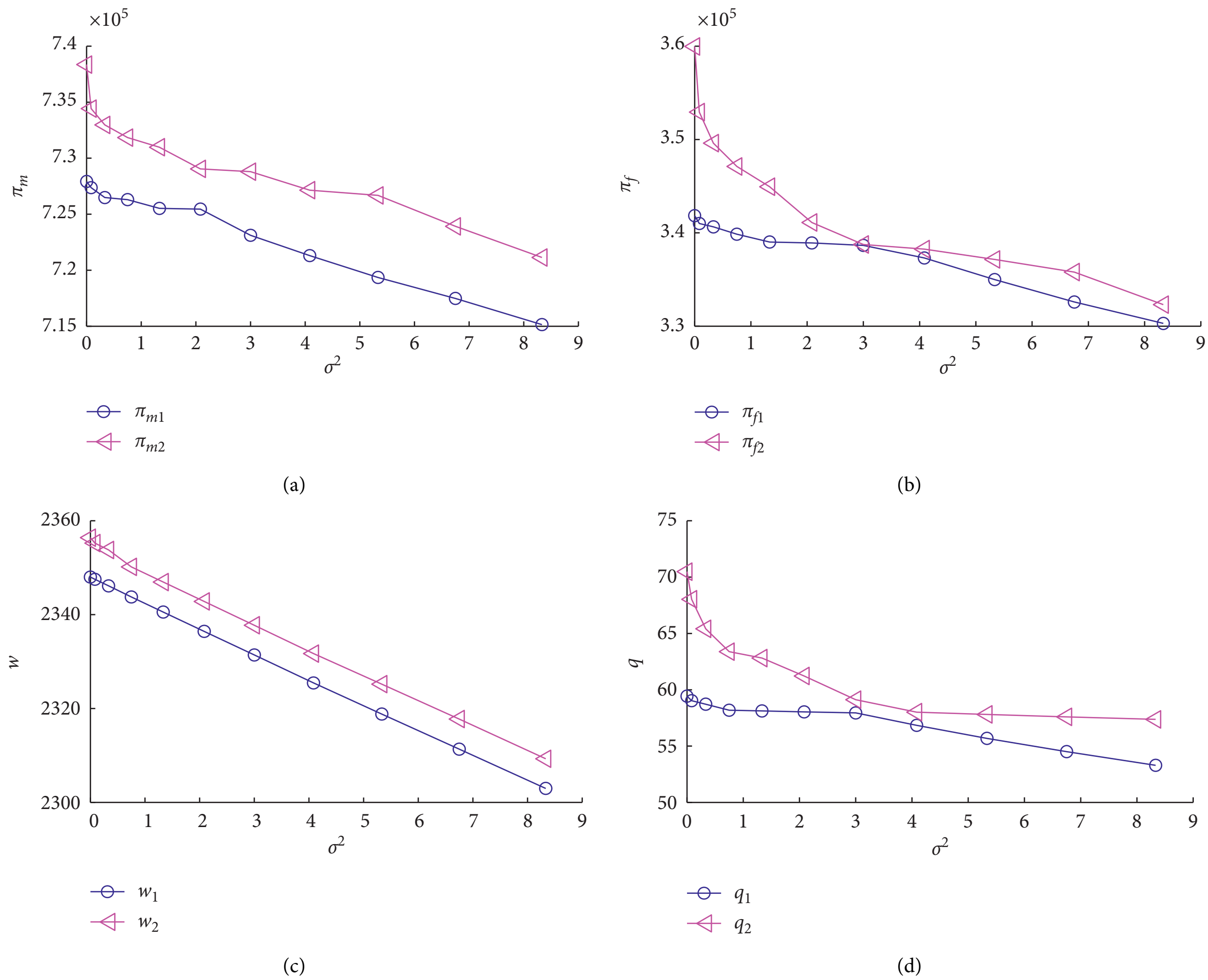

Figure 5: Effects of random risk of yield on the family farm and food processing enterprise when bank financing.

It can be observed intuitively from Tables 1–3 that the profits of the family farm and the food processing enterprise in the case of no financing are far greater than those in the case of financing under the same random risk of yield, which indicates that the costs generated in the financing process cannot be ignored.

6.4. Effects of Random Risk of Yield on the Family Farm and Food Processing Enterprise When Bank Financing. As shown in Figure 5(a)–5(d) in the case of bank financing, when the minimum purchase price policy is not considered, as the risk of yield uncertainty increases, the family farm will reduce the input amount, and the food processing enterprise will reduce the purchase price. Meanwhile, the profits of the family farm and food processing enterprise will decrease as the risk of yield uncertainty increases. This verifies Corollary 2 and Corollary 3.

From Figure 5(a), it can be seen that the profit of the food processing enterprise when "government, bank, and insurance" participate together is obviously greater than when only the bank participates. From Figure 5(b), it can be seen that the profit of family farms when "government, bank, and insurance" participate together is greater than when only banks participate. It can be observed from Figure 5(a) and Figure 5(b) that the welfare improvement of the food processing enterprise in the case of bank financing with "government, bank, and insurance" coparticipation is more significant than that of the family farm.

As can be seen from Figure 5(c), the purchase price in the case of bank financing with "government, bank, and insurance" coparticipation is lower than that in the case of bank financing with bank participation only. The possible reason is that the food processing enterprise has the obligation to guarantee the loan repayment in the case of bank financing with bank participation only, and the purchase price is moderately increased to encourage the family farm to repay the loan. At the same time, we have learned from the foregoing analysis that $w_1^* = mc(1+r_1)/(2c(1+r_1)+\beta(\sigma^2+\mu^2))$ and $w_2^* = mc[1+(1+s)r_2]/\{2c[1+(1+s)r_2]+\beta(\sigma^2+\mu^2)+b(1-j)(1+r_2)c\}$, and $w_1^* > w_2^*$ can be obtained, which is consistent with the graphic description. It can be seen from Figure 5(d) that the input amount of the family farm in the case of bank financing with "government, bank, and insurance" coparticipation is greater than that in the case of bank financing with bank participation only. Meanwhile, it can be seen that the greater or smaller the risk of yield uncertainty is, the more favorable the bank financing with "government, bank, and insurance" coparticipation is to the family farm.

7. Conclusion

In this study, the optimal bank financing decisions for a two-echelon contract food supply chain composed of a family farm with capital constraints and a food processing enterprise are analyzed. We consider both the bank financing with "government, bank, and insurance" coparticipation and the bank financing with bank participation only which has been widely used in the manufacturing industry. At the same time, the case of sufficient supply chain funds is used as the benchmark model, and we find that the profits of supply chain members in the benchmark case are far greater than that in the financing case, which indicates that the financing cost cannot be ignored. This is consistent with the actual operation of enterprises, where "financing difficulty" and "financing expensive" are common, especially for SMEs. The yield random factor is introduced into the model to measure yield uncertainty, which is different from the measurement of yield uncertainty by Huang and Lin [7]. We also conduct theoretical discussions on government subsidies. Given the exogenous variables, the improvement of the welfare of supply chain members is more obvious when bank financing with "government, bank, and insurance" coparticipation than when bank financing with bank participation only, indicating that the loan interest rate and the risk of repayment in the supply chain are reduced when bank financing with "government, bank, and insurance" coparticipation, which is consistent with the conclusion of Huang and Lin [7]. Under the same risk of yield uncertainty, the profits of supply chain members in bank financing with "government, bank, and insurance" coparticipation are significantly higher than the profits in bank financing with bank participation only, indicating that government subsidies improve the profits of members of the supply chain, which is consistent with the conclusion of Ye et al. [38]. Meanwhile, we consider the minimum purchase price policy in the model. Numerical examples show that the profit of the family farm is much higher than that without the minimum purchase price policy when the price is too low. It indicates that the implementation of the minimum purchase price policy increases the welfare of the family farm, which improves the enthusiasm of the family farm, and ensures national food security. Therefore, it is of practical significance for the government to participate in the financing process of the food supply chain [7, 16, 38].

Some management implications are as follows: first, contract farming should be vigorously developed based on the special properties of the food, which will increase the income of the farmers [25–33], improve their enthusiasm for growing, and then ensure national food security. At present, the contract farming mode of "company + farmer" and "company + farmer cooperative + farmer" has been practiced in China. The government encourages leading enterprises to extend the industrial chain, guarantee the supply chain, and improve the interest chain by means of "company + farmers" and "company + farmer cooperatives + farmers", so as to bring small farmers into the modern agricultural industrial system. Second, financing in a capital-constrained supply chain will improve the welfare of the supply chain members while the costs incurred in the financing process cannot be ignored [9, 37], so financing will be an optimal choice for the capital-constrained supply chain. Third, it is necessary to promote the bank financing with "government, bank, and insurance" coparticipation model to solve the problem of financial constraints in the food supply chain. In fact, the bank financing with "government, bank, and insurance" coparticipation has been applied in the agricultural supply chain. For example, Sanshui District People's Government of Foshan City, Guangdong Province, China, Sanshui Rural Credit Cooperative Association of Sanshui District, and People's Insurance Company of China (PICC) Foshan Sanshui Branch signed a tripartite agreement to explore a new agricultural loan model of "government-bank-insurance" cooperation in July 2009. And Sanshui "government-bank-insurance" cooperation mode was proved to be an effective way to solve the farmers' loans difficult after more than eight-year practice, which made the "government-bank-insurance" loans in Sanshui District exceed 900 million yuan, benefiting more than 5000 peasant households by 2016, while the district finance only invested a total of 8.5 million yuan in premium subsidies but promoted more than 900 million social capital investment in agricultural production, which played a leverage role of the financial fund. Therefore, it is of great practical significance to explore the bank financing mechanism of the "government-bank-insurance" cooperation in the capital-constrained contract farming supply chain.

There are several limitations in the study, which may be worth further exploration. First, the family farm produces only a single variety of rice in our study, and it may be interesting to consider that the family farm produces multiple varieties of food in the future. Second, we consider a two-echelon contract food supply chain composed of a family farm with capital constraints and a food processing enterprise in the study; however, selecting multiple suppliers is one of the effective ways to deal with random yield for the downstream of the supply chain since agricultural production is susceptible to natural conditions and the yield is uncertain [10–14], so the optimal financing decisions for a two-echelon contract food supply chain composed of two or more family farms with capital constraints and a food processing enterprise can be explored in the future. Thirdly, blockchain technology is not involved in this study, and future research can explore how to reduce financing risks through blockchain [45].

Appendix

Proof of Proposition 1

The expected profit of the family farm is shown in the following equation:

$$E\pi_{f0} = w_0 q_0 \mu - c q_0^2. \tag{A.1}$$

The optimal planned input of the family farm can be obtained in equation (A.2) by solving the first derivative of q_0 of $E\pi_{f0}$ and setting it equal to 0:

$$q_0^* = \frac{w_0 \mu}{2c}. \tag{A.2}$$

The expected profit of the food processing enterprise is shown as follows:

$$E\pi_{m0} = m q_0 \mu - w_0 q_0 \mu + \beta q_0^2 \left(\sigma^2 + \mu^2\right). \tag{A.3}$$

After substituting $q_0^* = w_0 \mu / (2c)$ into equation (A.3), we can obtain the optimal purchase price of the food processing enterprise in equation (A.4) by solving the first derivative of w_0 of $E\pi_{m0}$ and setting it equal to 0:

$$w_0^* = \frac{mc}{2c - \beta\left(\sigma^2 + \mu^2\right)}. \tag{A.4}$$

Due to the quasi-public property of food, when the rice price is too low, government participates in regulation and sets the minimum purchase price; that is, the food processing enterprise purchases rice from the family farm at the minimum purchase price when $w_0 < w$.

It is easy to obtain the optimal planned input of the family farm by substituting $w_0^* = mc/[2c - \beta(\sigma^2 + \mu^2)]$ into equation (A.2) as follows:

$$q_0^* = \frac{m\mu}{4c - 2p\left(\sigma^2 + \mu^2\right)}. \tag{A.5}$$

□

Proof of Corollary 1

We solve the first derivative of equation (A.5) and obtain the following result:

$$\frac{dq_0^*}{d\sigma^2} = \frac{2\beta m \mu}{\left[4c - 2\beta\left(\sigma^2 + \mu^2\right)\right]^2} > 0. \tag{A.6}$$

According to equation (A.6), the family farm will expand the growing scale as the risk of yield uncertainty increases.

Other results can be drawn as well in the following:

$$\frac{dw_0^*}{d\sigma^2} = \frac{\beta mc}{\left[2c - \beta\left(\sigma^2 + \mu^2\right)\right]^2} > 0, \tag{A.7}$$

$$\frac{dE\pi_{f0}^*}{d\sigma^2} = \frac{-m^2\mu^2 c\left(8\beta^2\sigma^2 + 8\beta^2\mu^2 - 4c\beta\right)}{16\left[2c - \beta\left(\sigma^2 + \mu^2\right)\right]^4} > 0, \tag{A.8}$$

$$\frac{dE\pi_{m0}^*}{d\sigma^2} = \frac{4\beta m^2 \mu^2}{16\left[2c - \beta\left(\sigma^2 + \mu^2\right)\right]^2} > 0. \tag{A.9}$$

According to equations (A.7)–(A.9), we can draw that with the increase of the risk of yield uncertainty, the food processing enterprise will increase the purchase price, and his profit will increase accordingly, but the profit of the family farm will decrease. □

Proof of Proposition 2

We define $F_1(r_1, r_f)$ and solve the first derivative of $F_1(r_1, r_f)$ as follows:

$$F_1\left(r_1, r_f\right) = \int_{d_1}^{d_{th}} w_1 q_1 x g(x) dx + \int_{d_{th}}^{d_2} \left(1 + r_1\right) R_1 g(x) dx - R_1\left(1 + r_f\right), \tag{A.10}$$

$$\frac{\partial F_1 R_1, r\left(R_1\right)}{\partial r_1} = R_1 \overline{F_1}\left(\frac{\left(1 + r_1\right) R_1}{q_1 w_1}\right), \tag{A.11}$$

$$\frac{\partial F_1 R_1, r\left(R_1\right)}{\partial r_f} = -R_1. \tag{A.12}$$

The expression of dr/dr_f can be obtained as follows according to the definition of elasticity:

$$\frac{dr_1}{dr_f} = -\frac{\partial F_1 R_1, r\left(R_1\right)/\partial r_f}{\partial F_1 R_1, r\left(R_1\right)/\partial r_1} = 1/\overline{F_1}\left(\frac{\left(1 + r_1\right) R_1}{q_1 w_1}\right). \tag{A.13}$$

We can observe that $dr/dr_a > 0$ from equation (A.13), so Proposition 2 is proved. □

Proof of Proposition 3

We can obtain the optimal planned input of the family farm when bank financing with bank participation only from equation (15) by solving the first derivative of q_1 of $E\pi_{f1}$ and setting it equal to 0:

$$q_1^* = \frac{w_1 \mu}{2c\left(1 + r_1\right)}. \tag{A.14}$$

We obtain equation (A.15) after substituting $q_1^* = w_1\mu/2c(1 + r_1)$ into equation (18) and solve the first derivative of w_1 as follows:

$$E\pi_{m1} = \frac{m w_1 \mu^2}{2c\left(1 + r_1\right)} - \frac{w_1^2 \mu^2}{2c\left(1 + r_1\right)} - \frac{w_1^2 \mu^2 \beta\left(\sigma^2 + \mu^2\right)}{4c^2\left(1 + r_1\right)^2}, \tag{A.15}$$

$$\frac{dE\pi_{m1}}{dw_1} = \frac{m\mu^2}{2c\left(1 + r_1\right)} - \frac{\mu^2 w_1}{c\left(1 + r_1\right)} - \frac{\mu^2 \beta\left(\sigma^2 + \mu^2\right) w_1}{2c^2\left(1 + r_1\right)^2}. \tag{A.16}$$

Let equation (A.16) = 0, and we can obtain the optimal purchase price of the food processing enterprise in the following:

$$w_1^* = \frac{mc\left(1 + r_1\right)}{2c\left(1 + r_1\right) + \beta\left(\sigma^2 + \mu^2\right)}. \tag{A.17}$$

Due to the quasi-public property of food, when the rice price is too low, government participates in regulation and sets the minimum purchase price; that is, the food processing enterprise purchases rice from the family farm at the minimum purchase price when $w_1 < w$.

It is easy to obtain the optimal planned input of the family farm by substituting $w_1^* = mc(1+r_1)/[2c(1+r_1)+\beta(\sigma^2+\mu^2)]$ into equation (A.14) as follows:

$$q_1^* = \frac{m\mu}{2\left[2c(1+r_1)+\beta\left(\sigma^2+\mu^2\right)\right]}. \tag{A.18}$$

□

Proof of Corollary 2

We solve the first derivative of q_1^*, w_1^*, $E\pi_{f1}^*$, and $E\pi_{m1}^*$ as follows:

$$\frac{dq_1^*}{d\sigma^2} = \frac{-2\beta m\mu}{4\left[2c(1+r_1)+\beta\left(\sigma^2+\mu^2\right)\right]^2} < 0. \tag{A.19}$$

Other results can be drawn as well in the following:

$$\frac{dw_1^*}{d\sigma^2} = \frac{-\beta mc(1+r_1)}{\left[2c(1+r_1)+\beta\left(\sigma^2+\mu^2\right)\right]^2} < 0, \tag{A.20}$$

$$\frac{dE\pi_{f1}^*}{d\sigma^2} = \frac{-m^2\mu^2 c(1+r_1)\left[8c(1+r_1)+8\beta^2\left(\sigma^2+\mu^2\right)\right]}{16\left[2c(1+r_1)+\beta\left(\sigma^2+\mu^2\right)\right]^4} < 0, \tag{A.21}$$

$$\frac{dE\pi_{m1}^*}{d\sigma^2} = \frac{-4m^2\mu^2\beta}{16\left[2c(1+r_1)+\beta\left(\sigma^2+\mu^2\right)\right]^2} < 0. \tag{A.22}$$

According to equation (A.20)–(A.22), Corollary 2 is proved. □

Proof of Proposition 4

Solve the first derivative of $E\pi_{f2}$, and set it equal to 0:

$$q_2^* = \frac{w_2\mu}{2c[1+(1-s)r_2]}, \tag{A.23}$$

$$\begin{aligned}\pi_{m2} &= p_2q_2X - w_2q_2X - b(1-j)(1+r_2)cq_2^2\\ &= (m-\beta q_2X)q_2X - w_2q_2X - b(1-j)(1+r_2)cq_2^2\\ &= mq_2X - w_2q_2X - \beta q_2^2X^2 - b(1-j)(1+r_2)cq_2^2.\end{aligned} \tag{A.24}$$

Then, we can obtain $E\pi_{m2}$ as follows:

$$E\pi_{m2} = mq_2\mu - w_2q_2\mu - \beta q_2^2\left(\sigma^2+\mu^2\right) - b(1-j)(1+r_2)cq_2^2. \tag{A.25}$$

We obtain equation (A.26) after substituting $q_2^* = w_2\mu/\{2c[1+(1-s)r_2]\}$ into equation (A.25) and solve the first derivative of $E\pi_{m2}$ as follows:

$$E\pi_{m2} = \frac{m\mu^2 w_2}{2c[1+(1-s)r_2]} - \frac{\left\{2c[1+(1-s)r_2]+\beta\left(\sigma^2+\mu^2\right)+b(1-j)(1+r_2)c\right\}\mu^2w_2^2}{\left\{2c[1+(1-s)r_2]\right\}^2}, \tag{A.26}$$

$$\frac{dE\pi_{m2}}{dw_2} = \frac{m\mu^2}{2c[1+(1-s)r_2]} - \frac{2\left\{2c[1+(1-s)r_2]+\beta\left(\sigma^2+\mu^2\right)+b(1-j)(1+r_2)c\right\}\mu^2w_2}{\left\{2c[1+(1-s)r_2]\right\}^2}. \tag{A.27}$$

Let equation (A.27) = 0, and we can obtain the optimal purchase price of the food processing enterprise in the following:

$$w_2^* = \frac{mc[1+(1-s)r_2]}{\left\{2c[1+(1-s)r_2]+\beta\left(\sigma^2+\mu^2\right)+b(1-j)(1+r_2)c\right\}}. \tag{A.28}$$

Due to the quasi-public property of food, when the rice price is too low, government participates in regulation and sets the minimum purchase price; that is, the food processing enterprise purchases rice from the family farm at the minimum purchase price when $w_2 < w$.

It is easy to obtain the optimal planned input of the family farm by substituting $w_2^* = mc[1+(1-s)r_2]/\{2c[1+(1-s)r_2]+\beta(\sigma^2+\mu^2)+b(1-j)(1+r_2)c\}$ into equation (A.23) as follows:

$$q_2^* = \frac{w_2\mu}{2c[1+(1-s)r_2]} = \frac{m\mu}{2\left\{2c[1+(1-s)r_2]+\beta\left(\sigma^2+\mu^2\right)+b(1-j)(1+r_2)c\right\}}. \tag{A.29}$$

□

Proof of Corollary 3

We solve the first derivative of q_2^*, w_2^*, $E\pi_{f2}^*$, and $E\pi_{m2}^*$ as follows:

$$\frac{dq_2^*}{d\sigma^2} = \frac{-\beta m\mu}{2\left\{2c\left[1+(1-s)r_2\right]+\beta\left(\sigma^2+\mu^2\right)+b(1-j)(1+r_2)c\right\}^2} < 0, \tag{A.30}$$

$$\frac{dw_2^*}{d\sigma^2} = \frac{-\beta mc\left[1+(1-s)r_2\right]}{\left\{2c\left[1+(1-s)r_2\right]+\beta\left(\sigma^2+\mu^2\right)+b(1-j)(1+r_2)c\right\}^2} < 0, \tag{A.31}$$

$$\frac{dE\pi_{f2}^*}{d\sigma^2} = \frac{-m^2c\mu^2\left[1+(1-s)r_2\right]\left\{2\beta\sigma^2+2\mu^2+4c\beta\left[1+(1-s)r_2\right]+\beta b(1-j)(1+r_2)c\right\}}{16\left\{2c\left[1+(1-s)r_2\right]+\beta\left(\sigma^2+\mu^2\right)+b(1-j)(1+r_2)c\right\}^4} < 0, \tag{A.32}$$

$$\frac{dE\pi_{m2}^*}{d\sigma^2} = \frac{-4\beta\mu^2m^2}{16\left\{2c\left[1+(1-s)r_2\right]+\beta\left(\sigma^2+\mu^2\right)+b(1-j)(1+r_2)c\right\}^2} < 0. \tag{A.33}$$

According to equations (A.30)–(A.33), Corollary 3 is proved. □

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declared that there are no conflicts of interest.

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Research Article

Research on the Impact of Government R&D Funding on Regional Innovation Quality: Analysis of Spatial Durbin Model Based on 283 Cities in China

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Based on the perspective of the regional innovation system, this study constructs an analytical framework for the influence of government R&D funding on regional innovation quality and uses 283 Chinese cities as research samples to empirically test the influence of government R&D funding methods such as subsidies and tax preferences on regional innovation quality by the spatial Durbin model. According to the study, China's regional innovation quality has a positive spatial correlation. Subsidies can improve regional innovation quality, which is mainly realized by increasing the input of innovation resources from local direct innovation subjects, attracting the inflow of innovation resources from neighboring areas, and increasing the innovation support from local indirect innovation subjects. Besides, spatial competition for subsidies makes it beneficial to improve the regional innovation quality in neighboring regions, while the promotion effect of tax preferences is not significant. When considering the heterogeneity of the city location and administrative hierarchy, it shows that the government R&D funding cannot improve the innovation quality of the Eastern cities and higher-administrative-hierarchy cities, while it can improve that of the Middle and Western cities and general-administrative-hierarchy cities. Furthermore, government R&D funding widens the gap of regional innovation quality, which may be related to the existing "insufficient intervention" and "excessive intervention" of government R&D funding. This study provides insights into the implementation of R&D funding by the government to promote the development of regional innovation quality.

1. Introduction

In the context of China's economic development model changing from resource-driven to innovation-driven, innovation has increasingly become the key to promoting high-quality development. It has become an objective requirement of China's economic growth to improve innovation quality and promote high-quality development through high-quality innovation [1]. While the Global Innovation Index 2019 shows that, in 2019, China's innovation output index ranked 5th globally, but its innovation quality index only ranked 15th, proving that China is facing the innovation dilemma of high quantity but low quality. Therefore, how to improve the quality of innovation has become an urgent issue in the process of innovation development. In the regional innovation system, firms, universities, and research institutions are the main subjects of innovation activities. However, the public nature of innovation makes innovation subjects less motivated to carry out high-quality innovation, leading to a lack of high-quality innovation activities. In this context, as additional innovation resources, government R&D funding in the form of subsidies and tax preferences effectively strengthens regional innovation resources and stimulates innovation activities, and hence, it has been adopted by most countries around the world [1–4].

While the current practice of R&D funding by the Chinese government may be problematic in two ways: on the one hand, the increasing intensity of funding has had a limited effect on improving regional innovation quality.

Taking subsidies as an example, China's local fiscal S&T expenditure increased from 188.588 billion yuan in 2011 to 520.638 billion yuan in 2018, with an average annual growth rate of 25.15%, which was much higher than the growth rate of GDP in the same period (the growth rates of subsidies and GDP are calculated based on raw data from the China Statistical Yearbook). The increasing funding does not significantly improve regional innovation quality but raises concerns about creating an illusion of innovation [5]. Thus, it is necessary to deeply examine the effect of government R&D funding on regional innovation quality and its mechanism. On the other hand, the increasingly tightening of fiscal revenue puts higher requirements for implementing government R&D funding precisely. The State Council Government Work Report 2021 states that a total of 2.60 trillion yuan in tax cuts and fee reductions have been achieved throughout 2020, and it is expected that systematic tax reduction policies will continue to be implemented in the coming year. The continued increase in tax cuts has put local governments under unprecedented financial pressure, indicating that government R&D funding cannot be increased indefinitely. Coupled with the rigidity of local governments' fiscal expenditures, it is particularly critical to improving the efficiency of fiscal funds [6]. Meanwhile, it is necessary to clarify its impact on different regions to fund more efficiently and enhance regional innovation quality.

The impact of government R&D funding on innovation activities has received extensive attention from scholars at home and abroad, and relevant studies have been mainly conducted in three aspects as follows. (1) The impact of government R&D funding on the quantity of innovation. These studies focus on the input and output dimensions of innovation, and the conclusions are broadly presented as the positive effect [7, 8], the negative effect [4, 9], and the uncertain effect [10]. (2) The impact of government R&D funding on the quality of innovation at the firm level. Firms tend to spend their efforts pursuing innovation quantity rather than innovation quality to cater to the government's preference for the scale and speed of innovation [11]. In this situation, previous studies based on innovation quantity may overestimate the effects of government R&D funding. Thus, some studies have begun to examine its effect on innovation quality at the firm level. Dang and Motohashi [12] found that subsidies for patent filing and examination fees cannot incentivize firms to improve patent quality but instead trigger them to file low-quality patents strategically. However, also based on firm data, some scholars reach opposite conclusions. Ernst et al. [13] showed that taxes distort the quality of R&D projects and that reducing the patent income tax rate can improve patent quality. Mukherjee et al. [14] found that, with the increase of tax, the innovation quality at the firm level measured by the number of patent citations is declining instead. (3) The spatial characteristics in the process of government R&D funding affecting innovation quality. Akcigit et al. [15] found that higher enterprise income tax triggers a shift in innovation activities' spatial location due to cross-state spillover effects. The study by Lu and Liu [16] is closely related to this paper. Lu and Liu [16], based on provincial panel data from 1997 to 2012, found that subsidies can enhance regional innovation quality.

Studies have begun to focus on the impact of government R&D funding on regional innovation quality, which inspires this study. Unfortunately, there are still some shortcomings in prior studies. (1) They lack a comprehensive examination of the basic connotation of innovation quality. Most previous studies focus on the impact of government R&D funding on innovation quantity [4, 7–10]. Few studies that focus on innovation quality only concentrate on its technological value and use the number of invention patents [11, 12] or the index system constructed based on patents [17] to measure it. However, innovation should satisfy market demand, and innovation quality should not only be reflected in its technological value (e.g., patents) but also in its economic value. (2) They neglect other innovation subjects within the regional innovation system. Most of the existing studies that focus on innovation quality analyze at the firm level, but the regional innovation system also includes other innovation subjects such as universities and research institutions. In the context of the growing importance of collaborative agglomeration of innovation by industry-university-research institutions [18], ignoring other innovation subjects' contribution is not conducive to examining the overall effect of government R&D funding. (3) They ignore the spatial competitiveness and spatial heterogeneity in the process of government R&D funding affecting innovation quality. Although Akcigit et al. [15] argued that increased enterprise income tax causes a spatial location shift of innovation activities due to inter-regional spillover effects, they have not explored the underlying causes in depth. With the deepening of the innovation-driven development strategy, local governments' strategic interaction around R&D funding [19] may make government R&D funding spatially competitive. Meanwhile, government R&D funding is a regional economic phenomenon in the Chinese context, so there is spatial competition for government R&D funding between geographically adjacent regions and regions with little economic disparity. Besides, although Lu and Liu [16] argued that there might be spatial heterogeneity in the impact of subsidies on regional innovation quality, they have not discussed it deeply, either. There are differences in the marketization degree and innovation resources among regions, and thus, there may be differences in the need for government R&D funding and its effectiveness in improving regional innovation quality. Ignorance of spatial heterogeneity may lead to bias in relevant studies.

Compared with existing studies, the main contributions of this study are reflected in the following aspects. (1) This study explores the connotation of regional innovation quality from technological, economic, and comprehensive aspects and then measures it from the above aspects. Thus, it provides new ideas for an in-depth exploration of the impact of government R&D funding on regional innovation quality. (2) Based on the regional innovation system's perspective, this paper establishes a theoretical framework to analyze the impact of government R&D funding on regional innovation quality. Then, it uses this framework to examine the impact of government R&D funding on direct innovation subjects (e.g., firms, universities, and research institutions) and indirect innovation subjects (e.g., financial institutions) within the regional innovation system. (3) Based on a spatial weight matrix obtained by nesting geographical and economic distances, this study examines the spatial competition of government R&D funding to influence regional innovation quality and explores its mechanism. Also, it examines the spatial heterogeneity due to the location and administrative hierarchy of the city in the effect of government R&D funding on regional innovation quality.

The rest of this study is organized as follows. Section 2 discusses the theoretical framework and proposes the research hypothesis; Section 3 describes the empirical framework; Section 4 reports and discusses the empirical results; Section 5 presents and discusses the results of the further analysis, and Section 6 contains the conclusions and implications.

2. Theoretical Framework and Research Hypothesis

2.1. Connotation and Measurement of Innovation Quality. In related studies, scholars have defined innovation quality from different perspectives. The main representative views are as follows. Firstly, in the technological aspect, innovation quality is equivalent to patent quality. The improvement of innovation quality implies technological progress and breakthroughs, which concentrate on the patent quality [11]. Given that only high-quality innovations can be patented [20], Chen et al. [1], Dang and Motohashi [12], and Tseng et al. [21] also focused on the technological value of innovation quality. They argued that innovation quality equals patent quality and then selected some patent-related indicators such as the number of invention patents and the breadth of patent knowledge to measure it. Secondly, in the economic aspect, innovation quality should be reflected in economic benefits. Although firms can develop plenty of innovation achievements, not each of them can produce economic value. Therefore, He [22] paid attention to the economic benefits brought by innovation, regarded the value of firms as the economic embodiment of innovation quality, and then selected Tobin *Q* to measure it. Makkonen and Inkinen [23] focused on the market potential and market value of innovation quality. They argued that innovation prizes designed to stimulate new business activities could be used to measure it. Thirdly, in the integrated aspect, innovation quality should consider both the innovation quantity and innovation structure. Zheng et al. [17] also focused on the technological aspects of innovation quality. However, unlike previous scholars, they believed that innovation quality is comprehensive, including both the growth of innovation quantity and the optimization of innovation structure. Thus, they built an index system from the growth of patent quantity and the optimization of patent structure to measure innovation quality.

Based on the basic connotation of innovation quality and the fact that the traditional model of driving economic development by innovation quantity facing considerable resistance, it has been an objective requirement to improve innovation quality and drive high-quality development by high-quality innovation under the new economic normal. Thus, this study argues that innovation quality includes the technological value and the economic benefit of innovation, and it concerns both the quantity growth and the structure optimization of innovation.

2.2. Government R&D Funding and Regional Innovation Quality. Great capital demand, high risk, and positive externalities make innovation activities vulnerable to market failure. Compared with low-quality innovation activities, high-quality innovation activities may face more severe market failures as they require more available capital, take higher risks, and undertake more significant externalities [24]. Arrow's theory [25] provides a theoretical rationale for using government R&D funding to alleviate the market failure in high-quality innovation activities. Based on it, some scholars have discussed the impact of government R&D funding on firm innovation activities from easing the constraint of innovation resources, sharing innovation risks, and correcting positive externalities of innovation achievements [24, 26]. However, in addition to firms, there are other direct innovation subjects (e.g., universities and research institutions that play the role of knowledge creators in the regional innovation system) and indirect innovation agents (e.g., financial institutions that provide financial support for direct innovation subjects) in the regional innovation system [27, 28]. Therefore, considering the attributes of government R&D funding and the attributes of different subjects within the regional innovation system, this study constructs a theoretical analysis framework for examining the impact of government R&D funding on regional innovation quality (Figure 1).

Firstly, government R&D funding has resource attributes and is conducive to increasing the region's innovation resources of direct innovation subjects. It is because government R&D funding is an available innovation resource for direct regional subjects, which directly alleviate the shortage of innovation resources. Moreover, it assumes the cost of innovation activities through subsidies or tax preferences, thus sharing innovation risk [29]. In this situation, some direct subjects who worry about the future will invest more resources and bring in qualified talents to carry out innovation activities. Meanwhile, it can reduce the private costs of innovation activities [30] and increase their private benefit [31]. Therefore, government R&D funding helps correct the innovation inertia caused by positive externalities, stimulate innovation subjects to invest more, and optimize the allocation of innovation resources, thus contributing to regional innovation quality.

Further, government R&D funding has signaling attributes that facilitate direct innovation subjects to obtain support from indirect innovation subjects such as financial institutions. The implementation of government R&D funding sends signals to indirect innovation subjects that the direct innovation subjects are recognized by the government [32, 33]. It helps direct innovation subjects obtain long-term

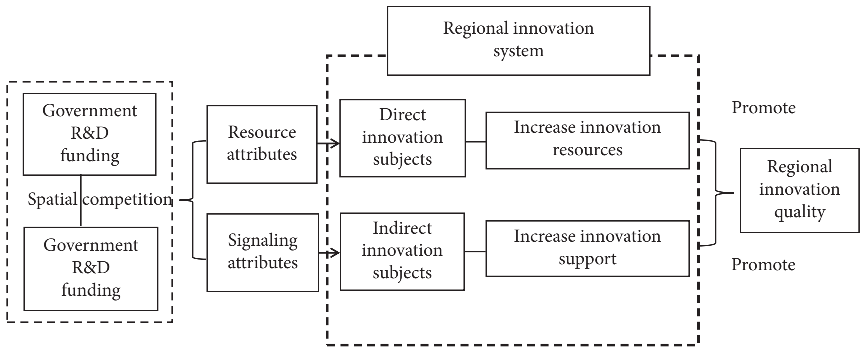

Figure 1: Framework of theoretical analysis.

financial support for innovation activities and enables innovation resources to be more and longer-lasting, and thus, it enhances the innovation quality in the region.

Finally, spatial competition exists in government R&D funding, which is conducive to improving regional innovation quality. In the context of the fiscal decentralization system and the continuous promotion of innovative cities, local governments engage in a series of strategic competition around funding R&D activities to develop the economy and innovation, which are eventually reflected in the continued expansion and increasing rigidity of fiscal expenditures on Science and Technology (S&T) [19]. The competition around funding R&D activities leads to an increase in innovation resources and innovation support, accelerates the flow of innovation resources, and strengthens the role of government R&D funding in improving regional innovation quality. Based on the above analysis, this study proposes the following hypothesis.

Hypothesis 1. Government R&D funding can enhance regional innovation quality.

The resource attributes and signaling attributes of government R&D funding make it conducive to improving regional innovation quality. However, subsidies and tax preferences have different characteristics, thus may have different effects on regional innovation quality. As an ex-post innovation compensation, tax preferences are hardly effective for innovation subjects with ex-ante financing difficulties or no tax obligations [26]. Thus, they may have a limited effect on improving regional innovation quality. In contrast, subsidies are ex-ante innovation support. They can promptly make up for the shortage of innovation resources, enhance the motivation of direct innovation subjects, and optimize the allocation of innovation resources by undertaking innovation funding in a timely manner. Therefore, subsidies may be more likely to enhance regional innovation quality. Based on the above analysis, this study proposes the following hypothesis.

Hypothesis 2. Of the two methods of government R&D funding (i.e., subsidies and tax preferences), subsidies may have a more significant effect on regional innovation quality.

2.3. Heterogeneity Analysis of Government R&D Funding Affecting Regional Innovation Quality

2.3.1. Heterogeneity of the City Location. There are differences in the marketization process among the Eastern, Middle, and Western regions of China. The degree of marketization in the Eastern region is relatively higher than that in the Middle and Western region [34]. Thus, the market failure faced by the Eastern region in innovation activities is relatively minor. As the original purpose of government R&D funding is to alleviate the market failure in innovation activities, the degree of marketization will impact the effect of R&D subsidies [17]. Relatively speaking, regions with a higher degree of marketization have lower information asymmetry, and direct innovation subjects can access financial support through financial institutions. Therefore, in these regions, the degree of market failure in innovation activities is lower [35], and there is less scope for government R&D funding to play a role. Thus, the effect on regional innovation quality may be relatively weak or even insignificant. However, the cities in the Middle and Western region are less market-oriented, with more severe market failures. The resource and signaling attributes of government R&D funding can be effectively leveraged, thus facilitating the regional innovation quality in these cities. Based on the above analysis, this study proposes the following hypothesis.

Hypothesis 3. Government R&D funding is more likely to improve the regional innovation quality in Middle and Western cities with a lower marketization degree than that in Eastern cities with a higher marketization degree.

2.3.2. Heterogeneity of the City Administrative Hierarchy. Under China's current system, most of the elements, such as capital and talent, mainly distribute from the central government to local governments and from superior cities to subordinate cities [36]. Thus, cities with higher administrative hierarchy tend to have more advantages in accumulating innovation resources than those with ordinary administrative hierarchy. There is an optimal scale of government R&D funding [16], and it may lead to an excessive accumulation of innovation resources within the region when exceeding a specific size. Influenced by the law of diminishing marginal returns, the efficiency of government R&D funding will decrease as its size increases [37, 38], which may not be conducive to improving regional innovation quality. As a result, government R&D funding has a limited and possibly negative impact on improving the innovation quality in higher-administrative-hierarchy cities with relatively adequate innovation resources. In contrast, as additional resources, it can effectively alleviate the lack of innovation resources faced by general-administrative-hierarchy cities. Based on the above analysis, this study proposes the following hypothesis.

Hypothesis 4. Government R&D funding is more likely to improve the regional innovation quality in general-administrative-hierarchy cities with fewer innovation resources than higher-administrative-hierarchy cities with more abundant innovation resources.

3. Empirical Framework

3.1. Model. This study establishes a basic model to test the impact of government R&D funding on regional innovation quality. The model, with regional innovation quality as the dependent variable and subsidies and tax preferences as the independent variables, is set as follows:

$$\text{innovation}_{it} = \alpha l_n + \beta_1 \text{subsidy}_{it} + \beta_2 \text{tax}_{it} + \beta_3 Z_{it} + \varepsilon_{it}. \quad (1)$$

In equation (1), innovation denotes regional innovation quality, subsidy and tax denote subsidies and tax preferences, respectively, i and t denote the number of cross sections and the number of periods, α is a constant term, l_n is an $N \times 1$ order unit vector, Z are control variables representing other factors that may affect regional innovation quality, ε is a random perturbation term, and β_1, β_2, and β_3 are the estimated coefficients of each parameter.

The spillover effect of innovation activities may make regional innovation quality spatially correlated. Simultaneously, competition for government R&D funding carried by regions may make government R&D funding spatially correlated across regions. In this case, nonspatial econometrics models that assume that regions are independent of each other fail to account for the spatial correlation of regional innovation quality and government R&D funding, which may bias the results. Therefore, based on equation (1), the spatial Durbin model (SDM) is established by introducing the spatial interaction terms of regional innovation quality, subsidies and tax preferences, and control variables, as shown in the following equation:

$$\begin{aligned}\text{innovation}_{it} = {} & \alpha l_n + \beta_1 \text{subsidy}_{it} + \beta_2 \text{tax}_{it} + \beta_3 Z_{it} + \theta_1 W \times \text{subsidy}_{it} \\ & + \theta_2 W \times \text{tax}_{it} + \theta_3 W \times Z_{it} + \rho W \times \text{innovation}_{it} + \varepsilon_{it},\end{aligned} \quad (2)$$

where innovation denotes regional innovation quality, subsidy and tax denote subsidies and tax preferences, respectively, i and t denote the number of cross sections and the number of periods, α is a constant term, l_n is an $N \times 1$ order unit vector, Z are control variables representing other factors that may affect the regional innovation quality, ε is a random perturbation term, β_1, β_2, and β_3 are the estimated coefficients of each parameter, representing the influence of local independent and control variables on local innovation quality, θ_1, θ_2, and θ_3 are the spatial correlation coefficients, representing the influence of local independent and control variables on the innovation quality of neighboring regions, ρ is the spatial autocorrelation coefficient, representing the influence of local innovation quality on the innovation quality of neighboring regions, and W is a spatial weight matrix.

3.2. Description of Variables

3.2.1. Dependent Variable: Regional Innovation Quality. This study constructs an evaluation index system of regional innovation quality containing technological, economic, and comprehensive indicators to measure regional innovation quality. Compared with previous studies that measure it by indicators with a single dimension [11, 12] or an index system constructed from a single dimension [21], this approach may be more objective and accurate.

Table 1 shows the evaluation index system of regional innovation quality. The first-level index is composed of the technological and economic aspects of innovation quality. The second-level index reflects the comprehensive aspect of it, which measures the technological and economic aspects of innovation quality from the quantitative and structural dimensions, respectively. Moreover, the number of granted patents for invention and the proportion of granted patents for invention reflect the technological aspect of innovation quality in quantitative and structural terms, respectively. The firm profits and average asset margins reflect the economic aspect of innovation quality in quantitative and structural terms, respectively.

Note that the proportion of granted patents for the invention is calculated by dividing the number of granted patents for the invention by the total number of granted patents. The main reason for selecting the number of invention patents instead of other types is that, under China's current patent law, patent applications for inventions are usually subject to a rigorous substantive examination, with a higher requirement for novelty and, therefore, more innovative [12]. Besides, the reason for selecting the number of granted patents rather than applied ones is that patent applications are not always granted, and granted parents tend to be of higher quality than ungranted ones [39].

Additionally, the firm profits are the ones of industrial enterprises above the state-designated scale. The average

Table 1: Evaluation index system of regional innovation quality.

First-level index	Second-level index	Unit
Technological aspect of innovation quality	Number of patents granted for the invention	Piece
	Proportion of patents granted for the invention	%
Economic aspect of innovation quality	Firm profits	10000 yuan
	Average asset margins	%

asset margins are calculated by dividing the firm profits by their average annual total assets. The reasons for choosing firm profits and their share of average total assets to measure the economic aspect of innovation quality are as follows. On the one hand, they are common indicators to measure the economic value of firms [40], and profit maximization is in line with the economic objective of firms to improve the quality of innovation. On the other hand, as industry-university-research cooperation becomes closer, the profits of firms in the region include, to a certain extent, the economic contributions generated by universities, research institutes, and firms in collaborative innovation.

After constructing the index system, it is critical to select an appropriate method to calculate the multiple indicators. In related studies, Fan et al. [41], [42] evaluated regional innovation efficiency from the perspectives of innovation input and innovation output using the improved Data Envelopment Analysis (DEA) model and the Slack-Based Measure (SBM) model, respectively. Moreover, Yang et al. [43] evaluated patent quality from six dimensions using the Principal Component Analysis (PCA) method. However, compared with regional innovation efficiency, regional innovation quality is more concerned with the technological and economic value of innovation rather than the efficiency of converting innovation input into innovation output. Therefore, the DEA model and the SBM model, which are more suitable for evaluating efficiency [41], may not be suitable for this study. And, the PCA method, as a method of dimensionality reduction analysis, is more suitable for evaluating index systems containing a large number of indicators. However, the regional innovation quality index system constructed in this paper contains fewer indicators. Therefore, this study adopts the Global Entropy Value (GEV) method [44] to assign weights to the evaluation index system of regional innovation quality. The GEV method is an objective assignment method based on the change of the data itself, which can retain the information of all indicators and is relatively accurate.

Assume that there are P evaluation indicators and that the regional innovation quality of n cities in T years needs to be evaluated (there are a total of nT evaluation subjects). Meantime, the matrix $X_{ij}\,(i = 1, 2, \ldots, nT;\ j = 1, 2, \ldots, p)$ represents the jth indicator of the ith evaluation object. The main steps for assigning weights using the GEV method are as follows:

Step 1. Standardize the matrix:

$$Y_{ij} = \frac{X_{ij} - \min\left(X_{ij}\right)}{\max\left(X_{ij}\right) - \min\left(X_{ij}\right)}. \tag{3}$$

Note that Y_{ij} is the matrix element after normalization.

Step 2. Calculate the entropy value of the jth index:

$$E_j = -\frac{1}{\ln(nT)} \sum_{i=1}^{nT} p_{ij} \times \ln\left(p_{ij}\right), \tag{4}$$

where $p_{ij} = -(Y_{ij}/\sum_{i=1}^{nT} Y_{ij})$.

Step 3. Calculate the redundancy of the entropy:

$$D_j = 1 - E_j. \tag{5}$$

Step 4. Calculate the weight of each index:

$$W_j = -\frac{D_j}{\sum_{j=1}^{p} D_j}. \tag{6}$$

Step 5. Calculate the composite evaluation index of the regional innovation quality:

$$C_{ij} = \sum_{j=1}^{p} W_j \times Y_{ij}. \tag{7}$$

3.2.2. Independent Variable: Government R&D Funding. This study considers two primary forms of government R&D funding, namely, subsidies and tax preferences.

(1) *Subsidies (Subsidy).* The share of fiscal expenditure on S&T in each region's GDP is selected to measure subsidies in the benchmark regression (this paper uses GDP to remove the effect of regional size factors on the estimated results when constructing measurements of government R&D funding). Fiscal expenditure on S&T is a common indicator of government R&D funding at the city level [19]. It refers to the expenditure on basic research, applied research, technology research and development, S&T management affairs, S&T popularization, S&T cooperation, etc. It can increase innovation resources directly and attract indirect innovation subjects to increase their innovation support by sending a signal, thus improving regional innovation quality. Besides, referring to Wu and Deng [45] and Zhang and Huang [46], this study re-measures subsidies in two ways (i.e., fiscal S&T expenditure and its share of total fiscal expenditure) to perform robustness tests. The former is named the size of subsidies, and the

latter is called the intensity of subsidies to facilitate the distinction.

(2) *Tax Preferences (Tax).* As for the tax preferences, this paper selects the share of enterprise income tax of each region's fiscal revenue in GDP to measure them in the benchmark regression. Currently, China's tax preferences' policies for innovation activities mainly include accelerated depreciation of assets, deductions for R&D expenses, and preferential tax rates for high-tech firms. These will ultimately be reflected in the enterprise income tax paid by firms [47], that is, the lower the enterprise income tax, to some extent, the stronger the tax preferences. It should be noted that this study re-measures the tax preferences in two ways (i.e., enterprise income tax and its share of total fiscal revenue) to perform robustness tests. The former is named the size of tax preferences, and the latter is called the intensity of tax preferences to facilitate the distinction.

3.2.3. Control Variables. The following control variables are selected to control for the possible influence of other variables on regional innovation quality:

(1) *Innovation Resources (Resources).* The improvement of innovation quality is inseparable from the input of innovation resources, including innovation funds and innovation personnel. However, this study concentrates on innovation personnel mainly for the reasons below. Firstly, as the carrier of knowledge, the importance of innovation personnel in regional innovation activities is becoming increasingly prominent in today's knowledge economy. High-quality innovation activities cannot be achieved without the intellectual support of innovators. Another reason for it is the lack of statistics on R&D funds at the city level in China. After extensively consulting statistical information such as the China City Statistical Yearbook and the China Regional Economic Statistical Yearbook, we have not obtained statistical information on R&D funds or personnel based on the same statistical caliber. Therefore, with reference to Lu and Wang [48], the number of employees in scientific research and technological services is selected to measure innovation resources.

(2) *Innovation Support (Support).* In the regional innovation system, there are also indirect innovation subjects besides direct innovation subjects. The improvement of regional innovation quality requires not only the efforts of direct innovation subjects but also the innovation support from indirect innovation subjects, especially the financial support from banks in the situation where direct innovation subjects are generally facing financing constraints [49]. In the Chinese context, financing from banks is common for direct innovation subjects to obtain financial innovation support due to the difficulty in financing through capital markets [50].

(3) *Economic Development Level (Economy).* The level of economic development reflects the economic strength in each region. Generally speaking, the stronger the economy, the stronger the innovation. This study selects the per capita GDP to measure the economic development level.

(4) *Industrial Structure Upgrading (Industry).* The spatial reallocation of resources, competition, and synergies arising from the process of industrial upgrading can have an impact on innovation [51]. The proportion of tertiary industry employees in total employees is selected to measure the upgrading of industrial structure.

(5) *Firm Size (Size).* Some scholars argue that the larger the firm, the greater its innovation [52]. Others argue that larger is not better, and small-scale firms account for a higher share of R&D outcomes instead [53]. This study selects the value of total assets of industrial enterprises above the state-designated scale divided by the number of firms to measure the firm size.

(6) *Infrastructure Level (Infrastructure).* A well-developed infrastructure can facilitate the communication of information and the exchange of knowledge [54], which are beneficial to regional innovation quality. The combined value of postal and telecommunications services as a share of GDP is selected to measure the infrastructure level.

(7) *Opening-Up Degree (Opening).* In an open economy, a country can improve innovation quality by optimizing the allocation of innovation resources through various channels, such as foreign direct investment (FDI) and exports. In this study, the combined value of FDI and exports as a share of GDP is chosen to measure the opening-up degree.

(8) *Institutional Environment (Institution).* The institutional environment is a crucial component of the regional innovation environment. The clear function of the government and market and the development of the nonstate economy are conducive to stimulating innovation [55]. This study chooses total assets of state-owned and state-controlled firms as a proportion of all firms in the province where the city is located as the proxy indicator. Note that a smaller value indicates a better institutional environment in this study.

(9) *Education Level (Education).* Education helps develop the talent needed for innovation, and hence, the education level is an essential factor in innovation [56]. The number of students enrolled in higher education institutions is selected to measure the education level.

3.2.4. Spatial Weight Matrix. The first law of geography states that geographic proximity makes things more closely related. Geographic proximity creates favorable conditions for mutual learning, competition, and imitation of government R&D funding policies [19], as well as the spillover effect of innovation activities [57]. Meanwhile, economic disparity also influences government R&D funding and regional innovation quality. It is because, on the one hand, regions with small economic disparity tend to have closer assessment targets and pressures. In this situation, the interactions of the local government around R&D funding are more intense. On the other hand, these regions tend to have closer innovation strength, which is more conducive to acquiring and absorbing appropriate technologies and further improving regional innovation quality. Therefore, this study constructs a nested spatial weight matrix of geographic distance and economic distance to depict the spatial correlation of government R&D funding and regional innovation quality. The specific form is as follows:

$$W_1 = \begin{cases} \frac{1}{|d|} \times \frac{1}{\left|\mathrm{GDP}_i - \mathrm{GDP}_j\right|}, & i \neq j, \\ 0, & i = j, \end{cases} \tag{8}$$

where i and j denote regions i and j, respectively, d is the spherical distance between the two regions, and GDP is the average annual GDP per capita for each region during the study period.

3.3. Instructions of Data Processing and Results of Descriptive Statistical Analysis. This study takes the panel data in 283 Chinese cities from 2011 to 2017 as the research sample. The original patent data is from the China Research Data Service Platform (CNRDS). The original data of direct subsidies and tax preferences are from "S&T Expenditure" and "Enterprise Income Tax" in the China Urban Statistical Yearbook and China Regional Economic Statistical Yearbook. Meanwhile, other related data are mainly derived from the China Urban Statistical Yearbook and China Regional Economic Statistical Yearbook. Moreover, in this study, the following cities are excluded from the sample: (1) cities undergoing administrative adjustments, such as Chaohu; (2) municipalities directly under the central government with special status, such as Beijing, Tianjin, Shanghai, and Chongqing; (3) cities with seriously missing data, such as Taiwan, Hong Kong, Macao, and some Western cities. As for the few missing data, this study completes it by looking up statistical yearbooks as well as statistical bulletins on national economic and social development for each city.

It should be noted that the processing of the original data is as follows. First, the data such as exports and FDI are converted into the unit of 10000 yuan based on the average exchange rate of the US dollar to the RMB for the corresponding year. Second, the variables involving the amount of money, such as GDP and exports, are converted into comparable prices with 2011 as the base period using the GDP deflator. Besides, this study uses Stata15 to calculate spatial weight matrix and Moran's index (Moran's I) and uses MATLAB R2016b to estimate models and perform corresponding tests. Table 2 reports the results of descriptive statistics.

4. Empirical Results and Discussion

4.1. Spatial Correlation Tests on Regional Innovation Quality. After using the GEV method to assign weights to the evaluation index system of regional innovation quality and calculate the scores of it, this study uses Moran's index (Moran's I) to determine whether there is a spatial correlation between regional innovation quality. Moran's I is calculated by the following equation:

$$\text{Morans}' \, I = \frac{n\sum_i\sum_j W_{ij}\left(x_i - \overline{x}\right)\left(x_j - \overline{x}\right)}{\sum_i\sum_j W_{ij}\sum_{i=1}\left(x_i - \overline{x}\right)^2} = \frac{\sum_{i=1}^n \sum_{j=1}^n W_{ij}\left(x_i - \overline{x}\right)x_j - \overline{x}}{S^2 \sum_{i=1}^n \sum_{j=1}^n W_{ij}}, \tag{9}$$

where $S^2 = (1/n)\sum_{i=1}^n (x_i - \overline{x})^2, \overline{x} = (1/n)\sum_{i=1}^n x_i$, x_i denotes the observation of region i, n is the sample size, and W_{ij} is the element of the spatial weight matrix. The value of Moran's I is between −1 and 1, with values greater than 0 indicating a strong positive spatial correlation and values less than 0 indicating a strong negative spatial correlation. Table 3 reports the results of Moran's I test for regional innovation quality.

The results in Table 3 show that Moran's I of regional innovation quality from 2011 to 2017 all pass the test at the 1% significance level, indicating a positive spatial correlation of regional innovation quality: the higher the quality of local innovation, the higher the quality of innovation in neighboring regions. It is necessary and reasonable to take the spatial correlation of regional innovation quality into consideration. Besides, Moran's I of regional innovation quality shows an increasing trend year by year, indicating that, with the increasing of inter-regional exchanges and linkages, the spillover effect of regional innovation quality is gradually enhanced, and hence, the spatial correlation of it is strengthened.

4.2. Basic Regression. In this study, the maximum likelihood method (MLE) is used to estimate the model [58], and the tests are carried out according to the lines proposed by Elhorst [59]. The test results of LM statistics and robust LM statistics show that the spatial Durbin model (SDM) should be established in this study. Meanwhile, the Wald test rejects the original hypothesis that the SDM should degenerate into a spatial lag model (SLM) or a spatial error model (SEM), which further confirms that the SDM is suitable for this study. In fact, SDM can take the spatial correlation of the dependent and independent variables into account

Table 2: Results of descriptive statistics ($N = 1981$).

Variables	Calculation methods	Expected symbol	Mean	SD	Min	Max	Unit
Regional innovation quality (Innovation)	According to the global entropy method	—	0.051	0.066	0.007	0.828	—
Subsidies (Subsidy)	S&T expenditure/GDP	+	0.006	0.004	0.001	0.030	%
Tax preferences (Tax)	Enterprise income tax revenue/GDP	-	0.003	0.003	0	0.063	%
Innovation resources (Resources)	Number of employees in scientific research and technological services	+	9730	18178	200	179665	Person
Innovation support (Support)	Loan balances of banking institutions/GDP	+	0.916	0.565	0.118	7.450	%
Economic development level (Economy)	GDP per capita	+	38891	26152	6457	402457	10000 yuan
Industrial structure upgrading (Industry)	Employees in the tertiary sector in urban units/ total number of employees	+	0.518	0.132	0.154	0.948	%
Firm size (Size)	Total assets of industrial enterprises above the state-designated scale/number of them	+ or -	22915	28258	1135	335259	10000 yuan/each
Infrastructure level (Infrastructure)	Combined value of postal and telecommunications services/GDP	+	0.018	0.011	0.002	0.205	%
Opening-up degree (Opening)	Combined value of the FDI and exports/GDP	+	0.130	0.270	0	6.625	%
Institutional environment (Institution)	Total assets of state-owned and state-controlled firms in the province/total assets of all firms	-	0.361	0.156	0.108	0.827	%
Education level (Education)	Number of students in higher education	+	84216	152627	0	1067335	Person

Note. The above variables are all logarithmically treated in the following regressions.

Table 3: Results of Moran's I test for the regional innovation quality.

Year	2011	2012	2013	2014	2015	2016	2017
Moran's I	0.2310*** (7.6680)	0.2760*** (9.1470)	0.2980*** (9.8530)	0.3120*** (10.3120)	0.3390*** (11.1800)	0.3720*** (12.2560)	0.3680*** (12.1490)

Note. ***, **, and * denote a significance level of 1%, 5%, and 10%, respectively. The z-statistic is in parentheses.

simultaneously, which just meets the research need of this study. Although the Hausman test shows that the fixed effects are better than the random effect, to enhance the reliability of the results, this study reports the estimated results of SDM in five estimation forms, as shown in Table 4. From left to right, the estimates are for no fixed effect (nonF), spatial fixed effect (sF), time fixed effect (tF), time and spatial fixed effect (stF), and random effect (r).

The results in Table 4 show that $\overline{R}^2$ is high in the results of the five estimation forms, indicating that the SDM is a better fit overall and can better reflect the impact of government R&D funding on regional innovation quality when considering spatial correlation. This study focuses on stF when analyzing the estimation results. Because the strength of government R&D funding may vary over time and space, its impact on regional innovation quality may also vary. In the form of stF, the effects of time- and space-varying factors on the steady state can be observed simultaneously [60], which meets this paper's research need.

The stF estimated results show that regional innovation quality is not only influenced by factors such as subsidies and economic development level in the region but also by the innovation quality in neighboring regions. The spatial autocorrelation coefficient is positive and passes the test at the 1% significance level, further indicating a positive spatial correlation in regional innovation quality. The reason may be that the geographical proximity and the narrowing of the economic gap create convenient conditions for the flow of innovation resources. Meanwhile, the spillover effect of regional innovation quality also enables a region to learn from and imitate neighboring regions with high-quality innovation to improve their innovation quality.

In terms of the effect of subsidies, they passed the test at the 5% level in all five estimation forms, indicating that subsidies contribute significantly to regional innovation quality. Thus, Hypothesis 1 is partially confirmed. By meeting the financial need for high-quality innovation activities, sharing risks, and correcting positive externalities, subsidies compensate for market failures and stimulate the high-quality innovation effectively, thus contributing to the improvement of regional innovation quality. However, the result is inconsistent with Dang and Motohashi [12], who found that subsidies cannot improve China's innovation quality. The possible reason may be that they focused on the subsidies for the patent application, approval fees, and patent awards, but incentivizing patents is not the only purpose of government R&D funding. Moreover, in contrast to their study, this study considers both the technological,

Table 4: Results of the spatial Durbin model (SDM).

	nonF	sF	tF	stF	r
Intercept	−5.0825*** (−6.8209)	—	—	—	—
Subsidy	0.0954*** (5.5844)	0.1140*** (6.2473)	0.1017*** (5.9513)	0.1203*** (7.1503)	0.1021*** (5.9862)
Tax	0.0251 (0.9754)	0.0269 (0.9698)	0.0177 (0.6930)	0.0201 (0.7888)	0.0177 (0.6949)
Resources	0.2692*** (18.4879)	0.2514*** (15.6939)	0.2695*** (18.5306)	0.2517*** (17.0355)	0.2691*** (18.5299)
Support	0.1563*** (5.4227)	0.1777*** (5.6715)	0.1583*** (5.5116)	0.1812*** (6.2941)	0.1588*** (5.5380)
Economy	0.3599*** (12.4953)	0.3773*** (12.1791)	0.3707*** (12.9481)	0.3883*** (13.6717)	0.3711*** (12.9835)
Industry	0.1047** (2.3695)	0.0905* (1.8962)	0.1113** (2.5208)	0.0963** (2.1889)	0.1110** (2.5192)
Size	0.0094 (0.4830)	0.0009 (0.0445)	0.0035 (0.1847)	−0.0066 (−0.3493)	0.0034 (0.1754)
Infrastructure	−0.0137 (−0.5992)	−0.0124 (−0.5090)	−0.0068 (−0.2975)	−0.0061 (−0.2657)	−0.0068 (−0.2981)
Opening	0.0354*** (3.3336)	0.0355*** (3.1014)	0.0380*** (3.5948)	0.0382*** (3.6285)	0.0380*** (3.6028)
Institution	−0.1738*** (−5.2167)	−0.2044*** (−5.6802)	−0.1665*** (−5.0181)	−0.1953*** (−5.9102)	−0.1671*** (−5.0448)
Education	0.0389*** (3.5618)	0.0427*** (3.6654)	0.0377*** (3.4681)	0.0410*** (3.8313)	0.0378*** (3.4820)
W*Subsidy	−0.0022 (−0.0643)	−0.0071 (−0.1971)	0.0571 (1.3762)	0.0629 (1.5407)	0.0571 (1.3805)
W*Tax	−0.0092 (−0.1865)	0.0198 (0.3838)	−0.0722 (−1.1218)	−0.0225 (−0.3558)	−0.0711 (−1.1067)
W*Resources	−0.0416 (−1.0647)	−0.0461 (−1.0842)	−0.0198 (−0.4582)	−0.0237 (−0.5288)	−0.0199 (−0.4608)
W*Support	−0.1333** (−2.3394)	−0.1764*** (−2.9224)	−0.0555 (−0.8099)	−0.0759 (−1.1146)	−0.0561 (−0.8207)
W*Economy	−0.2512*** (−3.8297)	−0.2782*** (−3.9802)	−0.0558 (−0.7775)	−0.0535 (−0.7534)	−0.0561 (−0.7824)
W*Industry	0.0265 (0.2657)	0.0155 (0.1456)	0.0699 (0.6176)	0.0263 (0.2302)	0.0693 (0.6130)
W*Size	0.0052 (0.1309)	0.0404 (0.9789)	−0.0717 (−1.4893)	−0.0703 (−1.4740)	−0.0716 (−1.4883)
W*Infrastructure	−0.0049 (−0.0943)	0.0202 (0.3561)	0.0638 (1.0775)	0.0792 (1.3486)	0.0641 (1.0831)
W*Opening	0.0001 (0.0054)	−0.0088 (−0.3283)	0.0197 (0.7567)	0.0156 (0.6008)	0.0197 (0.7581)
W*Institution	0.1064 (1.5362)	0.1049 (1.4188)	0.2033*** (2.6974)	0.1921** (2.5748)	0.2033*** (2.7027)
W*Education	−0.0184 (−0.6899)	−0.0271 (−0.9509)	−0.0271 (−0.8693)	−0.0384 (−1.2300)	−0.0273 (−0.8777)
W*Innovation	0.2779*** (7.1066)	0.2969*** (7.6701)	0.1959*** (4.8506)	0.1869*** (4.6176)	0.1959*** (4.8508)
Theta	—	—	—	—	0.9875*** (21.9099)
δ^2	0.1688	0.1679	0.1662	0.1406	0.1651
$\overline{R^2}$	0.6408	0.6561	0.6431	0.6603	0.6431
Log-L	−1059.3783	−914.0194	−1035.4341	−872.7333	−2023.1226

Note. ***, **, and * denote a significance level of 1%, 5%, and 10%, respectively. The t-statistic is in parentheses.

economic, and comprehensive aspects of innovation quality rather than just its technological aspect measured by the number of patents.

As for the effect of tax preferences, they fail the 5% significance level test in the estimated results of all five forms, indicating that they cannot enhance regional innovation quality. It is inconsistent with Ernst et al. [13] and Mukherjee et al. [14], who considered that tax preferences are beneficial to innovation quality due to the difference in the research sample, perspective, and empirical model. Their studies were based on the firm perspective and used non-spatial econometric methods for analysis. In contrast, this study is based on the regional level that includes innovation subjects such as firms, institutions, and financial institutions. Meanwhile, it uses a spatial econometric model to portray the spatially relevant features of government R&D funding and innovation quality, which may be relatively more accurate. Besides, the effect of tax preferences is not significant, but that of subsidies is positive and significant, which is inconsistent with Hypothesis 1 but validates Hypothesis 2. It may be due to the characteristic of tax preferences and the shortcomings of China's tax preference policy. Firstly, as ex-post subsidy policies, tax preference policies cannot meet the funds for innovation immediately. Further, in China, the current tax preferences are mainly based on enterprise income tax and aim to stimulate the inputs of innovation, thus not stimulating innovation quality directly [17]. Finally, the effect of tax preferences is deeply affected by taxable income, and fluctuating taxable income makes the intensity of tax preferences fluctuate greatly, which is detrimental to the long-term planning of high-quality innovation [47]. It can be found that there are some cities with negative profits in the sample, such as Taiyuan and Yangquan. These cities are likely to have little or even no taxable income for enterprise income tax, leading to tax preferences that may not work for them as they should [26].

For control variables, firstly, although the improvement of the institutional environment enhances local innovation quality, it is not conducive to the advancement of the innovation quality in neighboring regions. It may be because regions with a sound institutional environment attract the inflow of innovation resources but are not conducive to improving innovation quality in neighboring regions with a poor institutional environment. In the meantime, the effect of firm size on regional innovation quality is not significant, which is inconsistent with our expectation. It may be since both large and small firms have advantages in improving innovation quality. Thus, governments cannot decide whether to subsidize just based on the scale of firms alone. Furthermore, inconsistent with the expectation, the effect of the infrastructure level on regional innovation quality is not significant. One possible reason is that government investment in infrastructure may crowd out funds that will otherwise be invested in R&D activities, which is not conducive to improving regional innovation quality.

In order to analyze the influence path of government R&D funding on regional innovation quality further, this study adopts the decomposition method provided by Lesage and Pace [61, 62] to divide the combined impact of government R&D funding on regional innovation quality into two parts: direct effects and spillover effects, respectively. The former represents the average impact of government R&D funding on local innovation quality; the latter represents the average impact of government R&D funding on innovation quality in neighboring regions. The estimated results are reported in Table 5. It can be found that the increased strength of local subsidies is conducive to improving their innovation quality and the innovation quality in neighboring regions. The reasons for the positive direct effect have already been analyzed above, and the positive spillover effect may be related to the phenomenon of "competition for innovation" among regions. The fierce funding competition makes all regions devote themselves to increasing the input of regional innovation resources, attracting the inflow of innovation resources, and optimizing the allocation of regional innovation resources. Thus, government R&D funding is conducive to improving the innovation quality in neighboring regions. Besides, the direct, spillover, and total effects of tax preferences do not pass the significance test.

4.3. Robustness Tests. This study mainly carries out three kinds of robustness tests, which consider possible lagged effects of government R&D funding on regional innovation quality and replace the measurement variables of government R&D funding and the spatial weighting matrix. Firstly, the model is re-estimated by lagging all independent and control variables by one and two periods, respectively, since it may take time for government R&D funding to be implemented and to eventually improve regional innovation quality. Also, regions with previously high innovation quality may be more favored by government R&D funding [4], so lagging government R&D funding and control variables can reduce the interference of this reciprocal causality on the estimated results. Secondly, the model is re-estimated based on other variables measuring government R&D funding (i.e., the size and the intensity of it), as mentioned earlier (note that this paper discusses two forms of government R&D funding: subsidies and tax preferences, which are, respectively, measured by fiscal S&T expenditures as a share of regional GDP and enterprise income tax as a share of regional GDP in the benchmark regression. Here, in the robustness tests, the size of subsidies is re-measured by the fiscal S&T expenditures, and the size of tax preferences is re-measured by the enterprise income tax revenue. Meanwhile, the intensity of subsidies is re-measured by fiscal S&T expenditures as a share of total fiscal expenditures, and the intensity of tax preferences is re-measured by enterprise income tax as a share of total fiscal revenue). Thirdly, the model is re-estimated based on the spatial weight matrix of geographic distance and economic distance, respectively. The specific settings of the spatial weight matrix are shown in equations (10) and (11), where W_2 and W_3 are the spatial weight matrix of geographic distance and economic distance, respectively, i and j denote regions i and j, d is the spherical distance between the two regions, and GDP is the annual average of GDP per capita for each region in the sample period:

Table 5: Estimated results of the direct, indirect, and total effects based on the SDM.

Variables	Direct effects	Indirect effects	Total effects
Subsidy	0.1234*** (7.5099)	0.1033** (2.1831)	0.2267*** (4.5807)
Tax	0.0191 (0.7687)	−0.0283 (−0.3689)	−0.0091 (−0.1178)

Note. ***, **, and * denote a significance level of 1%, 5%, and 10%, respectively. The *t*-statistic is in parentheses.

$$W_2 = \begin{cases} \dfrac{1}{|d|}, & i \neq j, \\ 0, & i = j, \end{cases} \tag{10}$$

$$W_3 = \begin{cases} \dfrac{1}{\left|\mathrm{GDP}_i - \mathrm{GDP}_j\right|}, & i \neq j, \\ 0, & i = j. \end{cases} \tag{11}$$

The estimated results are reported in Table 6. It can be found that the coefficients of subsidies are all significantly positive at the 1% significant level, while those of tax preferences are not significantly negative. It indicates that subsidies can enhance regional innovation quality, while tax preferences cannot enhance regional innovation quality. Thus, the previous empirical results are robust and reliable.

4.4. Tests of Influence Mechanisms and Identification of the Spillover Effect

4.4.1. Tests of Influence Mechanisms. Theoretical analysis shows that the impact of subsidies on regional innovation quality is mainly manifested as follows. The resource attributes of subsidies enable direct innovation subjects to increase innovation resources, and their signaling attributes enable indirect innovation subjects to increase innovation support to the direct innovation subjects, thus contributing to the improvement of regional innovation quality (considering that the previous empirical results show that subsidies can significantly improve regional innovation quality, while tax preferences cannot improve it, this study focuses on examining the mechanism of subsidies on regional innovation quality). This section will empirically test each of these mechanisms. Firstly, to test whether subsidies can increase innovation resources by direct innovation subjects and then impact regional innovation quality, this paper develops an SDM with subsidies as the independent variable and innovation resources (Resources) as the dependent variable. It should be noted that three forms of subsidies are used in this section, namely, subsidies as a share of GDP (Subsidy1), the scale of subsidies (Subsidy2), and subsidies as a share of fiscal expenditure (Subsidy3) to enhance the reliability of the estimated results (note that Subsidy1, Subsidy2, and Subsidy3 are three measurements of subsidies mentioned earlier). The results are shown in Table 7. Secondly, to test whether subsidies can increase indirect innovation subjects' innovation support and then influence regional innovation quality, this paper develops an SDM with subsidies as the independent variable and innovation support (Support) as the dependent variable. Also, Subsidy1, Subsidy2, and Subsidy3 are used to measure subsidies. The estimated results are shown in Table 8. Note that the definition and description of data sources for Subsidy1, Subsidy2, Subsidy3, Resources, and Support have been described in the description of variables. The specific analysis is as follows:

As shown in Table 7, for the impact of subsidies on the innovation resources of regional direct innovation subjects, the direct effects of Subsidy1, Subsidy2, and Subsidy3 are all significantly positive, while the estimated coefficients of the spillover effects are mostly negative. It indicates that the increase in local subsidies can promote local direct innovation subjects to increase innovation resources while decrease those in neighboring regions. The reason may be that regions with larger subsidies attract the inflow of innovation resources from geographically adjacent and economically nearby regions.

Table 8 shows the results of the impact of subsidies on the innovation support of regional indirect innovation subjects. In terms of direct effects, it shows that the estimated coefficients of Subsidy1, Subsidy2, and Subsidy3 are all significantly positive, indicating that local subsidies can promote local indirect innovation subjects to increase innovation support. However, the estimated coefficient of the spillover effect is not significant. In the Chinese context, the positioning of indirect innovation subjects (e.g., banks) to serve local areas and administrative barriers may make it difficult for subsidies to attract banks from other places to increase their support for local innovation.

4.4.2. Identification of the Spillover Effect. From the results in Table 5, it can be seen that subsidies enhance the innovation quality of neighboring regions (i.e., there is a spillover effect) due to the phenomenon of spatial competition for subsidies, as suggested in the previous analysis. Here, this study refers to Bian et al. [19] for further identification (the identification idea of Bian et al. [19] is as follows. Firstly, use Moran's *I* test for preliminary identification; secondly, build a spatial econometric model and identify it further based on the coefficient of the spatial lag term. Here, the result of Moran's *I* test indicates the existence of spatial competition for subsidies. However, to save space, it has not been reported in this section). To this end, an SLM with subsidies as the dependent variable is developed. The spatial lag coefficient (ρ) of subsidies is tested to examine whether there is spatial competition for subsidies. Subsidy1, Subsidy2, and Subsidy3 are used to measure subsidies as mentioned above, and the estimated results are shown in Table 9. It can be found that ρ for all three measuring forms passes the test at the 1% significance level, indicating a positive correlation between subsidies, that is, when a region increases its subsidies, regions that are geographically close to it and have small economic disparities with it will also increase subsidies strategically. Thus, it proves that there is spatial competition between regions in terms of subsidies.

Table 6: Results of the robustness test.

	Consider the lagged effects		Replace measurement variables of government R&D funding		Replace the spatial weight matrix	
	One period	Two periods	Size	Intensity	Geography distance	Economic distance
Subsidy	0.1295*** (7.2784)	0.0963*** (5.0052)	0.1656*** (9.6374)	0.1490*** (7.8619)	0.0988*** (4.7271)	0.1390*** (5.7808)
Tax	0.0115 (0.4279)	0.0405 (1.3768)	0.0916*** (4.3620)	0.0092 (0.3215)	0.0086 (0.2882)	0.0394 (1.1964)
Resources	0.2519*** (15.6856)	0.2426*** (14.6118)	0.1480*** (8.5438)	0.2499*** (15.6723)	0.2621*** (14.6832)	0.3024*** (16.3099)
Support	0.1865*** (6.2034)	0.2121*** (6.2609)	0.2020*** (7.4744)	0.2176*** (7.6062)	0.2434*** (6.7173)	0.2002*** (5.0483)
Economy	0.3865*** (12.8981)	0.3510*** (10.4551)	0.2336*** (7.3139)	0.3159*** (9.6777)	0.3547*** (10.2791)	0.3175*** (8.2847)
Industry	0.0903 * (1.9217)	0.0773 (1.5245)	0.1387*** (3.0412)	0.1351*** (2.8139)	0.1144* * (2.1943)	-0.0004 (−0.0085)
Size	−0.0144 (−0.7097)	0.0042 (0.1825)	0.0211 (1.0675)	0.0001 (0.0022)	−0.0177 (−0.7346)	−0.0003 (−0.0136)
Infrastructure	−0.0061 (−0.2476)	-0.0171 (-0.6674)	−0.0336 (−1.4328)	−0.0101 (−0.4136)	−0.0344 (−1.2215)	−0.0377 (−1.1920)
Opening	0.0364*** (3.2359)	0.0416*** (3.3602)	0.0250*** (2.2922)	0.0333*** (2.9304)	0.0386*** (2.9890)	0.0318** (2.2050)
Institution	−0.1742*** (−5.3986)	−0.1679*** (−3.8075)	−0.1325*** (−3.8520)	−0.1912*** (−5.3639)	−0.1074*** (−2.7627)	−0.1309*** (−2.9552)
Education	0.0404*** (3.5553)	0.0303*** (2.3777)	0.0113*** (1.0056)	0.0312*** (2.6867)	0.0379*** (2.8273)	0.0355*** (2.6360)
W*Subsidy	0.0266 (0.5327)	0.2800** (2.2800)	0.0441 (1.0340)	0.0466 (1.0287)	0.0085 (0.1619)	0.0396 (0.5992)
W*Tax	0.0951 (1.1704)	−0.2807 (−1.4357)	−0.0980* (−1.8559)	−0.1783** (−2.3891)	0.1314* (1.7013)	0.0373 (0.4494)
W*Resources	−0.0531 (−0.9799)	−0.0232 (−0.1417)	−0.0085 (−0.1710)	−0.0183 (−0.3800)	−0.1150** (−2.4019)	−0.0467 (−0.9274)
W*Support	−0.0361 (−0.4068)	−0.5263** (−2.3175)	−0.0329 (−0.5077)	−0.0364 (−0.5272)	−0.3751*** (−4.3627)	−0.1925* (−1.9273)
W*Economy	−0.0174 (−0.2016)	0.0274 (0.1398)	−0.0057 (−1.1255)	−0.0359 (−0.4578)	−0.1027 (−1.1960)	0.1474 (1.5047)
W*Industry	0.0608 (0.4256)	0.1192 (0.2913)	0.0122 (0.1025)	0.0083 (0.0658)	0.0016 (0.0114)	0.4495*** (2.9638)
W*Size	−0.0905 (−1.4982)	−0.0321 (−0.2254)	−0.0683 (−1.3903)	−0.0623 (−1.2241)	0.0586 (0.0114)	−0.0949 (−1.5774)
W*Infrastructure	0.0369 (0.5142)	0.4113* (1.9199)	0.0733 (1.2039)	0.0966 (1.5309)	0.0422 (0.5672)	−0.0757 (−0.9662)
W*Opening	0.0052 (0.1680)	−0.0674 (−0.8096)	0.0249 (0.9288)	0.0171 (0.6109)	0.0088 (0.2447)	−0.0346 (−0.9770)
W*Institution	0.1496* (1.6486)	0.3590* (1.7155)	0.2320*** (2.9486)	0.2196*** (2.7206)	0.0996 (1.0862)	0.0072 (0.0671)
W*Education	−0.0417 (−1.1061)	−0.0351 (−0.3586)	−0.0375 (−1.1255)	−0.0406 (−1.1936)	0.1056*** (2.9514)	−0.0259 (−0.7071)
W*Innovation	0.0993** (2.1438)	0.8777*** (32.3208)	0.1927*** (4.7666)	0.1967*** (4.8767)	0.1827*** (4.1576)	0.1706*** (3.5283)
δ^2	0.1671	0.1584	0.1509	0.1633	0.1768	0.1627
$\overline{R^2}$	0.6593	0.6148	0.6886	0.6631	0.6255	0.6732
Log-L	−882.7404	−845.4902	−786.7291	−865.1183	−784.4594	−565.6055

Note. ***, **, and * denote a significance level of 1%, 5%, and 10%, respectively, and the t-statistic is in parentheses. According to the Hausman test, most models should be estimated with fixed effects, and thus, this study analyzes the results based on the estimation of time and space fixed effects for the sake of comparison.

Table 7: Results of the impact mechanism test: impact on innovation resources.

		nonF	sF	tF	stF	r
Subsidy1	Direct effect	0.0421*	0.0499*	0.0432*	0.0493*	0.0434*
		(1.6946)	(1.9225)	(1.7216)	(2.0656)	(1.7212)
	Spillover effect	−0.1392**	−0.1256 *	−0.0758	−0.0381	−0.0681
		(−2.2821)	(−1.9258)	(−1.165)	(−0.6174)	(−1.0432)
Subsidy2	Direct effect	0.3549***	0.3367***	0.3575***	0.3394***	0.3537***
		(18.6667)	(17.1314)	(18.6371)	(18.4044)	(18.6869)
	Spillover effect	−0.2089***	0.2175***	−0.1517***	−0.1537***	−0.152***
		(−3.6912)	(−3.8151)	(−2.8521)	(−2.8922)	(−2.8037)
Subsidy3	Direct effect	0.0695***	0.0748***	0.0740***	0.0807***	0.0751***
		(2.5278)	(2.6487)	(2.6932)	(2.8412)	(2.7798)
	Spillover effect	0.2162***	−0.1950***	−0.0951	−0.0566	−0.0832
		(−3.3301)	(−2.8162)	(−1.3188)	(−0.7660)	(−1.1439)

Note. ***, **, and * denote a significance level of 1%, 5%, and 10%, respectively. The t-statistic is in parentheses.

Table 8: Results of the impact mechanism test: impact on innovation support.

		nonF	sF	tF	stF	r
Subsidy1	Direct effect	0.1521***	0.1534***	0.1456***	0.1469***	0.1458***
		(11.2262)	(10.8430)	(10.5898)	(11.3750)	(11.1162)
	Spillover effect	0.1256***	0.1114***	0.0246	−0.0120	0.0212
		(2.8525)	(2.3940)	(0.5585)	(−0.2726)	(0.4747)
Subsidy2	Direct effect	0.0356***	0.0404***	0.0291**	0.0332***	0.0291**
		(2.8296)	(2.9614)	(2.2801)	(2.7043)	(2.3722)
	Spillover effect	0.0944 *	0.0773	0.0076	−0.0217	0.0089
		(1.9063)	(1.3962)	(0.1806)	(−0.5081)	(0.2047)
Subsidy3	Direct effect	0.0714***	0.0740***	0.0643***	0.0654***	0.0648***
		(4.5724)	(4.4483)	(4.2198)	(4.2664)	(4.0507)
	Spillover effect	0.1669***	0.1599***	0.0551	0.0248	0.0561
		(3.1771)	(2.7489)	(1.0628)	(0.5024)	(1.1500)

Note. ***, **, and * denote a significance level of 1%, 5%, and 10%, respectively. The t-statistic is in parentheses.

Table 9: Identification of spatial competition effects of subsidies.

	Subsidy1	Subsidy2	Subsidy3
ρ	0.3583***	0.2611***	0.2553***
	(9.9679)	(8.9613)	(7.7439)
Controls	YES	YES	YES
δ^2	0.3438	0.4452	0.2868
$\overline{R^2}$	0.1582	0.6391	0.4771
Log-L	−1615.3235	−1862.7471	−1426.7387

Note. ***, **, and * denote a significance level of 1%, 5%, and 10%, respectively, and the t-statistic is in parentheses. The regression results reported are based on time and space fixed effects; dynamic spatial lag models are built to test again, and the results remain consistent, but are not reported to save space.

Thus, combined with the results of the above tests on the mechanism of subsidies affecting regional innovation quality, it can be seen that the spillover effect of subsidies on the innovation quality in neighboring regions (i.e., the impact of subsidies on improving the innovation quality in neighboring regions) can be reflected as follows: when one region increases the intensity of subsidies, neighboring regions usually strategically increase subsidies, which leads to an increase in innovation resources for direct innovation subjects and an increase in innovation support for indirect innovation subjects in neighboring regions, attracts the inflow of innovation resources from other regions, and, thus, helps neighboring regions to improve regional innovation quality.

5. Further Analysis and Discussion

5.1. Heterogeneity Tests

5.1.1. Heterogeneity of the City Location. Among the 283 cities, there are 98 Eastern cities, 100 Middle cities, and 85 Western cities (the Eastern cities are located in Hebei, Liaoning, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan. The Middle cities are located in Shanxi, Jilin,

Table 10: Estimated results of heterogeneity tests.

	Heterogeneity of the city location			Heterogeneity of the city administrative hierarchy	
	Eastern cities	Middle cities	Western cities	Cities with higher administrative hierarchy	Cities with general administrative hierarchy
Subsidy	−0.0622** (−2.1304)	0.1252*** (4.9261)	0.1010*** (3.6978)	−0.2828*** (−3.8747)	0.0856*** (5.0891)
Tax	0.0981*** (2.7189)	−0.1607*** (−5.3033)	−0.1212*** (15.7478)	0.1851*** (3.2489)	−0.0408* (−1.9289)
Resources	0.2503*** (15.4173)	0.2546*** (15.8718)	0.2542*** (15.7478)	0.2350*** (13.8213)	0.2257*** (13.3414)
Support	0.0430*** (7.8741)	0.2453*** (8.7266)	0.2450*** (8.6525)	0.1797*** (5.5944)	0.1431*** (4.2035)
Economy	0.4225*** (13.8172)	0.4176*** (13.3931)	0.4239*** (13.8922)	0.3749*** (12.0447)	0.3622*** (11.4288)
Industry	0.0843* (1.7610)	0.0651 (1.3664)	0.0765 (1.5958)	0.0551 (1.1350)	0.0326 (0.6822)
Size	−0.0195 (−0.9413)	0.0052 (0.2494)	−0.0136 (−0.6592)	−0.0124 (−0.6052)	−0.0085 (−0.4148)
Infrastructure	0.0055 (0.2194)	0.0138 (0.5613)	-0.0045 (-0.1856)	−0.0161 (−0.6601)	−0.0178 (−0.7256)
Opening	0.0527*** (4.5568)	0.0487*** (4.2469)	0.0466*** (4.0612)	0.0408*** (3.5682)	0.0378*** (3.3106)
Institution	−0.2852*** (−6.8726)	−0.2344*** (−5.9675)	−0.1946*** (−5.3351)	−0.2518*** (−6.7071)	−0.2507*** (−6.7179)
Education	0.0430*** (3.6693)	0.0407*** (3.4907)	0.0457*** (3.8854)	0.0356*** (3.0228)	0.0338*** (2.8987)
W*Subsidy	−0.0232 (−0.3289)	0.1195** (1.9770)	−0.0199 (−0.2704)	0.1353 (0.7002)	0.0433 (1.0120)
W*Tax	0.0328 (0.3762)	−0.1321* (−1.8380)	−0.0161 (−0.1839)	−0.0564 (−0.3735)	−0.0932* (−1.7476)
W ∗ Resources	−0.0336 (−0.6862)	−0.0323 (−0.6646)	−0.0485 (−0.9855)	−0.0044 (−0.0866)	−0.0162 (−0.3169)
W*Support	−0.0746 (−1.0948)	−0.0567 (−0.8366)	−0.0872 (−1.2859)	−0.0135 (−0.1777)	0.0043 (0.0533)
W*Economy	−0.0904 (−1.1789)	−0.1053 (−1.3649)	−0.0994 (−1.2761)	−0.0549 (−0.6936)	−0.0372 (−0.4630)
W*Industry	−0.0071 (−0.0579)	−0.0325 (−0.2638)	−0.0089 (−0.0718)	0.0252 (0.2005)	−0.0185 (−0.1499)
W*Size	−0.0622 (−1.1855)	−0.0189 (−0.3591)	−0.0557 (−1.0762)	−0.0643 (−1.2452)	−0.0707 (−1.3733)
W*Infrastructure	0.0909 (1.4116)	0.1053* (1.6559)	0.1107* (1.6720)	0.0995 (1.5574)	0.1066* (1.6619)
W*Opening	0.0293 (1.0269)	0.0286 (1.0058)	0.0161 (0.5744)	0.0167 (0.5937)	0.0271 (0.9707)
W*Institution	0.0676 (0.6961)	0.1118 (1.2608)	0.1126 (1.3557)	0.1774** (2.0770)	0.1896** (2.2482)
W*Education	−0.0283 (−0.8274)	−0.0354 (−1.0392)	−0.0201 (−0.5825)	−0.0213 (−0.6237)	−0.0271 (−0.7981)
W*Innovation	0.2119*** (5.2661)	0.2078*** (5.1659)	0.2330*** (5.8436)	0.2330*** (5.8432)	0.2219*** (5.5461)
δ^2	0.1684	0.1664	0.1685	0.1674	0.1652
$\overline{R^2}$	0.6511	0.6557	0.6502	0.6521	0.6574
Log-L	−896.3932	−884.6521	−898.3479	−892.1746	−878.3045

Note. ***, **, and * denote a significance level of 1%, 5%, and 10%, respectively, and the *t*-statistic is in parentheses. For the same reasons as above, the regression results based on stF are reported here.

Heilongjiang, Anhui, Jiangxi, Henan, Hubei, and Hunan. The Western cities are located in Inner Mongolia, Guangxi, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang). Columns 2 to 4 of Table 10 show the estimated results when considering the heterogeneity of the city location. It can be found that both subsidies and tax preferences can enhance the innovation quality of the Middle and Western cities but hinder that of the Eastern cities, which confirms Hypothesis 3. The Eastern cities are more market-oriented and face relatively less market failure. Therefore, government R&D subsidies are likely to be redundant resources for them, which may cause government failure, and thus, they are not conducive to innovation quality. In addition, consistent with Wu et al. [63], the tax burden stimulates innovation in the Eastern cities. Overall, in innovation, the Eastern cities rely more on the market, while the Middle and Western cities rely more on the government, which is consistent with Xu and Huang [64].

5.1.2. Heterogeneity of the City Administrative Hierarchy. There are 31 higher-administrative-hierarchy cities and 252 general-administrative-hierarchy cities among the 283 cities (this study defines higher-administrative-hierarchy cities as either provincial capitals or subprovincial cities, namely, Shijiazhuang, Taiyuan, Hohhot, Shenyang, Dalian, Changchun, Harbin, Nanjing, Hangzhou, Ningbo, Hefei, Fuzhou, Xiamen, Nanchang, Qingdao, Jinan, Zhengzhou, Wuhan, Changsha, Guangzhou, Shenzhen, Nanning, Haikou, Chengdu, Guiyang, Kunming, Xi'an, Lanzhou, Xining, Yinchuan, and Urumqi. And, general-administrative-hierarchy cities are cities other than those listed above). Columns 5 and 6 of Table 7 present the estimated results when considering the heterogeneity of the city administrative hierarchy. It can be found that subsidies and tax preferences are detrimental to improving the regional innovation quality of higher-administrative-hierarchy cities but are favorable to general-administrative-hierarchy cities, which confirms Hypothesis 4. Although China's R&D funding policy of "picking the winners" favors firms located in the developed areas [4], the results achieved are not satisfactory. It may be because provincial capitals and subprovincial cities already have advantages in acquiring innovation resources, and the government's intervention through R&D funding may cause them to be crowded with funds and talents, which reduces the allocation efficiency of innovation resources and is not conducive to improving their regional innovation quality.

5.2. Impact of Government R&D Funding on the Regional Innovation Quality Gap. The results of the heterogeneity test above indicate that government R&D funding is beneficial to the improvement of regional innovation quality in the Middle and Western cities and the general-administrative-hierarchy cities. It indicates that the regional innovation quality in regions without innovation advantages has been improved with the help of government R&D funding. Meanwhile, considering the current decreasing trend of the innovation quality gap in China (by calculating the Thiel index for 283 cities, it is found that the innovation quality gap shows a fluctuating downward trend during the sample period. And, the Thiel indices of regional innovation quality for 2011, 2012, 2013, 2014, 2015, 2016, and 2017 are 0.164, 0.137, 0.134, 0.128, 0.130, 0.136, and 0.110, respectively), whether government R&D funding can narrow the regional innovation quality gap?

This study establishes an SDM to investigate the influence of government R&D funding on the regional innovation quality gap. In this model, the dependent variable is the regional innovation quality gap, the independent variables are the two types of government R&D funding (i.e., subsidies and tax preferences), and the control variables are consistent with the previous section. Moreover, the regional innovation quality gap is expressed as the regional innovation quality in a city in a particular year minus the minimum value of regional innovation quality in all cities in that year. This study expects a negative sign for subsidies and a positive sign for tax preferences.

Table 11 reports the estimated results. This study focuses on stF when analyzing for the same reasons mentioned earlier. It shows that the coefficient of subsidies is significantly positive and that of tax preferences, although positive, does not pass the significance test, which is inconsistent with our expectations. It indicates that government R&D funding cannot reduce the regional innovation quality gap but widen it instead. The reason may be that currently, government R&D funding has been heavily concentrated in the Eastern cities and general-administrative-hierarchy cities. Still, funding for these cities has not had the desired effect. Meanwhile, the Middle and Western cities and general-administrative-hierarchy cities with positive effects have received less government R&D funding. For example, in 2017, the minimum value of S&T expenditures as a share of GDP in the Eastern cities was 0.03%, while that in the Middle and Western cities was 0.02%, a difference of 1.5 times; the minimum value in higher-administrative-hierarchy cities was 0.08%, while that in general-administrative-hierarchy cities was only 0.02%, with a difference of 4 times. Furthermore, the Middle and Western cities and the general-administrative-hierarchy cities have negative aggregate profits of industrial enterprises above the state-designated scale in some years. In this situation, their tax liabilities are lower, which may not be conducive to tax preferences in enhancing the innovation quality in these regions, thus not closing the gap of regional innovation quality. The above analysis shows that there is "insufficient intervention" in the regions with good effects and "excessive intervention" in the

Table 11: Results of the impact of government R&D funding on the regional innovation quality gap.

	nonF	sF	tF	stF	r
Intercept	−6.7792*** (-5.9751)	—	—	—	—
Subsidy	0.1285*** (4.7125)	0.1518*** (5.1990)	0.1386*** (5.0752)	0.1617*** (6.0032)	0.1389*** (5.0967)
Tax	0.0728* (1.7777)	0.0583 (1.3111)	0.0592 (1.4466)	0.0453 (1.1069)	0.0591 (1.4443)
Resources	0.3691*** (15.8769)	0.3551*** (13.8574)	0.3721*** (16.0003)	0.3575*** (15.1131)	0.3719*** (16.0157)
Support	0.1388*** (3.0155)	0.1845*** (3.6823)	0.1423*** (3.0996)	0.1906*** (4.1352)	0.1430*** (3.1192)
Economy	0.3719*** (8.0881)	0.3852*** (7.7766)	0.3866*** (8.4449)	0.4012*** (8.8193)	0.3868*** (8.4641)
Industry	0.0368 (0.5221)	0.0026 (0.0347)	0.0371 (0.5261)	0.0025 (0.0364)	0.0367 (0.5214)
Size	0.0278 (0.8957)	0.0238 (0.7251)	0.0196 (0.6312)	0.0131 (0.4303)	0.0195 (0.6311)
Infrastructure	−0.0228 (−0.6208)	−0.0241 (−0.6155)	−0.0136 (−0.3697)	−0.0151 (−0.4169)	−0.0136 (−0.3720)
Opening	0.0278 (1.6417)	0.0296 (1.6186)	0.0309* (1.8275)	0.0326* (1.9384)	0.0309* (1.8327)
Institution	−0.1809*** (−3.3995)	−0.2011*** (−3.4945)	−0.1699*** (−3.2029)	−0.1891*** (−3.5742)	−0.1702*** (−3.2150)
Education	0.0331* (1.9007)	0.0371** (1.9940)	0.0301* (1.7310)	0.0335** (1.9543)	0.0301* (1.7381)
W*Subsidy	−0.0248 (−0.4525)	−0.0146 (−0.2530)	0.0638 (0.9644)	0.0899 (1.3782)	0.0639 (0.9681)
W*Tax	0.0188 (−0.2385)	0.0391 (0.4724)	−0.1404 (−1.3641)	−0.0582 (−0.5739)	−0.1393 (−1.3562)
W*Resources	−0.0475 (−0.7696)	−0.0653 (0.3087)	0.0007 (−1.3641)	−0.0234 (−0.5739)	0.0001 (0.0013)
W*Support	−0.1181 (−1.2995)	−0.2058** (−2.1011)	−0.0157 (3.0996)	−0.0651 (−0.5982)	−0.0166 (−0.1523)
W*Economy	−0.2519** (−2.4265)	−0.2657** (−0.9681)	0.0151 (0.1322)	0.0356 (0.3178)	0.0144 (0.1278)
W*Industry	−0.0043 (−0.0276)	0.0471 (0.7326)	−0.0302 (−0.1673)	−0.0265 (−0.5739)	−0.0303 (−0.1681)
W*Size	−0.0109 (−0.1720)	−0.0689 (0.7326)	−0.1291* (−1.6761)	−0.1191 (−1.5597)	−0.1288* (−1.6750)
W*Infrastructure	−0.0441 (−0.5216)	−0.0141 (−0.1562)	0.0614 (−0.3697)	0.0818 (0.8697)	0.0616 (−0.1523)
W*Opening	0.0159 (0.3987)	0.0082 (0.1912)	0.0352 (1.8275)	0.0331 (0.7978)	0.0352 (0.8474)
W*Institution	0.1142 (1.0344)	0.0426 (0.7326)	0.2468** (2.0492)	0.1872 (1.5698)	0.2463** (2.0496)
W*Education	0.0095 (0.2235)	−0.0021 (−0.0469)	−0.0179 (−0.3605)	−0.0333 (−0.6661)	−0.0183 (−0.3679)
W*Innovation	0.1889*** (4.6270)	0.1819*** (4.4440)	0.1199*** (2.8813)	0.0999** (2.3884)	0.1209*** (2.9058)
Theta	— —	— —	— —	— —	0.9917*** (21.9495)
δ^2	0.4303	0.4295	0.4251	0.3606	0.4225
$\overline{R}^2$	0.5176	0.5363	0.5141	0.5338	0.5141
Log-L	−1980.7821	−1836.7633	−1962.3415	−1802.9891	−2386.0721

Note. ***, **, and * denote a significance level of 1%, 5%, and 10%, respectively. The *t*-statistic is in parentheses.

regions with poor effects, resulting in government R&D funding failing to meet the expectations of reducing the regional innovation quality gap but instead widening it.

6. Conclusions and Implications

Based on 283 Chinese cities from 2011 to 2017 and the basic connotation of regional innovation quality, this study empirically analyzes the impact of government R&D funding on regional innovation quality and its influence mechanism. Furthermore, it analyses the heterogeneity of government R&D funding affecting regional innovation quality and explores whether government R&D funding can narrow the regional innovation quality gap. This paper finds a positive spatial correlation between regional innovation qualities; the improvement of local innovation quality can promote the innovation quality in neighboring regions. Subsidies can significantly improve the innovation quality in local and neighboring regions, whereas the effect of tax preferences on regional innovation quality is not significant. The above results remain robust when accounting for possible lags in government R&D funding, replacing the measurements of government R&D funding and the spatial weighting matrix. The analysis of the mechanism reveals that subsidies are conducive to increasing the investment of innovation resources by local direct innovation subjects and innovation support of indirect innovation subjects and attracting the inflow of innovation resources from close regions, thus contributing to the improvement of regional innovation quality. Simultaneously, there is spatial competition for subsidies, which makes them conducive to improving the innovation quality in neighboring regions. Moreover, when considering the city location's heterogeneity, it is found that government R&D funding cannot improve the innovation quality in the Eastern cities but improve that in the Middle and Western cities. When considering the heterogeneity of the city administrative hierarchy, it finds that government R&D funding cannot improve the innovation quality in the higher-administrative-hierarchy cities but improve that in the general-administrative-hierarchy cities. Further, after receiving government R&D funding, cities without innovation advantages, such as the Middle and Western cities and the general-administrative-hierarchy cities, have not narrowed the innovation quality gap with the Eastern cities and higher-administrative-hierarchy cities.

Based on this, the paper draws the following research implications.

Firstly, improve subsidy policies and enhance the intensity of subsidies. This study shows that subsidies are conducive to improving regional innovation quality by increasing the input of innovation resources by direct innovation subjects, increasing the innovation support of indirect innovation subjects, and attracting the inflow of innovation resources from other regions. Therefore, when formulating relevant strategies and plans, the central government should actively carry out and appropriately strengthen subsidies. At the same time, to better utilize the policy effect, the government should improve the screening system before the implementation of subsidies and the information disclosure and the tracking management system after the implementation of subsidies. Moreover, spatial competition for subsidies makes innovation resources tend to flow into regions with larger subsidies, so the central government should actively guard against the possible vicious competition for subsidies by local governments.

Secondly, optimize preferential tax policies to stimulate high-quality innovation outcomes. The study finds that tax preferences on regional innovation quality are not significant on the whole, but are conducive to improving the regional innovation quality in the Middle and Western cities and general-administrative-hierarchy cities. Therefore, the government needs to further optimize and improve preferential tax policies. For example, the government can increase the tax deduction of the income from the patent assignment. It may not only encourage innovation subjects to actively apply for patents to protect innovation achievements but also reduce the assignment cost, improve the transfer income, and stimulate the transfer enthusiasm to improve regional innovation quality. At the same time, the strength of tax preferences is influenced by the amount of enterprise income tax payable so that innovation subjects should focus on improving their business performance and carry out reasonable tax planning in their daily operation to maximize the positive effect of tax preferences on regional innovation quality.

Thirdly, implement government R&D funding policies according to local conditions and cities. The study shows that government R&D funding cannot improve the innovation quality in the Eastern cities and higher-administrative-hierarchy cities, while it can improve that in Middle and Western cities and general-administrative-hierarchy cities. Therefore, government R&D funding should be more targeted and flexible, especially against the background of tightening revenue and pressure on fiscal expenditure. In addition, due to both existences of "underintervention" and "overintervention," government R&D funding fails to narrow the gap of regional innovation quality. This further suggests that the government should focus on increasing R&D funding for regions with innovation disadvantages so that government R&D funding can improve regional innovation quality and also help reduce the regional innovation quality gap.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Systemic Risk Assessment: Aggregated and Disaggregated Analysis on Selected Indian Banks

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Exposure of the banking system to the Global Financial Crisis attracted attention to the study of riskiness and spillover. This paper studies the pattern of systemic risk and size effect in the Indian banking sector. Based on market capitalization, three public sector banks and three from the private sector were taken. Data are taken from the year 2007 to 2020. The analysis is done through quantile-CoVaR (Conditional Value at Risk) and TENET (Tail-Event-Driven Network) measure. State variables like Indian market volatility and global risk measures negatively influence the Indian banks' returns. Liquidity risk is a crucial aspect of private banks. Public banks experience public confidence even in the distress period. Large banks like HDFC and SBI bank offer the highest degree of systemic risk contribution. The role of private banks in transmitting systemic risk has been intensifying since 2015. Small-sized banks like PNB and BOB have become significant receivers and transmitters of risk.

1. Introduction

As per the famous saying, "Never let a crisis go waste," the Global Financial Crisis (GFC) 2008 created an opportunity for revamping the financial system of the world's economies. It then became imperative to identify and address the pattern of dynamic linkages produced through common exposures and risk concentration across financial institutions, as corroborated by Adrian and Brunnermeier [1].

Consequently, the Financial Stability Board was established in the G20 summit by the International Monetary Fund and Bank of International Settlements in 2010. Borio [2] emphasized that the former's objective was to contain the system-wide risks and concurrent downswings posed by key financial institutions in terms of disruptions and losses to the real economy. The goal was to achieve financial stability.

Banks are the primary institution to fuse financial liquidity for the proper functioning of the financial system and ensure stability, as proposed by Mishra, Mohan, and Sanjay [3]. However, they are equally considered a principal channel of stress transmission through their complex web of lending-borrowing relationships [4]. The risk spreads to other financial institutions in the form of liquidity crunches; those are exposed to the same securitized asset or repo. According to Acharya and Steffen [5], the systemic risk arises if there is a systemic liquidity crisis such that the interbank funding dries up. Its source of generation is also complex due to the involvement of both country-level and institution-specific factors. Chakrabarty [6] says that in the Indian domain, financial sector assets contribute 150% of its GDP.

As per India Brand Equity Foundation [7], the share of commercial banks in its financial sector is 64% of total assets, the majority of which is under government ownership, Eichengreen and Gupta [8]; i.e., public banks own 72% of commercial banks' assets as per Indian Banking Industry report of India Brand Equity Foundation, [9]. India set up the Financial Stability and Development Council (FSDC) in 2010. It addresses the interconnectedness of the Indian financial system through proper systemic risk assessment measures.

Its banking sector is also crippled in the unique problem of “Twin Balance Sheet Syndrome” since 2015 and reflected unique characteristics of expansionary demand growth with overleveraged companies facing debt-servicing issues as per the Indian Economic Survey [10]. The outcome was the double digits nonperforming assets, miring of the commercial banks with Nonbanking Financial Companies (NBFCs), and Housing Finance Companies (HFCs), thereby exposing the commercial banks to a greater degree of interconnectedness as per the Financial Stability Report of RBI [11]. Subramanian and Felman [12] suggested that the earlier syndromes transformed into the “Four Balance Sheet Challenge”, entangling the four sectors banking, infrastructure, shadow banking, and real estate companies.

Four approaches measured the estimation of systemic risk. The primary one was the stress test proved inadequate by Brunnermeier [13] and Gorton and Metrick [14]. This was followed by the macrostress testing approach by Greenlaw et al. [15], Burrows et al. [16], and Erdem et al. [17]. Then, tail dependence measures, systemic risk index, and expected shortfall measures were developed by Brownlees and Engle [18], Adrian and Brunnermeier [1], and Acharya et al. [19]. These approaches were based on local interdependence, i.e., between the financial institution and the whole system. At the same time, a relatively new approach was through network graphs which were followed by Demirer et al. [20], Wang et al. [21], and Härdle et al. [22]. These graphs are powerful enough to represent the complexity within the financial system, which could be revealed through nodes and edges.

The paper is an attempt to understand the pattern of the interconnectedness of Indian public and private banks. It contributes to the issue of systemic risk of Indian banks [23] of the various topics like the performance of banks [24], nonperforming assets [25], credit risk [26], etc. This is further assessed through the sensitivity of each bank to the macroeconomic variables and each other, as Adrian and Brunnermeier [1] suggested that the interaction of banks cannot be studied in isolation to its exogenous factors. It also overcomes the limitation of the earlier measure of systemic risk, which assumed variables to be normally distributed.

It adopts tail-based systemic risk measures like CoVaR (Conditional Value at Risk) and TENET (Tail-Event-Driven Network Risk). TENET methodology is better than the one adopted by Billio et al. [27], based on Granger-causality connectedness as the events of the latter capture at means of the returns distribution and give fewer weights to the information at the extreme ends.

This allows us to bring out a holistic picture of systemic risk at both disaggregated and aggregated levels. The time-varying aspect is also added. Finally, it assesses the contribution risk in the form of a significant systemic risk receiver (SRR) and systemic risk emitters (SRE) through the directional spillover networks. The paper extends the study by Verma et al. [23] by investigating whether the NBFC crisis initiated in September 2018 triggered tail interconnectedness or showed resilience among the topmost private and public banks in terms of market capitalization. NBFC crisis has enhanced the risk exposure of Indian commercial banks in subscription of commercial papers, extending the line of credit, and repurchasing the existing loans [28]. The liquidity crunch in NBFCs will be followed by contagion risk to the commercial banking sector. Along with the NBFC crisis, the COVID-19 effect was examined. The six topmost banks are selected as these banks are considered to be Systemically Important Banks (SIBs), and any solvency shocks create an alarming signal for the government and policymakers to offer a timely resolution.

It proposes seeking the answers to the following questions. Does heterogeneity in banks persist in the Indian banking system due to its size effect? Are the large banks so large enough to cause risk spillover? Are small banks vital sufficient to deepen a crisis, as proposed by Jiang and Zhang [29]?

The paper is structured as follows: In Section 2, the theoretical background is built upon the systemic risk and is titled “Literature Review.” Section 3 explains the “Methodology and Data” used for the study, followed by “Empirical Analysis” in Section 4. The last section presents the “Conclusions” of the study.

2. Literature Review

Most of the studies were based on developing a new measure for systemic risk, which could converge both institutional and country-specific factors to provide a broader outlook.

Kleinow and Nell [4] attempted to analyze the factors driving the systemic risk among the set of European banks. The study applied both the contribution and sensitivity approach in terms of CoVaR and MES (Marginal Expected Shortfall) measures to capture the systemic risk. The new index called the systemic risk index was developed. The highest systemic exposure was found during the crisis periods. Some banks became relatively “too big” to systemically influence others. The study by Le [30], by applying the same measure to the banking sector of 6 ASEAN economies, has found that systemic risk is linked to size, quality of the loan, and market to book value. Banks experienced strong regional connectedness rather than the one experienced during the time of GFC. Elyasiani and Jia [31] investigated whether the size matters to trigger systemic risk via the systemic risk index measure. It was found that downsizing measures would not be better as the small banks could trigger the crisis. The focus should be given to the net effect of the strength and weakness of large banks in the US.

While the study was done by Acharya and Steffen [5] on European banks using the MES risk measure from 2007 to 2011, it was found that sovereign debt holdings significantly could explain the systematic risk. The study emphasized that the undercapitalization of banks could alter the findings of the study. Karimalis and Nomikos [32] investigated each European bank’s contribution to systemic risk via copula-based CoVaR and Conditional Expected Shortfall from 2007 to 2012. French and Spanish banks have the highest systemic risk. Common market factors like industrial production, GDP, unemployment, and stock market were important for propagating systemic risk. Yun and Moon [33] explored the systemic risk phenomena in 10

Korean banks from 2002 to 2013. The two estimates of systemic risk, i.e., the CoVaR and MES, were estimated via DCC models. The relation between systemic risk and bank-specific characteristics was studied. VaR of individual banks influenced the systemic risk. Roengpitya and Rungcharoenkitkul [34] found the systemic risk in six central Thai banks from 1996 to 2009 through CoVaR via quantile regression. It was found that Thai banks stimulated the risk factor of the banking industry during the Asian Crisis. The banks with greater size caused the systemic risk.

Hashem and Abdeljawad [35], through CoVaR and MES, have measured the vulnerability between Bangladeshi Islamic and Conventional Banks. It was found that the conventional banking system was riskier than the Islamic banking system. Huang, De Haan, and Scholtens [36] attempted to capture the systemic risk in 16 Chinese banks from 2007 to 2014 through CoVaR, MES, Systemic Impact Index, and Vulnerability Index measures. It was revealed that the rankings by different methods tend to diverge but were correlated. The systemic risk narrowed after the GFC but again galloped after 2014.

Jiang and Zhang [29] also attempted to investigate the systemic risk in 16 Chinese banks from 2011 to 2018 via an indicator approach and a market-based approach. It was found that the indicator approach complements the other one. Dynamic CoVaR was further modeled to include state variables. It was found that small banks became vital for the system in one phase, while for the other phase, the large banks were identified as systemically important. Acharya et al. [19] measure the institutional contribution of US institutions to systemic risk via MES and SES (Systemic Expected Shortfall) measures. The models could predict such contributions. Further, short-term leverages like repos, commercial papers, and deposits were found to have a pronounced effect in causing the systemic risk during the crisis.

Some studies highlighted the interconnections between the banks and financial institutions which may arise due to systemic risk. Härdle et al. [22] introduced TENET and the Single Index Model to study the systemic risk and then the interconnectedness among the financial institutions. It was evidenced that depositories were the ones who were the systemic risk-takers and emitters, while the insurer's role was minimal during GFC. Verma et al. [23] identified the interlinkages between the government-owned and private Indian banks with a sample of 18 and 13 banks, respectively, from 2007 to 2017. The results from the VaR, CoVaR, and Single Index Model in quantile regression revealed systemic risk during the crisis periods. Huang et al. [37] investigated the systemic risk contribution of 39 financial institutions in China from 2011 to 2015. CoVaR was estimated using the DCC-GARCH model. It was found that firms with greater node strength had more significant contributions to systemic risk. Demirer et al. [20] have estimated the global bank interconnections with the sample of 150 banks from the USA, Australia, Japan, Canada, China, Singapore, Malaysia, Korea, and India from 2004 to 2014. It was found that the connectedness has extended over bad times. The small banks could transmit shocks to the whole system during bad times, causing systemic inferences.

Clemente et al. [38] have investigated the systemic risk in the European banking system from 2003 to 2017 using market data. The evidence of systemic risk via clustering coefficients indicating the strength of interconnectedness was found during the crisis. Chabot and Bertrand [39] investigated the financial connectedness of 262 financial institutions from 2000 to 2015 through network analysis. The results revealed that the banks were connected to those with a high reputation, i.e., those which can be rescued by the government and enjoy implicit guarantees.

Some studies have pointed out that the bank's role in contributing to systemic risk is the maximum across all other financial institutions. Oscar et al. [40] investigated the contribution of banks, insurance, and other financial sectors to systemic risk in Europe and the USA from 2004 to 2012. CoVaR risk was used to measure the risk. The quantile regression estimates highlighted that other financial firms and banks were the systemically riskiest in Europe during the distress periods. At the same time, insurance was systemically riskiest in the USA. Girardi and Ergün [41] investigated the systemic risk contribution of 74 US financial institutions from 2000 to 2008. An investigation was done on four groups: banks, insurance, brokerage, and other financial firms. Industrywise, time-varying CoVaR was obtained via the DCC-GARCH model. Castro and Ferrari [42] made an investigation from a sample of 26 European banks from 1999 to 2012. It was found that only a few banks could be considered systemically crucial following the CoVaR approach. Diebold and Yilmaz [43] have investigated connectedness in US financial institutions from 1999 to 2010. The sample includes 13 institutions of categories like commercial banks, investment banks, insurance companies, and mortgage companies.

Billio et al. [27] investigated the interlinkages between the four categories of financial institutions, i.e., banks, brokers, hedge funds, and insurers. The interlinkages were found to be solid and complex due to asymmetry and nonlinearities estimated by Granger causality. However, banks were identified as the financial institutions responsible for transmitting shocks to others. Wang et al. [44] investigated the multilayer interconnectedness across the Chinese SIBs and an insurance group called SIFIs (Systemically Important Financial Institutions) from 2008 to 2018. The Granger-causality test was extended for capturing mean, volatility, and extreme risk nuances. The results revealed that such a model provided an early warning signal before the eve of the European and Chinese stock market crash of 2015-2016. Banks exhibited a greater degree of overlap. Wang et al. [45] extended the study to include 30 Chinese financial institutions from three groups, i.e., banks, securities, and insurance, from 2011 to 2018. A similar multilayer technique was adopted at variance decomposition setting. The spike in spillover was found before the Chinese stock market crisis and weak information transmission between volatility and extreme risk layers.

Studies like [46] showed how systemic risk occurring in financial markets can percolate to the real economy and how the gap between real activity and financial activity is blurred. The study was based on finding the relation between the financial market-wide systemic risk and the macroeconomic downturn in the USA and Europe from 1946 to 2011 and from 1994 to 2011. It was found that Industrial Production growth, Chicago Fed National Activity Index, equity volatility, and Fed Fund rate were all severely influenced by the rise in the systemic risk. Bianconi et al. [47] showed how market sentiment could aggravate the systemic risk in financial markets. The two measures, i.e., the VIX and consumer pessimism, were adopted to analyze 14 US financial institutions from 1992 to 2006.

From the existing literature review, it is clear that the studies on assessing the systemic risk in the Indian context are limited either to the conventional measures or to the time dimension. Since the pattern of riskiness is a continuously evolving pattern, it is thus imperative to study the systemic risk in Indian banks in recent times when it is feeling the stress from the NBFC sector. Further, the possible channels of systemic risks in Indian banks were needed to be demystified. The study also compares both the conventional and advancing measure of systemic risk, which was yet to be studied.

3. Methodology and Data

3.1. Methodology. To measure the interbank risk spillover emerging from the extreme events in a single financial institution, Adrian and Brunnermeier [1] proposed the Conditional Value at Risk (CoVaR) model through a bivariate setting of linear quantile regression. This model was better than VaR because it effectively measures an institution's contribution to system-wide risk [29] while the latter only measured the risk prevalent in a single institution on a standalone basis.

Accordingly, the institutional VaR is defined as

$$P\left(X_t^i \leq \mathrm{VaR}_{t,\tau}^i\right) = \tau\%, \tag{1}$$

where τ is the specified quantile and X_t^i is the returns of bank i by t th time.

The risk spillover measured through CoVaR takes accounts for the state variables to capture the tail risk connectedness. The CoVaR of institution k at time t is denoted by

$$P\left(X_t^k \leq \mathrm{CoVaR}_{t,\tau}^{k|i} | I_t^i\right) = \tau\%, \tag{2}$$

where I_t^i is the conditional information on the event of $X_t^i = \mathrm{VaR}_{t,\tau}^i$, and S_{t-1} as a vector of state variables. Accordingly, $\Delta\mathrm{CoVaR}_{t,\tau}^{k|i} = \mathrm{CoVaR}_{t,\tau}^{k|X_t^i=\mathrm{VaR}_{t,\tau}^i} - \mathrm{CoVaR}_{t,\tau}^{k|X_t^i=\mathrm{Median}_{t,\tau}^i}$ measures the incremental contribution of the financial institution to system-wide risk when i is shifting from a normal situation to a distress situation.

3.2. Tail-Event-Driven Network (TENET). Adrian and Brunnermeier [1] measured the systemic risk between two institutions with quantile regression independently. This setup ignored the high dimensionality, which causes the interactions between all the financial institutions in the setup. This problem was subdued by Härdle et al. [22]. The TENET procedure consists of three steps.

First, a linear quantile regression model is estimated as

$$\begin{aligned} X_t^i &= C_i + \theta_i S_{t-1} + \varepsilon_t^i, \\ X_t^k &= C_{k|t} + \theta_{k|i} S_{t-1} + \Phi_{k|i} X_t^i + \varepsilon_t^{k|i}, \end{aligned} \tag{3}$$

where X_t^i and X_t^k are the returns of bank i and k at time t. $\Phi_{k\,|\,i}$ is the responsiveness of bank k to changes in returns of bank i corresponding to the tail event. Second, CoVaR is estimated by placing the estimated $\mathrm{VaR}_{t,\tau}^i$ in equation (5) to equation (6).

$$\mathrm{VaR}_{t,\tau}^{\prime i} = C_i' + \theta_i' S_{t-1}, \tag{4}$$

$$\mathrm{CoVaR}_{t,\tau}^{\prime k|i} = C_{k|t}{}' + \theta_{k|i}{}' S_{t-1} + \Phi_{k|i}{}' \mathrm{VaR}_{t,\tau}^{\prime i}, \tag{5}$$

where $\Phi_{k|}{}'$ represents the extent of interconnectedness. Here, k is the system-wide returns and i is the individual returns of the institution. This step was obtained through a single index model via quantile regression to obtain the contribution CoVaR of the individual bank with the relevant banks based on tail events and interactions.

Furthermore, the directional spillover can be estimated as follows:

$$\Phi_{k,t} = f.\left(\Phi_{k|i}^T . M_{k,t}\right) + \varepsilon_{k,t}, \tag{6}$$

$$\mathrm{CoVaR}_{t,\tau}^{\prime k|i} = f'.\left(\Phi_{k|M_k}^{\prime T} . M_{k,t}{}'\right), \tag{7}$$

$$D_{k,M_{k,t}}{}' = \delta f'\left(\Phi_{k|M_k}^{\prime T} . M_{k,t}{}'\right)\Phi_{k|M_k}{}', \tag{8}$$

where $M_{k,t} = \left\{x_{kt}, S_{k,t-1}\right\}$ represents the including $x_{kt} = \left\{x_{1t}, x_{2t}, \ldots, x_{nt}\right\}$ which are independent variables of all the banks taken in the sample except for k th bank. $\Phi_{k|M_k} = \left\{\Phi_{k|-k}, \Phi_{k|s}\right\}$ are the static parameters.

For dynamic estimations, the rolling window size is taken as $n = 48$ for a year's weekly data. $D_{k,M_{k,t}}'$ represents the marginal covariate effects through gradient descent measure. $\mathrm{MC}_{k,s}$ stands for market capitalization of the kth entity. This shows the network spillovers. Networks are based on partial derivatives of other banks; i.e., $\Phi_{k|-k} \cdot \tau$ th quantile is considered 1% and 5%.

In the final step, the Systemically Important Banks are identified on SRR (Systemic Risk Receivers) and SRE (Systemic Risk Emitters) estimates as follows:

$$\begin{aligned} \mathrm{SRR}_{k,s} &= \mathrm{MC}_{k,s} \cdot \left(\sum_{i \in Z_s^{in}} \left(\left|D_{k,i}^{\prime s}\right| \cdot \mathrm{MC}_{k,s}\right)\right), \\ \mathrm{SRE}_{k,s} &= \mathrm{MC}_{k,s} \cdot \left(\sum_{i \in Z_s^{\mathrm{out}}} \left(\left|D_{i,k}^{\prime s}\right| \cdot \mathrm{MC}_{k,s}\right)\right). \end{aligned} \tag{9}$$

3.3. Data. For the study, weekly data from 1st January 2007 to 31st March 2020 is taken consisting of a sample of 3 public and 3 public sector banks in India. The list of banks considered for the study is presented in Table 1.

TABLE 1: List of banks and macrostate variables.

Public banks	Public banks market capitalization in Rs	Symbols
State Bank of India	2727.73 billion	SBI
Punjab National Bank	23.478 billion	PNB
Bank of Baroda	38.452 billion	BOB
Private banks	*Market capitalization in Rs*	
HDFC Bank	5605.4 billion	HDFC
ICICI Bank	2128.7 billion	ICICI
AXIS Bank	1643.59 billion	AXIS
Macrostate variables	*Description*	
Global risk	VIX is an implied volatility (IV) measure of investor fear gauge derived from S&P 500 options	VIX
Market risk	Indian stock market risk derived from implied volatility measure of nifty 50 options price	IVIX
Exchange rate volatility	Realized volatility measure of USD/INR exchange rate calculated *	EV
Liquidity spread	Weighted average call rate - RBI repo rate captures the liquidity stress among banks	LIS

*$VOL_t = \sum_{t=0}^{n} ER_t^2$; here, ER is the change in the exchange rate and t is a window of 10 days.

Ideally, the Twin Balance Sheet Syndrome was vigilant in 2015 in the Indian banking system; however, its history was related to the 2007-2008 crisis period as per the Indian Economic Survey [10]. Hence, it motivated us to trace the pattern of connectedness among Indian banks from the 2007 crisis. Apart from that, the period could also capture the effect of the IL&FS crisis during 2018-2019 and reflect the initial signs of the Coronavirus pandemic on the Indian banking system.

The bank's selection is based on market capitalization values, as quoted from the Business Today report. The data on the macrostate variable is taken from the Reserve Bank of India. Four state variables were included for the study, i.e., the global risk, exchange rate volatility, market volatility, and funding risk as identified by a systemic risk survey conducted by the Reserve Bank of India [48]. Further, Shin [49] proposes that excessive asset growth contributes to systemic risk by fostering interconnectedness in financial institutions.

3.4. Empirical Analysis

3.4.1. Preliminary Analysis. From the descriptive summary in Table 2, inferences on the essential characteristics of the set of public and private banks can be drawn. All three public sector banks offer a weekly negative return. Of the three public banks, the SBI offers the highest weekly returns on average, followed by BOB. SBI returns tend to exhibit the lowest volatility, and PNB shows the highest volatility. While the private sector banks offer positive weekly returns on average. HDFC bank offers the highest returns and highest volatility. The lowest return is exhibited by ICICI bank.

From the skewness estimates, it can be observed that the weekly returns of all the public sector banks are positively skewed, signaling that a lot of observations lie on the right end of the returns distribution with a fatter tail. In comparison, private sector banks like HDFC displayed a fatter right end tail. But the other two banks exhibited negative skewness with a lot of observations on the left end. The kurtosis measures depict that the two public sector banks' returns distribution is platykurtic. In comparison, PNB describes leptokurtic distribution with a lot of extreme events. The two private sector banks like HDFC and ICICI show the leptokurtic distribution. At the same time, AXIS shows the platykurtic distribution.

From these preliminary findings, it can be concluded that the bank's returns series have asymmetry and contain extreme events which cannot be captured by standard regression measure.

Quantile regression estimates from Table 3 and 4 depict the relationship between the set of macrovariables and set of banks at normal (50% quantile) and stress periods (1% and 5% quantile). Table 3 reveals that, during the stress period, all the private sector banks taken together are negatively influenced by the change in VIX and change in IVIX as macrofactors. During a normal period, liquidity spread exhibits positive relationships with all public banks. Exchange rate volatility does not influence any of the banks.

The returns of ICICI and AXIS banks positively influence all the public banks during all periods. HDFC banks affect the returns of public banks only during the normal period. During the normal period, the change in IVIX negatively influences only the SBI returns. Liquidity spread also positively influences PNB and AXIS banks only during a normal period. HDFC bank exhibits a negative influence on PNB at 50% quantile. Both ICICI and AXIS banks are directly related to the SBI, PNB, and BOB at stress and a normal period.

Table 4 reveals that all the private sector banks taken together exhibit aversion to any of the macrofactors during the stress period. They only get impacted by SBI returns during the stress period. During a normal period, changes in VIX produce a negative impact on all private banks. All the public banks potentially influence the returns of all private banks during a normal period. The VIX changes negatively impact the ICICI and AXIS banks during the stress period and on the normal period. But the IVIX negatively influences the ICICI and AXIS bank only during the stress period.

The liquidity spread exhibits negative relation with ICICI and AXIS banks during the stress period only. Exchange rate volatility negatively influences the AXIS bank's returns at both 1% and 5% quantiles. SBI returns exhibit a positive influence on the returns of all banks during normal periods

Table 2: Descriptive summary.

	Public banks			Private banks		
	SBI	PNB	BOB	HDFC	ICICI	AXIS
Median	0.0015	0.0011	0.0011	0.0037	0.0012	0.0014
Mean	−0.0001	−0.0018	−0.0006	0.0029	0.0009	0.0014
Maximum	0.2766	0.4174	0.2568	0.7145	0.2415	0.2554
Minimum	−0.1978	−0.2514	−0.217	−0.6874	−0.3271	−0.2841
Variance	0.0028	0.0036	0.0033	0.0072	0.0035	0.0033
Std dev	0.0524	0.0604	0.0575	0.0851	0.0588	0.0572
Skewness	0.3061	0.403	0.0995	0.3424	−0.3954	−0.3994
Kurtosis	2.318	4.6099	1.9353	50.1626	3.6042	2.5428
Observations	652	652	652	652	652	652

and ICICI and AXIS banks during stress periods. The magnitude of the effect of SBI is the most during the stress period in both these banks. PNB and BOB influence the ICICI bank and AXIS bank, respectively, during the stress period.

Several inferences can be drawn from the static quantile regression estimates:

(i) The general perception of investor's fear reflected through "volatility indices" negatively influences the bank's returns, especially during the stress period. The public and private banks tend to be substantially affected by Indian volatility index measures than the US measure reflected through the absolute value of coefficients. The liquidity spread used as a measure for "liquidity risk" exhibits a negative relation with the two private banks, i.e., ICICI and AXIS banks, during the stress period. In comparison, the public banks show a positive relationship with liquidity spread during a normal period. This signals that a rise in the liquidity spread during the stress period does not induce panic behavior of investors leading to the sale of stocks of public banks. But this trend is reversed in the case of private banks except for HDFC, which still displays resilience to liquidity risk

(ii) The public banks display resilience to exchange rate volatility, but AXIS bank does not. As a result, the returns of only AXIS bank tumbles with the sudden fluctuations in exchange rate experienced during the stress period

(iii) Of the private sector banks, HDFC shows resilience to all the macroeconomic factors

(iv) The public banks, especially SBI, exert a greater positive influence on private banks during stress and normal periods while two private banks, the ICICI and AXIS banks, substantially influence the public banks

3.5. Disaggregated Analysis. This section provides an institutional-level analysis of systemic risk. The contribution of each bank was estimated through VaR and CoVaR estimates.

Table 5 presents the summary of time-varying VaR estimates in which there is the individual risk contribution of each bank at both 5% and 50% quantiles. PNB has the highest VaR of 8.96% among all the banks. HDFC has the highest VaR of 7.77% among the private banks. ICICI has the lowest VaR of 6.68% during the period of stress. This would mean that investors holding PNB stock in the portfolio have a 5% chance of losing at least 8.96% of the portfolio and a 50% chance of losing 0.17% of the portfolio. Among all the banks, the maximum loss on investment in ICICI stocks is limited to 6.68% with a 95% confidence level.

A high VaR does not mean that the bank will have an increased contribution to the systemic risk during the distress period. For assessing the systemic risk contribution produced by each bank, CoVaR is estimated.

Table 6 presents the summary of the time-varying CoVaR model. PNB has the highest CoVaR of 6.4% and 6.34%, respectively, at 1% and 5% quantiles among the public banks. This would mean that in the distress period at PNB, the bank contributes to the system-wide average loss of 6.34% to 6.4%. Among all banks, HDFC bank has the highest CoVaR of 7.05% and 7.59% at 1% and 5% quantiles, respectively, with the highest volatility in CoVaR of 6.13% to 8.81%. This signals that if the HDFC bank faces distress, it contributes an average loss of 7.05% to 7.59% to other banks. The least contribution to systemic risk is offered by ICICI bank, i.e., 5.2% to 5.36%. On the other hand, the average contribution to systemic risk by private banks is observed to be higher.

Figure 1 presents the time-varying estimates of returns of specific banks, VaR (at 50%) and CoVaR (at 5%) represented in black, green, and red colors. From the figure, it can be seen that all the Indian banks exhibit the volatility clustering effects that are specifically substantial during 2007–2009 as also observed by Ramprasad et al. [23] and also observed in 2017–2019. The CoVaR range was maximum in the case of PNB, i.e., from 0 to 40%. But the rest of the public banks contributed to systemic risk to a maximum level of 20%. PNB displays the highest CoVaR values during 2017-2018 due to the 1.8 billion dollars fraud.

While comparing the private sector banks, the CoVaR values ranged from 0% to 99% in the case of HDFC banks and 0% to 40% in ICICI and AXIS banks. The HDFC and ICICI banks spread the systemic risk to others during the subprime crisis periods the most, and hence after they contributed the most, around 20%. In comparison, the AXIS

Table 3: Quantile regression for public banks as dependent variables.

	All			SBI			PNB			BOB		
	1%	5%	50%	1%	5%	50%	1%	5%	50%	1%	5%	50%
VIXR	−0.0263	−0.1114**	−0.0345	−0.0132	−0.0132	−0.0018	0.03515	−0.0573	−0.0028	−0.1288	−0.0687	0.00572
	[0.764]	[0.0131]	[0.299]	[0.744]	[0.535]	[0.867]	[0.689]	[0.026]	−0.0028	[0.077]	[0.104]	[0.6667]
IVIXR	−0.3517 *	−0.1023	−0.0459	−0.0287	−0.0137	−0.0264***	−0.1033	0.00552	[0.798]	−0.0521	−0.0361	−0.0077
	[0.0007]	[0.101]	[0.233]	[0.5593]	[0.639]	[0.055]	[0.302]	[0.871]	−0.0049	[0.511]	[0.453]	[0.6231]
LIS	0.00299	0.00593	0.0426 *	−0.0137	−0.0043	0.01053	0.01713	−0.0011	[0.703]	0.00369	−0.0122	0.0109**
	[0.963]	[0.736]	[0.00]	[0.183]	[0.771]	[0.182]	[0.783]	[0.918]	0.01504 *	[0.949]	[0.596]	[0.0534]
EV	−0.1907	−0.3186	0.07396	−0.0794	−0.0881	0.01474	−0.0703	0.0392	[0.00]	0.10297	−0.0812	0.01372
	[0.5959]	[0.307]	[0.431]	[0.6963]	[0.419]	[0.737]	[0.821]	[0.7654]	0.0086	[0.612]	−0.0812	0.01372
HDFCR	0.06409	−0.0602	−0.0674***	−0.0154	−0.0104	−0.0079	−0.1956	−0.0708	[0.864]	0.14081	[0.274]	[0.7203]
	[0.8743]	[0.298]	[0.098]	[0.9418]	[0.773]	[0.692]	[0.759]	[0.1058]	−0.0302*	[0.236]	[0.936]	[0.271]
CICIR	0.9612*	0.6442*	1.13743*	0.08966	0.3337*	0.44183*	0.54585***	0.19772***	[0.00]	0.18777**	0.29623***	0.39278*
	[0.001]	[0.0015]	[0.00]	[0.4279]	[0.0007]	[0.00]	[0.075]	[0.0706]	0.39047*	[0.028]	[0.068]	[0.00]
AXISR	0.6243***	1.34703*	0.88783*	0.50759*	0.3489*	0.22658*	0.11802	0.40582*	0.30159*	0.2209	0.34423***	0.27859*
	[0.094]	[0.00]	[0.00]	[0.00047]	[0.0002]	[0.00]	[0.685]	[0.0003]	[0.00]	[0.151]	[0.0376]	[0.00]

Note. The symbols *, **, and *** denote the significance level at 1%, 5%, and 10%, respectively. Values in square brackets represent the p values for the QR coefficients.

Table 4: Quantile regression for private banks as dependent variables.

	All			HDFC			ICICI			AXIS		
	1%	5%	50%	1%	5%	50%	1%	5%	50%	1%	5%	50%
VIXR	0.07843	−0.0506	−0.0083*	0.2732	−0.0258	−0.0161**	−0.1053*	−0.0611**	−0.0405*	[0.0039]	−0.0483***	−0.0359*
	[0.828]	[0.6206]	[0.00]	[0.401]	[0.382]	[0.032]	[0.00]	[0.00]	0218]	[0.0039]	[0.088]	[0.0003]
IVIXR	−0.3474	−0.1023	−0.0459	−0.0287	−0.0118	−0.0121	0.0263	−0.068**	0.00002	[0.00]	−0.0485**	−0.0008
	[0.266]	[0.238]	[0.7192]	[0.298]	[0.809]	[0.234]	[0.652]	[0.0295]	[0.998]	[0.00]	[0.0411]	[0.951]
LIS	−0.3108	−0.0933	−0.0071	−0.3327	−0.0364	0.0026	0.01713	−0.0351**	−0.0351**	−0.0283	−0.0523**	0.00309
	[0.1808]	[0.308]	[0.6091]	[0.377]	[0.418]	0.3062]	[0.391]	[0.0511]	[0.2773]	[0.415]	[0.0501]	[0.651]
EV	−0.2238	−0.3332	0.03727	0.54919	−0.1555	0.02313	−0.3725	−0.0813	[0.00]	−0.2936**	−0.0856*	−0.0058
	[0.8104]	[0.263]	[0.4787]	[0.695]	[0.1518]	[0.549]	[0.331]	[0.629]	[0.7846]	[0.014]	[0.0004]	[0.863]
SBIR	2.156***	1.4501*	1.20135*	0.91724	−0.14069	0.2513*	0.77996*	0.6937*	0.5626*	0.5324*	0.48083*	0.3974*
	[0.076]	[0.0008]	[0.00]	[0.508]	[0.445]	[0.00]	[0.000]	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]
PNBR	−1.1854	−0.1199	0.2317*	−0.6989	0.05965	0.03705	−0.2767**	−0.0127	0.0702**	−0.0717	0.1345	0.1091**
	[0.3201]	[0.732]	[0.0008]	[0.591]	[0.712]	[0.262]	[0.029]	[0.914]	[0.025]	[0.548]	[0.286]	[0.014]
AXISR	0.57456	0.54222	0.284*	−0.1529	0.16617	0.02083	0.15933	0.17664	0.1072*	0.22417**	0.10979	0.1416*
	[0.6197]	[0.1527]	[0.0003]	[0.923]	[0.251]	[0.559]	[0.163]	[0.148]	[0.0037]	[0.036]	[0.263]	[0.0019]

Note. The symbols *, **, and *** denote the significance level at 1%, 5%, and 10%, respectively. Values in square brackets represent the p values for the QR coefficients.

Table 5: Summary of time-varying VaR estimates.

	VaR of public banks			VaR of private banks	
	5%	50%		5%	50%
	SBI			*HDFC*	
Median	−0.07145	0.00021	Median	−0.04033	0.0047
Mean	−0.08017	−0.0007	Mean	−0.07718	0.00489
Std dev	0.02113	0.02113	Std dev	0.01699	0.01699
	PNB			*ICICI*	
Median	−0.0823	0.00056	Median	−0.0597	0.002234
Mean	−0.08967	−0.0017	Mean	−0.0687	0.002627
Std dev	0.02438	0.0244	Std dev	0.02904	0.029036
	BOB			*AXIS*	
Median	−0.07512	0.00071	Median	−0.06764	0.001845
Mean	−0.08337	0.00025	Mean	−0.07525	0.002456
Std dev	0.02345	0.02344	Std dev	0.02655	0.02655

Table 6: Summary of time-varying CoVaR estimates.

	CoVaR of public banks				CoVaR of private banks		
	1%	5%	50%		1%	5%	50%
SBI						*HDFC*	
Median	−0.05014	−0.05182	−0.0021	Median	−0.06288	−0.06409	0.01997
Mean	−0.05516	−0.05609	−0.00114	Mean	−0.07048	−0.07595	0.01785
Std dev	0.04379	0.03162	0.01665	Std dev	0.06133	0.088085	0.25186
PNB						*ICICI*	
Median	−0.05395	−0.05337	−0.00098	Median	−0.04621	−0.04466	0.004288
Mean	−0.06401	−0.06342	−0.0037	Mean	−0.05365	−0.05233	0.001625
Std dev	0.053387	0.05328	0.04391	Std dev	0.055012	0.054234	0.05466
BOB						*AXIS*	
Median	−0.05168	−0.05044	0.001654	Median	−0.05102	−0.04996	0.00639
Mean	−0.05591	−0.05545	0.006376	Mean	−0.05772	−0.05642	0.00647
Std dev	0.041145	0.040391	0.09052	Std dev	0.05106	0.05085	0.04956

bank exhibited the highest CoVaR during the COVID-19 crisis period, which ranged up to 40%. Thus, from the time-varying estimates, it can be concluded that the contribution of private banks to the systemic risk is marginally higher than the public banks. Further, the contribution of public banks stands visibly enhanced during the recent period.

Figure 2 presents the rolling ΔCoVaR estimates depicting the difference in CoVaR when the bank i is in a normal state defined by 50% quantile (marked in blue) and CoVaR when the bank i is in a distressed state defined by 1% quantile (marked in red). ΔCoVaR is the incremental Value at Risk inflicted on the financial system when it is in distress. It can be observed that the incremental contribution for SBI when it is shifting from median VaR to extreme tail VaR at 5% is high during the financial crisis. However, it remains constant throughout the whole sample period. Only during 2019, incremental contribution narrowed down. For PNB, the incremental contribution was high during GFC, then it narrowed to a constant range and witnessed a spike in the ΔCoVaR during 1.8-billion-dollar fraud in 2017 and 2018, which continued until the end of the sample period. For BOB, ΔCoVaR values were extremely high during the financial crisis followed by a sustained ΔCoVaR till 2017. But after 2018, a sudden spike in ΔCoVaR was observed due to the merger announced in September 2018, subsumed to a normal range until the end.

The ΔCoVaR values were extraordinarily high and volatile for all the private sector banks during the financial crisis. For HDFC bank, ΔCoVaR reached a new high during late 2016 and 2017; henceforth, it reached a normal range. For ICICI and AXIS banks, ΔCoVaR widened after 2015 to mark the growing importance of private banks.

It can be concluded that ΔCoVaR was time-varying and heterogeneous across the set of public and private banks. Where SBI maintained its incremental contribution throughout the system of banks, HDFC observed a sudden rise in the incremental contribution, possibly due to the greater exposure to unsecured retail credit and company credit resulting in the mounting of the nonperforming assets, Nachiket [50].

The ICICI and AXIS banks progressively contributed after the Chinese stock market crash. Therefore, evidence for size and systemic risk contribution linkage can be inferred at this stage. HDFC bank is the highest risk contributor, followed by SBI, ICICI, and AXIS banks. But a clear ranking is not possible to allocate across the banks as the ΔCoVaR tends to vary with time. The tail interconnected network graphs were analyzed to facilitate a clear comparison of the significant risk contributor and receiver.

3.6. Aggregated Analysis. Figure 3 depicts the pattern of total connectedness and average connectedness denoted by blue and dashed lines, respectively, from 2007 to 2020 at 5%

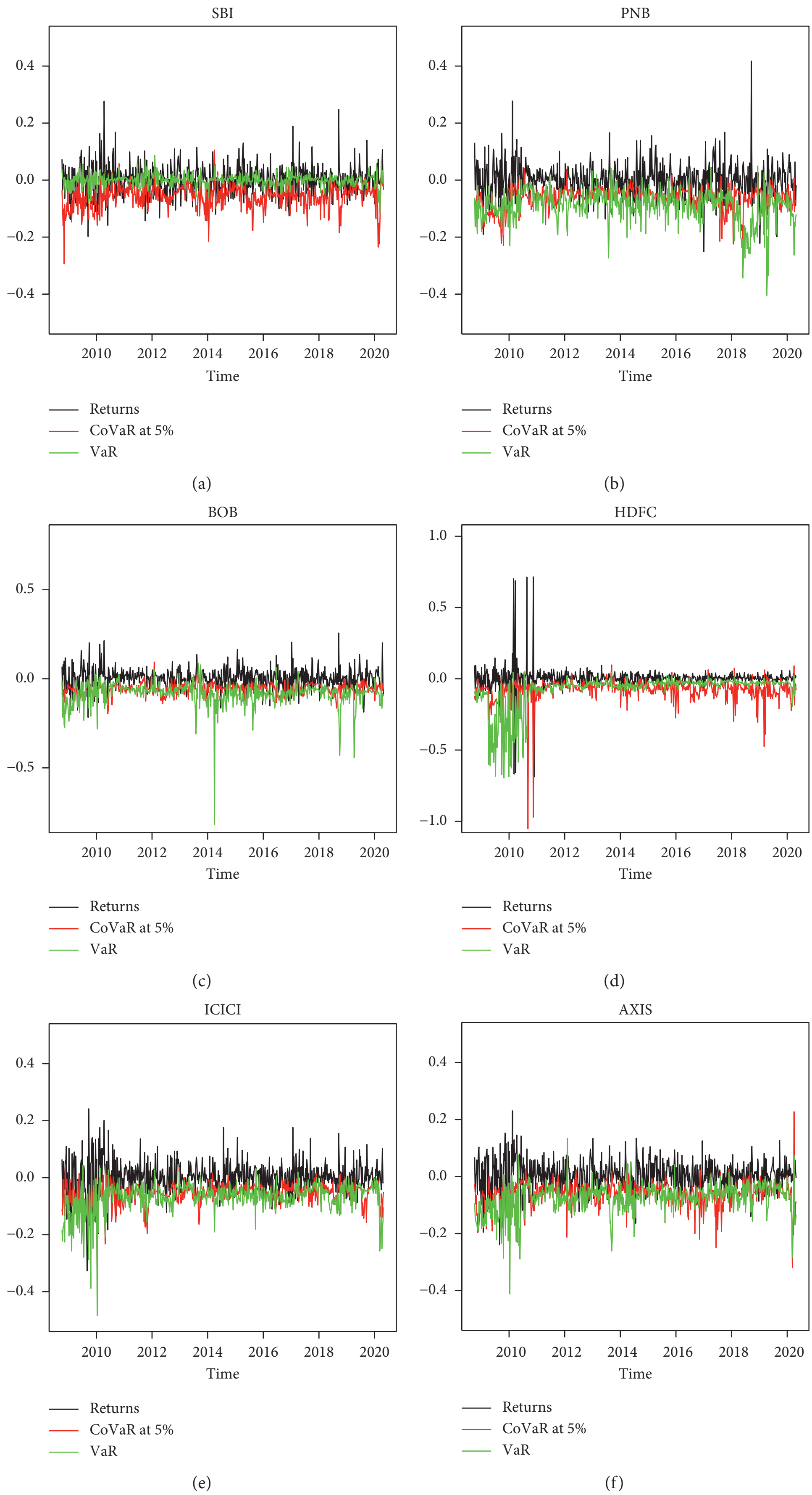

Figure 1: (a) SBI, (b) PNB, (c) BOB, (d) HDFC, (e) ICIC, and (f) AXIS.

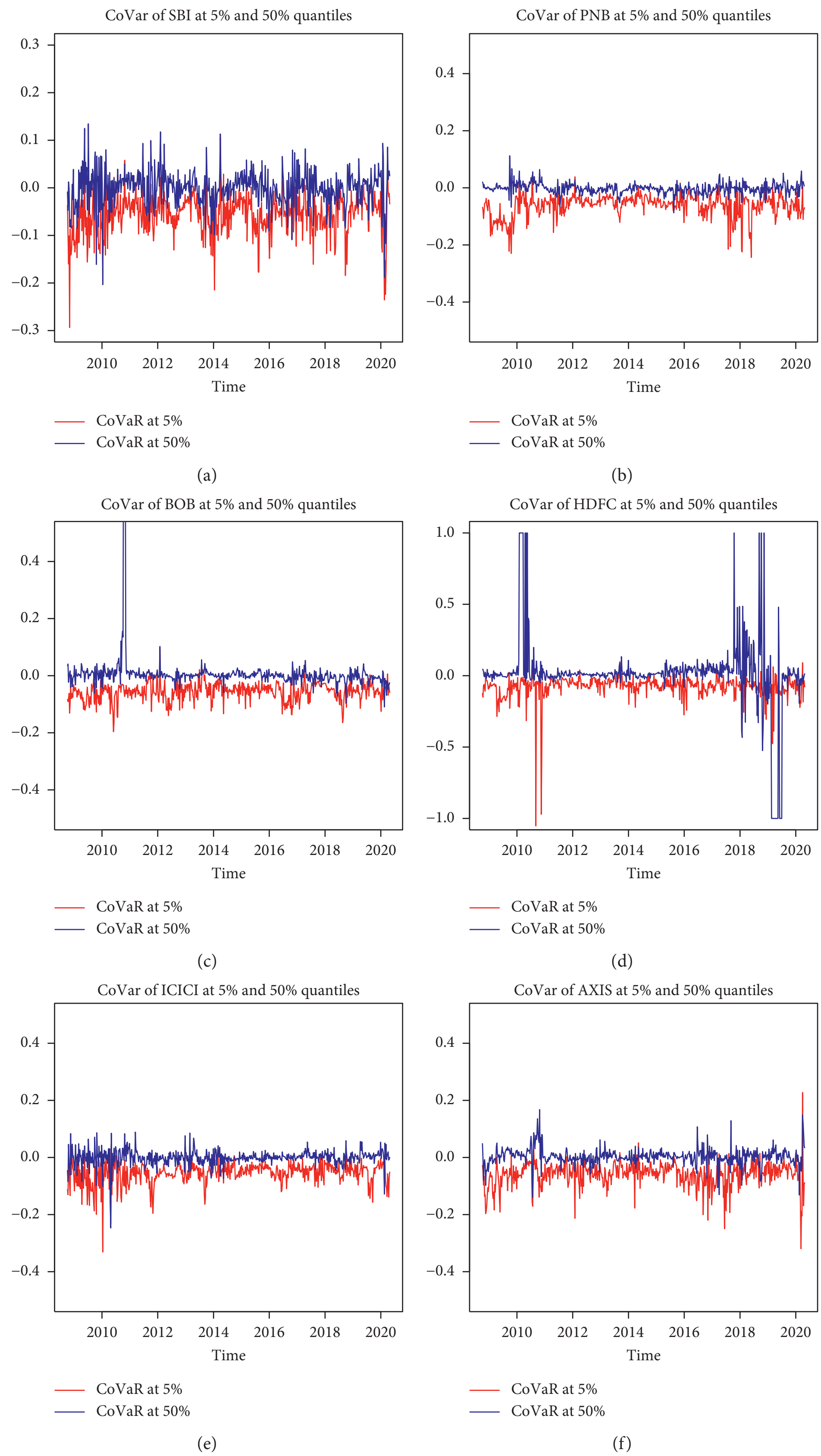

Figure 2: (a) CoVar of SBI at 5% and 50% quantiles. (b) CoVar of PNB at 5% and 50% quantiles. (c) CoVar of BOB at 5% and 50% quantiles. (d) CoVar of HDFC at 5% and 50% quantiles. (e) CoVar of ICICI at 5% and 50% quantiles. (f) CoVar of AXIS at 5% and 50% quantiles.

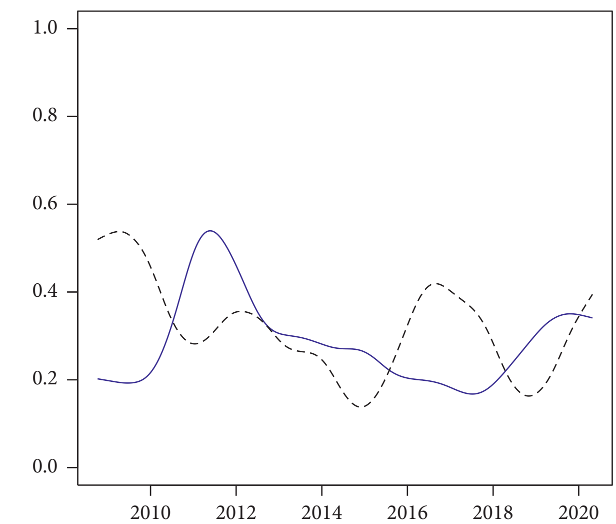

Figure 3: The pattern of total connectedness and average connectedness.

quantile. On comparing the results at 1% quantile, a similar pattern of total connectedness was revealed. To avoid any redundancy, only the 5% quantile graph was presented. It represents the total spillover arising in the banking industry as a whole.

This graph reveals that the top Indian banks were connected strongly throughout the Global Financial Crisis, which was captured by average lambda measure and continued until the end of the European Financial Crisis of 2012. It was only at the inception of 2010 that total connectedness was soaring to the highest level due to the mounting of the stressed asset in the banks' balance sheet. The strong correlations faded away from 2012 to 2015. From 2016 to 2018, the average correlation strengthened. It was due to the efforts taken by RBI to recapitalize the bank's balance sheet and the introduction of the Indian Bankruptcy Code in 2016. But the total connectedness appears to rise again after 2018 due to the severe liquidity crunch experienced by the Indian banking system due to the IL&FS crisis as per the Economic Survey [51]. Even after the consolidation and recapitalization measures taken by the government and RBI in 2019, the total connectedness remains elevated.

Figure 4 represents the tail interconnectedness of all the Indian banks. The node represents the bank size which is denoted by market capitalization. The edges represent the tail interdependence of the Indian banks. The strength of connectedness was the highest in BOB and SBI, BOB and PNB, AXIS and PNB, PNB and HDFC, and PNB and ICICI pairs. The interdependence of BOB and PNB was the strongest.

Further examination reveals that medium-sized banks like PNB and BOB show a stronger degree of connectedness. PNB reflects bilateral and unilateral connections to every bank and acts as a risk emitter except for SBI. The government banks, like BOB and PNB, exhibited strong directional linkages with other banks.

According to the ranking based on the market capitalization depicted from Table 7, the top three banks which are

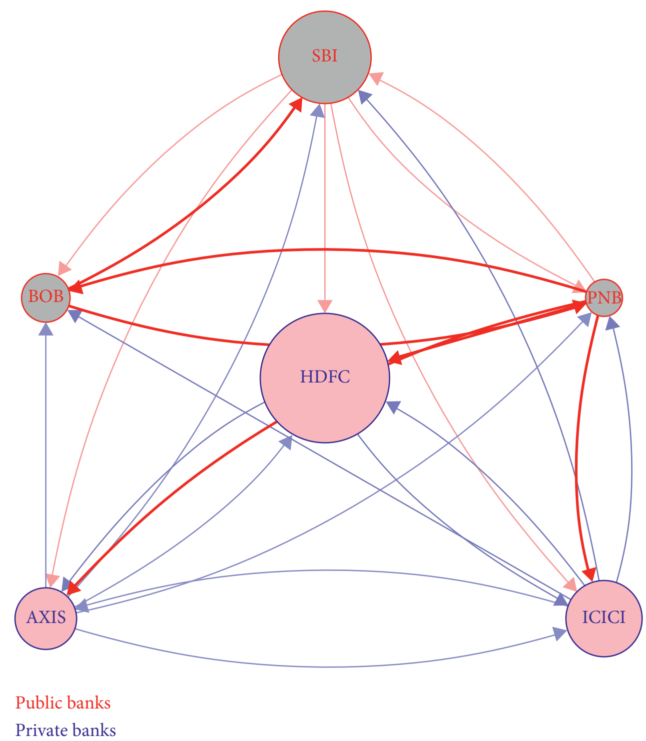

Figure 4: Interconnectedness of all the Indian banks.

Table 7: Rankings of Indian banks based on the market capitalization.

Systemic risk receiver				Systemic risk emitters			
SL. no.	Banks	SRR	Ranks	SL. no.	Banks	SRR	Ranks
1	SBI	$8.36E+22$	5	1	SBI	$5.20E+24$	3
2	BOB	$5.12E+22$	6	2	BOB	$7.32E+24$	1
3	PNB	$8.67E+24$	1	3	PNB	$7.75E+22$	6
4	HDFC	$5.24E+24$	2	4	HDFC	$7.00E+24$	2
5	ICICI	$4.16E+24$	3	5	ICICI	$2.46E+24$	4
6	AXIS	$3.94E+24$	4	6	AXIS	$9.46E+22$	5

classified as systemic risk receiver are PNB, HDFC, and ICICI. In comparison, the banks which are systemic risk emitters are BOB, HDFC, and SBI. The banks with lower market capitalization seem to strengthen their influence over the central banks.

4. Conclusion

The results suggest that both the public and private banks are sensitive to state variables in the distress period like Indian VIX and US VIX. However, the sensitivity of private banks to liquidity risk is negative, implying a panic behavior of investors leading to the sale of stocks of private banks and less public confidence in private banks except for HDFC.

HDFC bank displayed resilience to state variables but still observed the highest Value at Risk during GFC, as found by Eichengreen and Gupta [8]. Finally, the systemic risk contribution exhibited dynamic behavior across the banks when an extreme situation arises, as seen by Jiang and Zhang

[29]. The contribution of private banks like AXIS and ICICI banks substantially increased after 2015. On the other hand, SBI continues to maintain a standard range of marginal contribution to systemic risk, indicating its importance over the years. The TENET graphs depict that the overall connectedness was high during the GFC. The elevated level of connectedness was reverted during 2016, which got eventually subdued by efforts taken by RBI. Further, the new pattern of connectedness was vigilant after the 2018 NBFC crisis.

BOB, HDFC, and ICICI were the risk contributors to the whole system in terms of market capitalization. Thus, the large-size banks in terms of market capitalization like HDFC and SBI tend to contribute more, as was found by Ramprasad et al. [23].

The intensification of the systemic risk contribution across the private banks and banks with a lower market capitalization in India forms the peculiarity of the Indian banking system. It is a cause of concern for the regulators. With the banks' growing market capitalization and asset base, distress in these banks will potentially bring distress to the other financial institutions and the economy. Moreover, these banks can act as a conduit to transfer risk to larger and public banks like SBI through "deposit flight," which encourages them to leverage in risky projects Eichengreen and Gupta [8].

This problem aggravated by the implicit government guarantee eventually will cause "too big to fail" consequences.

However, to inflict public confidence in private bank deposits, recent measures to enhance the deposit insurance limit to Rs 0.5 million, and direct fund transfer to depositors along with a stricter vigilance over its defaults as put by Nathan [52] is a step forward. Similarly, valuable insights can be drawn from the study to develop early warning signals [53].

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Additional Points

Further Readings. Contagion risk in financial sector: Fitch says 30% of banks' NBFC exposure could turn bad (The Financial Express).

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Dynamic Contract Design of Product-Service Supply Chain considering Consumers' Strategic Behavior and Service Quality

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With increasing market competition and rapid development of service economy, more and more enterprises are shifting from providing products or services to providing product-service systems (PSSs) that integrate products and services, in order to improve competitiveness and profitability. Meanwhile, consumers have strategic delayed purchasing behavior when purchasing the PSS and high requirements for service quality. This paper investigates the two-period pricing and service quality decisions of product-service supply chain (PSSC) considering consumers' strategic behavior under decentralized and centralized scenarios. The equilibrium results are compared in two scenarios. In order to eliminate performance loss under the decentralized scenario, we design two-period dynamic contracts to coordinate the PSSC. Furthermore, numerical simulation is provided to verify the feasibility of the contracts. The following conclusions can be drawn: (1) the higher the service input-efficiency, the more beneficial for alleviating consumers' strategic purchase behavior under two scenarios, but this mitigation effect is more obvious under the centralized scenario. (2) Compared with the centralized scenario, the service quality is lower, the two-period PSS sales prices are higher, and the two-period profit is lower under the decentralized scenario. The proportion of service valuation (accounts for the valuation of PSS) will promote the widening of the service quality gap under two scenarios, but in some cases, the service input-efficiency will weaken the promotion effect of the proportion of service valuation. (3) The design of the two-period combined contracts depends on the proportion of service valuation. When the proportion of service valuation is high, the "two-period revenue sharing + service-cost sharing" combined dynamic contract can achieve PSSC perfect coordination. However, when the proportion of service valuation is low, it is necessary to design complexity combined dynamic contract which can achieve PSSC perfect coordination.

1. Introduction

In the face of fierce market competition and the product lifecycle which is constantly shortened, dynamic price reduction strategy has become an effective way for firms to respond to competition and increase sales. For example, in China, during the 618 (June 18th) and Singles' Day (November 11th) each year, many firms adopt price-cutting promotion strategies to attract more consumers to buy, such as the distribution of red envelopes and coupons. During the 618 period in 2019, Jingdong's total revenue was 201.5 billion CNY, up by 26.57% year on year [1]. Tmall's income on Singles' Day was 268.4 billion CNY in 2019, growing by 25.71%, and logistics orders are 1.292 billion orders, an increase of 24% [2]. Because firms often cut prices for promotion, consumers become more and more rational when buying. Consumers are aware that firms may cut prices, and consumers will strategically choose the time to purchase to maximize their own utility. This type of consumer is called strategic consumer, and the corresponding strategic purchase behavior is called consumers' strategic behavior. If a firm ignores consumers' strategic behavior in pricing decisions, it will cause huge losses to the firm's profit [3, 4]. Therefore, firms pay more and more attention to consumers' strategic behavior in the pricing process.

In a product-service supply chain (PSSC) that provides both product and service, consumers' strategic behavior still exists. In this paper, the PSSC is composed of a manufacturer and a service provider, the manufacturer provides a product to the service provider, and the service provider integrates the product and the service into a product-service system (PSS) and provides the PSS to consumers. Obviously, the impact of consumers' strategic behavior on the PSSC is more complex, which will not only affect the product demand of the manufacturer in different sales periods but also delay in purchasing and using the product due to consumers waiting for price reduction. The consumers' strategic behavior will affect the service demands of the service provider at different sales periods and ultimately affect the product revenue and service revenue of the entire PSSC. This situation is common in the mobile communication industry, such as the mobile phone manufacturer provides the mobile phone to the communication operator, and the communication operator packs the mobile phone and the communication service and sells it to consumers. Due to the high frequency of mobile phone price changes, for example, the price of the iPhone 11 Pro Max just launched in September 2019 was up to 10,000 CNY, and the price was reduced by 1,300 CNY after a month [5]. As of August 2020, the price of this phone had been reduced by 2,500 CNY [6]. Consumers are more inclined to buy after lowering prices, which will not only affect the current mobile phone sales, but also reduce the use time of communication services due to delayed use of mobile phones, which will adversely affect the service revenue of communication operators. On the other hand, with the rapid development of the service economy, consumers have higher requirements for service quality. The firm improves consumer satisfaction by improving service quality, which in turn promotes service demand. In reality, consumers often complain about service problems such as slow network speeds and unstable communication signals of the communication operator, so the communication operator has adopted a variety of measures to improve service quality, such as technology upgrades from the original 4G to 5G, and the addition of base stations and network optimization. However, the improvement of service quality is bound to increase the service cost of the service provider. Therefore, in the face of consumers' increasing requirements for service quality and strategic purchase behavior, how should supply chain members set prices, and how to design effective dynamic contracts to coordinate supply chain members' pricing decisions behavior to achieve the best supply chain performance, that is a problem worthy of investigating. The research of this paper is mainly to solve the following problems:

(1) How should supply chain members make decisions under decentralized and centralized scenarios? What are the relationships between the equilibrium results under the two scenarios?

(2) How does the service element in the PSS affect the consumers' strategic behavior and the deviation of the two-period equilibrium results under the two scenarios?

(3) Facing the consumers' strategic behavior in the PSS under the condition of improving service quality, how to design effective contracts to achieve the perfect coordination of the PSSC?

In order to solve the above problems, we consider a PSSC, which consists of a manufacturer and a service provider. The manufacturer sells products, and the service provider integrates the product and service into PSS to sell to consumers. We also consider the impact of service quality on consumers' purchasing behavior. In order to analyze the performance loss of the PSSC under the decentralized scenario, we construct two dynamic decision models in the centralized and the decentralized scenarios. Comparing the equilibrium results in both scenarios, which finds that the two-period sales prices of the PSS are higher, the quality of service and the supply chain profit are lower under the decentralized scenario, which mean that there are decision bias and performance loss of supply chain. Moreover, with the increase of the proportion of service valuation, the degree of distortion of the PSS price is exacerbated, and the gap of service qualities is more obvious under two scenarios. The service provider improves service input-efficiency will inhibit the promotion effect of the proportion of service valuation to price distortion in the first period. In order to eliminate supply chain performance loss, we design two-period dynamic contracts related to the proportion of service valuation to adjust decision behavior of supply chain members and achieve optimal improvement of supply chain performance.

The remainder of this paper is arranged as follows. Section 2 reviews the related literature. Section 3 contains the problem description and model assumptions. Centralized and decentralized PSSC decision models are discussed in Sections 4 and 5, respectively. The comparative analysis of the two PSSC decision models is given in Section 6. Section 7 designs two combined dynamic contracts to coordinate the PSSC. Numerical simulations and conclusions are given in Sections 8 and 9, respectively. We postpone all of the proofs to Appendix.

2. Literature Review

The impact of consumers' strategic behavior on the firm decision attracts more scholars' attention, and scholars conduct in-depth research on this topic. Some scholars study the impact of consumers' strategic behavior on the firm dynamic pricing under monopoly and competitive environment [7, 8]. Besanko and Winston investigate the dynamic pricing problem of a monopoly seller based on multiple sales periods and find that monopolist should adopt price skimming strategy when facing strategic consumers [7]. Based on the literature [7], Liu and Zhang expand a single firm to two firms, investigating the multiperiod price competition of two firms with different product quality, finding that consumers' strategic behavior has larger adverse impact on the firm that provides low-quality products [8]. In response to product upgrading, some scholars discuss the impact of consumers' strategic behavior on the product rollover strategies and the firm pricing [9–12]. For example, Liang et al. consider a firm selling products to strategic consumers under two strategies of single rollover and dual rollover, studying the optimal pricing and inventory level of the firm, finding that when the proportion of strategic consumers is high and the degree of new product innovation is low, the firm should adopt single rollover strategy [9]. Liang et al. further study the impact of consumers' strategic behavior on product innovation level and find that consumers' strategic behavior will harm the profit of the firm, but it will increase the product innovation level [10]. Guo and Chen consider the challenges of new product releases to the proliferation of multiple generations of continuous product, studying the impact of consumers' strategic behavior on the two-generation product diffusion strategy. They find that the impact of consumers' strategic behavior on sales and profits largely depends on the price discount rate of the first-generation product under the second-generation product performance improvement [11]. Liu et al. discuss the impact of consumers' strategic behavior on the firm pricing strategies under the conditions of the introduction of a new generation of products and trade-in and find that when the residual value of the old-generation products is high enough, the firm is willing to sell the old-generation products to the second period new consumers [12].

In addition, some scholars study pricing issues that consider consumers' strategic behavior under quick response [13–16]. For example, Cachon and Swinney investigate the pricing and ordering decisions of the firm under the quick response and find that the quick response can alleviate the adverse effects of consumers' strategic behavior, achieve the matching of supply and demand, and increase the firm revenue [13]. Cachon and Swinney further study the fast fashion system that combines quick response and enhanced product design and find that both enhanced design and quick response can alleviate consumers' strategic behavior [14]. Wang et al consider that strategic consumers have risk preferences, discussing the impact of quick response on retailers' pricing and ordering decisions, finding that retailers' optimal pricing gradually decreases with strategic consumers' risk preferences, while optimal inventory has nothing to do with it [15]. Dong and Wu study the impact of consumers' strategic behavior on pricing and inventory decisions under the quick response and find that there is a unique equilibrium solution if and only if the degree of consumers' strategic behavior is sufficiently high [16]. Furthermore, Yu et al. consider the uncertainty of new experience product quality information and consumers' strategic behavior, studying the influence of consumer reviews on the dynamic pricing strategy, finding that the firm can control consumer reviews by adjusting the initial price of product, and the more consumer reviews which are possible will have a negative impact on consumer surplus [17]. Du and Chen take into account the uncertainty of the number of strategic consumers and the uncertainty of product evaluation in the market, studying the pricing strategy of new product, finding that the applicable conditions of the two pricing strategies of skimming pricing and penetration pricing [18]. Some scholars separately study the impact of consumers' strategic behavior on pricing in different situations such as product demand learning [19], quality information disclosure [20], cost reduction [21], reference price effects [22, 23], e-commerce platforms [24], and two alternative products (low-carbon products and ordinary products) [25].

Furthermore, some scholars study the impact of consumers' strategic behavior on the decision and contract coordination of supply chain members from the supply chain structure. Su and Zhang discuss the impact of consumers' strategic behavior on the decisions of supply chain members and supply chain performance and find that consumers' strategic behavior will reduce the amount of orders for retailers, and retailers can increase revenue through price commitments [26]. Yang et al. consider different supply chain structures and consumers' strategic behavior, studying the impact of quick response on supply chain decisions [27]. Ahmadi et al. discuss the impact of the gray market and consumers' strategic behavior on supply chain performance under wholesale price contract and quantity discount contract [28]. Lin et al. investigate the pricing and ordering decisions of supply chain members and find that consumers' strategic behavior is beneficial to the manufacturer, and in some cases, it is also beneficial to the retailer and the entire supply chain [29]. Kabul and Parlaktürk discuss the supply chain performance under price commitment or quantity commitment, finding that the commitment is not only detrimental to itself but also detrimental to other members of the supply chain, and the commitment can benefit by designing two-part tariff contract or quantity discount contract [30].

The above literature studies consider the impact of consumers' strategic behavior on product pricing decisions from an enterprise perspective or supply chain perspective and do not consider the impact of service. This paper will extend to the PSSC, construct multiperiod dynamic decision models including consumers' strategic behavior and service, analyzing and comparing dynamic equilibrium results and supply chain profits in two different scenarios, and design dynamic contracts to eliminate performance loss of the decentralized supply chain.

Another type of literature related to this paper is research on PSS and PSSC, which mainly includes qualitative analysis and quantitative analysis. Qualitative research mainly involves basic concepts, classification, design, operation models and methods, application value, etc. [31–36], which provides favorable theoretical support for the research of mathematical models. Quantitative research mainly involves product pricing and service decision [37–41] and contracts design [42–45]. Regarding pricing and service decision, Ferrer et al. consider the mixed bundling of products and multiple services, studying the optimal pricing decisions, applying dynamic programming to obtain the optimal pricing strategy, considering that some firms may not be suitable for adopting dynamic pricing, giving two suboptimal fixed prices and comparing with the optimal pricing [37]. Pang and Etzion focus on the firm selling products and complementary online services, among which online services have positive network effects, analyzing bundled pricing and individual pricing, finding that although bundled pricing can increase consumer surplus and social welfare, the monopolist do not use bundling sales, and network effects will lead to insufficient service supply [38]. Yang and Ng investigate the problem of bundling sales of products and services in the communications industry, using nonlinear integer programming to obtain the optimal pricing strategy, comparing the three strategies of individual sales, mixed bundling, and pure bundling, giving the condition that the mixed bundling strategy is the optimal strategy [39]. Zhang et al. consider a manufacturer to provide product and value-added service and discuss the pricing of value-added service and product under information asymmetry about value-added service quality [40]. Dan et al. further consider a manufacturer and a retailer to provide product and value-added services in double-channel PSSC, research warranty service, and value-added service decisions [41].

Moreover, some scholars investigate the effect of contract design on improving the performance of supply chain members from the perspective of PSSC. Xie et al. consider that the retailer has private value-added service-cost information, studying optimal pricing and service level decision, discussing three types of contracts, finding that retail price maintenance contract is more beneficial to the manufacturer and consumers, and franchise fee contract is more beneficial to the retailer [42]. Yang and Xiao study product pricing and service quality decision based on consumers' loss-averse and reference effect on service quality and design a combination contract of quantity discount and service subsidy to coordinate the PSSC [43]. Chen et al. consider a two-level PSSC composed of a manufacturer and a retailer facing random demand and discuss the product pricing and after-sales service level under a wholesale price contract or a revenue sharing contract when the manufacturer or retailer provides after-sales service [44]. Pascual et al. propose a quantitative method of contract design for use-oriented PSS and demonstrate the performance of applying this method through a case [45]. Furthermore, some scholars have studied capacity allocation problem of PSS. Wang et al. consider production service systems consisting of a service center and a manufacturing facility, which provides products and related services, and study the capacity allocation problem of the production service systems [46]. Moreover, Xu et al. review 71 research literature studies of the PSSC and analyze the future research opportunities and research strategies of the PSSC [47]. In addition, there is also research related to the paper involving contract design in the supply chain. Taleizadeh et al. consider product demand affected by sales price, greenness, and refund price and study supply chain decisions under cost sharing contract [48].

The literature just listed mainly studies pricing and contract design of product and service from the perspective of the firm or supply chain, without considering consumers' strategic behavior. In reality, due to the rapid development of information technology and the Internet, it has become increasingly convenient for consumers to obtain information about products and services, leading consumers to become more and more rational in the purchase process and to choose the right time to purchase. Moreover, consumers' strategic behavior is more complicated on PSSC, and consumers' strategic delayed purchasing behavior will not only reduce the purchase of product under the current price but also cause a reduction in service use, which will inevitably have an impact on product demand and service demand. Therefore, it is necessary to consider consumers' strategic behavior in the relevant research of PSSC.

3. Problem Description and Model Assumption

We consider a PSSC consisting of a manufacturer, a service provider, and strategic consumers. In each period, the manufacturer wholesales the product to the service provider, and the service provider not only provides the service that matches the product but also integrates the service and product into PSS to sell to consumers. This paper divides the selling season into n sales periods. Because the sales price of the PSS usually changes within n periods, strategic consumers will not only consider the current sales price when purchasing but also anticipate the sales price in the future. In the period t $(t = 1, 2, \ldots, n)$, the manufacturer sets the wholesale price of the product w_t, the service provider sets the price of the PSS $p_{\mathrm{G}t}$, which is composed of two parts: product price p_t^p and service price p_t^s; thus, $p_{\mathrm{G}t} = p_t^p + p_t^s$. Each consumer can purchase at most one unit of the PSS during the selling season. The so-called one unit PSS is composed of one unit product and one single-period service. Assuming that the consumer purchases the product-service system in the period t, the consumer will continue to purchase and use the service in the remaining sales periods. The above situation is more common in mobile communication. For example, when consumers purchase the mobile phone and communication package service, they usually need to pay for the mobile phone product at a time, while the communication package service fee needs to be paid in periods. As consumers have higher and higher requirements for service quality, the service provider will not only provide basic service quality to meet consumers' basic service requirements but also improve service quality by increasing service investment. The service provider determines service quality q before the start of the sales season and the service cost that the service provider needs to invest $C(q)$. We assume that the service provider's service investment contributes to the improvement of service quality to satisfy the law of diminishing margin, and $C(q)$ is a strictly convex function of q, which satisfies the relations $(\mathrm{d}C(q)/\mathrm{d}q) > 0$, $(\mathrm{d}^2C(q)/\mathrm{d}q^2) > 0$. We use a quadratic convex function to express the service input cost, i.e., $C(q) = (kq^2/2)$ (e.g., [42]), and k is the service input cost coefficient. The smaller k means the lower the marginal cost of service input, and the higher the efficiency of service input.

The consumers' valuation of the unit PSS is V. Since the valuations of different consumers are generally heterogeneous in reality, we use the random variable V to represent, the probability density function is $f(v)$, and the cumulative distribution function is $F(v)$. The consumer's valuation of the service in the unit PSS is λV, where λ $(0<\lambda<1)$ represents the proportion of service valuation (accounts for the valuation of the unit PSS). The larger λ means the higher the value of the service in the unit PSS. Let $\mathbf{w}=\{w_1,w_2,\ldots,w_n\}$ be the vector of wholesale prices during the selling season, $\mathbf{P}^p=\{p_1^p,p_2^p,\ldots,p_n^p\}$ be the vector of product sales prices during the selling season, and $\mathbf{P}^s=\{p_1^s,p_2^s,\ldots,p_n^s\}$ be the vector of service sales prices during the selling season. The utility obtained by the consumer purchasing the PSS in each period is

$$U_t=V-\left(p_t^p+p_t^s\right)+q+\sum_{j=t+1}^{n}\left(\lambda V-p_j^s+q\right),\quad \forall t=1,2,\ldots,n. \tag{1}$$

Strategic consumers must not only decide whether to purchase the PSS but also at which period to purchase, and they make purchase decision based on the principle of maximizing multiperiod utility. At the determined time for buying the PSS, call it $t_g(V,\mathbf{P}^p,\mathbf{P}^s,q)$. More specifically, we have

$$t_g(V,\mathbf{P}^p,\mathbf{P}^s,q)=\min_t \arg\max\left\{U_t=V-\left(p_t^p+p_t^s\right)+q+\sum_{j=t+1}^{n}\left(\lambda V-p_j^s+q\right)\middle|U_t\geq 0\right\}. \tag{2}$$

Assuming the market size is N, the demand for the PSS at each period is

$$\begin{aligned}Q_t&=N\int_{\Omega_t} I_{\{t_g(V,\mathbf{P}^p,\mathbf{P}^s,q)=t\}}f(v)\mathrm{d}v,\\ \Omega_t&=\left\{v|U_t(v)\geq\left(U_j(v)\right)^+,\quad \forall j=1,2,\ldots,n,\ j\neq t\right\},\end{aligned} \tag{3}$$

where $(U_j(v))^+=\max\{U_j(v),0\}$ and $I_{\{\cdot\}}$ is an indicator function. Suppose the unit production cost of the product is c_m. Since the service cost of improving service quality in the early period is relatively large and the service cost in the later period is relatively low, so we can assume the unit cost of the service is zero. Therefore, the optimal decision problem of the manufacturer in n sales periods is

$$\max_{\mathbf{w}} \Pi_M(\mathbf{w})=\sum_{t=1}^{n}(\mathbf{w}_t-c_m)Q_t. \tag{4}$$

The optimal decision problem of the service provider is

$$\begin{aligned}&\max_{\mathbf{p}^p,\mathbf{p}^s,q}\Pi_S(\mathbf{p}^p,\mathbf{p}^s,q)\\ &=\sum_{t=1}^{n}(p_t^p+p_t^s-w_t)Q_t+\sum_{t=1}^{n}(n-t)p_t^sQ_t-\frac{k}{2}q^2.\end{aligned} \tag{5}$$

In order to facilitate analysis and obtain some valuable management enlightenment, this paper will analyze and solve the problem of dynamic decision with two-period in the selling season. For ease of illustration, let p_1 and p_2 be product sales prices in the first and second periods separately. Let p_{Gt} be the combination price of PSS. In addition, consider that service prices are more stable relative to product prices in the mobile communication industry. For example, the prices of some new mobile phones are cut shortly after they are launched, and the price of communication package services usually remains unchanged for a long time. So, it is assumed that the service price does not change in the two sales periods, and the service price is represented by p_s. The condition for consumers to choose to buy at the i-th period is $U_i(V,p_i,p_s,q)\geq(U_{3-i}(V,p_{3-i},p_s,q))^+$, $(i=1,2)$. Let V_0 be the threshold of consumers' strategic delayed purchasing behavior, that is, the critical valuation of consumers buying in the first period or choosing to delay purchase. When $V\geq V_0$, consumers buy in the first period. When $V<V_0$, consumers do not buy in the first period and delay to the second period to consider whether to buy. The demands for the first and second periods of the PSS are, respectively,

$$\begin{aligned}Q_1&=N\Pr(V-V_0\geq 0)=N\int_{\{v|v-V_0\geq 0,v\geq 0\}}f(v)\mathrm{d}v,\\ Q_2&=N\Pr(p_2+p_s-q\leq V<V_0)=N\int_{\{v|p_2+p_s-q\leq v<V_0\}}f(v)\mathrm{d}v.\end{aligned} \tag{6}$$

Without loss of generality, the market size is deterministic and normalized to 1 (e.g., [8, 29, 30]). Consumers' valuations V of the PSS are heterogeneous, and those valuations are distributed uniformly in the interval $[0,V_1]$ (e.g., [17, 28–30]). V_1 represents the consumers' highest valuation for the PSS. The larger V_1 means the higher the value of the PSS. The demands for the first and second periods are, respectively,

$$Q_1=1-\frac{V_0}{V_1}, \tag{7}$$

$$Q_2=\frac{V_0-p_2-p_s+q}{V_1}. \tag{8}$$

From formulas (7) and (8), when the threshold of consumers' strategic delayed purchasing behavior is larger, the fewer consumers choose to buy in the first period, and the more consumers choose to buy in the second period; it means that consumers are more inclined to delay purchase; that is, the consumers' strategic delayed purchasing behavior is more serious. Therefore, let $\Upsilon \equiv V_0/V_1$ be the intensity of consumers' strategic delayed purchasing behavior, $\Upsilon \in (0,1)$. Add formulas (7) and (8) together, and the total demand in the two-period can be obtained as $Q_1 + Q_2 = (V_1 - p_2 - p_s + q)/V_1$. It can be seen that the total demand in the two-period $(Q_1 + Q_2)$ is positively related to the quality of service (q) and negatively correlated with the second period PSS portfolio price $(p_2 + p_s)$. The larger q means the higher the total demand, and the service provider needs to bear higher service input cost, and the lower the price of the second period PSS $(p_2 + p_s)$, the higher the total demand. In order to ensure that the sales volumes of the two periods are positive and facilitate discussion, we need to assume $k > 5/c_m$ and $V_1 > 3c_m + (5/k)$; that is, the service provider's service investment cost cannot be ignored, and the consumers' highest valuation for the PSS cannot be too low.

In this paper, the superscript "C" means the centralized scenario; the superscript "D" means the decentralized scenario; the superscript "RC" means the coordination scenario under contract design; the superscript asterisk " $*$ " represents the subgame perfect Nash equilibrium strategies; the subscript "M" means the manufacturer; the subscript "S" means the service provider. All the notations are summarized in Table 1.

4. PSSC under the Centralized Scenario

Under the centralized supply chain scenario, the manufacturer and the service provider are regarded as an integrated whole, and their common goal is to maximize the profit of the supply chain system. They determine the service quality and the price of the PSS. The total profit function of the system in the two-period is

$$\pi^C = \left(p_1^C + p_s^C - c_m\right)Q_1^C + \left(p_2^C + p_s^C - c_m\right)Q_2^C + p_s^C Q_1^C - \frac{k}{2}\left(q^C\right)^2. \tag{9}$$

In formula (9), the first and second items on the right side of the equal sign, respectively, represent the profit of the first and second period sales PSS, and the third item represents the service profit generated by consumers who originally purchased in the first period who continue to use the service in the second period. Moreover, the last item represents the service-cost invested in improving service quality. Because the third item depends on the decision of the first period, it is combined with the first item as the supply chain system profit of the first period, and the second item represents the supply chain system profit of the second period. Because of $p_{G1}^C = p_1^C + 2p_s^C$, $p_{G2}^C = p_2^C + p_s^C$, therefore, formula (9) is rearranged as follows:

$$\pi^C = \left(p_{G1}^C - c_m\right)Q_1^C + \left(p_{G2}^C - c_m\right)Q_2^C - \frac{k}{2}\left(q^C\right)^2. \tag{10}$$

The decision process in the centralized scenario is as follows: (1) the system first decides the service quality and the price of the first period PSS. (2) Consumers decide whether to purchase in the first period or wait for a delayed purchase based on the service quality, the first period combination price, and their expectations of the second period combination price. (3) The system sets the second period combination price. (4) The remaining consumers decide whether to buy or leave in the second period. In this paper, the backward induction method is used to solve the decision problems (see, [29, 30, 49]), and the subgame perfect Nash equilibrium between the system and consumers in the centralized scenario is solved in the following order:

$$p_{G2}^{C*} = \arg\max_{p_{G2}^C}\left[\left(p_{G2}^C - c_m\right)\left(\frac{V_0^C}{V_1} - \frac{p_{G2}^C - q^C}{V_1}\right)\right], \tag{11}$$

$$V_0^{C*} = \inf\left\{V_0^C \mid (1+\lambda)V_0^C - p_{G1}^C + 2q^C \geq \left(V_0^C - p_{G2}^{C*} + q^C\right)^+\right\}, \tag{12}$$

$$\left(q^{C*}, p_{G1}^{C*}\right) = \arg\max_{q^C, p_{G1}^C}\left[\left(p_{G1}^C - c_m\right)\left(1 - \frac{V_0^{C*}}{V_1}\right) + \left(p_{G2}^{C*} - c_m\right)\left(\frac{V_0^{C*}}{V_1} - \frac{p_{G2}^{C*} - q^C}{V_1}\right) - \frac{k}{2}\left(q^C\right)^2\right]. \tag{13}$$

According to formulas (11)–(13), Proposition 1 is as follows.

Proposition 1. *Under the centralized supply chain scenario, the optimal combination price of the first period PSS is* $p_{G1}^{C*} = (V_1(1+2\lambda)^2/2(1+4\lambda)) + (c_m/2) + (((1+8\lambda)(8\lambda V_1 - 4\lambda c_m + V_1 - c_m))/(2(2kV_1(1+4\lambda) - 4\lambda - 5)(1+4\lambda)))$. *The optimal service quality is* $q^{C*} = (V_1 - c_m + 4\lambda(2V_1 - c_m))/(2kV_1(1+4\lambda) - 4\lambda - 5)$. *The threshold of consumers' strategic delayed purchasing behavior is* $V_0^{C*} = (V_1(1+2\lambda)/(1+4\lambda)) - (2(8\lambda V_1 - 4\lambda c_m + V_1 - c_m)/((1+4\lambda)(2kV_1(1+4\lambda) - 4\lambda - 5)))$. *The optimal price of the second period PSS is* $p_{G2}^{C*} = (V_1(1+2\lambda)/2(1+4\lambda)) + (c_m/2) - ((1-4\lambda)(8\lambda V_1 - 4\lambda c_m + V_1 - c_m)/(2(1+4\lambda)(2kV_1(1+4\lambda) - 4\lambda - 5)))$.

Proposition 1 gives the optimal equilibrium solution of the system under the centralized scenario. It can be seen that when the service input-efficiency is higher, the system will provide higher service quality, while the threshold of consumers' strategic delayed purchasing behavior will decrease, and the system will increase the first period combination

Table 1: Notations for the models.

Notation	Description
V	Consumers' valuations of the PSS
c_m	Unit production cost
k	Service input cost coefficient
λ	The proportion of service valuation (accounts for the valuation of the unit PSS)
Υ	The intensity of consumers' strategic delayed purchasing behavior
$p_i^D\,(p_i^C)$	Product sales price in the i-th period under the decentralized (centralized) scenario, $i = 1, 2$
$p_s^D\,(p_s^C)$	Service price at each period under the decentralized (centralized) scenario
$p_{Gi}^D\,(p_{Gi}^C)$	Combination price of PSS in the i-th period under the decentralized (centralized) scenario
$q^D\,(q^C)$	Service quality under the decentralized (centralized) scenario
$w_i^D\,(w_i^C)$	Product wholesale price in the i-th period under the decentralized (centralized) scenario
$V_0^D\,(V_0^C)$	The threshold of consumers' strategic delayed purchasing behavior under the decentralized (centralized) scenario
$\varphi_1\,(\varphi_2)$	The proportion of the service provider's income from the first (second) period of the PSSC
T	Transfer payment
ξ	The proportion of the manufacturer sharing service-cost

price of the PSS and reduce the second period combination price.

Corollary 1. *Under the centralized supply chain scenario, the demand for the first period PSS is*

$$Q_1^{C*} = \frac{2\lambda}{1+4\lambda} + \frac{2(8\lambda V_1 - 4\lambda c_m + V_1 - c_m)}{V_1(1+4\lambda)(2kV_1(1+4\lambda) - 4\lambda - 5)}. \quad (14)$$

The demand for the second period PSS is

$$Q_2^{C*} = \frac{1+2\lambda}{2(1+4\lambda)} - \frac{c_m}{2V_1} - \frac{(1-4\lambda)(8\lambda V_1 - 4\lambda c_m + V_1 - c_m)}{2V_1(1+4\lambda)(2kV_1(1+4\lambda) - 4\lambda - 5)}. \quad (15)$$

The total profit of the system is

$$\pi^{C*} = \frac{\lambda^2 V_1}{1+4\lambda} + \frac{(V_1 - c_m)^2}{4V_1} + \frac{(8\lambda V_1 - 4\lambda c_m + V_1 - c_m)^2}{4V_1(1+4\lambda)(2kV_1(1+4\lambda) - 4\lambda - 5)}. \quad (16)$$

Corollary 1 gives the two-period demands and the total profit of system under centralized supply chain scenario. When the service input-efficiency is lower, the higher the threshold of consumers' strategic delayed purchasing behavior, it means that more consumers are willing to delay purchase, which will make the first period demand lower. Due to lower service input-efficiency, the system will increase the second period combination price to inhibit consumers from delaying purchase. Nevertheless, because consumers are more willing to buy later, it will lead to higher demand in the second period. In addition, the lower the service input-efficiency, the lower the total profit of the system.

5. PSSC under the Decentralized Scenario

Under the decentralized supply chain scenario, the manufacturer decides the product wholesale price before the start of each sales period, the service provider decides service quality and PSS combination price. The manufacturer and the service provider make independent decisions with the goal of maximizing their own interests.

The total profit of the manufacturer in the two-period is

$$\pi_M^D = (w_1^D - c_m)Q_1^D + (w_2^D - c_m)Q_2^D. \quad (17)$$

The total profit of the service provider in the two-period is

$$\pi_S^D = (p_1^D - w_1^D + p_s^D)Q_1^D + (p_2^D - w_2^D + p_s^D)Q_2^D + p_s^D Q_1^D - \frac{k}{2}(q^D)^2. \quad (18)$$

Reorganize formula (18) to get

$$\pi_S^D = (p_{G1}^D - w_1^D)Q_1^D + (p_{G2}^D - w_2^D)Q_2^D - \frac{k}{2}(q^D)^2. \quad (19)$$

The decision process of the decentralized scenario is as follows: (1) the manufacturer first sets the first period wholesale price w_1^D. (2) The service provider sets service quality q^D and the first period PSS price p_{G1}^D. (3) Consumers decide whether to purchase in the first period or wait for a delayed purchase according to the service quality, the first period price, and their expectations of the second period price. (4) The manufacturer sets the second period product wholesale price w_2^D. (5) The service provider sets the second period PSS price p_{G2}^D. (6) The remaining consumers decide whether to buy or leave in the second period. Using the backward induction method, the subgame perfect Nash equilibrium between the manufacturer, the service provider, and consumers in the decentralized scenario can be solved in the following order:

$$p_{G2}^{D*} = \arg\max_{p_{G2}^{D}}\left[\left(p_{G2}^{D} - w_2^{D}\right)\left(\frac{V_0^{D}}{V_1} - \frac{p_{G2}^{D} - q^{D}}{V_1}\right)\right], \tag{20}$$

$$w_2^{D*} = \arg\max_{w_2^{D}}\left[\left(w_2^{D} - c_m\right)\left(\frac{V_0^{D}}{V_1} - \frac{p_{G2}^{D*} - q^{D}}{V_1}\right)\right], \tag{21}$$

$$V_0^{D*} = \inf\left\{V_0^{D} \mid (1+\lambda)V_0^{D} - p_{G1}^{D} + 2q^{D} \geq \left(V_0^{D} - p_{G2}^{D*} + q^{D}\right)^{+}\right\}, \tag{22}$$

$$\left(q^{D*}, p_{G1}^{D*}\right) = \arg\max_{q^{D}, p_{G1}^{D}}\left[\left(p_{G1}^{D} - w_1^{D}\right)\left(1 - \frac{V_0^{D*}}{V_1}\right) + \left(p_{G2}^{D*} - w_2^{D*}\right)\frac{\left(V_0^{D*} - p_{G2}^{D*} + q^{D}\right)}{V_1} - \frac{k}{2}\left(q^{D}\right)^2\right]. \tag{23}$$

$$w_1^{D*} = \arg\max_{w_1^{D}}\left[\left(w_1^{D} - c_m\right)\left(1 - \frac{V_0^{D*}}{V_1}\right) + \left(w_2^{D*} - c_m\right)\frac{\left(V_0^{D*} - p_{G2}^{D*} + q^{D*}\right)}{V_1}\right]. \tag{24}$$

From formulas (20)–(24), Proposition 2 is as follows.

Proposition 2. *Under the decentralized supply chain scenario, the optimal wholesale prices of the first and second periods are*

$$\begin{aligned} w_1^{D*} &= \frac{\begin{bmatrix} 2k^2V_1^3\left(67 + 184\lambda + 128\lambda^2\right) + V_1A_1 - c_m(61 - 12\lambda) \\ -kV_1^2\left(301 - 6kc_m(31 + 48\lambda) + 370\lambda + 64\lambda^2\right) \end{bmatrix}}{4\left(16k^2V_1^2(5 + 8\lambda) - kV_1(163 + 32\lambda) - 2(1 - \lambda)\right)}, \\ w_2^{D*} &= \frac{\begin{bmatrix} 4k^2V_1^3(17 + 24\lambda) + V_1\left(7(1 - \lambda) - 3kc_m(59 + 16\lambda)\right) \\ -kV_1^2(149 - 4kc_m(23 + 32\lambda) - 44\lambda) - c_m(11 - 4\lambda) \end{bmatrix}}{2\left(16k^2V_1^2(5 + 8\lambda) - kV_1(163 + 32\lambda) - 2(1 - \lambda)\right)}. \end{aligned} \tag{25}$$

The optimal service quality is

$$q^{D*} = \frac{\begin{bmatrix} kV_1^2(59 + 136\lambda) - c_m(17 - 4\lambda) \\ +V_1\left(17(1 - \lambda) - kc_m(59 + 32\lambda)\right) \end{bmatrix}}{2\left(16k^2V_1^2(5 + 8\lambda) - kV_1(163 + 32\lambda) - 2(1 - \lambda)\right)}. \tag{26}$$

The threshold of consumers' strategic delayed purchasing behavior is

$$V_0^{D*} = \frac{\begin{bmatrix} 8k^2V_1^3(17 + 24\lambda) - V_1\left(3 - 31kc_m - 3\lambda\right) \\ -3kV_1^2(119 - 8kc_m + 16\lambda) - c_m \end{bmatrix}}{16k^2V_1^2(5 + 8\lambda) - kV_1(163 + 32\lambda) - 2(1 - \lambda)}. \tag{27}$$

The optimal combination prices of the first and second period PSS are

$$p_{G1}^{D*} = \frac{\begin{bmatrix} 4k^2V_1^3(3+4\lambda)(17+24\lambda) + V_1A_2 - 7c_m(9-2\lambda) \\ -kV_1^2\left(329 - 4kc_m(29+44\lambda) + 310\lambda + 96\lambda^2\right) \end{bmatrix}}{4\left(16k^2V_1^2(5+8\lambda) - kV_1(163+32\lambda) - 2(1-\lambda)\right)},$$
$$p_{G2}^{D*} = \frac{\begin{bmatrix} 12k^2V_1^3(17+24\lambda) + V_1\left(21(1-\lambda) - 5kc_m(41+16\lambda)\right) \\ -kV_1^2(447 - 4kc_m(29+32\lambda) - 132\lambda) - c_m(29-8\lambda) \end{bmatrix}}{4\left(16k^2V_1^2(5+8\lambda) - kV_1(163+32\lambda) - 2(1-\lambda)\right)}. \quad (28)$$

In addition, $A_1 = 53 - kc_m(351+28\lambda) - 57\lambda + 4\lambda^2$ and

$$A_2 = (1-\lambda)(55-6\lambda) - kc_m(323+82\lambda). \quad (29)$$

Proposition 2 gives the optimal equilibrium solution under the decentralized supply chain scenario. The equilibrium solutions are all related to service input-efficiency (k), the proportion of service valuation (λ), consumers' highest valuation of unit PSS (V_1), and the unit production cost of the product (c_m). When the unit production cost is higher, the manufacturer will increase the wholesale price of the first period product, and the service provider will increase the combination price of the first period PSS and reduce service quality.

Corollary 2. *Under the decentralized supply chain scenario, the demands for the first and second period PSS are*

$$Q_1^{D*} = \frac{\begin{bmatrix} 8k^2V_1^3(3+8\lambda) - V_1(1+31kc_m-\lambda) \\ -kV_1^2(24kc_m + 16\lambda - 31) + c_m \end{bmatrix}}{2V_1\left(16k^2V_1^2(5+8\lambda) - kV_1(163+32\lambda) - 2(1-\lambda)\right)},$$
$$Q_2^{D*} = \frac{\begin{bmatrix} 4k^2V_1^3(17+24\lambda) + V_1\left(7 + kc_m(149+16\lambda) - 7\lambda\right) \\ -kV_1^2(149 + 4kc_m(17+32\lambda) - 44\lambda) - 7c_m \end{bmatrix}}{4V_1\left(16k^2V_1^2(5+8\lambda) - kV_1(163+32\lambda) - 2(1-\lambda)\right)}. \quad (30)$$

The total profits of the service provider and the manufacturer are

$$\pi_S^{D*} = \frac{\begin{bmatrix} 4\lambda^3V_1^2(8kV_1-1)^4 + B_1\lambda^2V_1(8kV_1-1)^2 \\ +2B_2\lambda(V_1-c_m) + B_3(V_1-c_m)^2 \end{bmatrix}}{16V_1\left(16k^2V_1^2(5+8\lambda) - kV_1(163+32\lambda) - 2(1-\lambda)\right)^2},$$
$$\pi_M^{D*} = \frac{\begin{bmatrix} \lambda^2V_1^2(8kV_1-1) + (V_1-c_m)^2\left(49k^2V_1^2 - 46kV_1 + 1\right)^2 \\ +2\lambda V_1(V_1-c_m)\left(56k^2V_1^2 - 32k^2c_mV_1 + 31kV_1 - 1\right) \end{bmatrix}}{4V_1\left(16k^2V_1^2(5+8\lambda) - kV_1(163+32\lambda) - 2(1-\lambda)\right)}. \quad (31)$$

In addition,

$$\begin{aligned} B_1 &= 624k^2V_1^3 - 2kV_1^2(352kc_m + 83) - 32kc_m^2 + 8c_m \\ &\quad + V_1\left(256k^2c_m^2 - 184kc_m + 37\right), \\ B_2 &= 15616k^4V_1^5 - 32k^3V_1^4(356kc_m + 715) + V_1(92kc_m - 43) \\ &\quad - kV_1^2(4178kc_m - 1685) + 8k^2V_1^3(2396kc_m - 845) - 2c_m, \\ B_3 &= 7984k^4V_1^4 - 24230k^3V_1^3 + 17361k^2V_1^2 - 2484kV_1 + 45. \end{aligned} \quad (32)$$

6. Comparative Analysis of Two PSSC Scenarios

According to the equilibrium results given by Propositions 1 and 2 and Corollaries 1 and 2, comparing and analyzing the intensity of consumers' strategic delayed purchasing behavior, service quality, PSS combination prices, PSS demands, and PSSC performance under the centralized and decentralized scenarios, we reveal the problem of decision bias and system profit loss under the decentralized scenario.

Proposition 3. *The intensity of consumers' strategic delayed purchasing behavior under the two scenarios has the following relationships:*

(1) $\Upsilon^{D*} < \Upsilon^{C*}$ *if and only if* $0 < \lambda < \lambda_a$, *otherwise* $\Upsilon^{D*} \geq \Upsilon^{C*}$;

(2) $(\partial\Upsilon^{C*}/\partial\lambda) < (\partial\Upsilon^{D*}/\partial\lambda) < 0$, $(\partial\Upsilon^{C*}/\partial k) > (\partial\Upsilon^{D*}/\partial k) > 0$, $(\partial\Upsilon^{C*}/\partial V_1) > 0 > (\partial\Upsilon^{D*}/\partial V_1)$,

where

$$\lambda_a = \frac{\begin{bmatrix} 16c_m^2\left(48k^3V_1^3 - 90k^2V_1^2 - kV_1 - 1\right)^2 \\ +8E_1c_mV_1 + E_2V_1^2 \end{bmatrix}^{1/2} - E_3}{8V_1\left(2kV_1 - 1\right)\left(8kV_1 - 1\right)^2},$$

$$E_1 = 3072k^6V_1^6 + 33408k^5V_1^5 - 92480k^4V_1^4 + 56604k^3V_1^3 - 17256k^2V_1^2 - 53kV_1 + 9,$$

$$E_2 = 200704k^6V_1^6 - 1431552k^5V_1^5 + 2797056k^4V_1^4 - 1850240k^3V_1^3 + 408996k^2V_1^2 + 14796kV_1 + 81,$$

$$E_3 = 320k^3V_1^4 + 48k^2V_1^3\left(4kc_m - 19\right) - V_1\left(4kc_m - 17\right) - 18kV_1^2\left(20kc_m - 31\right) - 4c_m. \quad (33)$$

From Proposition 3, when the proportion of service valuation is relatively high (low), the intensity of consumers' strategic delayed purchasing behavior under the decentralized scenario is stronger (weaker) than centralized scenario, which means that consumers are more inclined to wait for a delayed purchase under the decentralized (centralized) scenario. As the proportion of service valuation increases, the intensity of consumers' strategic delayed purchasing behavior will gradually decrease, which shows that the proportion of service valuation can alleviate consumers' strategic purchasing behavior under the two scenarios. Compared with the centralized scenario, the change in the proportion of service valuation causes a smaller change in the intensity of consumers' strategic delayed purchasing behavior under the decentralized scenario, which means that the proportion of service valuation has a weaker inhibitory effect on consumers' strategic purchasing behavior under the decentralized scenario. Moreover, the service provider improves service input-efficiency which will reduce the intensity of consumers' strategic delayed purchasing behavior under the two scenarios, and the inhibitory effect on the intensity of consumers' strategic delayed purchasing behavior is more obvious under the centralized scenario. When consumers' highest valuation of the PSS is higher, the intensity of consumers' strategic delayed purchasing behavior is weaker (stronger) under the decentralized (centralized) scenario, which means that the value of the PSS will inhibit (promote) consumers' strategic purchase behavior under the decentralized (centralized) scenario.

Proposition 4. *The equilibrium results under the two scenarios have the following relationships:*

(1) $q^{D*} < q^{C*}$, $p_{G1}^{D*} > p_{G1}^{C*}$, $p_{G2}^{D*} > p_{G2}^{C*}$;

(2) $Q_1^{D*} > Q_1^{C*}$ *if and only if* $0 < \lambda < \lambda_a$, *otherwise* $Q_1^{D*} \leq Q_1^{C*}$; $Q_2^{D*} < Q_2^{C*}$; $Q_1^{D*} + Q_2^{D*} < Q_1^{C*} + Q_2^{C*}$;

(3) *Let* $\eta = (\pi^{C*} - (\pi_M^{D*} + \pi_S^{D*}))/\pi^{C*}$, *which indicates the loss rate of system profit in the two-period of the PSSC, where* $0 < \eta < 1$.

In addition, λ_a is shown in Proposition 3.

Proposition 4 shows the following: (1) under the decentralized scenario, the optimal service quality is lower than that under the centralized scenario, and the prices of the PSS are higher than those under the centralized scenario, which means that the service utility and the net utility of the PSS are lower under the decentralized scenario than those under the centralized scenario. (2) When the proportion of service valuation is relatively high, according to Proposition 3, it can be seen that the intensity of consumers' strategic delayed purchasing behavior under the decentralized scenario is stronger than that under the centralized scenario. Therefore, the first period demand under the centralized scenario is greater than that under the decentralized scenario. When the proportion of service valuation is relatively low, consumers' strategic purchasing behavior is more obvious under the centralized scenario, so the first period demand under the decentralized scenario is greater than that under the centralized scenario. Compared with the centralized scenario, the service quality is lower and the price of the second PSS is higher under the decentralized scenario, which means that consumers have a higher purchase threshold of the second period under the decentralized scenario, which leads to the demand of the second period PSS which is less under the decentralized scenario. In addition, because the total demand is negatively correlated with the second period purchase threshold, the total demand in the two-period is less than that under the centralized scenario. (3) The manufacturer and service provider make decisions based on their own interests under the decentralized scenario, which will lead to double marginalization, causing a decrease in the optimal service quality, and PSS prices increase and total demand decreases. As a result, the total profit of the supply chain system under the decentralized scenario is lower than that under the centralized scenario; that is, the efficiency of the supply chain system decreases.

Proposition 5. *The influence of the proportion of service valuation on the deviation of equilibrium results under two scenarios:*

(1) $(\partial(q^{C*} - q^{D*})/\partial\lambda) > 0$, $(\partial^2(q^{C*} - q^{D*})/\partial\lambda^2) < 0$, $(\partial^2(q^{C*} - q^{D*})/\partial\lambda\,\partial k) < 0$;

(2) $(\partial(p_{G1}^{D*} - p_{G1}^{C*})/\partial\lambda) > 0$, $(\partial^2(p_{G1}^{D*} - p_{G1}^{C*})/\partial\lambda^2) < 0$, $(\partial^2(p_{G1}^{D*} - p_{G1}^{C*})/\partial\lambda\,\partial k) > 0$;

(3) $(\partial(p_{G2}^{D*} - p_{G2}^{C*})/\partial\lambda) > 0$, $(\partial^2(p_{G2}^{D*} - p_{G2}^{C*})/\partial\lambda^2) < 0$;

(4) *When* $k > \Delta_g/c_m$, $V_1 < V_g$ *and* $0 < \lambda < \lambda_g$, $(\partial^2(p_{G2}^{D*} - p_{G2}^{C*})/\partial\lambda\,\partial k) < 0$; *when* $k \leq \Delta_g/c_m$, *or*

$k > \Delta_g/c_m$ *and* $V_1 \geq V_g$, *or* $k > \Delta_g/c_m$, $V_1 < V_g$ *and* $\lambda_g \leq \lambda < 1$, $(\partial^2(p_{G2}^{D*} - p_{G2}^{C*})/\partial\lambda\,\partial k) \geq 0$,

where

$$\Delta_g = \{\Delta > 0 | G(\Delta) = 0\} \approx 46.6753,$$
$$V_g = \left\{V_1 > 3c_m + \frac{5}{k} | L(V_1) = 0\right\}. \tag{34}$$

λ_g *fits* $(\partial^2(p_{G2}^{D*} - p_{G2}^{C*})/\partial\lambda\,\partial k)|_{\lambda=\lambda_g} = 0$,

$$\begin{aligned} L(V_1) &= 6885376k^7V_1^5 - 256k^6V_1^7(87776kc_m - 50343) \\ &\quad + 2560k^5V_1^6(48046kc_m - 103527) \\ &\quad - 8k^4V_1^5(23284128kc_m - 90912755) \\ &\quad - 4k^3V_1^4(6235172kc_m + 181344681) \\ &\quad + 2k^2V_1^3(105348380kc_m + 147699033) \\ &\quad - kV_1^2(102668604kc_m + 118369519) \\ &\quad + V_1(43205570kc_m + 1180866) - 2127256c_m, \\ G(\Delta) &= -3968372736\Delta^8 + 146844907776\Delta^7 \\ &\quad + 1633928951808\Delta^6 + 6994653963192\Delta^5 \\ &\quad + 16096435123356\Delta^4 + 21785841003186\Delta^3 \\ &\quad + 17409073383429\Delta^2 + 7616922711372\Delta \\ &\quad + 1408808597105. \end{aligned} \tag{35}$$

From Proposition 5, (1) when the proportion of service valuation is higher, the difference in service quality between centralized scenario and decentralized scenario is greater. As the proportion of service valuation increases, the service provider is willing to improve service quality under the two scenarios. In addition, the high proportion of service valuation will cause the manufacturer to increase the wholesale price in the first period under the decentralized scenario, which will inhibit the service provider from improving service quality, and make the service quality increase less than that under the centralized scenario. That is, the difference in service quality under the two scenarios will aggravate as the proportion of service valuation increases, and this degree of aggravation will gradually weaken. The service provider improves the service input-efficiency which will intensify the role of the proportion of service valuation in promoting the expansion of service quality gap between the two scenarios. (2)~(3) The higher the proportion of service valuation, the greater the price difference between the first and second periods of the two scenarios. As the proportion of service valuation increases, the intensity of consumers' strategic delayed purchasing behavior decreases, which means that the demand in the first period increases. Meanwhile, the manufacturer will increase the wholesale price of the first period product to obtain more profit, and the service provider faces high service cost and high wholesale prices will increase the price of the first period PSS, which leads to price distortion of the first period PSS under the decentralized scenario. As the proportion of service valuation increases, price distortion will aggravate and the degree of aggravation will gradually decrease. The service provider improves service input-efficiency which will inhibit the promotion effect of the proportion of service valuation to price difference of the first period under the two scenarios, which means that the higher the efficiency of service input, and as the proportion of service valuation increases, the degree of increase in the first period price difference gradually decreases. The higher proportion of service valuation will lead to more consumers buying in the first period, and in order to attract surplus consumers to purchase in the second period, both the manufacturer and the service provider will lower the second period price. However, due to the influence of wholesale price, the service provider' pricing in the second period is higher than that under the centralized scenario, leading to price distortion in the second period, and as the proportion of service valuation increases, the price distortion will aggravate and show a trend of decreasing marginal. (4) The impact of service input-efficiency on the change in the second period price difference with the proportion of service valuation is related to the value of the PSS, the proportion of service valuation, and the efficiency of service input. When the service input-efficiency is high, or the service input-efficiency is low and the PSS value is high, the higher the service input-efficiency, the more it can alleviate the promotion effect of the proportion of service valuation to price difference of the second period. Moreover, when service input-efficiency is low, PSS value is low, and the proportion of service valuation is relatively high (low), the lower the efficiency of service input, the more it can facilitate (alleviate) the promotion effect of the proportion of service valuation to price difference of the second period.

From Propositions 3~5, it can be seen that the optimal service quality and the PSS prices under the decentralized scenario deviate from the optimal scenario of the system. As the proportion of service valuation increases, this degree of deviation will increase. Especially, when the proportion of service valuation is relatively high, the intensity of consumers' strategic delayed purchasing behavior under the decentralized scenario is higher than that under the centralized scenario, which shows that consumers are more inclined to wait for delayed purchase under the decentralized scenario. Therefore, in order to improve the performance of the supply chain system under the decentralized scenario, the two-period prices can be adjusted to ease the consumers' strategic purchasing behavior and encourage more consumers to purchase in the first period. Aiming at the problem of decision bias under the decentralized scenario, we will design the "two-period revenue sharing + service-cost sharing" combined contract mechanism to coordinate the decision behaviors of supply chain members and influence consumers' strategic purchasing behavior, and ultimately realize the optimal performance of the PSSC.

7. "Two-Period Revenue Sharing + Service-Cost Sharing" Combined Dynamic Contract

This section adopts the combined dynamic contract of "two-period revenue sharing + service-cost sharing" $\{w_1, w_2, \varphi_1, \varphi_2, \xi\}$ to coordinate decision behaviors of the manufacturer and the service provider under the decentralized scenario. φ_1 and φ_2, respectively, represent the proportion of the service provider's income from the first period and the second period of the PSSC, where $\varphi_1, \varphi_2 \in (0,1)$. Therefore, $1-\varphi_1$ and $1-\varphi_2$, respectively, represent the proportion of the manufacturer's revenue in the two-period. ξ represents the proportion of the manufacturer sharing service cost, where $\xi \in (0,1)$. Under the "two-period revenue sharing + service-cost sharing" combined contract, the service provider's two-period profit function is

$$\pi_S^{RC} = (\varphi_1 p_{G1} - w_1)Q_1 + (\varphi_2 p_{G2} - w_2)Q_2 - (1-\xi)\frac{k}{2}q^2. \tag{36}$$

The manufacturer's two-period profit function is

$$\begin{aligned}\pi_M^{RC} = &(w_1 - c_m + (1-\varphi_1)p_{G1})Q_1 \\ &+ (w_2 - c_m + (1-\varphi_2)p_{G2})Q_2 - \xi\frac{k}{2}q^2.\end{aligned} \tag{37}$$

Proposition 6. *Under the decentralized scenario, the "two-period revenue sharing + service-cost sharing" combined dynamic contract given by the manufacturer can coordinate the PSSC, and the contract parameters need to meet the following conditions:*

(1) $w_1^{RC} = (kV_1^2\alpha_1 + V_1\alpha_2 - c_m(\varphi_1(3+4\lambda) + 6\varphi_2))/\ (2kV_1(1+4\lambda) - 4\lambda - 5)$;

(2) $w_2^{RC} = \varphi_2 c_m$;

(3) $\xi = (kV_1^2\alpha_3 + kc_mV_1(2\varphi_2 - 1)(1+4\lambda) + 2\alpha_4)/kV_1(V_1(1+8\lambda) - c_m(1+4\lambda))$;

(4) $0 < \varphi_2 < \lambda\varphi_1$;

(5) $\varphi_1^2 < 2kV_1(1-\xi)(\lambda\varphi_1 - \varphi_2) + 4\varphi_1\varphi_2(1-\lambda)$,

where

$$\begin{aligned}\alpha_1 &= \varphi_1 - 2\varphi_2 + 4\lambda(\varphi_1 - \varphi_2),\\ \alpha_2 &= kc_m(1+4\lambda)(\varphi_1 + 2\varphi_2) + 2(1-\lambda)(3\varphi_2 - \varphi_1),\\ \alpha_3 &= 1 - 2\varphi_2 + 4\lambda(2 - \varphi_1 - \varphi_2),\\ \alpha_4 &= (3\varphi_2 - \varphi_1)(V_1(1-\lambda) - c_m).\end{aligned} \tag{38}$$

From the analysis of Proposition 6, it can be found that the design of reasonable revenue sharing ratio and cost sharing ratio can make the decision of supply chain members consistent with the optimal decision of the system. Under the combined dynamic contract designed by the manufacturer, when the two-period revenue sharing ratio and service-cost sharing ratio meet certain conditions, the profit loss of the supply chain system under the decentralized scenario will be eliminated, and the optimal profit of the supply chain system will be achieved. According to the conditions satisfied by the coordination contract parameters, the service provider's supply chain revenue sharing ratio φ_2 in the second period is lower than the first period sharing ratio φ_1. In addition, the first period wholesale price of the manufacturer under contract coordination is related to the first and second period revenue sharing ratios φ_1 and φ_2. The establishment of the second period wholesale price has nothing to do with the first period revenue sharing ratio φ_1 but is related to the second period revenue sharing ratio φ_2. The service-cost sharing ratio ξ is related to the first and second period revenue sharing ratios φ_1 and φ_2 and service input-efficiency k. We can get the following propositions through further analysis.

Proposition 7

(1) $(\partial w_1^{RC}/\partial\varphi_1) > 0$, $(\partial w_1^{RC}/\partial\varphi_2) < 0$, $(\partial w_2^{RC}/\partial\varphi_1) = 0$, $(\partial w_2^{RC}/\partial\varphi_2) > 0$;

(2) $(\partial\xi/\partial\varphi_1) < 0$, $(\partial\xi/\partial\varphi_2) < 0$;

(3) If $\lambda \le (1/3)$, *or* $\lambda > (1/3)$ *and* $\varphi_2 < (1/3)\varphi_1$, $(\partial\xi/\partial\lambda) < 0$; *if* $\lambda > (1/3)$ *and* $\varphi_2 \ge (1/3)\varphi_1$, $(\partial\xi/\partial\lambda) \ge 0$;

(4) If $\lambda \le (1/3)$, *or* $(1/3) < \lambda \le 1 - (c_m/V_1)$ *and* $\varphi_2 \le (1/3)\varphi_1$, *or* $\lambda > 1 - (c_m/V_1)$ *and* $\varphi_2 \ge (1/3)\varphi_1$, $(\partial\xi/\partial k) \ge 0$; *if* $(1/3) < \lambda < 1 - (c_m/V_1)$ *and* $\varphi_2 > (1/3)\varphi_1$, *or* $\lambda > 1 - (c_m/V_1)$ *and* $\varphi_2 < (1/3)\varphi_1$, $(\partial\xi/\partial k) < 0$.

Proposition 7 shows that when the first and second period revenue sharing ratios φ_1 and φ_2 are higher, the manufacturer will increase the first and second period wholesale prices. Because when the service provider accounts for a higher proportion of profits in the first and second periods of the supply chain system, which means that the manufacturer has a lower proportion of profits, the manufacturer will increase its profits by increasing wholesale prices. When the second period revenue sharing ratio φ_2 is high, the manufacturer will lower the first period wholesale price. The establishment of the wholesale price of the service provider in the second period has nothing to do with the revenue sharing ratio φ_1 in the first period. When the first and second period revenue sharing ratios φ_1 and φ_2 are higher, the manufacturer will reduce the service-cost sharing ratio ξ; that is, when the manufacturer has a low proportion of profits in the first and second periods of the supply chain system, the manufacturer will reduce sharing ratio of the service cost. The effect of the service provider's service input-efficiency k on the manufacturer's service-cost ratio ξ is related to the proportion of service valuation λ and the second period revenue sharing ratio φ_2. When the proportion of service valuation is relatively low, the lower the service input-efficiency (that is, the larger the k), the higher the manufacturer's service-cost sharing ratio. When the proportion of service valuation is medium (high), with the increase in the revenue sharing proportion in the second period, the service input-efficiency will first have a negative (positive) influence on the manufacturer's service-cost sharing proportion and then a positive (negative) influence.

In Proposition 6, the service provider can increase service input to improve service quality and reduce the sale prices of the two-period PSS under the implementation of combined dynamic contract, which will achieve the optimal supply chain system under the centralized scenario. However, due to the establishment of higher or lower system revenue sharing ratios φ_1 and φ_2, the manufacturer or service provider may be reluctant to participate in the contract. Therefore, the designed "two-period revenue sharing + service-cost sharing" combined dynamic contract not only needs to be able to coordinate the PSSC but also needs to enable both the manufacturer and the service provider to achieve Pareto improvement. Thus, Proposition 8 gives new conditions for the combined dynamic contract to achieve perfect coordination of the PSSC.

Proposition 8. *Under the "two-period revenue sharing + service-cost sharing" combined dynamic contract, when the revenue sharing ratios φ_1 and φ_2 of the first and second periods need to meet the following conditions:*

$$\begin{cases} 0 < \varphi_2 < \lambda\varphi_1, \\ \varphi_1^2 < 2kV_1(1-\xi)(\lambda\varphi_1 - \varphi_2) + 4\varphi_1\varphi_2(1-\lambda), \\ \dfrac{F^2\Theta}{16K_0^2K_1K_2} - \Psi\varphi_1 \le \varphi_2 \le \dfrac{F\Omega}{4K_0K_1K_2} - \Psi\varphi_1. \end{cases} \tag{39}$$

If and only if $\lambda_r < \lambda < 1$ and revenue sharing ratios φ_1 and φ_2 satisfy formula (39), both the manufacturer and the service provider can achieve Pareto improvement, that is, perfect coordination of the PSSC. When $0 < \lambda \le \lambda_r$, formula (39) has no solution, which indicates that the combined dynamic contract cannot achieve perfect coordination, where

$$\begin{aligned}
\lambda_r &= \left\{0<\lambda<1 \mid F^2\Theta - 16K_0^2K_1K_2(\lambda+\Psi) = 0\right\}, \\
K_0 &= 16k^2V_1^2(5+8\lambda) - kV_1(163+32\lambda) - 2 + 2\lambda, \\
K_1 &= kV_1^2(1+10\lambda) - V_1(kc_m(1+4\lambda)+9\lambda) + 4\lambda c_m, \\
K_2 &= kV_1^2(1+2\lambda) - V_1(kc_m(1+4\lambda) - 3\lambda + 3) + 3c_m, \\
F &= 2kV_1(1+4\lambda) - 4\lambda - 5, \\
\Psi &= \frac{\left(2k\lambda V_1^2 - \lambda V_1 + V_1 - c_m\right)\left(8k\lambda^2V_1^2 - V_1(2\lambda+1)^2 + c_m\right)}{K_1K_2}, \\
\Omega &= 4\lambda^3V_1^2(2kV_1-1)(8kV_1-1)^2 + K_3\lambda^2V_1 + 2K_4\lambda(V_1-c_m) \\
&\quad + (V_1-c_m)^2\left(62k^3V_1^3 - 309k^2V_1^2 + 416kV_1 + 13\right), \\
\Theta &= 4\lambda^3V_1^2(8kV_1-1)^4 + K_5\lambda^2V_1(8kV_1-1)^2 \\
&\quad + 2K_6\lambda(V_1-c_m) + K_7(V_1-c_m)^2.
\end{aligned} \tag{40}$$

ξ is shown in Proposition 6. In addition,

$$K_3 = 128k^3V_1^2\left(5V_1(V_1 - c_m) + 4c_m^2\right) - 24k^2V_1^2(23V_1 + 30c_m) + k\left(578V_1^2 - 40c_mV_1 + 16c_m^2\right) + 21V_1 - 8c_m,$$
$$K_4 = 2(V_1 - c_m)\begin{bmatrix} 4k^3V_1^3(35V_1 - 47c_m) - kV_1(533V_1 - 38c_m) \\ -6k^2V_1^2(20V_1 - 83c_m) - 15V_1 + 2c_m \end{bmatrix},$$
$$K_5 = 16k^2V_1\left(39V_1^2 - 44V_1c_m + 16c_m^2\right) - 2k\left(83V_1^2 + 92V_1c_m + 16c_m^2\right) + 37V_1 + 8c_m, \quad (41)$$
$$K_6 = kV_1(1685V_1 + 92c_m) - 2k^2V_1^2(3380V_1 + 2089c_m) - 2c_m + 128k^4V_1^4(122V_1 - 89c_m) - 32k^3V_1^3(715V_1 - 599c_m) - 43V_1,$$
$$K_7 = 45 + kV_1\left(7984k^3V_1^3 - 24230k^2V_1^2 + 17361kV_1 - 2484\right).$$

Proposition 8 shows that if and only if the service value is relatively high $(\lambda > \lambda_r)$ and the two-period system revenue sharing ratios satisfy the conditions given in formula (39), the "two-period revenue sharing + service-cost sharing" contract can achieve perfect coordination of the PSCC. It can be seen from the certification process that when the proportion of service valuation is relatively high, there will be $\Psi > 0$; from a condition $\varphi_2 \in [(F^2\Theta/16K_0^2K_1K_2) - \Psi\varphi_1, (F\Omega/4K_0K_1K_2) - \Psi\varphi_1]$ given by formula (39), it can be seen that when φ_1 is larger, the upper and lower bounds of possible values of φ_2 become smaller. When the proportion of service valuation is relatively low $(\lambda \le \lambda_r)$, there will be $(F^2\Theta/16K_0^2K_1K_2) - \Psi\varphi_1 \ge \lambda\varphi_1$, which leads to formula (39) without solution; that is, it is impossible to guarantee that the service provider has both the optimal solution and the Pareto improvement under the contract coordination, and the service provider is unwilling to participate in the contract. Therefore, in the case of $\lambda \le \lambda_r$, the contract cannot achieve perfect coordination. In order to enable the service provider to participate in the contract, the manufacturer will provide the service provider with a transfer payment T as a compensation, enabling the service provider to achieve Pareto improvement.

Proposition 9. *When $0 < \lambda \le \lambda_r$, under the "two-period revenue sharing + service-cost sharing + transfer payment" new combined dynamic contract, the first and second period revenue sharing ratios φ_1 and φ_2 and transfer payment T meet the following conditions:*

$$\begin{cases} 0 < \varphi_2 < \lambda\varphi_1, \\ \varphi_1^2 < 2kV_1(1-\xi)(\lambda\varphi_1 - \varphi_2) + 4\varphi_1\varphi_2(1-\lambda), \\ T \in \left[\pi_S^{D*} - \pi_S^{RC}, \pi_M^{RC} - \pi_M^{D*}\right]. \end{cases} \quad (42)$$

This contract can enable the manufacturer and the service provider to achieve Pareto improvement, that is, to achieve perfect coordination of the PSSC, where

$$\pi_S^{RC} = \frac{\begin{pmatrix} \varphi_1\left(2k\lambda V_1^2 - \lambda V_1 + V_1 - c_m\right) \\ \times\left(8k\lambda^2V_1^2 - V_1(1+2\lambda)^2 + c_m\right) + \varphi_2K_1K_2 \end{pmatrix}}{\left(V_1F^2\right)},$$
$$\pi_M^{RC} = \pi^{C*} - \pi_S^{RC}. \quad (43)$$

In addition, F, K_1, andK_2 are shown in Proposition 8, and π^{C*} is shown in Corollary 1.

Proposition 9 indicates that when the proportion of service valuation is relatively small, the "two-period revenue sharing + service-cost sharing + transfer payment" contract can encourage the service provider to participate in the contract and realize the Pareto improvement. In addition to meeting the requirements of formula (42), the value of revenue sharing ratios φ_1 and φ_2 and transfer payment T in the two-period system is also related to the bargaining power between the manufacturer and the service provider.

8. Numerical Simulation

Based on the propositions derived from the above theoretical analysis, this section provides intuitive results and verifications through numerical simulation to get more management enlightenment. Let $c_m = 150$, $V_1 = 600$, $\lambda = 1/10$, and $k = 1$. First, analyze the impact of service input-efficiency k and the proportion of service valuation λ on the intensity of consumers' strategic delayed purchasing behavior $\Upsilon^{C"*}$ and $\Upsilon^{D"*}$ under the two scenarios, as shown in Figure 1.

From Figure 1(a), it can be seen that the lower the service input-efficiency (that is, the larger k), the higher the intensity of consumers' strategic delayed purchasing behavior in both decentralized and centralized scenarios, and the relatively higher decentralized scenario. This indicates that if the service provider improves the service input-efficiency, which will reduce the intensity of consumers' strategic delayed purchasing behavior and promote more consumers to

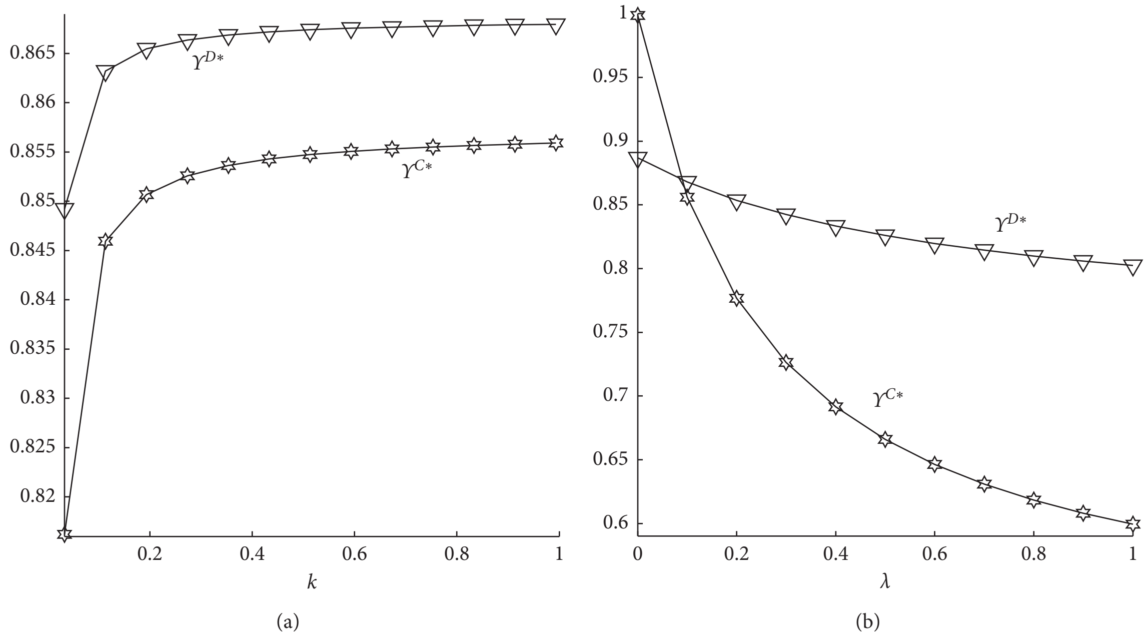

Figure 1: The impact of k and λ on Υ^{C*} and Υ^{D*}.

choose to purchase in the first period. In addition, compared with decentralized scenario, under the centralized scenario, k has a more obvious impact on the intensity of consumers' strategic delayed purchasing behavior. From Figure 1(b), we can know that the larger the proportion of service valuation, the lower the intensity of consumers' strategic delayed purchasing behavior under the two scenarios, which means that higher proportion of service valuation can promote more consumers to choose early purchase. In particular, when the proportion of service valuation is relatively low, consumers are more inclined to delay purchase under the centralized scenario; when the proportion of service valuation is relatively high, consumers are more inclined to delay purchase under the decentralized scenario. Next, we analyze the impact of k and λ on the corresponding two-period price differences under the two scenarios. Among them, the first period price difference is $p_{G1}^{D*} - p_{G1}^{C*}$, and the second period price difference is $p_{G2}^{D*} - p_{G2}^{C*}$, as shown in Figure 2.

It can be seen from Figure 2(a) that when the service input-efficiency is low (that is, k is larger), the first period price difference is higher under the two scenarios, while the second period price difference is lower. This means that as k increases, the first period PSS price under the decentralized scenario deviates from the optimal price of system, but the second period PSS price under the decentralized scenario gradually approaches the optimal price of system. This shows that k will increase the degree of price distortion in the first period and reduce the degree of price distortion in the second period. From Figure 2(b), we can know that the price differences between the first and second periods of the two scenarios are increasing as the proportion of service valuation λ increases, and the price difference in the first period increases faster than the price difference in the second period. This shows that higher proportion of service valuation can increase the degree of price distortion in the first and second periods under the decentralized scenario, and the degree of price distortion in the first period is more obvious. The following analyzes the influence of k and λ on the difference of service quality ($q^{C*} - q^{D*}$) under the two scenarios, as shown in Figure 3.

From Figure 3(a), it can be seen that the difference between the two service qualities under the two scenarios will show a decreasing trend as k increases, and when the proportion of service valuation λ is larger, the difference in service qualities decreases more obviously. This indicates that the improvement of service input-efficiency will lead to a bigger gap between the optimal service quality under the decentralized scenario and centralized scenario. In addition, the proportion of service valuation can increase the impact of k on the difference in service quality. It can be seen from Figure 3(b) that the higher the proportion of service valuation, the bigger the difference in service quality, which means that the proportion of service valuation can widen the gap between optimal service quality under the decentralized scenario and centralized scenario. When the service input-efficiency is higher (that is, k is smaller), the impact of the proportion of service valuation on the difference in service quality is more obvious. The following analyzes the impact of k and λ on the loss rate of the system profit η, as shown in Figure 4.

From Figure 4(a), it can be seen that the loss rate of system profit η under the decentralized scenario will increase with the increase of k, and in particular, when the proportion of service valuation is relatively high, the loss rate of the system profit is relatively high. This means that if the service provider improves service input-efficiency will reduce the loss rate of the system profit. From Figure 4(b), it can be seen that when the proportion of service valuation is relatively low (high), the loss rate of the system profit is relatively low

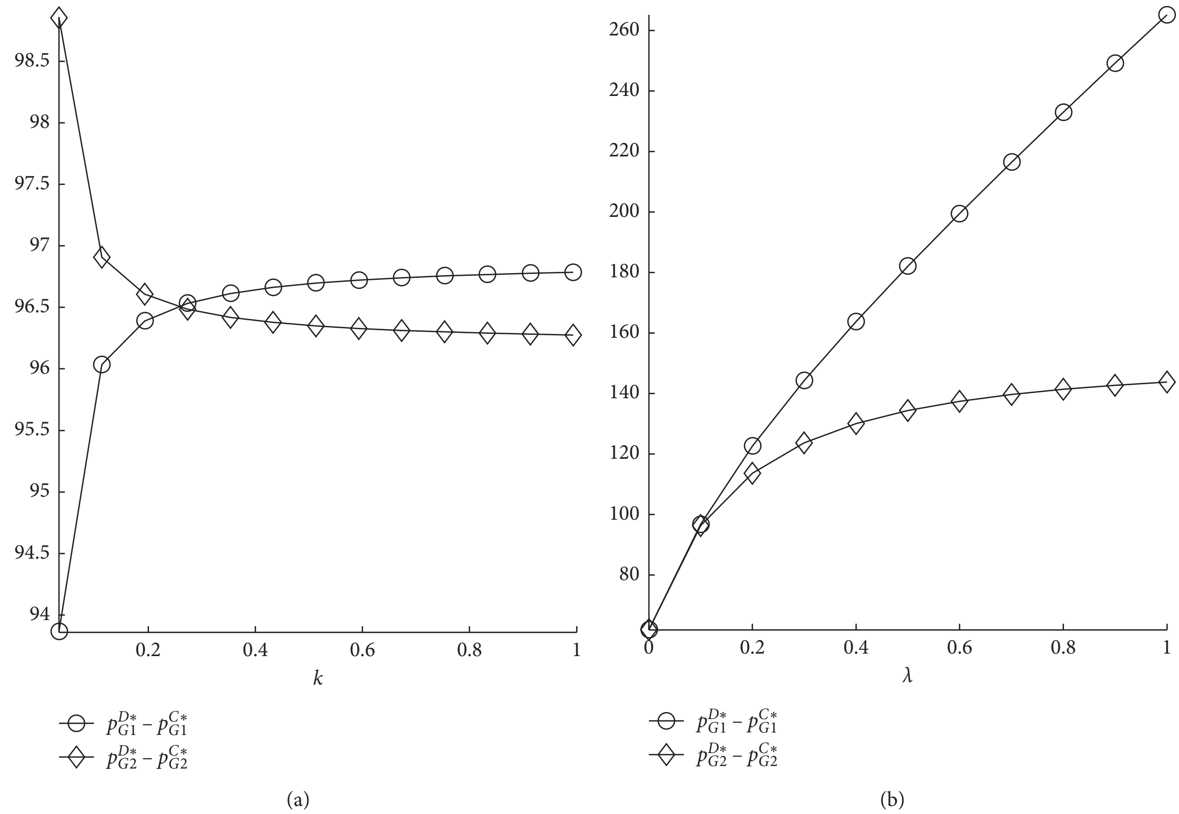

Figure 2: The impact of k and λ on $p_{Gi}^{D*} - p_{Gi}^{C*}$ $(i = 1, 2)$.

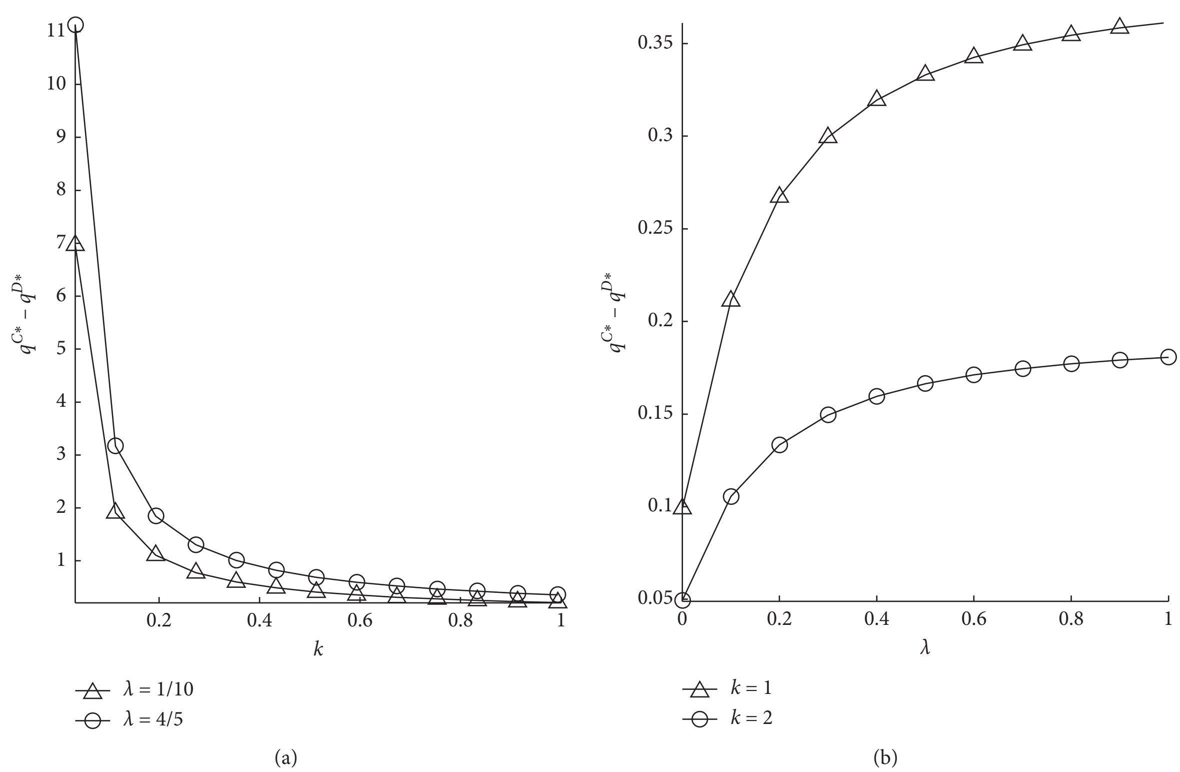

Figure 3: The impact of k and λ on $q^{C*} - q^{D*}$.

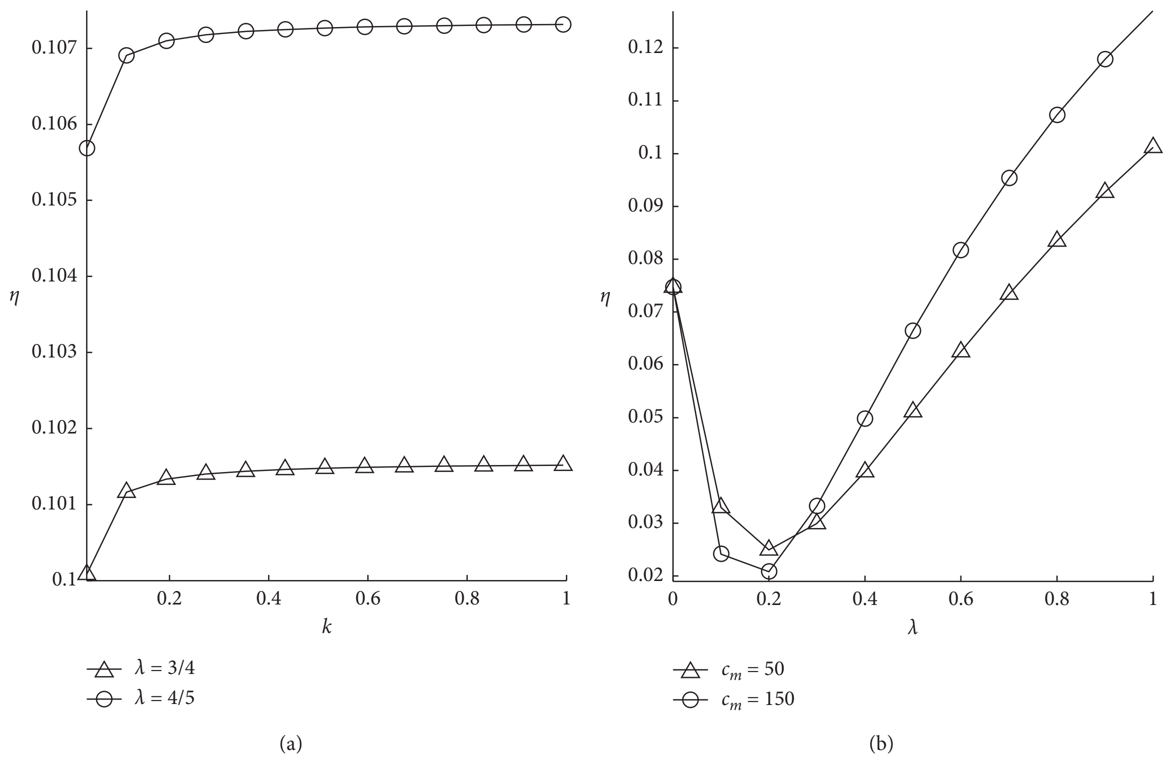

FIGURE 4: The impact of k and λ on η.

(high), and in particular, if the manufacturer reduces the unit product cost, the loss rate of system profit will increase (decrease). The following analyzes the impact of the two-period revenue sharing ratios φ_1 and φ_2 on the profit difference of the manufacturer and the service provider ($\Delta\pi_M = \pi_M^{RC} - \pi_M^{D*}, \Delta\pi_S = \pi_S^{RC} - \pi_S^{D*}$) before and after coordination. Let $\lambda = 3/5$, as shown in Figure 5.

It can be seen from Figure 5(a) that when the second period revenue sharing ratio φ_2 is given, the manufacturer's profit difference and the service provider's profit difference before and after coordination are both linear functions of the first period revenue sharing ratio φ_1. The manufacturer's profit difference before and after coordination decreases monotonically with the increase of φ_1, while the service provider's profit difference before and after coordination increases monotonically with the increase of φ_1. When $\varphi_1 \geq \varphi_1^a$, the profit obtained by the manufacturer after coordination is not less than that before coordination, which shows that the manufacturer can achieve Pareto improvement. When $\varphi_1 \leq \varphi_1^b$, the profit obtained by the service provider after coordination is not less than that before coordination; that is, the service provider can realize Pareto improvement. In addition, formula (39) given by Proposition 8 can be substituted into the verification; when $\varphi_1 \in [\varphi_1^a, \varphi_1^b]$, the PSSC can achieve perfect coordination. By calculation, $\varphi_1^a = 0.547$ and $\varphi_1^b = 0.817$. From Figure 5(a), we can see that the revenue sharing ratio φ_1 in the first period has a certain degree of flexibility. Therefore, the distribution of system revenue between the manufacturer and the service provider in the first period will change with the bargaining power of both parties. Similarly, from Figure 5(b), when the first period revenue sharing ratio φ_1 is given and and the second period revenue sharing ratio $\varphi_2 \in [\varphi_2^a, \varphi_2^b]$, the PSSC can also achieve perfect coordination. By calculation, $\varphi_2^a = 0.178$ and $\varphi_2^b = 0.290$. It can also be seen that the second period revenue sharing ratio φ_2 has a certain degree of flexibility, so the distribution of the second period system revenue between the manufacturer and the service provider will change accordingly with the changes in the bargaining power of both parties. The following analyzes the influence of the proportion of service valuation and service input-efficiency on the transfer payment in the new combined dynamic contract. Let $T_{\min} = \pi_S^{D*} - \pi_S^{RC}$, $T_{\max} = \pi_M^{RC} - \pi_M^{D*}$, $\varphi_1 = 9/10$, and $\varphi_2 = 1/1000$, as shown in Figure 6.

It can be seen from Figure 6(a) that when the two-period revenue sharing ratios φ_1 and φ_2 are given, the transfer payment $T \in [T_{\min}, T_{\max}]$. As the proportion of service valuation λ increases, $T_{\min}$ increases first and then decreases, while $T_{\max}$ gradually decreases, which shows that when λ gradually increases, the service provider's two-period profit loss gradually increases and then gradually decreases, while the manufacturer's increased profit gradually decreases after coordination. It can also be found from Figure 6(a) that as λ increases, the value range of transfer payment T provided to the service provider gradually decreases, which means that the flexibility of the transfer payment contract gradually decreases. From Figure 6(b), we can see that with the decrease of service input-efficiency (that is, k is large), both $T_{\min}$ and $T_{\max}$ gradually decrease, which shows that when k is large, the two-period profit loss of the service provider gradually decreases, and the manufacturer's increased profit also gradually decreases after coordination. It can also be found from Figure 6(b) that as k increases, the value range of

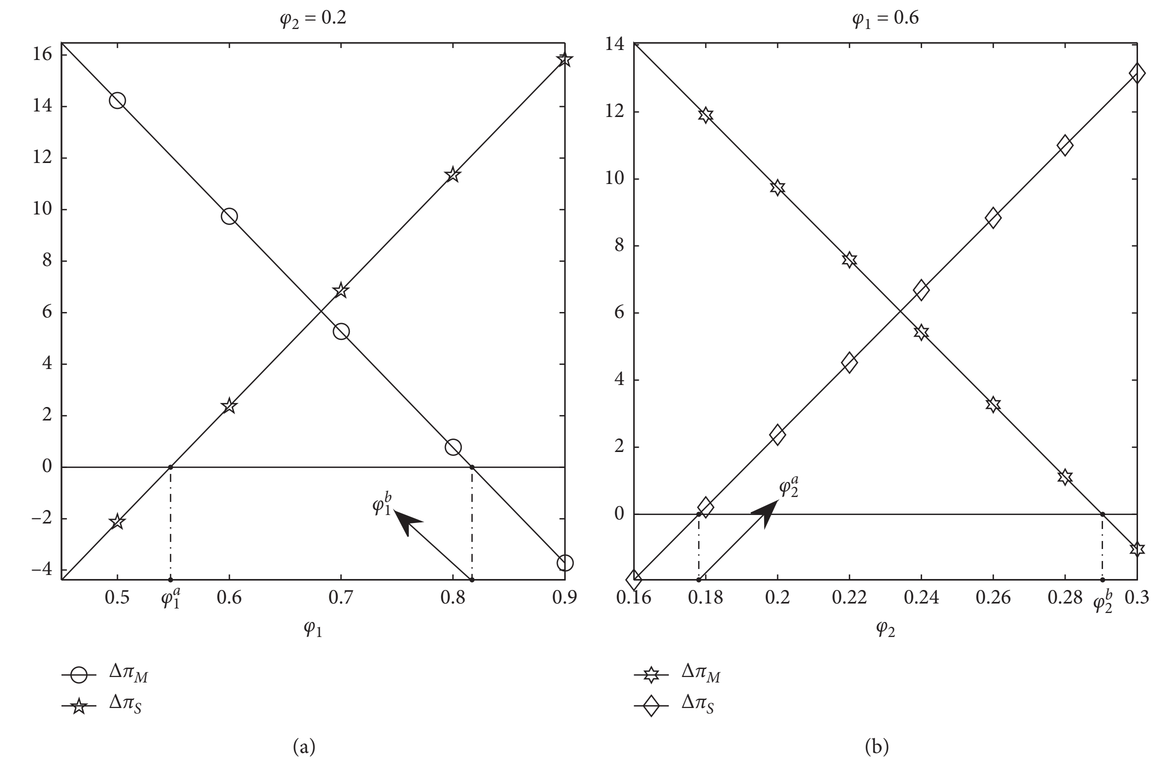

FIGURE 5: The impact of φ_1 and φ_2 on the profit difference $\Delta\pi_M$ and $\Delta\pi_S$.

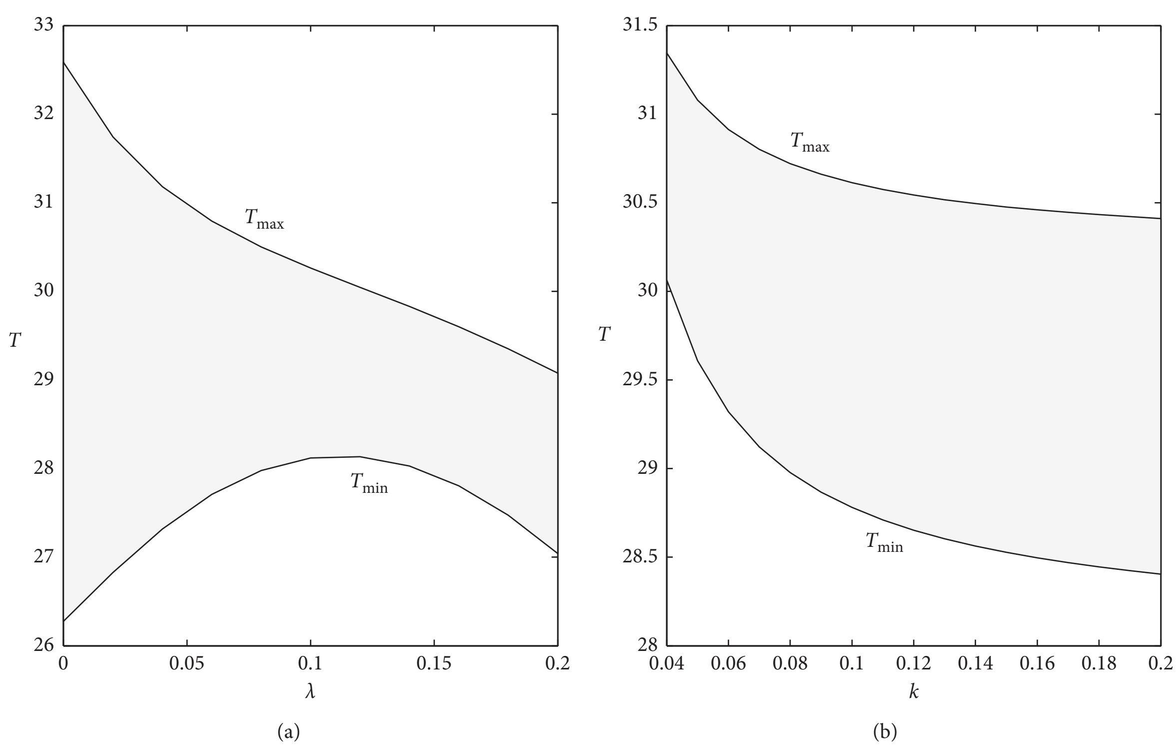

FIGURE 6: The impact of λ and k on transfer payment.

the transfer payment T provided to the service provider gradually expands, which means that the flexibility of the transfer payment contract gradually increases.

9. Conclusion

As the level of product homogenization is getting more serious and consumers' service requirements are getting higher and higher, firms will increase service investment to improve service quality to obtain market competitive advantage. Meanwhile, firms will bear higher service costs. On the other hand, with the rapid development of the Internet and information technology, consumers get product information or service information is becoming more convenient, which makes consumers getting more and more rational in the purchase process. In the face of consumers' strategic purchasing behavior, how do firms determine service quality and multiperiod sales prices is a problem worth studying. In response to this problem, we build multiperiod dynamic pricing models, which consider consumers' strategic purchasing behavior and service quality. This paper investigates the dynamic decisions of the PSSC in the centralized and decentralized scenarios, compares equilibrium results and supply chain profits under two scenarios, and finds that there are supply chain performance loss and decision bias in the decentralized situation. In order to eliminate the performance loss and decision bias, this paper designs multiperiod combined dynamic contracts that can adjust the decision behavior of supply chain members and ultimately achieves the optimal performance of the PSSC. The main conclusions of this paper are as follows:

(1) The service provider provides the PSS with a higher proportion of service valuation, which will effectively inhibit consumers' strategic purchasing behavior in two scenarios, and this inhibitory effect will be more obvious under the centralized scenario. This means that as the proportion of service valuation increases, the intensity of consumers' strategic delayed purchasing behavior will decrease in two scenarios, and the degree of decline in the centralized scenario is larger. Similarly, the service provider increases service input-efficiency which will inhibit consumers' strategic purchasing behavior, which means that the higher the service input-efficiency, the weaker the intensity of consumers' strategic delayed purchasing behavior. Furthermore, the service provider provides high-value PSS, which will reduce (enhance) the intensity of consumers' strategic delayed purchasing behavior in the decentralized (centralized) scenario.

(2) By comparing equilibrium results of two scenarios, it is found that there are decision bias and performance loss of the PSSC in the decentralized scenario. For example, the service quality is low, the sales prices of two-period PSS are high, and the total profit of PSSC is low. In addition, the increase in the proportion of service valuation will aggravate decision bias in the decentralized scenario. This means that the proportion of service valuation will promote the widening of the service quality gap and increase the price distortion. However, the service provider improves the service input-efficiency which will enhance the promotion effect of the proportion of service valuation to service quality gap in two scenarios and reduce the price distortion of the first period. Nevertheless, in some cases, the improvement of service input-efficiency will enhance the promotion effect of the proportion of service valuation to price distortion in the second period.

(3) In order to eliminate supply chain performance loss, the two-period dynamic contracts are designed to coordinate the decision behavior of the supply chain members. The design of the contracts is closely related to the proportion of service valuation. When the proportion of service valuation is relatively high, the "two-period revenue sharing + service-cost sharing" combined dynamic contract can make the PSSC achieve perfect coordination. However, when the proportion of service valuation is relatively low, the above contract cannot achieve perfect coordination. It is necessary to adopt a "two-period revenue sharing + service-cost sharing + transfer payment" new combined dynamic contract to achieve perfect coordination. Moreover, in the case of supply chain coordination, with the increase of the revenue sharing ratio of the second period, the manufacturer will reduce the wholesale price of the first period and increase the wholesale price of the second period. In addition, the impact of the service input-efficiency (the proportion of service valuation) on service-cost sharing ratio is not monotonous and relates to the revenue sharing ratios of two-period.

The limitation of this paper is that we assume that all consumers are strategic consumers. However, there may be different types of consumers in the market. On the other hand, we assume that both the manufacturer and the service provider know all the information, but the information of both parties may be asymmetric. Therefore, we need to explore the optimal equilibrium results in the case of asymmetric information or multiple types of consumers. Furthermore, we can expand to the situation where firms sell green products to strategic consumers, which will be an interesting study.

Appendix

Proof. of Proposition 1. First, we solve the price for the second period PSS p_{G2}^C. From formula (11), the optimal solution $p_{G2}^C = (V_0^C + q^C + c_m)/2$ can be solved; combining formula (9), $V_0^C = (2p_{G1}^C - 3q^C - c_m)/(1 + 2\lambda)$ can be solved. Substituting the above results into formula (9), we can sort out as follows:

$$\pi^C = \left(p_{G1}^C - c_m\right)\left(1 - \frac{2p_{G1}^C - 3q^C - c_m}{V_1(1+2\lambda)}\right) + \frac{\left(p_{G1}^C - q^C(1-\lambda) - c_m(1+\lambda)\right)^2}{V_1(1+2\lambda)^2} - \frac{k}{2}\left(q^C\right)^2. \quad (A.1)$$

Next, solving the Hessian matrix of π^C with respect to (p_{G1}^C, q^C) below, we can get $H(p_{G1}^C, q^C)$:

$$H\left(p_{G1}^C, q^C\right) = \begin{bmatrix} -\frac{2(1+4\lambda)}{V_1(1+2\lambda)^2} & \frac{1+8\lambda}{V_1(1+2\lambda)^2} \\ \frac{1+8\lambda}{V_1(1+2\lambda)^2} & -\frac{kV_1(1+2\lambda)^2 - 2(1-\lambda)^2}{V_1(1+2\lambda)^2} \end{bmatrix}. \quad (A.2)$$

Owing to

$$\frac{\partial^2 \pi^C}{\partial p_{G1}^2} = -\frac{2(1+4\lambda)}{(1+2\lambda)^2 V_1} < 0, \quad (A.3)$$

$|H(p_{G1}^C, q^C)| = ((2kV_1(1+4\lambda) - 4\lambda - 5)/V_1^2(1+2\lambda)^2) > 0$, which can be seen that $H(p_{G1}^C, q^C)$ is a negative definite matrix; that is, π^C is the joint concave function of p_{G1}^C and q^C, solving $(\partial\pi^C/\partial p_{G1}^C) = 0$ and $(\partial\pi^C/\partial q^C) = 0$ simultaneously; then, p_{G1}^{C*} and q^{C*} can be obtained. Finally, p_{G2}^{C*} and V_0^{C*} are obtained. □

Proof of Corollary 1. Easy to get from Proposition 1, omitted. □

Proof of Proposition 2. Similar to the proof process of Proposition 1, omitted. □

Proof of Corollary 1. Easy to get from Proposition 2, omitted. □

Proof of Proposition 3. According to the equilibrium solutions given by Propositions 1 and 2 under the two scenarios, we can get: (1)

$$\Upsilon^{D*} - \Upsilon^{C*} = \frac{4\lambda^2 V_1(2kV_1 - 1)(8kV_1 - 1)^2 + E_4\lambda - E_5(V_1 - c_m)}{2V_1 E_0(2kV_1(1+4\lambda) - 4\lambda - 5)}, \quad (A.4)$$

where $E_0 = 16k^2V_1^2(8\lambda + 5) - kV_1(163 + 32\lambda) - 2 + 2\lambda$,

$$E_4 = 320k^3V_1^4 + 48k^2V_1^3(4kc_m - 19) - 18kV_1^2(20kc_m - 31) - V_1(4kc_m - 17) - 4c_m,$$
$$E_5 = 48k^3V_1^3 - 378k^2V_1^2 + 495kV_1 + 13. \quad (A.5)$$

Let $E(\lambda) = 4\lambda^2V_1(2kV_1 - 1)(8kV_1 - 1)^2 + E_4\lambda - E_5(V_1 - c_m)$.

Next, we need to determine the positive and negative of function $E(\lambda)$. It is easy to know $E_5 > 0$, so we can get $E(\lambda = 0) < 0$. In addition, because

$$E(\lambda = 1) = 784k^3V_1^4 + 6k^2V_1^3(40kc_m - 153) - 9kV_1^2(82kc_m - 15) + c_m(491kV_1 + 9) > 0, \quad (A.6)$$

so there is a unique λ_a (as shown in Proposition 3), when $0 < \lambda < \lambda_a$, $E(\lambda) < 0$; when $\lambda_a \le \lambda < 1$, $E(\lambda) \ge 0$. Because $\mathrm{sgn}(V_0^{D*} - V_0^{C*}) = \mathrm{sgn}(E(\lambda))$, so when $0 < \lambda < \lambda_a$, $V_0^{D*} < V_0^{C*}$; when $\lambda_a \le \lambda < 1$, $V_0^{D*} \ge V_0^{C*}$.

(2) This part conclusion is easy to get, so it is omitted. □

Proof of Proposition 4. Since Proposition 4 (1) is easily obtained, it is omitted. The equilibrium solutions under the two scenarios are given by Propositions 1 and 2 and Corollaries 1 and 2, and we can get the following conclusions:

(2) $Q_1^{C*} - Q_1^{D*} = (V_0^{D*} - V_0^{C*})/V_1$, according to Proposition 3 (1), when $0 < \lambda < \lambda_a$, $Q_1^{D*} > Q_1^{C*}$; when $\lambda_a \le \lambda < 1$, $Q_1^{D*} \le Q_1^{C*}$.

$$Q_2^{C*} - Q_2^{D*} = \frac{4F_1\lambda^2V_1(8kV_1 - 1) + F_2\lambda + F_3(V_1 - c_m)}{4V_1E_0(2kV_1(1+4\lambda) - 4\lambda - 5)}, \quad (A.7)$$

where

$$F_1 = 8k^2V_1^2 - 32k^2c_mV_1 + 42kV_1 - 8kc_m + 1,$$
$$F_2 = 416k^3V_1^4 - 8k^2V_1^3(124kc_m + 19) + 6kV_1^2(356kc_m - 333) + V_1(372kc_m - 55) - 4c_m,$$
$$F_3 = 184k^3V_1^3 - 974k^2V_1^2 + 1189kV_1 + 59. \tag{A.8}$$

Let $A(\lambda) = 4F_1\lambda^2V_1(8kV_1 - 1) + F_2\lambda + F_3(V_1 - c_m)$, and $\operatorname{sgn}(Q_2^{C*} - Q_2^{D*}) = \operatorname{sgn}(A(\lambda))$. We can know that the positive and negative of F_1 are uncertain. When $k \geq (33 + \sqrt{2185})/(8c_m)$, $F_1 \geq 0$, and get $A(\lambda) > 0$; when $k < (33 + \sqrt{2185})/(8c_m)$, $F_1 < 0$, and get $A(\lambda) = 0$ has a positive root and a negative root, since

$$A(\lambda = 1) = 856k^3V_1^4 - 2k^2V_1^3(1100kc_m - 93) + 21kV_1^2(142kc_m - 45) - c_m(785kV_1 + 63) > 0, \tag{A.9}$$

so get $A(\lambda) > 0$. Therefore, we can get $Q_2^{C*} > Q_2^{D*}$. $Q_1^{C*} + Q_2^{C*} - (Q_1^{D*} + Q_2^{D*}) = (p_{G2}^{D*} - q^{D*} - (p_{G2}^{C*} - q^{C*}))/V_1$, according to Proposition 3 (2), we can get

$$Q_1^{C*} + Q_2^{C*} > Q_1^{D*} + Q_2^{D*}. \tag{A.10}$$

(3) The profit of the manufacturer and the service provider under the decentralized scenario are added to obtain the profit of the supply chain system. That is, the expressions of total profit in two periods of $\pi_M^D + \pi_S^D$ and π^C are the same, and the optimal profit of the system under the centralized scenario is $\pi^{C*}(q^{C*}, p_{G1}^{C*}, p_{G2}^{C*})$, because $q^{D*} \neq q^{C*}$, $p_{G1}^{D*} \neq p_{G1}^{C*}$, and $p_{G2}^{D*} \neq p_{G2}^{C*}$, so we can get $\pi_M^{D*}(w_1^{D*}, w_2^{D*}) + \pi_S^{D*}(q^{D*}, p_{G1}^{D*}, p_{G2}^{D*}) = \pi^{C*}(q^{D*}, p_{G1}^{D*}, p_{G2}^{D*}) < \pi^{C*}(q^{C*}, p_{G1}^{C*}, p_{G2}^{C*})$. □

Proof of Proposition 5. In this section, we only give the proof of Proposition 5 (4). According to the equilibrium solutions given by Propositions 1 and 2, we can get (4)

$$\frac{\partial^2(p_{G2}^{D*} - p_{G2}^{C*})}{\partial\lambda\,\partial k} = \frac{V_1\begin{bmatrix} H_1 - 128H_2\lambda^4(8kV_1 - 1)^2 \\ +H_3\lambda^3 + H_4\lambda^2 + H_5\lambda \end{bmatrix}}{4E_0^3(2kV_1(1 + 4\lambda) - 4\lambda - 5)^3}, \tag{A.11}$$

where

$$H_1 = 6885376k^7V_1^8 - 256k^6V_1^7(87776kc_m - 50343) + 2560k^5V_1^6(48046kc_m - 103527) - 8k^4V_1^5(23284128kc_m - 90912755) - 4k^3V_1^4(6235172kc_m + 181344681) + 2k^2V_1^3(105348380kc_m + 147699033) - kV_1^2(102668604kc_m + 118369519) + V_1(43205570kc_m + 1180866) - 2127256c_m,$$
$$H_2 = 42752k^5V_1^6 - 4k^2V_1^3(42004kc_m + 87181) - 358c_m + 64k^4V_1^5(1072kc_m - 6793) + 2kV_1^2(55196kc_m + 18889) - V_1(18540kc_m - 4809) - 24k^3V_1^4(1136kc_m - 31501),$$
$$H_3 = 706478080k^7V_1^8 - 16384k^6V_1^7(30560kc_m + 89241) + 8192k^5V_1^6(268472kc_m - 459807) - 512k^4V_1^5(2674464kc_m - 18298435) - 512k^3V_1^4(4285058kc_m + 8550279) + 1024k^2V_1^3(1418015kc_m + 727548) - 128kV_1^2(2489496kc_m + 380317) + V_1(33936640kc_m - 1630560) - 951488c_m,$$
$$H_4 = 925433856k^7V_1^8 - 12288k^6V_1^7(31840kc_m + 418553) + 6144k^5V_1^6(374136kc_m + 1522015) - 384k^4V_1^5(12688160kc_m + 9670709) + 52992k^3V_1^4(58523kc_m - 77914) + 576k^2V_1^3(1972568kc_m + 2891393) - 384kV_1^2(1614603kc_m + 591526) + V_1(107816832kc_m - 600408) - 3878448c_m,$$
$$H_5 = 265895936k^7V_1^8 + V_1(114940208kc_m + 1665654) + 512k^5V_1^6(1936552kc_m + 9395367) - 32k^4V_1^5(75175392kc_m + 180135155) + 32k^3V_1^4(90260882kc_m + 53534511) - 64k^2V_1^3(18066199kc_m - 24997884) - 8kV_1^2(72777096kc_m + 35312443) - 1024k^6V_1^7(161312kc_m + 1761963) - 5029652c_m. \tag{A.12}$$

We can judge $H_2>0$, $H_3>0$, $H_4>0$, $H_5>0$, and $-128H_2\lambda^4(8kV_1-1)^2+H_3\lambda^3>0$, but we cannot determine the positive and negative of H_1, and we know H_1 is a function of increasing V_1. So, when$k\le\Delta_g/c_m$, or $k>\Delta_g/c_m$ and $V_1\ge V_g$, $H_1\ge 0$, so$\partial^2(p_{G2}^{D*}-p_{G2}^{C*})/\partial\lambda\,\partial k>0$; when $k>\Delta_g/c_m$ and $V_1<V_g$, $H_1<0$, where Δ_g and V_g are shown in Proposition 5.

Let $H_\lambda=H_1-128H_2\lambda^4(8kV_1-1)^2+H_3\lambda^3+H_4\lambda^2+H_5\lambda$. Consider below when $H_1<0$, the positive and negative of the expression H_λ, which can be judged that the expression increases with λ, and $H_\lambda|_{\lambda=1}>0$, so there is only one λ_g, when $0<\lambda<\lambda_g$, $H_\lambda<0$; when $\lambda_g\le\lambda<1$, $H_\lambda\ge 0$. So, when$k>\Delta_g/c_m$, $V_1<V_g$ and $0<\lambda<\lambda_g$, $\partial^2(p_{G2}^{D*}-p_{G2}^{C*})/\partial\lambda\,\partial k<0$; when $k>\Delta_g/c_m$, $V_1<V_g$ and $\lambda_g\le\lambda<1$, $\partial^2(p_{G2}^{D*}-p_{G2}^{C*})/\partial\lambda\,\partial k\ge 0$. □

Proof of Proposition 6. First, we solve the second period PSS price p_{G2} under contract coordination, and the second period profit function of the service provider is $\pi_{S2}^{RC}(p_{G2})=(\varphi_2p_{G2}-w_2)(V_0/V_1-(p_{G2}-q)/V_1)$, so we can get $p_{G2}^{RC*}=(w_2+\varphi_2(q+V_0))/2\varphi_2$. In order to achieve supply chain coordination, the price of the second period PSS under contract coordination should be equal to that under the centralized scenario, that is $p_{G2}^{RC*}=p_{G2}^{C*}$, and we can solve $w_2=\left(\varphi_2\begin{bmatrix}2kV_1^2(1+2\lambda)-6V_1(1-\lambda)\\+c_m(1-4\lambda)\end{bmatrix}/(2kV_1(1+4\lambda)-4\lambda-5)\right)-\varphi_2(q+V_0-c_m)$.

Replace p_{G2}^{D*} in formula (22) with p_{G2}^{C*}, and then get

$$V_0=\frac{\left(2c_m(1+2\lambda)-kV_1^2(1+2\lambda)+V_1\beta_1\right)}{\lambda(2kV_1(1+4\lambda)-4\lambda-5)}+\frac{p_{G1}-q}{\lambda}. \tag{A.13}$$

Substitute p_{G2}^{C*}, w_2, and V_0into formula (36), and we can get

$$\begin{aligned}\pi_S^{RC}&(p_{G1},q)\\&=(\varphi_1p_{G1}-w_1)\left[\frac{kV_1^2\beta_2+V_1\beta_3-2c_m(1+2\lambda)}{\lambda V_1(2kV_1(1+4\lambda)-4\lambda-5)}-\beta_4\right]\\&\quad+\frac{\varphi_2\begin{bmatrix}(p_{G1}-(1-\lambda)q)(2kV_1(1+4\lambda)-4\lambda-5)\\-(1+\lambda)((1+2\lambda)(kV_1^2-2c_m)-\beta_1V_1)\end{bmatrix}^2}{V_1\lambda^2(2kV_1(1+4\lambda)-4\lambda-5)^2}-\beta_5,\end{aligned} \tag{A.14}$$

where $\beta_1=3-3\lambda-kc_m(1+4\lambda)$, $\beta_2=1+4\lambda+8\lambda^2$, $\beta_3=kc_m(1+4\lambda)-4\lambda^2-2\lambda-3$, and $\beta_4=((p_{G1}-q)/\lambda V_1)$, $\beta_5=kq^2(1-\xi)/2$.

In order to ensure that the profit function of the service provider has an optimal solution, that is, to ensure that the above formula is a concave function, it is necessary to satisfy $\varphi_1^2<2kV_1(1-\xi)(\lambda\varphi_1-\varphi_2)+4\varphi_1\varphi_2(1-\lambda)$ and $\varphi_2<\lambda\varphi_1$, and then solve

$$\begin{aligned}p_{G1}^{RC*}&=\frac{2L_1\varphi_2kV_1(1+\lambda)(1-\xi)-\varphi_1(L_2+k\lambda V_1L_3(1-\xi))}{(2kV_1(1+4\lambda)-4\lambda-5)(\varphi_1(\varphi_1-4\varphi_2(1-\lambda))-L_4)}\\&\quad+\frac{w_1(\varphi_1-2\varphi_2(1-\lambda)-k\lambda V_1(1-\xi))}{\varphi_1(\varphi_1-4\varphi_2(1-\lambda))-L_4},\\q^{RC*}&=\frac{\varphi_1\varphi_2\left(4kV_1^2(1+4\lambda-2\lambda^2)-L_5+V_1L_6\right)-L_3\varphi_1^2}{(2kV_1(1+4\lambda)-4\lambda-5)(\varphi_1(\varphi_1-4\varphi_2(1-\lambda))-L_4)},\end{aligned} \tag{A.15}$$

where

$$\begin{aligned}L_1&=kV_1^2(1+2\lambda)+V_1(kc_m(1+4\lambda)+3\lambda-3)-2c_m(1+2\lambda),\\L_2&=2\varphi_2(1-\lambda)\begin{bmatrix}2k\lambda V_1^2(4\lambda-1)-4c_m(1+2\lambda)\\+V_1\left(2kc_m(1+4\lambda)-4\lambda^2+5\lambda-1\right)\end{bmatrix},\\L_3&=kV_1^2\left(1+4\lambda+8\lambda^2\right)-2c_m(1+2\lambda)\\&\quad+V_1\left(kc_m(1+4\lambda)-4\lambda^2-2\lambda-3\right),\\L_4&=2kV_1(1-\xi)(\lambda\varphi_1-\varphi_2),\\L_5&=8c_m\lambda(1+2\lambda),\\L_6&=4kc_m\lambda(1+4\lambda)+10\left(2\lambda^2-\lambda-1\right).\end{aligned} \tag{A.16}$$

In order to achieve supply chain coordination, the first period PSS price and service quality under contract coordination scenario should be equal to those under the centralized scenario, namely, $p_{G1}^{RC*}=p_{G1}^{C*}$ and $q^{RC*}=q^{C*}$. Furthermore, we can solve the first period product wholesale price w_1^{RC} and service-cost sharing ratio ξ under contract coordination scenario and then solve the second period product wholesale price w_2^{RC} under contract coordination scenario. □

Proof of Proposition 7. Since (1) and (2) in Proposition 7 are easily obtained, it is omitted. According to Proposition 6, we can get

(3) $(\partial\xi/\partial\lambda)=-((2(\varphi_1-3\varphi_2)(V_1-c_m)(2kV_1^2-9V_1+4c_m))/kV_1(8V_1\lambda-4\lambda c_m+V_1-c_m)^2)$, and we can know $\text{sgn}(\partial\xi/\partial\lambda)=\text{sgn}(\varphi_1-3\varphi_2)$, since $\varphi_2<\lambda\varphi_1$, so when$\lambda\le(1/3)$, $\varphi_1-3\varphi_2>0$ and $(\partial\xi/\partial\lambda)<0$; when $\lambda>(1/3)$ and $\varphi_2<(1/3)\varphi_1$, $\varphi_1-3\varphi_2>0$ and $(\partial\xi/\partial\lambda)<0$; when $\lambda>(1/3)$ and $(1/3)\varphi_1\le\varphi_2<\lambda\varphi_1$, $\varphi_1-3\varphi_2\le 0$ and $(\partial\xi/\partial\lambda)\ge 0$. In

summary, we can get the conclusion given by Proposition 7 (3).

(4) $(\partial\xi/\partial k) = -((2(\varphi_1 - 3\varphi_2)(\lambda V_1 - V_1 + c_m))/k^2 V_1 (8\lambda V_1 - 4\lambda c_m + V_1 - c_m))$, since $\operatorname{sgn}(\partial\xi/\partial k) = \operatorname{sgn}((\varphi_1 - 3\varphi_2)(\lambda V_1 - V_1 + c_m))$, when $\lambda > 1 - (c_m/V_1)$, $\lambda V_1 - V_1 + c_m > 0$; when $\lambda \leq 1 - (c_m/V_1)$, $\lambda V_1 - V_1 + c_m \leq 0$. Because $V_1 > 3c_m + (5/k)$, we can get $1 - (c_m/V_1) > (2/3)$. Combined with the conclusion of Proposition 7 (3), we can obtain the conclusion of Proposition 7 (4). □

Proof. of Proposition 8. In order to encourage supply chain members to participate in the contract to achieve coordination, it is necessary to ensure that all supply chain members achieve Pareto improvement; that is, $\pi_M^{RC} - \pi_M^D \geq 0$ and $\pi_S^{RC} - \pi_S^D \geq 0$ are satisfied. First, according to the conditions satisfied by the parameters under the combined contract given in Proposition 6, the total profits of the manufacturer and the service provider in the two-period can be solved as follows:

$$\pi_M^{RC} = \frac{\begin{bmatrix} 2\lambda V_1\left(2k\lambda V_1^2 - \lambda V_1 + 2V_1 - 2c_m\right) \\ +\left(V_1 - c_m\right)^2\left(4k\lambda V_1 + kV_1 - 2\right) \end{bmatrix}}{2V_1\left(2kV_1(1+4\lambda) - 4\lambda - 5\right)} - \pi_S^{RC},$$
$$\pi_S^{RC} = \frac{\begin{pmatrix} \varphi_1\left(2k\lambda V_1^2 - \lambda V_1 + V_1 - c_m\right) \\ \times\left(8k\lambda^2 V_1^2 - V_1(1+2\lambda)^2 + c_m\right) + \varphi_2 K_1 K_2 \end{pmatrix}}{\left(V_1 F^2\right)}, \tag{A.17}$$

where F, K_1, and K_2 are shown in Proposition 8. Since $\pi_M^{RC} - \pi_M^D \geq 0$, we can solve $\varphi_2 \leq (F\Omega/4K_0K_1K_2) - \Psi\varphi_1$, where F_0, Ω, and Ψ are shown in Proposition 8. Since $\pi_S^{RC} - \pi_S^D \geq 0$, we can get $\varphi_2 \geq (F^2\Theta/16K_0^2K_1K_2) - \Psi\varphi_1$, where Θ is shown in Proposition 8. It can be found by calculation that in some cases there will be $(F^2\Theta/16K_0^2K_1K_2) - \Psi\varphi_1 \geq \lambda\varphi_1$, which leads to formula (39) without solution. Next, solve the case of $(F^2\Theta/16K_0^2K_1K_2) - \Psi\varphi_1 \geq \lambda\varphi_1$. First judge the positive and negative of $\lambda + \Psi$, since $\lambda + \Psi = J_0(\lambda)/(K_1K_2)$, where

$$\begin{aligned} J_0(\lambda) = {} & \lambda^3 V_1\begin{bmatrix} 4V_1k^2(3V_1 - 2c_m)^2 - 23V_1 + 12c_m \\ +4k\left(3V_1^2 - 4(V_1 - c_m)^2\right) \end{bmatrix} \\ & + \lambda^2\begin{pmatrix} 4k^2V_1^2(V_1 - c_m)(3V_1 - 2c_m) + 27V_1^2 - 35V_1c_m \\ -4kV_1\left(9V_1^2 - 11V_1c_m + 4c_m^2\right) + 12c_m^2 \end{pmatrix} \\ & + \lambda V_1(V_1 - c_m)\left(k(V_1 - c_m)(kV_1 - 3) - 2kV_1 - 3\right) - (V_1 - c_m)^2. \end{aligned} \tag{A.18}$$

Just judge the positive or negative of $J_0(\lambda)$, and we can judge $(\partial J_0(\lambda)/\partial\lambda) > 0$, $J_0(\lambda = 0) < 0$, $J_0(\lambda = 1) > 0$, so there is only one λ_k, when $0 < \lambda \leq \lambda_k$, $J_0(\lambda) \leq 0$; when $\lambda_k < \lambda < 1$, $J_0(\lambda) > 0$. Therefore, when $0 < \lambda \leq \lambda_k$, or $\lambda_k < \lambda < 1$ and $\varphi_1 \leq (F^2\Theta/16K_0^2K_1K_2(\lambda + \Psi))$, $(F^2\Theta/16K_0^2K_1K_2) - \Psi\varphi_1 \geq \lambda\varphi_1$; when $\lambda_k < \lambda < 1$ and $(F^2\Theta/16K_0^2K_1K_2(\lambda + \Psi)) < \varphi_1 < 1$, $(F^2\Theta/16K_0^2K_1K_2) - \Psi\varphi_1 < \lambda\varphi_1$, where $\lambda_k = \{0 < \lambda < 1 | J_0(\lambda) = 0\}$. Through calculations, it may exist $(F^2\Theta/16K_0^2K_1K_2(\lambda + \Psi)) \geq 1$, that is, $F^2\Theta - 16K_0^2K_1K_2(\lambda + \Psi) \geq 0$. In addition, $\partial(F^2\Theta - 16K_0^2K_1K_2(\lambda + \Psi))/\partial\lambda$ is not monotonous to increase first and then decrease, $\partial(F^2\Theta - 16K_0^2K_1K_2(\lambda + \Psi))/\partial\lambda$ is first positive and then negative, and $(F^2\Theta - 16K_0^2K_1K_2(\lambda + \Psi))|_{\lambda=\lambda_k} > 0$, $(F^2\Theta - 16K_0^2K_1K_2(\lambda + \Psi))|_{\lambda=1} < 0$, so there is only one λ_r $(\lambda_k < \lambda_r < 1)$, when $\lambda_k < \lambda \leq \lambda_r$, $(F^2\Theta/16K_0^2K_1K_2(\lambda + \Psi)) \geq 1$; when $\lambda_r < \lambda < 1$, $(F^2\Theta/16K_0^2K_1K_2(\lambda + \Psi)) < 1$, where

$$\lambda_r = \left\{\lambda_k < \lambda < 1 | F^2\Theta - 16K_0^2K_1K_2(\lambda + \Psi) = 0\right\}. \tag{A.19}$$

In summary, when $0 < \lambda \leq \lambda_r$, we can get $(F^2\Theta/16K_0^2K_1K_2) - \Psi\varphi_1 \geq \lambda\varphi_1$, which leads to equation (39) without solution; that is, the contract cannot achieve perfect coordination; when $\lambda_r < \lambda < 1$, the contract can achieve perfect coordination. □

Proof of Proposition 9. Easy to get from Proposition 6, omitted. □

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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Research Article

Economic Policy Uncertainty and Local Carbon Emission Trading: A Multifractal Analysis from US and Guangdong

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This paper investigates the long-term dynamic cross-correlation evolution between US economic policy uncertainty index (USEPU) and Guangdong carbon emission trading price (GDCP) from the multifractal detrended cross-correlation analysis (MF-DCCA) perspective. With the calculation of correlation statistics and fluctuation function, the beginning procedures of MF-DCCA, we find that the cross-correlation between USEPU and GDCP is significant and presents power law property. Also, with the Hurst exponent, we find that the long-horizon correlations between series are persistent. Moreover, we perform Rényi exponent and spectrum singularity check. The empirical findings reveal that the all the correlations are of multifractality and the correlation of GDCP holds the highest degree.

1. Introduction

It is well acknowledged that climate change is the most challenging task the human being has ever encountered. As an effective solution for carbon emission reduction, carbon emission trading market has been widely accepted by many countries [1]. With this view, numerous studies contribute to the carbon emission trading field with regard to the mechanism and consequences of carbon emission trading market [2–14]. Also, as an ideal proxy for the measurement of macroeconomic fluctuation, economic policy uncertainty index has been commonly employed by the financial researchers [15–30]. Due to the huge impact of economic policy changes, several studies link economic policy uncertainty with carbon emissions to check the correlations between them. Adams et al. [31] took an investigation of economic policy uncertainty and carbon emission along with energy consumption through the autoregressive model. They find that compared with energy consumption, the influence of economic policy uncertainty to carbon emission can be ignored. Yu et al. [32] carried out a study regarding the economic policy uncertainty (EPU) and firm carbon emissions from provincial levels. They found that with rise in the economic policy uncertainty, firms intend to employ cheap and low quality fossil fuels, which would result in an increase in carbon emission. However, these studies usually depict linear property between variables and take little concern over carbon emission trading market. Multiple research studies have recorded that it is hard for traditional statistical vehicle to discover the nonlinear correlation between series due to nonstationary evolution pattern of economic time series. [33–38]. With this view, researchers are trying to utilize multifractal analysis in modeling the nonlinear dynamic correlation between economic time series. Liu et al. [15] examined the cross-correlation between economic policy uncertainty and stock market volatility with multifractal analysis. They found that with the involvements of economic policy uncertainty and the multifractal model, the forecasting accuracy for future volatility can be greatly improved. Yao et al. [39] studied multifractal correlation among crude oil market, US stock market, and economic policy uncertainty. They found that the nonlinear long-range correlation between series is persistent and strong evidence for the existence of series correlation multifractality.

As the richest province of China, Guangdong weighs 10% of China total GDP and has been the economic champion among China's provinces over decades. Also, as a pioneer in China's reform and opening-up process and neighboring province of Hong Kong, Guangdong is the first province opening for foreign investment. With decades of development, the US has been the largest trade partner of China, indicating that considerable Guangdong firms engage in the Sino-US trade. Besides, as the first batch of pilot provinces in carbon emission trading, Guangdong is of the longest history and largest volume in carbon emission trading. With this view, we connect US economic policy uncertainty index, as the representative of US macroeconomic policy change, with the Guangdong carbon emission trading price to check whether US policy changes would demonstrate impact to local carbon emission trading. Also, as a common statistical vehicle for multifractality, we employ the MF-DCCA to check whether cross-correlation multifractality exists between US policy uncertainty and Guangdong carbon emission trading. With significant cross-correlation statistics, we find the existence of long-horizon cross-correlation between US economic policy uncertainty and Guangdong carbon emission trading price. Additionally, we find that the cross-correlations between series are of power law property with the upward trend of fluctuation function with no regard to changes of scaling orders. Furthermore, we calculate the Hurst exponent to check the persistence of the correlation. We find that all the exponent values are above critical values, proving the persistence of correlation. Also, we find that none of the exponents are of constant values, confirming the cross-correlation multifractality. Moreover, we calculate the Rényi exponent and spectrum singularity as other checks for multifractality. We find that none of the Rényi exponent curves are of typical linear characters, confirming the multifractality existence. In addition, with the calculation of Hölder exponent difference, we find that Guangdong carbon price is of greatest difference, informing the richest multifractality.

Our study enriches the current literature from two dimensions. First, we utilize the novel US economic policy uncertainty index as an indicator for the US macroeconomic policy fluctuation and link it with Guangdong carbon emission trading price from the multifractal perspective. Particularly, we find that long-horizon cross-correlation between US economic policy uncertainty and Guangdong carbon emission trading price exists. Moreover, with the Hurst and Rényi exponent, we find that the cross-correlation between series demonstrates solid evidence for the multifractality existence. From this point of view, our empirical findings are in line with prior economic research studies related to multifractality analysis [39–45]. Second, our study originated from the multifractal perspective, enabling in-depth investigation for the cross-correlation dynamics between economic policy uncertainty and carbon emission trading. Furthermore, as the most important economic zone in China, our findings would shed light on the carbon emission market risk management for not only Guangdong but also China policy makers and investors by avoiding the imported economic uncertainty.

The rest of this paper is organized as follows. Section 2 describes the data. Section 3 illustrates the multifractal cross-correlation methodology. Section 4 shows the empirical results. Section 5 concludes the paper.

2. Data

Our data consisted of US economic policy uncertainty index and Guangdong carbon emission price. US economic policy uncertainty index is developed by Baker et al. [20]. We directly download the index from the websites (http://policyuncertainty.com). As stated by the website, the US economic policy uncertainty index is constructed by counting article number of thousands of national and local newspapers archived in the Access World News' NewsBank service with three sets of terms. The first set refers to the terms economic or economy, such as monetary policy. The second set terms are uncertain or uncertainty, such as COVID-19. The third terms are related to government actions, such as deficit. The Guangdong carbon emission price is derived from the Wind Financial Services, a widely accepted financial data provider in China. For the US and Guangdong data pairing, we chose the sample time period from December 19, 2013, the earliest day of carbon emission trading, to April 29, 2021.

Table 1 presents the descriptive statistics of the US economic policy uncertainty index (USEPU) and Guangdong carbon emission trading price (GDCP). We can find from Table 1 that both GDCP and USEPU series present right-skew characters with greater averages of the GDCP and USEPU (22.57 and 120.82) over their medians (18.56 and 86.73). Also, the skewness of both series is positive (2.08 and 2.36), confirming the right-skew distribution findings. For the kurtosis, it is easy to find that the values of both series (7.89 and 9.45) are larger than 3, indicating sharp peak characteristics. Moreover, we utilize the prevailing Jarque–Bera tests to check whether both series demonstrate normality properties. We can find from Table 1 that JB statistics of both series (2555.47 and 3975.91) are much greater than zeros. As a result, the p values of JB tests are zeros, presenting strong evidence of the non-normal distribution existence.

Figures 1 and 2 present the evolution patterns of the Guangdong carbon emission trading price and US economic policy uncertainty index. As shown in Figure 1, the GDCP reaches its peak at the beginning of the series. After that, the GDCP series experience continuous drop and bounce back at 2018. On the contrary, in Figure 2, the USEPU series demonstrate moderate fluctuation from 2013 to 2019. However, entering 2020, the USEPU raises sharply, which may be caused by the uncertainty of US election and heavier situation of COVID-19. Furthermore, both series patterns show strong rejections to normality distributions with apparent sharp peaks and fat tails, which are consistent with statistics presented in Table 1.

3. Methodology

In this section, we employ the prevailing multifractal cross-correlation analysis (MF-DCCA) as an instrument to investigate whether multifractality exists between the Guangdong carbon emission trading price (GDCP) and US economic policy uncertainty index (USEPU). First, we utilize the cross-correlation statistics proposed by

Table 1: Descriptive statistics.

Variable	GDCP	USEPU
Mean	22.57	120.82
Median	18.56	86.73
Maximum	77.00	738.02
Minimum	8.10	10.92
Std. Dev.	11.97	103.60
Skewness	2.08	2.36
Kurtosis	7.89	9.45
Jarque–Bera	2555.47	3975.91
Probability	≤0.01	≤0.01
N	1491	1491

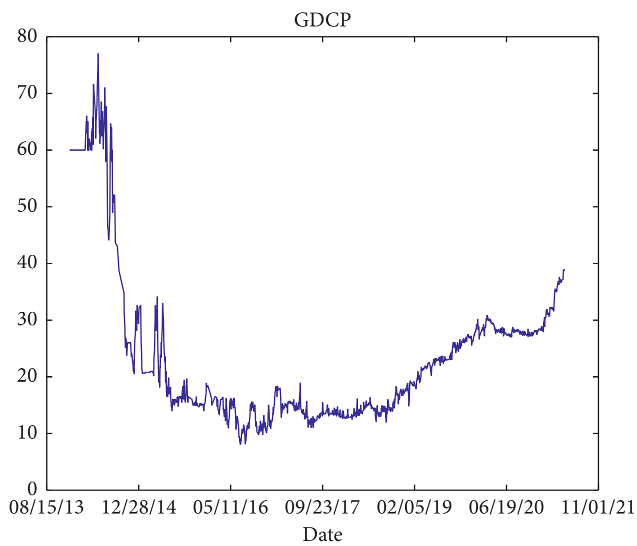

Figure 1: Evolution pattern of Guangdong carbon emission price (GDCP).

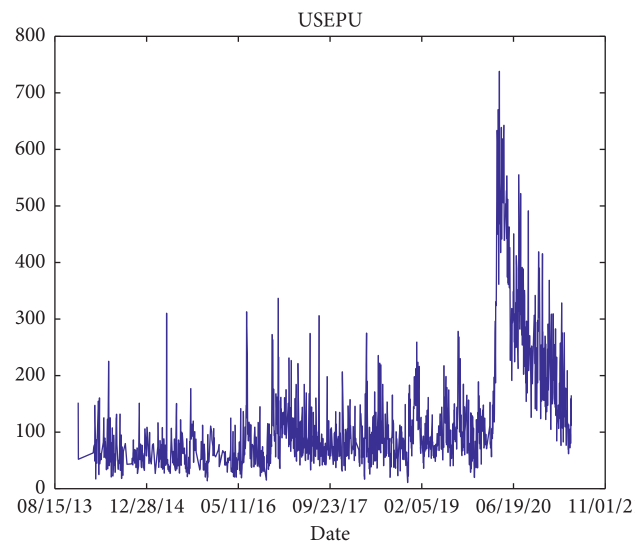

Figure 2: Evolution pattern of US economic policy uncertainty index (USEPU).

Podobnik and Stanley [46] to check the existence of the cross-correlation between the series in a qualitative way. Second, we apply the MF-DCCA approach to inspect if the correlations between series would vary conditionally on the changes of scaling orders, which would result in multifractality.

3.1. Cross-Correlation Analysis. To have a general view of cross-correlation between GDCP and USEPU, we first introduce a cross-correlation indicator proposed by Podobnik and Stanley [8]. The indicator C_i is constructed through the following equation:

$$C_i = \frac{\sum_{k=i+1}^{N} x_k y_{k-i}}{\sqrt{\sum_{k=1}^{N} x_k^2 \sum_{k=1}^{N} y_k^2}}, \quad (1)$$

where $\{x_k\}$ and $\{y_k\}$ are responsible for two equal length time series.

With the involvement of cross-correlation indicator C_i, we further begin to construct the cross-correlation statistics. The detailed construction process is shown in the following equation:

$$Q_{cc}(m) = N^2 \sum_{i=1}^{m} \frac{C_i^2}{N-i}, \quad (2)$$

where C_i refers to the cross-correlation indicator, N is the total length of the series, and m means the degree of freedom. We can indicate from the equation that the cross-correlation statistics $Q_{cc}(m)$ would follow the $\chi^2(m)$ distribution with m degrees of freedom. To check if the cross-correlation between series is significant, we are required to compare the cross-correlation statistics $Q_{cc}(m)$ with chi-square critical value $\chi^2(m)$ under m degrees of freedom proposed by Podobnik and Stanley [46]. If the value of the cross-correlation statistics $Q_{cc}(m)$ is above the critical value of chi-square $\chi^2(m)$, we believe a significant cross-correlation exists between the two time series.

3.2. MF-DCCA. Zhou [47] proposed the prevailing multifractal cross-correlation analysis (MF-DCCA) methodology to check the nonlinear cross-correlation between detrended time series. The MF-DCCA, derived from the detrended fluctuation analysis, is constructed through following five steps:

Step 1. To eliminate the trending character of each series, we process the original time series $\{x_k\}$ and $\{y_k\}$, which are responsible for GDCP and USEPU, with a deduction of each series average, respectively. The detailed calculation process is presented by the following equation:

$$X(i) = \sum_{k=1}^{i} (x_k - \overline{x}),$$
$$Y(i) = \sum_{k=1}^{i} (y_k - \overline{y}), \tag{3}$$

where $\overline{x}$ and $\overline{y}$ are the means of $\{x_k\}$ and $\{y_k\}$, $k = 1, 2, 3, \ldots, N$. It is easy to deduce from equation (3) that $X(N)$ and (N) are equal to zero.

Step 2. To have a microinvestigation of each series, we split the detrended profiles $X(i)$ and $Y(i)$ into N_s nonoverlapping segments with the equal time lengths of s. The length interval N_s is generated as follows:

$$N_s = \text{int}\frac{N}{s}, \tag{4}$$

where N is the total length of observation and int stands for the integer function, collecting the maximum integer toward the real number. Nevertheless, in some occasions, the total length N cannot be divided by scale s with no reminder, which would leave a short part segment at the end of each profile. Considering this scenario, we regenerate the segment with the length interval N_s from the last to the first value of the series for maximum usage of the whole time series. Thus, we can get two N_s segments for each time series with repeated generation process.

Step 3. With divided N_s segments, we start to investigate the local trend of each segment, v, through a polynomial fitness check. Therefore, the variance of each segment, denoted as $F^2(v, s)$, can be acquired through equations (5) and (6).

If $v = 1, 2, 3, \ldots, N_s$, the variance of segment v, $F^2(v, s)$, is as follows:

$$F^2(v, s) = \frac{1}{s}\sum_{i=1}^{s}\left|X((v-1)s + i) - p_v^n(i)\right| \bullet \left|Y((v-1)s + i) - p_v^n(i)\right|. \tag{5}$$

If $v = N_s + 1, N_s + 2, N_s + 3, \ldots, 2N_s$, the variance of segment v, $F^2(v, s)$, is as follows:

$$F^2(v, s) = \frac{1}{s}\sum_{i=1}^{s}\left|X(N - (v - N_s)s + i) - p_v^n(i)\right| \bullet \left|Y(N - (v - N_s)s + i) - p_v^n(i)\right|, \tag{6}$$

where $p_v^n(i)$ is the n-th order polynomial fitness check of segment v.

Step 4. To have a measurement of nonlinear correlation between series, we calculate the q-th order of the fluctuation function by averaging variances of all the detrended segments. The construction processes of the fluctuation function are presented by equations (7) and (8).

If $q \neq 0$,

$$F_q(s) = \left[\frac{1}{2N_s}\sum_{v=1}^{2N_s}\left[F^2(v, s)\right]^{q/2}\right]^{1/q}. \tag{7}$$

If $q = 0$,

$$F_0(s) = \exp\left[\frac{1}{4N_s}\sum_{v=1}^{2N_s}\ln\left[F^2(v, s)\right]\right]. \tag{8}$$

It is easy to learn from equations (7) and (8) that the moving trend of fluctuation function $F_q(s)$ lies on the selection of the time length s under given value of q. In addition, to have a deep understanding of multifractal property between series, we repeat procedures from No. 2 to No. 4 upon various selections of s and finally draw forth our last fifth procedure.

Step 5. With the multiselection of time length s, fluctuation function $F_q(s)$ moving trend could be observed by the gradient of the log – log plot of $F_q(s)$ versus s conditional on various selections of scaling order q. If a long-term multifractal cross-correlation character could be detected between the detrended series $X(i)$ and $Y(i)$, the fluctuation function $F_q(s)$ would demonstrate a power law relationship as presented in the following equation:

$$F_q(s) \sim s^{H_{XY}(q)}, \tag{9}$$

where $H_{XY}(q)$ is on behalf of the gradient of the log-log plots of $F_q(s)$ conditional on the variation of scaling order q and $H_{XY}(q)$ is estimated by the ordinary least square regression.

We can learn from equation (9) that the gradient of fluctuation function, $H_{XY}(q)$, varies upon change of scaling order q. Also, when $q = 2$, if the generalized scaling exponent $H_{XY}(2)$ is larger than 0.5, a long-term and consistent cross-correlation between detrended series $X(i)$ and $Y(i)$ would be confirmed. Nevertheless, if the scaling exponent of $H_{XY}(2)$ is smaller than 0.5, we believe the cross-correlation between detrended series $X(i)$ and $Y(i)$ is of no consistence. Also, if the scaling exponent $H_{XY}(2)$ equals 0.5, no significance of the cross-correlation between detrended series $X(i)$ and $Y(i)$ would be founded. With the consideration of the broad application, $H_{XY}(2)$ is widely recognized as the generalized Hurst exponent. With this view, we define that if the scaling exponent $H_{XY}(q)$ equals to a constant with no regard to any change of scaling order q, the cross-correlation between series is monofractal. Otherwise, we regard the cross-correlation between detrended series as multifractal. Moreover, we could learn from equations (3) and (5) that when q is larger than zero, the segment v works as a core factor in valuing fluctuation function $F_q(s)$ with the large variance of $F^2(v, s)$. With this view, when q is over zero, the exponent $H_{XY}(q)$ would be responsible for the large fluctuation scaling property. Conversely, when q is below zero, the exponent $H_{XY}(q)$ would be the indicator for the small fluctuation scaling property.

With the Hurst exponent $H_{XY}(q)$, we start to construct the Rényi exponent, the key proxy for the multifractality investigation between series. The exponent is denoted as $\tau_{XY}(q)$. The calculation process is as follows:

$$\tau_{XY}(q) = qH_{XY}(q) - 1. \tag{10}$$

Moreover, to enhance the credibility of multifractality, we perform the singularity spectrum, marked by $f_{XY}(\alpha)$, as an additional check. With the Legendre transformation, the singularity spectrum, $f_{XY}(\alpha)$, can be obtained by the following equations, with the participation of the Rényi exponent, $\tau_{XY}(q)$, and the Hölder exponent α_{XY}. The detailed calculation process of $f_{XY}(\alpha)$ is as follows:

$$\begin{aligned} \alpha_{XY} &= \tau_{XY}{}'(q), \\ f_{XY}(\alpha) &= q\alpha_{XY} - \tau_{XY}(q), \end{aligned} \tag{11}$$

where α_{XY} is the Hölder exponent. As the key parameter in the singularity spectrum analysis, α_{XY} is the representative of the strength of the singularity spectrum. With this view, we employ the strength difference or the spectrum width, $\Delta\alpha_{XY}$, as the measurement for multifractality degree, where $\Delta\alpha_{XY} = \alpha_{XY\,\max} - \alpha_{XY\,\min}$. We can infer from the equation that a larger value of $\Delta\alpha_{XY}$ would indicate a larger degree of multifractality.

4. Empirical Results

4.1. Cross-Correlation Test. In this section, to have a basic knowledge of statistical correlation between Guangdong carbon emission trading price and US economic policy uncertainty, we employ equations (1) and (2) to calculate the cross-correlation statistics, $Q_{cc}(m)$, as an instrument to investigate the correlation significance between series. Figure 3 shows the cross-correlation statistics, $Q_{cc}(m)$, and its corresponding chi-square critical value $\chi^2(m)$ at 5% significant level is depicted by green and red lines conditional on the degrees of freedom varying from 1 to $N-1$. We can find from Figure 3 that the cross-correlation statistic $Q_{cc}(m)$ demonstrates clear edge over its corresponding chi-square critical value $\chi^2(m)$ by noticeable distances between variables, which would strongly reject the null hypothesis and prove the long-term cross-correlation existence between GDCP and USEPU.

4.2. Multifractal Detrended Cross-Correlation Analysis. With significant correlation statistics, $Q_{cc}(m)$, as presented in Figure 3, we could infer a long-term correlation between Guangdong carbon emission trading price and US economic policy uncertainty in a qualitative way. However, to have a detailed quantitative investigation of the nonlinear correlation character between Guangdong carbon emission trading price and US economic policy uncertainty, we utilize the multifractal detrended cross-correlation analysis proposed by Zhou [47] as the instrument. To perform the analysis, we first follow the work of Zhang et al. [48] by setting scaling order q from −10 to 10 with an interval of 1. Also, we can infer from the illustration in Section 3.2 that if scaling order q is smaller than zero, we believe two time series demonstrate weak fluctuation. On the contrary, the time series show strong fluctuation. Figure 4 plots the log-log fluctuation function $F_q(s)$ evolution pattern conditional on the time length of s with scaling orders from −10 to 10 between Guangdong carbon emission trading price and US economic policy uncertainty (GDCP and USEPU). It is easy to find that all of the lines demonstrate similar evolution patterns by moving upward upon gradual increase in time length s with no regard to the changes of scaling orders, indicating a long-term power law correlation existence between GDCP and USEPU.

Also, to have an investigation of cross-correlation persistence and multifractality between Guangdong carbon emission trading price and US economic policy uncertainty series, we further calculate the Hurst exponent with the variation of scaling order q as presented in Figure 5. In Figure 5, we can find that the Hurst exponent values of the Guangdong carbon emission trading price and US economic policy uncertainty (GDCP-USEPU cross-correlation), the Guangdong carbon emission trading price (GDCP), and the US economic policy uncertainty (USEPU) are all above the critical values (0.5), providing strong evidence that the cross-correlation of GDCP-USEPU, the correlation within GDCP series, and the correlation within USEPU series are persistent. In addition, we can find from Figure 5 that GDCP-USEPU and GDCP present downward trend with decreased Hurst exponent values upon the rise of scaling order q. However, for USEPU, the line goes down with gradual increase in scaling order q from −10 to −2. After that, the line

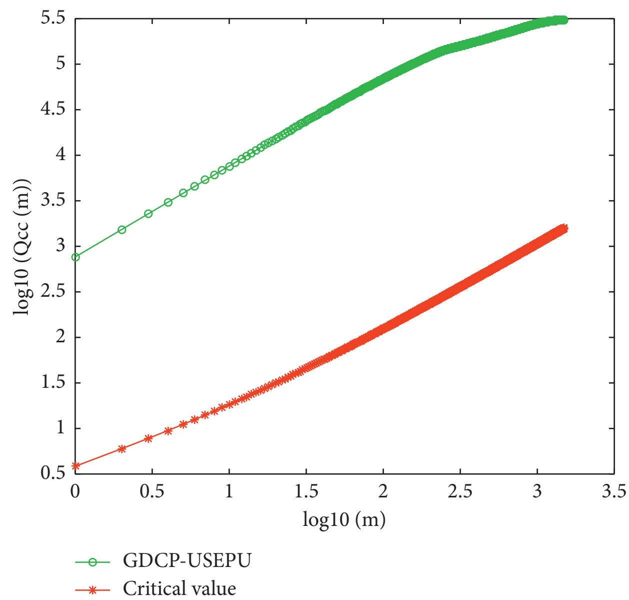

Figure 3: Log – log plot of the cross-correlation statistics ($Q_{cc}(m)$) for GDCP and USEPU.

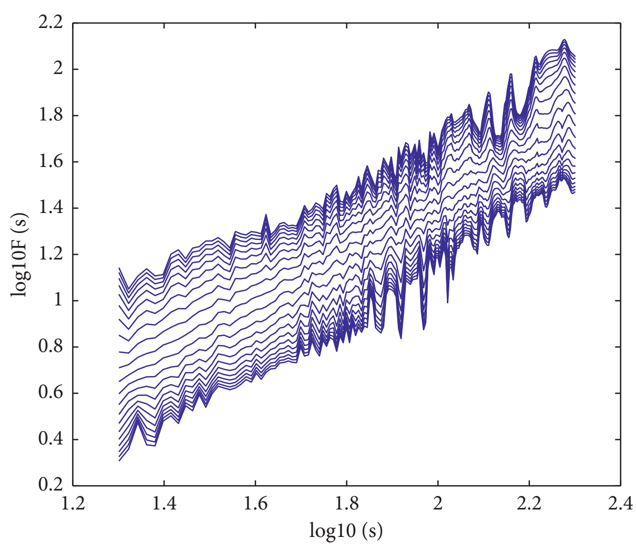

Figure 4: Log – log plot of $F(s)$ versus s for GDCP and USEPU.

starts to climb and reach its peak at $q = 4$, showing an S-shaped curve. Also, when q is below zero, the Hurst exponent of GDCP is greater than that of GDCP-USEPU and USEPU, demonstrating the highest level of persistence. On the contrary, when q is above zero, the Hurst exponent of USEPU moves upward sharply and tops the three series correlations. Also, we can find from Figure 5 that none of the curves are flat, indicating the multifractality existence between series.

In addition, we calculate the Rényi exponents, another indicator of multifractality, with the cross-correlation of GDCP-USEPU, the correlation within GDCP series, and the correlation within USEPU series. As presented in Figure 6, we can find that none of three curves present typical linear shapes, proving the existence of the multifractality character between GDCP and USEPU.

Finally, for the measurement of the multifractal richness of the cross-correlations between GDPC and USEPU, we perform another singularity spectrum check as shown in Figure 7. We can find that the none of the singularity spectrums, $f_{XY}(\alpha)$, demonstrate linear shapes, showing the multifractality between GDPC and USEPU. Moreover, we calculate the difference between min and max Hölder exponent, the delta, as the measurement for the multifractality degree, as presented in Table 2. It is easy to find that the GDCP delta of Hölder exponent is of the largest value (0.930), showing the strongest multifractality character.

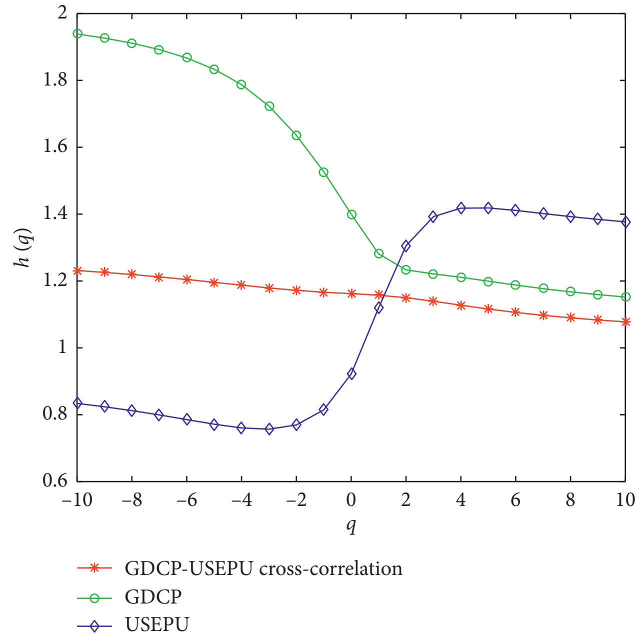

Figure 5: Generalized Hurst exponent of h (q) versus q for GDCP and USEPU cross-correlation, the correlation of GDCP, and the correlation of GDCP.

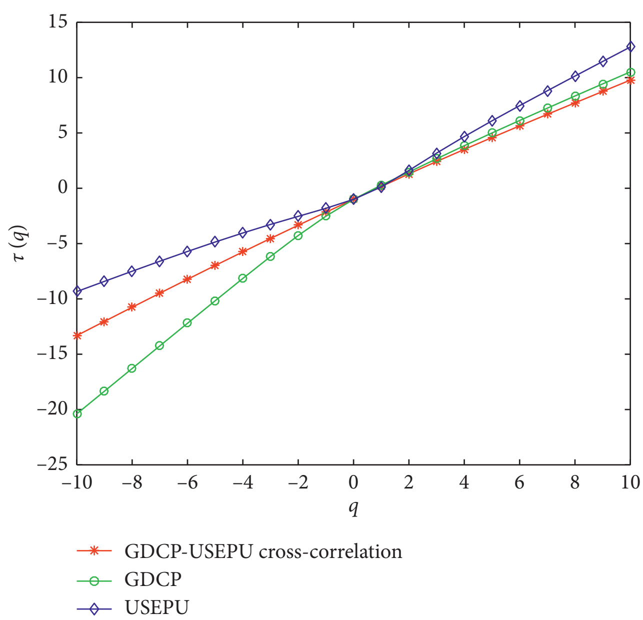

Figure 6: Rényi exponent of τ (q) versus q for GDCP and USEPU cross-correlation, the correlation of GDCP, and the correlation of USEPU.

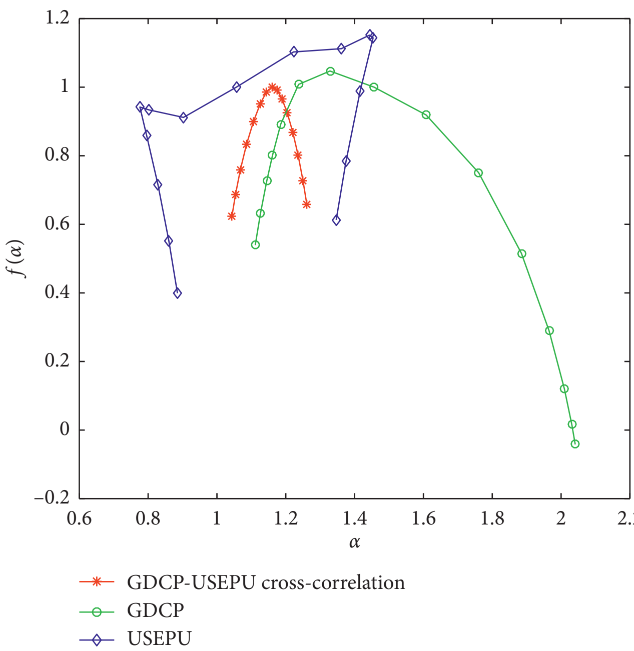

FIGURE 7: Spectrum singularity of $f(\alpha)$ versus α for GDCP and USEPU cross-correlation, the correlation of GDCP, and the correlation of USEPU.

TABLE 2: Max, min, and delta values of the Hölder exponent.

	α_{max}	α_{min}	$\Delta\alpha = \alpha_{max} - \alpha_{min}$
GDCP	2.041	1.111	0.930
USEPU	1.454	0.776	0.678
GDCP-USEPU cross-correlation	1.261	1.044	0.218

5. Conclusions

In this paper, we take an investigation of the correlation between China's most prosperous carbon emission trading market and US economic policy uncertainty. To have a deep insight of the long-term cross-correlation property between series, we employ the prevailing multifractal detrended cross-correlation analysis as the instrument. We first calculate the cross-correlation statistics Q_{cc} and find sufficient evidence for the correlation significance between Guangdong carbon emission trading price (GDCP) and US economic policy uncertainty (USEPU). Also, to have a more detailed understanding of the nonlinear cross-correlation property between GDCP and USEPU, we calculate the fluctuation function and find that all the function values demonstrate linear shapes, proving the long-term power law cross-correlation between GDCP and USEPU. In addition, we employ the Hurst exponent as the key parameter to check the persistence of correlation between GDCP and USEPU. We find that the parameters are all over the critical values, confirming the correlation persistence between GDCP and USEPU. Moreover, we calculate the Rényi exponent, the core factor in measuring the multifractality, to investigate the multifractal property between GDCP and USEPU. We find that none of the Rényi exponents demonstrate typical linear curves, supporting the multifractality character between GDCP and USEPU. We further perform another spectrum singularity check as enhancement for the multifractality character between GDCP and USEPU. We find that the delta values of the Hölder exponents are all far from zeros, confirming the existence of multifractality between GDCP and USEPU. With this view, multifractality character enables deep insight for the forecast of future movement of the carbon trading price, which would provide substantial suggestions for the carbon trading management of investors.

Data Availability

We affirm that the carbon emission trading price and economic policy uncertainty data used to support the findings of this study are available at http://policyuncertainty.com/and Wind Financial Services which is widely subscribed by the financial researchers, respectively.

Conflicts of Interest

The author declares that there are no conflicts of interest.

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Research Article

The Impact of Geopolitical Risk on Systemic Risk Spillover in Commodity Market: An EMD-Based Network Topology Approach

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Since the financialization of commodities, portfolio investments have become an important tool for investors to diversify risks. However, due to the nonlinear fluctuations brought about by extreme events, investors face more difficulties in the choice of risk portfolio. We adopt empirical mode decomposition and STVAR model, along with the basis data of optimized original sample interval. In addition, we retain the mature research of multiscale systemic risk under frequency and divide the dimension of systemic risk into two states. When frequency is combined with states, the risk spillover center undergoes subversive changes, particularly in the longest term, and metals become the risk spillover center, substituting the energy commodity, on the condition that the compositions of extreme value add persuasive power to the perspective of long term. We proposed that the joint fluctuation of agricultural commodities and energy commodities makes the former become another important risk spillover point. For investors, holding period and portfolio both need to be considered.

1. Introduction

When it comes to the commodity market, early studies generally focus on fluctuations of the commodity prices from the perspective of international trade, that is, the mechanism by which imports and exports disturb commodity price and change the commodity market structure, which is a microscopic analysis of the supply and demand relationship of commodities [1, 2]. However, with the emergence of potential benefits in the commodity market, financial institutions and retail investors have substantially increased their exposures to commodities and have a net long-term position which has promoted the development of commodity financialization and gradually freed them from the shackles of the real economy, thus being decoupled from the simple dynamics of supply and demand [3–5]. Chen and Xiong said that market participants may dramatically raise asset prices and deviate from the fundamentals of supply and demand, making them highly volatile. This is such a closely related commodity market that it becomes a valuable investment tool and needs financialization [6]. Particularly, in 2004 when the “financialization” reached peak, commodity prices have undoubtedly become much more complicated [7]. To make matters worse, since the stock market crash in 2002, the risk diversification ability of commodity futures in cross-market transactions was discovered [8], which can be corroborated by the fact that the level of financial activity measured by the open interest in commodity futures has increased from 103 billion to 509 billion in few years [9]. The interest in analyzing systemic risk contagion from a macroperspective has become increasingly strong, both cross-market or just inside the commodity market, and many scholars have been involved in this. From the perspective of risk theory, herding behavior is an important explanation in the field of behavioral finance when the joint fluctuations within the commodity market are mentioned, just taking energy and agricultural markets as example [10]. If inter-commodity volatility is higher than the dynamics of the single commodity itself, the valuable incremental information containing in the former can be used to determine future price volatility. Other scholars have followed this thread and used the joint volatility of commodities as an opportunity to expand their heterogeneous performance in different economies. Commodity market is an important financial submarket. The volatility of commodities and the resulting dynamics of cross-commodity linkages are crucial to many aspects of finance, especially in investment portfolio and risk management [12, 13]. Therefore, in such a situation where commodities have become the second largest evasive measure after equity assets, taking the requirements of investors for making reasonable decisions into account, it is of great significance to explore the risks of the commodity market.

Data with high volatility has become the main research object toward the current commodity market, and the higher the volatility, the higher the requirements for the portfolio risk control strategies [14, 15]. We regard the commodity market as a large system, and different commodities are subsystems. By examining the impact of a certain commodity on the entire system when it is in trouble, in other words, extreme price shocks, we can concretize the systemic risk caused by joint fluctuations with CoVaR, and Co represents joint functions [10]. Xu et al. have upgraded the intraday data commonly used in the empirical field [16] to a volatility calculated based on 5-minute prices [11]. The extensive use of high-frequency data has allowed systemic risk in the frequency domain to gain much attention, and the trend toward diversified risk has been applied in different investment periods, just like long term and short term. Taking oil market as an example, Gong and Lin pointed out that the commodity market has nonlinear characteristics [17], which puts forward further analysis of the performance of risk contagion in the commodity market under different states. The supply of oil is related to all aspects of the country's military and politics, and the geopolitical turmoil in the Middle East and Africa has increased geopolitical risk, even expanding to the economic field [18]. Bouoiyour et al. [19] and Su et al. [20] tested the possibility of combining geopolitical risk with commodity markets from a frequency perspective. The practice of replacing the entire economic system with macro-environmental indicators is very common in investigating the relationship between the external environment and various financial submarkets. Alqahtani et al. indicate that geopolitical risk is effective in linking stock prices to commodity markets [21]. Therefore, the multiscale analysis of the risk spillover in the commodity market under multiple conditions is closely related to the appetites for comprehensive risk diversification.

The existing literature on systemic risk spillover is insufficient. Many research works just concentrate on the external characteristics of the commodity index and lack the identification of the inherent characteristics of commodity volatility. In the meantime, many frontier studies based on the frequency domain only focus on single frequency domain or divide the state interval by external features, paying less attention to the state itself. The impact of variables such as endogenous variables on risk spillover is ignored. The main contributions of this article are as follows. Firstly, prescreening of samples is an innovative point of employing statistical ideas. We use the one-way variance decomposition to apply the precursor data widely used in earthquake prediction to identify irregular fluctuations in the commodity market, and examine the relevance of internal "system," which makes the research more pertinent and reasonable. Secondly, in research theory, we use the empirical mode decomposition method to explain the formation of systemic risk; that is, as a medium, the extreme value is composed of "peak superposition" and "continuous increase in amplitude," which work together to rationalize risk spillover. Thirdly, in application of the research mode, based on precursor data, we have enriched the current systemic risk research in the frequency domain, integrated the STVAR model into the empirical mode decomposition, and used the network diagram to show changes in risk centers and contagion paths under the influence of multiple frequencies and multiple states. We examine the joint volatility between different commodity markets and provide effective decision-making guidance for investors in diversifying risks in time and portfolio.

The rest of the paper is organized as follows. The next section describes the recent emerging literature on commodity market, including theoretical and applied perspectives. The subsequent section describes the methodology and data, and we present the results of our empirical analysis thereafter. The final section draws the main conclusions.

2. Literature Review

We arrange the papers in two ways. First of all, we report the literature on the study of systemic risk based on extreme value theory, mainly focusing on integrating extreme value factors into the computational systemic risk model, and we make necessary extensions to identify the characteristics of extreme value generation. Then, we compile the current literature on the nonlinearity of the commodity market based on macro variables, mainly focusing on the overall effect. Finally, we briefly explain the method used in this article.

Poon et al. demonstrate that extreme events play an important role in investment portfolios, and sometimes the only effective way to measure systemic risk is extreme value theory [22]. Li and Perez-Saiz use multivariate extremum methods to divide the whole financial market infrastructure into two or more FMIs to construct credit risk exposure indicators, and then estimate the systemic risk of the financial system [23]. Taking the banking system as an example, van Oordt and Zhou splits the systemic risk in dimensions to obtain the risk of a bank ("bank tail risk") and the link of the bank to the system in financial distress ("systemic linkage"), which distinguishes the micro and macro perspectives of research [24]. Di Clemente uses extreme value theory to expand the application range of systemic risk contribution measurement, allowing CoVaR to be realized in the macro system [25]. Motivated by the fact that the emergence of the 2007 financial crisis showed that the risk measures formulated so far did not achieve the expected performance, Gavronski and Ziegelmann innovatively constructed a new indicator, which uses the credit default swaps (CDS) of financial institutions as the data source, adding time dynamics, and finally formed the Financial System Dependence Index (FSDI) [26]. Extreme events are an important part of systemic risk, and tail characteristics are unique manifestations of financial markets. However, there are very few studies on extreme events themselves. In this article, we do not put extreme values into the model, but we analyze the components of extreme values from a theoretical perspective, looking forward to verifying the statement that "risks are often generated in a prosperous economic environment and then accumulate until it is activated" [27], which will also provide theoretical guidance for the use of monthly data. In parallel with the mainstream research, we continue to use CoVaR to examine the contagious effects of systemic risks in the commodity market. Systemic risks from the frequency perspective have become hot topics, which put forward new requirements for the selection of sample data. Bouri uses daily data to calculate the realized volatility and a time-varying parameter vector autoregressive model to analyze the risk spillover effect of the whole commodity market, representing high frequency [11]. Bakas and Triantafyllou weighted the daily excess return rate of each commodity to obtain the monthly achievable variance and finally discovered that the macro variable represented by economic uncertainty has a more lasting impact on the commodity market [28]. The Screening from the perspective of whether there exist systemic changes, being defined as the precursor data which better responds to the research on the formation mechanism of extreme values, we choose the monthly data. Similarly, based on the analysis in the frequency domain, this paper uses empirical mode decomposition instead of wavelet decomposition to investigate the internal trends of the commodity market.

Due to its high complexity, cross-border effects, random relationships, and nonlinear causal models with critical points, the negative impact of systemic risk has attracted more attention from scholars [29]. Asymmetric changes mean that there are different channels of infection, but considering the advantages of macroeconomic variables that can adjust commodity price fluctuations and enhance its stability [30–32], research from a macro perspective has been broadened [33, 34]. From simple regression and DCC-GARCH model to even copula function, scholars measured the contagion effect of systemic risk in commodity market covered by macro factors [35–37]. Yang examined the time-frequency correlation between the economic uncertainty and the commodity market [38], while Chen et al. focused on the risk contagion of sovereign credit default swaps towards the entire system [39]. However, they focus on external characteristics but ignore the abnormal changes of macrofactors, which can be reached into consensus. Ignoring the possible institutional transformation effects in the risk contagion, along with using the traditional linear framework for analysis, may lead to obvious deviations in conclusions which has explained by Teräsvirta [40]. Therefore, it is of great significance to study the nonlinear risk contagion. The introduction of indicators of economic policy uncertainty will weaken the impact of systemic risk, especially when there are strong differences in economic policies, coinciding with the view that the essence of systemic risk is its internal periodicity [27]. Some studies examine the impact of transitions in states on risk spillover from the perspective of quantile regression [10], using externally delineated state frequencies as the standard for state distinction, which is universal. Under the guidance of Markov characteristics, evaluation of system risk in different states in the network is considered as well [41], but none of them utilize the inherent properties of unique state variables. In era of endless geopolitical conflicts, the macro variable of geopolitical risk has penetrated into the financial market through its linkage with commodity trading, and its application is of immediate significance. We quote the STVAR model, in which GPR functions as an endogenous variable, and exploit its inherent characteristics to divide the expansion and recession state to compare changes of risk spillover.

With the continuous development of modern econometric methods, sociological network analysis has been widely used. Unlike Liu and Jiang [42], we only use weighted out-degree as the indicator of the network, for symmetrical out-degree and in-degree in Gephi. However, the same as Billio et al. [43], we will analyze the risk center and the path of infection, since the aggregation part of the network diagram will reveal the joint fluctuations of different categories of commodities.

3. Methodology and Data

3.1. Precursor Data. Precursor refers to the factor that drives changes in an event, that is, the symptoms before it occurs. At present, precursor research is widely used in natural science such as earthquake prediction, geological mining, and engineering geology [44–46], but it is rarely applied in the financial field. The precursor data sample containing the important generation information of extreme data [47] may improve the accuracy of risk spillover analysis. Too much sample data will bring about information redundancy and misjudgment, while too little sample data will lose important information and reduce recognition efficiency. Appropriate precursor data and sample intervals are critical to the validity of the results [48, 49]. Therefore, this paper uses precursor data as the basis to study the extreme value evolution information which is implicit in the sample, so as to provide a more effective data source for measuring systemic risk. Due to the uncertainty of extreme fluctuations[50], it is still difficult to directly observe and determine the generation interval throughout the whole time scale, and the results may be different by different sample intervals. Based on this, this paper draws on the one-way analysis of variance, constructs the F statistic to identify the difference between the hidden information inside the data, and determines the length of the precursor data sample.

Assuming that the total length of the time series data sample is N and that of single precursor data sample is n, all the sample data is divided into subsamples by N/n. Then, we select two adjacent subsamples and use the statistical properties of one-way analysis of variance [51] to determine whether to reject the null hypothesis, that is, whether the "precursor" of the extreme event has changed, meaning that whether there is any systemic difference between adjacent samples. If this difference is not statistically significant, this means that the two samples are very similar; in other words, there is no important information that implies the generation of extreme values and vice versa. Then, we change the sample length n and continue to repeat the above operation until a significant F statistic is determined. With reference to the classic principle of analysis of variance, this paper uses the sum of squares to express the degree of volatility in which the difference between mutual groups can be measured. The total sum of squares (SST) represents the fluctuations caused by systemic factors and shock factors. The error sum of squares (SSE) represents the internal fluctuations of a single sample. It also includes the explicit influence of external shocks and the implicit influence of extreme value generation information. The sum of squares between groups (SSA) represents volatility between samples. In order to avoid the influence of sample size, the method of dividing by degrees of freedom is customarily adopted; that is, after dividing by degrees of freedom n-k and k-1 in turn, SSE and SSA become MSA and MSE, respectively. K represents the number of factor levels which corresponds with the number of sample groups, being equal to 2 in this paper. Among them, $(x_{ij} - \overline{x}_j)^2$ represents the difference between the sample observation value and the sample mean, and $n_j(\overline{x}_j - \overline{x})^2$ represents the difference between the sample mean and the overall mean.

$$\begin{aligned}
\mathrm{SST} &= \mathrm{SSE} + \mathrm{SSA}, \\
\mathrm{SSE} &= \sum_{j=1}^{k} \sum_{i=1}^{n_j} \left(x_{ij} - \overline{x}_j\right)^2, \\
\mathrm{SSA} &= \sum_{j=1}^{k} \sum_{i=1}^{n_j} \left(\overline{x}_j - \overline{x}\right)^2 = \sum_{j=1}^{k} n_j \left(\overline{x}_j - \overline{x}\right)^2, \\
F &= \frac{\mathrm{MSA}}{\mathrm{MSE}} = \frac{(\mathrm{SSA}/(k-1))}{(\mathrm{SSE}/(n-k))} \sim F(k-1, n-k).
\end{aligned} \tag{1}$$

3.2. Empirical Mode Decomposition. In view of the in-depth application of precursor data in nonfinancial fields, frequency domain analysis has become a classic research paradigm [52, 53], such as Fourier transform, wavelet transform, and empirical mode decomposition. Fourier transform is one of the important methods of signal processing. After Fourier transform, various frequency components contained in the signal sequence can be obtained, but the time information of the signal is ruled out, making it difficult to confirm the timing of important properties such as transient characteristics. The wavelet transform links the frequency domain information of the signal with the time domain information and overcomes the shortcomings of the Fourier transform. However, the wavelet transform provides a time-frequency domain window with a variable scale, but without infinite high resolution in both the time domain and the frequency domain. In addition, different wavelet bases will affect the analysis results, while empirical mode decomposition (EMD) with good adaptability can decompose signals based on the time-scale characteristics of the data itself, without setting any prior wavelet basis functions [54]. Taking the extreme values and irregular fluctuations of financial time series data into account, this paper does not use Fourier transform and wavelet transform but uses EMD for data preprocessing.

The main idea of empirical mode decomposition is to transform an irregular frequency wave into multiple waves of single frequency (IMF) plus residual wave (residual). IMF meets two conditions: the functions have the same numbers of extrema and zero-crossings or differ at the most by one, and the functions are symmetric with respect to local zero mean. The two conditions ensure that an IMF is nearly periodic function and the mean is set to zero. IMF is a harmonic-like function, but with variable amplitude and frequency at different times. Inside the EMD model, the IMFs are extracted through a shifting process following six steps [55]: Firstly, we identify all the maxima and minima of time series $x(t)$. In the second step, we generate its upper and lower envelopes, $e_{\max}(t)$ and $e_{\min}(t)$, with cubic spline interpolation. In the third step, we calculate the point-by-point mean $(m(t))$ from upper and lower envelopes, which is as follows:

$$m(t) = \frac{e_{\max}(t) + e_{\min}(t)}{2}. \tag{2}$$

In the fourth step, we extract the mean from the time series and define the difference of $x(t)$ and $m(t)$ as $d(t)$:

$$d(t) = x(t) - m(t). \tag{3}$$

In the fifth step, we check the properties of $d(t)$: if it is an IMF, denote $d(t)$ as the ith IMF and replace $x(t)$ with residual $r(t) = x(t) - d(t)$. The ith IMF is often denoted as $c_i(t)$ and the i is called its index; if it is not, replace $x(t)$ with $d(t)$. Finally, we repeat steps one to five until the residual satisfies some stopping criterion.

One stopping criterion proposed by Huang et al. [56] for extracting an IMF is still applied, iterating predefined times after the residue satisfies the restriction that the numbers of zero-crossings and extrema do not differ by more than one and the whole sifting process can be stopped by any of the following predetermined criteria: either when the component $c_i(t)$ or the residue $r(t)$ becomes so small such that it is less than the predetermined value of a substantial consequence, or when the residue $r(t)$ becomes a monotonic function from which no more IMFs can be extracted. The total number of IMFs is limited to $\log_2 N$, where N is the length of data series. The original time series can be expressed as the sum of some IMFs and a residue:

$$x(t) = \sum_{j=1}^{N} c_j(t) + r(t), \tag{4}$$

where N is the number of IMFs and $r(t)$ means the final residue.

3.3. Smooth-Transition Vector Autoregression (STVAR). In order to characterize the nonlinear relationship of economic variables in different state intervals, Sims [57] made a pioneering exploration of vector autoregressive models and then developed a series of nonlinear VAR models. Among them, Markov-Switching Vector Autoregression (MSVAR), Threshold Vector Autoregression (TVAR), and Smooth-Transition Vector Autoregression (STVAR) are widely used. In the STVAR model, the state variables that drive interval transitions are preset observable variables and support continuous transition mechanisms, which have strong explanatory power for the economy. Within the framework of the STVAR model, according to the different settings of the conversion function, it can be subdivided into Logistic Smooth-Transition Vector Autoregression (LSTVAR) model and Exponential Smooth-Transition Vector Autoregression (ESTVAR) model. The former can describe the high state variable interval and the low state variable interval. The asymmetry mechanism of the state variable interval and the ESTVAR model is mainly used to reflect the transition of the symmetric interval [40].

In order to examine the asymmetric contagion mechanism of GPR on the commodity market which may correspond to the wave properties of different frequency series under EMD, we refer to the research of Caggiano et al. [58], thus establishing the following model:

$$Y_t = [1 - F(z_{t-1})]\left[\prod_b^p Y_{t-1} + F(z_{t-1})\prod_g^p Y_{t-1} + \varepsilon_t\right], \quad (5)$$

$$\varepsilon_t \sim N(0, \Omega), \quad (6)$$

$$F(z_t) = \{1 + \exp[-\gamma(z_t - c)]\}^{-1}, \quad \gamma > 0, E(z_t) = 0, \quad \operatorname{Var}(z_t) = 1, \quad (7)$$

where Y_t represents a set of endogenous variables that are partly selected from the commodity market. $F(z_t)$ is a logistic transition function which is used to describe the probability of the sample being divided into different "economic states" (recession and expansion at GPR). The nonnegative parameter γ determines the rapidity of the switch from a regime to another (the higher the γ, the faster the switch), and z_t is a state variable used to capture the periods of GPR. c is the threshold parameter identifying the two regimes. $\prod_b^p Y_t$ and $\prod_g^p Y_t$ indicate the coefficient matrix of GPR in two regimes, and ε_t is the vector of reduced-form residuals obeying a normal distribution.

In function (5), Y_t is the endogenous variables of STVAR model including state variable and CoVaR of each commodity at specific period which represents cocoa (Cc), wheat (Wh), corn (Cr), orange juice (Oj), nickel (Ni), sliver (Si), lean hogs (Lh), crude oil (CO), unleaded gas (Ug), natural gas (Ng), live cattle (Lc), aluminum (Al), and heating oil (Ho). z_t is the state variable processed by filtering, and the parameters is processed with maximum likelihood. The estimation model is $Y_t = [z_t, \mathrm{Cc}_t, \mathrm{Wh}_t, \mathrm{Cr}_t, \mathrm{Oj}_t, \mathrm{Ni}_t, \mathrm{Si}_t, \mathrm{Lh}_t, \mathrm{CO}_t, \mathrm{Ug}_t, \mathrm{Ng}_t, \mathrm{Lc}_t, \mathrm{Al}_t, \mathrm{HO}_t]$.

3.4. Risk Spillover Network. Network analysis also plays an important role in measuring systemic risks, because this analysis can better model and predict the behavior of complex financial systems, in which the center and contagion channel can be vividly observed. It is worth mentioning that, for the stability of the system as a whole, what is needed is a risk-based systemic approach; that is, the systemic risk is used as the original data. Existing research works show that systemic factors and random shock factors jointly drive sequence fluctuations. What is more, the important information of extreme value generation is implicit in shock factors, and systemic factors run through all sequence data [59–61]. EMD shows the formation process of extreme value fluctuations in a single commodity rate of return sequence, and then the impact of single commodity system fluctuations into the overall system is manifested through the stability of the network as mentioned above, even forming risk spillover. We adopted the typical network topology method proposed by Diebold and Yilmaz [62], which is the prototype of many other network analyses. We construct the following risk spillover matrix based on the prediction error variance decomposition, which shows the specific definition, as shown in Table 1.

In the spillover matrix in the table, the variables in the first row represent the source of risk spillovers, and the vectors in the first column denote the entity receiving the risk. We can calculate the degree of pairwise risk spillover based on the following decomposition:

$$S^H_{i\leftarrow j} = \frac{\sum_{h=0}^{H-1} a^2_{ij,h}}{\sum_{h=0}^{H-1} \operatorname{trace}(A_h A_h')}, \quad (8)$$

where $\sum_{h=0}^{H-1} a^2_{ij,h}$ is the error variance of the risk in commodity i in forecast period H caused by the impact of risk in commodity j, and $\sum_{h=0}^{H-1}\operatorname{trace}(A_h A_h')$ represents total forecast error variance in period H. Therefore, the above exhibits the proportion of single commodity. In general, $S^H_{i\leftarrow j} \neq S^H_{j\leftarrow i}$; we can define the effect of the net risk spillovers from commodity j to commodity i using the following formula:

$$NS^H_{i\leftarrow j} = S^H_{i\leftarrow j} - S^H_{j\leftarrow i}. \quad (9)$$

Moreover, the items in the "OUT" row denote the total items on the nondiagonal lines in each column, allowing us to measure the spillovers from commodity j to other commodities. The "IN" column and the total net effect are similar:

$$\begin{aligned} TS^H_{\mathrm{OUT},\cdot\leftarrow j} &= \sum_i S^H_{i\leftarrow j}, \quad \text{for } i \neq j, \\ TS^H_{\mathrm{IN},i\leftarrow\cdot} &= \sum_i S^H_{i\leftarrow j}, \quad \text{for } i \neq j, \\ NTS^H_i &= TS^H_{\mathrm{OUT},\cdot\leftarrow j} - TS^H_{\mathrm{IN},i\leftarrow\cdot} = \sum_i NS^H_{j\leftarrow i}. \end{aligned} \quad (10)$$

In addition, we can measure the overall system-wide total spillover effectively by summing and taking the average of the items in the "OUT" row or the "IN" column, as follows:

Table 1: Definition of risk spillover networks.

	ΔIV_1	ΔIV_2	…	ΔIV_n	IN
ΔIV_1	$S^H_{1\leftarrow 1}$	$S^H_{1\leftarrow 2}$	…	$S^H_{1\leftarrow n}$	$\sum_i S^H_{1\leftarrow j}, j \neq 1$
ΔIV_2	$S^H_{2\leftarrow 1}$	$S^H_{2\leftarrow 2}$	…	$S^H_{2\leftarrow n}$	$\sum_i S^H_{2\leftarrow j}, j \neq 1$
…	…	…	…	…	…
ΔIV_n	$S^H_{n\leftarrow 1}$	$S^H_{n\leftarrow 2}$	…	$S^H_{n\leftarrow n}$	$\sum_i S^H_{n\leftarrow j}, j \neq 1$
OUT	$\sum_i S^H_{i\leftarrow 1}, i \neq 1$	$\sum_i S^H_{i\leftarrow 2}, i \neq 2$	…	$\sum_i S^H_{i\leftarrow n}, i \neq n$	$\frac{1}{N}\sum_i S^H_{i\leftarrow j}, i \neq j$

$$STS^H_i = \frac{1}{N}\sum_i TS^H_{\mathrm{IN},i\leftarrow\cdot} = \frac{1}{N}\sum_i TS^H_{\mathrm{OUT},\cdot\leftarrow j} = \frac{1}{N}\sum_i \sum_j S^H_{j\leftarrow i}, \quad \text{for } i \neq j. \tag{11}$$

3.5. Data. When selecting samples, we do not consider energy trading indexes, such as Energy TR, because we focus on the three main categories of commodity markets: agriculture, metals, and energy. Considering the requirement of calculating systemic risk, we have selected market indexes (CRB) in the corresponding range. Considering the uniformity of the EMD, we only selected 13 commodity indexes to quantify the risk spillover between commodities from all the 16 commodities (the IMFs decomposed by sugar, soybeans, and gold are 3, 5, and 5, which are against the four IMFs of commodities). We choose global geopolitical risk to examine the spread of risks, even till commodity markets [63]. Since geopolitical risk (GPR) is monthly, in order to ensure data consistency, we choose monthly commodity index. In the meantime, providing the availability of data on the investing website, the initial sample was finally confirmed, from July 2005 to March 2021, with a total of 189 observation months. The logarithmic rate of return is the basis for calculating systemic risk, and we select the closing price of the 13 commodity indexes for calculation. As for the geopolitical risk index, we additionally perform HP filtering (Hodrick–Prescott filter) processing on it [59], because as a state variable in the STVAR model, it needs to have more obvious periodic attribute.

Figure 1 shows the fluctuations of GPR throughout 189 months, which shows an upward trend as a whole, and the purple shading marks the local maximum extreme points. In the past ten years, the global bulk commodity market has shown the following three trends: Major agricultural products fluctuated sharply at a relatively high level, especially undergoing a rapid rise from 2010 to 2011. Energy is showing a trend of upward volatility, and GPR seems to play an indispensable role in it, even being more pushing than other macro indicators [64]. However, after the gradual fading of the 9/11 incident and the breakthrough of the bottleneck in 2006, the metal just ushered in a rise. In order to further understand the mode of functioning extreme values, as to whether particular regularity exists, we sort out

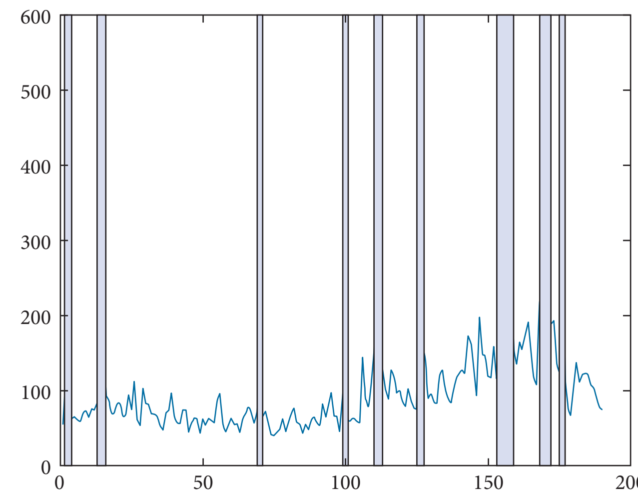

Figure 1: GPR index throughout 189 months.

the most effective precursor data according to the aforementioned research design.

Taking the actual observational law on extremum into consideration, it is uncommon to have multiple extrema within a month. Two or more consecutive fluctuations caused by one shock are usually regarded as one extremum. Therefore, the shortest precursor data sample period should be greater than one month, and the maximum period should not exceed one year, which match the habit of conducting economic accounting on an annual cycle. Based on this, we take half a year (6 months) and the first quarter (3 months) for one-element analysis of variance. Taking 3 months as a group, we found that, at a significance level of 10%, more possible subsamples will be generated, which meets the need for more samples for subsequent state decomposition. The entire data can be divided into 63 subsamples which are denoted as S_i, $i = 1, 2, \ldots, 63$, respectively. The samples that meet the definition of precursor data are the bold subsamples in Table 2, and there are 24 groups, for 72 observable months.

According to the F statistic, at a significance level of 10%, the above-mentioned 14 pairs of blackened samples all show strong rejection of the null hypothesis information; that is to say, extreme value generation information is most likely to be generated in this sample interval, since the statistic reaches its maximum locally. The excluded samples only reflect the "normal" data generation process and do not contain the important information of extremum generation; thus, those will not affect the accuracy of extremum analysis, which means that the elimination of some "redundant" samples greatly reduces the number of original samples to be studied. The precursor data sample improves the efficiency of extremum risk detection. Then, we associate the sample with time. The time period corresponding to $S2$-$S6$ is 2005-10 to 2006-12, $S10$-$S11$ is 2007-10 to 2008-03, and $S21$-$S22$ is 2010-07 to 2010-12. The time period corresponding to $S24$-$S25$ is 2011-04 to 2011-09, $S27$-$S28$ is 2012-01 to 2012-06, $S30$-$S31$ is 2012-10 to 2013-03, and $S36$-$S38$ is 2014-04 to 2014-12. Finally, the period corresponding to $S39$-$S40$ is 2015-01 to 2015-06, $S47$-$S48$ is 2017-01 to 2017-06, and

Table 2: Precursor data.

Sample	F value	P value	Sample	F value	P value
$S1$-$S2$	1.539	0.283	$S17$-$S18$	0.698	0.450
S2-S3	4.793	**0.094**	$S18$-$S19$	0.003	0.961
S3-S4	4.744	**0.095**	$S19$-$S20$	0.324	0.600
S4-S5	6.175	**0.068**	$S20$-$S21$	0.251	0.643
S5-S6	6.462	**0.064**	**S21-S22**	8.173	**0.046**
$S6$-$S7$	0.054	0.827	$S22$-$S23$	0.245	0.646
$S7$-$S8$	0.004	0.952	$S23$-$S24$	0.805	0.420
$S8$-$S9$	0.006	0.944	**S24-S25**	22.907	**0.009**
$S9$-$S10$	0.387	0.567	$S25$-$S26$	3.036	0.156
S10-S11	7.905	**0.048**	$S26$-$S27$	4.218	0.109
$S11$-$S12$	2.631	0.180	**S27-S28**	5.092	**0.087**
$S12$-$S13$	3.660	0.128	$S28$-$S29$	0.251	0.643
$S13$-$S14$	2.345	0.200	$S29$-$S30$	0.391	0.566
$S14$-$S15$	0.149	0.719	**S30-S31**	5.593	**0.077**
$S15$-$S16$	0.053	0.829	$S31$-$S32$	0.040	0.850
$S16$-$S17$	0.275	0.628	$S32$-$S33$	0.307	0.609
$S33$-$S34$	1.312	0.316	$S49$-$S50$	0.334	0.594
$S34$-$S35$	0.821	0.416	$S50$-$S51$	0.802	0.421
$S35$-$S36$	0.011	0.920	$S51$-$S52$	1.988	0.231
S36-S37	18.894	**0.012**	$S52$-$S53$	0.505	0.516
S37-S38	10.658	**0.031**	$S53$-$S54$	0.189	0.686
$S38$-$S39$	0.188	0.687	$S54$-$S55$	0.106	0.761
S39-S40	5.058	**0.088**	$S55$-$S56$	0.438	0.544
$S40$-$S41$	0.006	0.942	$S56$-$S57$	0.277	0.627
$S41$-$S42$	2.186	0.213	$S57$-$S58$	3.567	0.132
$S42$-$S43$	1.019	0.370	$S58$-$S59$	0.209	0.671
$S43$-$S44$	0.406	0.558	$S59$-$S60$	0.906	0.395
$S44$-$S45$	0.411	0.556	$S60$-$S61$	0.455	0.537
$S45$-$S46$	0.094	0.774	$S61$-$S62$	0.983	0.378
$S46$-$S47$	4.320	0.106	**S62-S63**	13.351	**0.022**
S47-S48	8.087	**0.047**			

$S62$-$S63$ is 2020-10 to 2021-03. Based on the time correlation of the above samples, the generation period range of extremum can be determined, and investors can hedge extremum risks and even predict part of systemic risk. The supervisory authority can select the early warning time to provide a preliminary risk disposal window. The 14 pairs of precursor data samples are further analyzed below, and the extremum generation law is further identified through EMD method.

The volatility of return has significant nonlinear characteristics [53, 65, 66]. In order to verify the rationality of the application of precursor data and STVAR model, plus the necessity of measuring systemic risk, we then perform the following mutation test. In this paper, BDS test [67], Chow test [68], and Quandt–Andrews test [69, 70] are used to test the stability of model parameters, which are constructed under the rate of return. Among them, Chow test is a known mutation point test, while Quandt–Andrews test is unknown points. Due to the small amount of sample data, for the BDS test in Table 3, EViews only supports nesting dimensions of 2, 3, and 4. The results show that the null hypothesis of independent and identical distribution is significantly rejected, indicating that there is a nonlinear relationship between the variables. The mutation point test indicates that the parameters of the model contain one or more mutation points, which means that the use of constant parameter estimation methods will lead to biased estimation results. In the Chow test, the known mutation points also appear in the precursor data reflecting the formation of extremum in Table 2, proving the rationality of applying the precursor data. The above sample selection and mutation test are based on the logarithmic rate of return.

4. Empirical Results

In this paper, we take the "disturbance" generated by extreme events as the starting point and define the sample as precursor data, which can be used as a driving factor to promote the generation of systemic differences, in turn contributing to the measurement of systemic risk. When the driving factors change, the future performance in the near future will be inevitably affected, which imposes higher demands on investors and regulators. Firstly, the EMD performs frequency decomposition according to the intrinsic attributes of the commodity index and obtains 5 frequencies which are denoted as IMF1, IMF2, IMF3, IMF4, and residual, respectively, representing high frequency (short term), low frequency (long term), and trend items. In addition, the IMF2 can be called medium-high frequency and the IMF3 can be called medium-low frequency. The signal in the figure represents the original time series. Then, using the GARCH-CoVaR model (Xu et al. argued that the method is effective) [71], the system risk in 13 commodities was obtained. This is the basic data for STVAR model and network analysis.

4.1. Empirical Mode Decomposition (EMD). From Figures 2–4 , we can see that all the decomposed IMFs gradually move from high frequency to low frequency, and their amplitude gradually increases. In addition, the last trend item is a time sequence for long-term trend of logarithmic rate of return of different commodities, which are described as the inner trajectory of the original sequence [55]. Both cocoa and natural gas are in a fluctuating state. The former rises after falling, while the latter rises and maintains fluctuations. "Live cattle" rises monotonically. Since the space of article is limited, we randomly selected one of the three types of commodity markets as a representative to show the effect of empirical mode decomposition, and take these three commodities as instances to analyze the main process of extremum formation and provide theoretical support for systemic risks.

When analyzing shocks in a typical sequence, the effects of shocks are usually viewed from the peak value, such as instantaneous, short-term and long-term effects. Shocks promote the formation of extreme values, and continuous shocks will drive the generation of systemic risks. Therefore, we start with peak value and look at the reflection of commodities in different frequency domains. We can grasp the following from the pattern of stock prices: if the stock price keeps rising without a callback, market risks will continue to accumulate, and even plummet and skyrocketing will occur, prompting the generation of extreme values, thereby finally making systemic risks high. However,

Table 3: Mutation point test.

BDS test at IMF1		Quandt–Andrews test at IMF1		Chow test at IMF1	
Dimension	Z statistic	Statistic	Value	Breaks	LLR F statistic
2	4.495935***	Max LR	4.217101***	2011.08	1.689893***
3	4.321284***	Exp LR	1.420065***	2013.03	3.549565***
4	4.289628***	Ave LR	2.583096***	2015.01	2.019895***
BDS test at IMF4		Quandt–Andrews test at IMF4		Chow test at IMF4	
2	11.06079***	Max LR	137.18***	2011.08.	108.105***
3	10.69458***	Exp LR	65.88216***	2013.03	22.81301***
4	11.51872***	Ave LR	77.28582***	2015.01	6.461639***

All data come from investing website, throughout 72 months. For the limited space, only two IMF components are displayed, and the rest are available on request. The BDS test is based on the residual series. *, **, and *** represent the significance test in which the model passed, respectively, under 10%, 5%, and 1%.

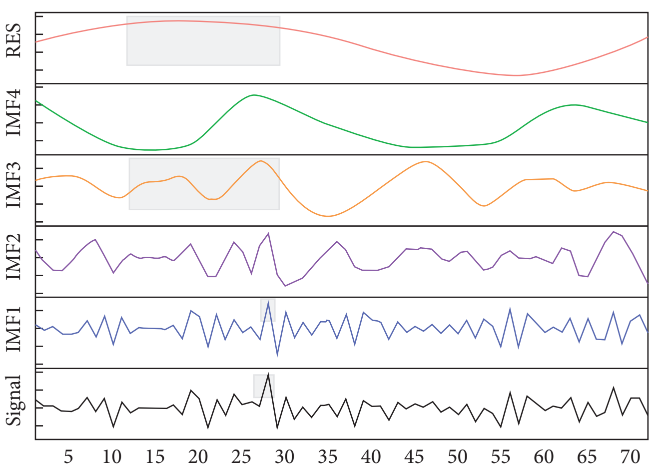

Figure 2: EMD under cocoa.

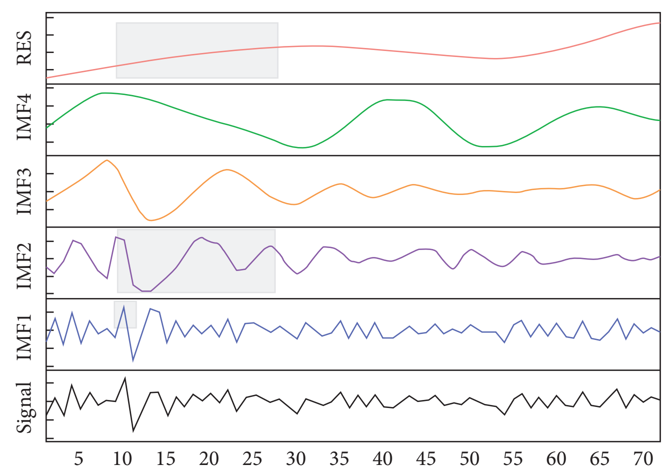

Figure 3: EMD under live cattle.

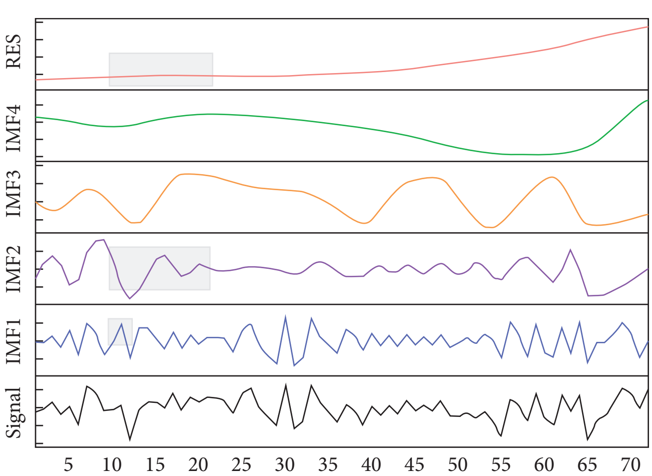

Figure 4: EMD under natural gas.

if the stock price is rising in a downward trend, the possibility of extreme value is relatively small, and the systemic risk is diversified. Based on this, we call the sequence that fluctuates periodically and becomes larger and larger at amplitude "continuous increase in amplitude," but there is no periodic feature and only the continuous increase in amplitude is called "peak superposition". What matters is whether the sign of "decay" was released.

In IMF1 representing the high frequency of Figure 2, we can clearly see that there are several obvious transitions, and we choose the transition within the scale 25-30 for analysis. In IMF3 representing low frequency, the characteristics of "continuous increase in amplitude" can be observed, while in the RES sequence that reflects the market trend [55], "peak superposition" is observed, and there is even no fallback displacement in the 0–25 segment, so cocoa generated an extremum at the corresponding position of the signal sequence, and the specific features have been marked with grey shadows in the figure. Similar analysis exists in Figure 3. Due to the significant "continuous reduction in amplitude" in IMF2 at scale 5-10, which offsets the "peak superposition" in the corresponding RES sequence, live cattle did not generate extreme values in the corresponding scale. However, in the scale 55-65, the shock appears and the following characteristics exist; thus, the extremum is shown naturally, which proves that combining the image features to explore the generation law is reasonable. The same is true for Figure 4, and the entire sequence of natural gas is relatively stable, compared to the previous two.

The frequency and amplitude of IMFs change over time, so that the period is not a constant value. Drawing lessons from Xia and Li [72], we use the fast Fourier transform method to calculate the IMF period. Because the commodity market price is affected by many factors [73], there is a small amount of "noise" in the spectrum, but the frequency of identifying the rate of return based on the peak in the power is still valid, and finally Table 4 is obtained. As far as the energy sequence is concerned, there is no significant increase or decrease in the period of transition from high frequency to low frequency, which can be understood as being in the center for a long time, which needs verifying. Only heating oil shows a sharp rise at high frequency. For metals, given their main attributes as substitutes, they are susceptible to external good or bad news and the risk transmission between commodities, such as the mutual fluctuations between oil prices and gold [74]. In contrast, agricultural products, as daily necessities, are stable, but due to certain force majeure effects, there is a lag in the transition to the low-frequency part, such as African swine fever. This may provide possible support for subsequent risk spillover network analysis.

Table 4: Fluctuation period under all IMFs.

	IMF1	IMF2	IMF3	IMF4
Cc	2.133333333	9.142439203	17.99856012	35.99712023
Wh	3.428532245	8	12.00048002	71.99424046
Cr	2.117657024	17.99856012	10.28594939	23.99808015
Oj	3.00003	7.1999424	10.28594939	71.99424046
Lc	3.27267967	5.999880002	14.40092166	71.99424046
Ni	2.32255667	10.28594939	17.99856012	71.99424046
Si	2.32255667	8	17.99856012	23.99808015
Lh	2.057147559	9.000090001	10.28594939	71.99424046
Al	3.00003	5.53832521	23.99808015	71.99424046
CO	2.571421225	5.53832521	23.99808015	35.99712023
Ug	2.057147559	5.53832521	14.40092166	35.99712023
Ng	2.057147559	14.40092166	14.40092166	23.99808015
Ho	2.117657024	5.53832521	23.99808015	71.99424046

The data in the table refers to the period calculated under FFT (fast Fourier transform).

4.2. Smooth-Transition Vector Autoregression (STVAR) Model Based on EMD. In the empirical mode decomposition, we obtain 4 frequency series. By analyzing the changing characteristics of the sequence, we converted some rules of extremum formation. The extreme value is a manifestation of systemic risk. Analyzing the contribution of different commodities to the entire commodity market constitutes systemic risk. From the previous analysis, the original time series exhibited nonlinear properties. Based on the unique performance of individual commodities in large categories of commodities, and the significant periodic differences between different frequencies, we will use frequency as the entry point. We use the STVAR model, combined with network analysis, and then try to analyze what functions as the center in the commodity market under different conditions at the same frequency and what the specific risk infection channels are.

Many research works involving commodity markets focus on GPR. When it comes to the external shock making a difference to the commodity market, the geopolitical risk won much attention. We continue to use geopolitical risk, a macroeconomic variable, to be linked to the overall macro environment [11]. The focus of the STVAR model is the state variable, which refers to GPR in this paper. The conversion of the state variable divides the original data into upward and downward intervals, that is, expansion and recession. With the year 2000 being considered as the boundary, Noguera-Santaella points out the asymmetry of GPR on the aspects of oil volatility [75], which coincides with the nonlinearity of the commodity market [12]. In the STVAR model, we regard the forecast periods as 60. The following data takes the 60th period as an example (we observed the risk spillover centers of periods 4, 8, 16, 32, and 60, respectively, and they are all consistent; the results are available on request). The basic data of STVAR is systemic risk. According to the SC criterion, the optimal lag order of basic VAR model is determined as 2. After estimating the GARCH-CoVaR model, 4 groups of systemic risk values are obtained.

As shown in Tables 5 and 6, we only select recession and expansion under IMF1 for display, and the results of other frequencies can be provided upon request. As Tan and Pedersen said, the combination of frequency domain analysis and network analysis will greatly improve data performance [76]. Taking Table 5 as an example, the values at the edges of the matrix are total values, representing the horizontal or vertical value of a certain commodity. The "TO" row represents the risk spillover of a certain commodity against other commodities in the market, which is an arrow. The "FROM" list indicates that, from the perspective of the total market size, to measure the risk spillover of a certain commodity against other commodities, it is an entry arrow corresponding to the network below. Therefore, the middle of the matrix refers to the risk spillover between the mutual one. The "NET" in the bottom row refers to the net spillover effect of a certain commodity; that is, the output value of the "IN" column offsets the input of "OUT". Figures 5–12 show the complex risk spillover network of the commodity market, which can be used to study the path of risk contagion. The network is composed of nodes and edges with arrows. The size of the node is set according to the degree of weight, and the net risk spillover amount represented by the value of the "NET" row of the spillover matrix (Table 5) is used as the weight. The larger the net spillover, the larger the node. The color of the node is determined according to the "modularity" value in the "Gephi" statistical attribute, which means that the similarity of risk between different commodities shows the same community attribute, and the color of the edge changes accordingly.

Risk spillover is a change throughout the overall system. We need to focus on not only a single commodity, but also the path conversion between different commodities in which Billio et al. introduce connectivity into the explanation [43]. We will perform analysis from three perspectives, which will also give investors more comprehensive guidance for portfolio investment. The first part is Figure 5 to Figure 12, a comprehensive visualization of the risk spillover network. The size of the node is composed of the weight of the risk spillover value between commodities and the net spillover of a single commodity; the second part for systemic risk of all commodities is just ranked at the net spillover, highlighting the top three commodities with different degrees of grey

Table 5: Risk spillover matrix under expansion of IMF1.

	Cc	Wh	Cr	Oj	Ni	Si	Lh	CO	Ug	Ng	Lc	Al	Ho	FROM
Cc	0.0428712	0.0332439	0.0731087	0.0319171	0.0495036	0.0247965	0.0416115	0.0842788	0.0515880	0.0493821	0.0755224	0.0608856	0.0605431	0.6792527
Wh	0.0397173	0.0352717	0.0729161	0.0318707	0.0504014	0.0242926	0.0420792	0.0855124	0.0508886	0.0490948	0.0740041	0.0617530	0.0591057	0.6769077
Cr	0.0431782	0.0346479	0.0773520	0.0326877	0.0485845	0.0241383	0.0402560	0.0815732	0.0569014	0.0455663	0.0740268	0.0610422	0.0659138	0.6858682
Oj	0.0401285	0.0344386	0.0737487	0.0327925	0.0495128	0.0244594	0.0419035	0.0861956	0.0520853	0.0487143	0.0739330	0.0621767	0.0599086	0.6799975
Ni	0.0421338	0.0348294	0.0753653	0.0328415	0.0496776	0.0241245	0.0399402	0.0812712	0.0556142	0.0453477	0.0730124	0.0600958	0.0635854	0.6778390
Si	0.0417091	0.0344404	0.0756533	0.0326129	0.0498404	0.0247570	0.0405579	0.0813094	0.0549826	0.0467451	0.0738298	0.0610038	0.0629708	0.6804125
Lh	0.0431206	0.0339864	0.0791298	0.0320563	0.0481215	0.0248148	0.0413052	0.0810868	0.0602149	0.0462484	0.0748332	0.0613111	0.0677526	0.6939818
CO	0.0394229	0.0344091	0.0722578	0.0330673	0.0495246	0.0247392	0.0414687	0.0835818	0.0525702	0.0480689	0.0742857	0.0621666	0.0602369	0.6757997
Ug	0.0395861	0.0344556	0.0720033	0.0331725	0.0496498	0.0246967	0.0413121	0.0826926	0.0521243	0.0480278	0.0741362	0.0619702	0.0604541	0.6742813
Ng	0.0402026	0.0343818	0.0738222	0.0327652	0.0501671	0.0251919	0.0403016	0.0841636	0.0523128	0.0474212	0.0735155	0.0572283	0.0624298	0.6739037
Lc	0.0403499	0.0334111	0.0751091	0.0319867	0.0485364	0.0249878	0.0426534	0.0844910	0.0559202	0.0483264	0.0775604	0.0612091	0.0625932	0.6871348
Al	0.0395946	0.0345461	0.0719476	0.0330817	0.0499285	0.0246620	0.0414280	0.0830090	0.0520959	0.0482458	0.0743956	0.0618692	0.0599996	0.6748038
Ho	0.0394387	0.0345845	0.0720316	0.0330661	0.0498825	0.0246449	0.0413996	0.0829154	0.0520275	0.0481313	0.0742176	0.0620176	0.0601568	0.6745141
TO	0.5314535	0.4466465	0.9644456	0.4239181	0.6433309	0.3203056	0.5362169	1.0820807	0.6993260	0.6193203	0.9672727	0.7947293	0.8056504	
NET	**−0.1477991**	**−0.2302611**	**0.2785774**	**−0.2560794**	**−0.0345081**	**−0.3601069**	**−0.1577649**	**0.4062811**	**0.0250447**	**−0.0545834**	**0.2801379**	**0.1199255**	**0.1311362**	

Table 6: Risk spillover matrix under recession of IMF1.

	Cc	Wh	Cr	Oj	Ni	Si	Lh	CO	Ug	Ng	Lc	Al	Ho	FROM
Cc	0.0757881	0.0540912	0.0894513	0.0336452	0.0337702	0.0340156	0.0349050	0.0791376	0.0601376	0.0417904	0.0966100	0.0419262	0.0553822	0.7306506
Wh	0.0664844	0.0596065	0.0907245	0.0340228	0.0340127	0.0343304	0.0354085	0.0792662	0.0600895	0.0412983	0.0956673	0.0420373	0.0549026	0.7278511
Cr	0.0707467	0.0534066	0.0936419	0.0340064	0.0336671	0.0315998	0.0355536	0.0811631	0.0654544	0.0419619	0.0941784	0.0431525	0.0556531	0.7341855
Oj	0.0668243	0.0571968	0.0911234	0.0365418	0.0339400	0.0349268	0.0351271	0.0802267	0.0607300	0.0413272	0.0955810	0.0422777	0.0552043	0.7310270
Ni	0.0687607	0.0545507	0.0915787	0.0346283	0.0360147	0.0324190	0.0348136	0.0786629	0.0639822	0.0411118	0.0928871	0.0417136	0.0561880	0.7273112
Si	0.0682506	0.0547886	0.0923899	0.0340142	0.0349567	0.0343874	0.0352450	0.0787353	0.0642043	0.0410569	0.0939340	0.0421593	0.0562046	0.7303268
Lh	0.0707486	0.0520683	0.0943607	0.0344371	0.0340977	0.0316344	0.0367723	0.0822939	0.0665167	0.0427484	0.0935673	0.0441149	0.0562893	0.7396496
CO	0.0662714	0.0578649	0.0906695	0.0349559	0.0341782	0.0351625	0.0350523	0.0794499	0.0601410	0.0408308	0.0955515	0.0422246	0.0556718	0.7280243
Ug	0.0669504	0.0577501	0.0901717	0.0347458	0.0342759	0.0349119	0.0349195	0.0780587	0.0602226	0.0407391	0.0954482	0.0421822	0.0555814	0.7259577
Ng	0.0659642	0.0558187	0.0907076	0.0346549	0.0365611	0.0338728	0.0338246	0.0775050	0.0614921	0.0430374	0.0935771	0.0406742	0.0562909	0.7239803
Lc	0.0665907	0.0534601	0.0922831	0.0342828	0.0335609	0.0343838	0.0381219	0.0808364	0.0608823	0.0422692	0.1015395	0.0427964	0.0554652	0.7364723
Al	0.0667808	0.0580175	0.0902212	0.0350977	0.0346018	0.0350204	0.0349336	0.0780529	0.0597844	0.0407649	0.0955099	0.0422881	0.0554430	0.7265164
Ho	0.0664569	0.0582704	0.0903898	0.0347809	0.0344021	0.0348949	0.0349428	0.0780189	0.0600241	0.0407123	0.0954832	0.0421323	0.0556362	0.7261448
TO	0.8866178	0.7268903	1.1877133	0.4498139	0.4480390	0.4415596	0.4596197	1.0314077	0.8036613	0.5396487	1.2395345	0.5496792	0.7239126	
NET	**0.1559672**	**−0.0009608**	**0.4535278**	**−0.2812131**	**−0.2792722**	**−0.2887672**	**−0.2800299**	**0.3033834**	**0.0777035**	**−0.1843316**	**0.5030622**	**−0.1768372**	**−0.0022322**	

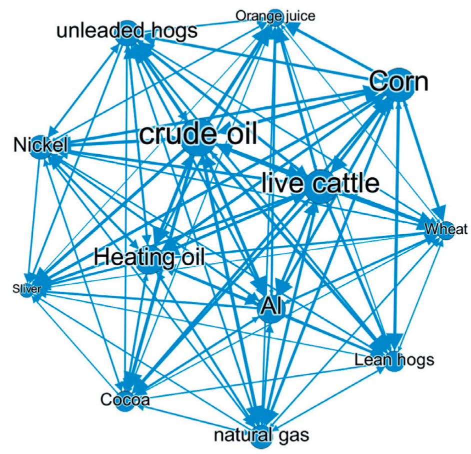

Figure 5: Risk spillover network under E1.

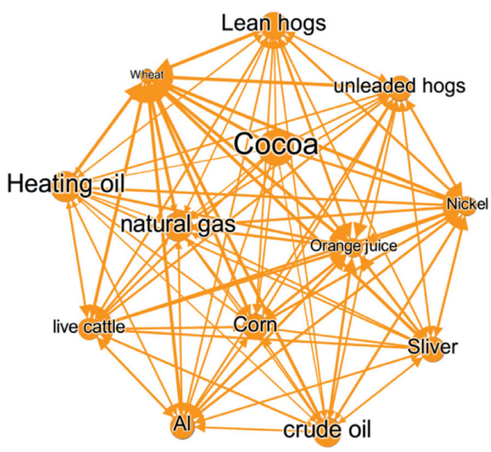

Figure 6: Risk spillover network under E2.

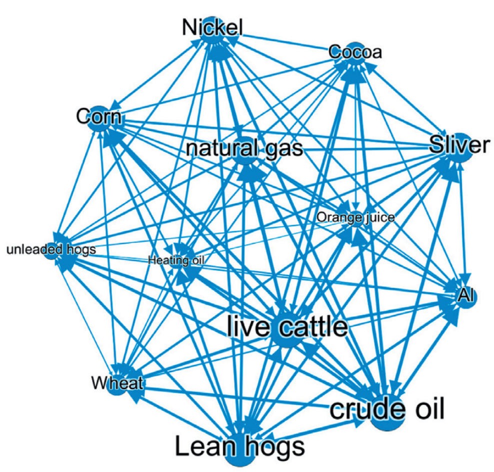

Figure 7: Risk spillover network under E3.

(Table 7); the third part is the risk spillover path of the top 5 under mutual commodities, meaning that one contributes to the whole (Table 8).

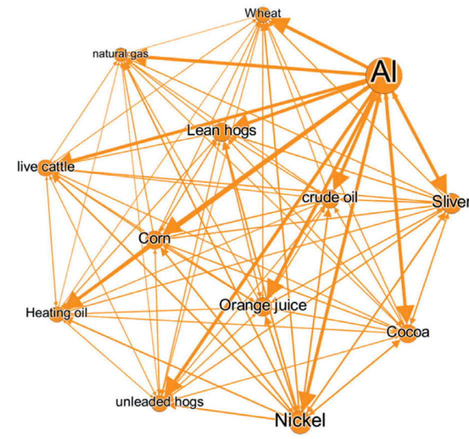

Figure 8: Risk spillover network under E4.

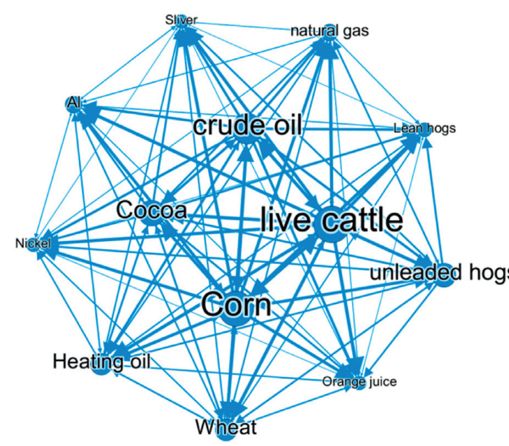

Figure 9: Risk spillover network under R1.

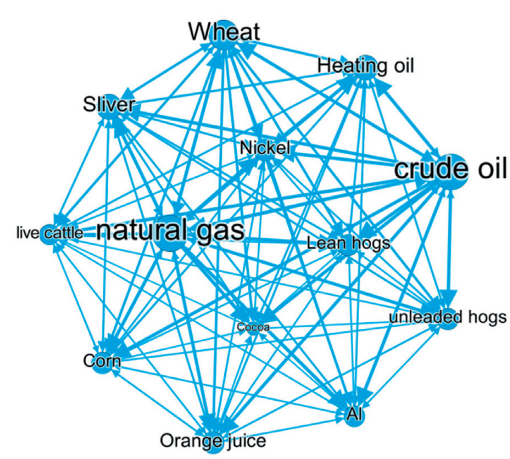

Figure 10: Risk spillover network under R2.

On the whole, the different frequencies under the pre cursor data did not change the "modularity" of different commodities, meaning that all characteristic is harmonious to some extent. In most cases, energy category of

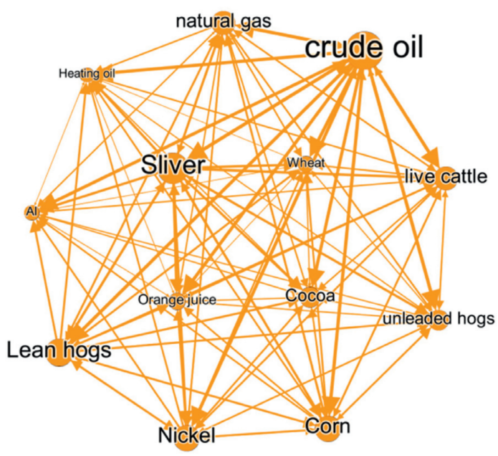

Figure 11: Risk spillover network under R3.

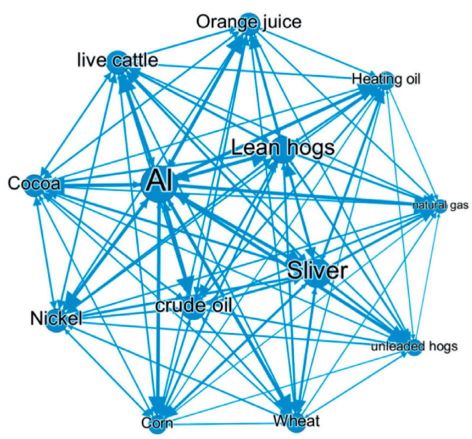

Figure 12: Risk spillover network under R4.

Table 7: Ranking under all regimes and IMFs at weight.

Rank	R1	E1	R2	E2	R3	E3	R4	E4
Cocoa	4	9	13	13	9	8	8	6
Wheat	6	11	3	1	11	10	9	12
Corn	2	3	8	8	4	7	10	7
Orange juice	12	12	7	2	10	12	7	4
Nickel	10	7	6	3	5	6	6	2
Sliver	13	13	4	7	2	4	2	3
Lean hogs	11	10	11	9	3	3	3	5
Crude oil	3	1	2	11	1	1	4	8
Unleaded gas	5	6	9	6	8	11	12	10
Natural gas	9	8	1	10	6	5	13	13
Live cattle	1	2	12	4	7	2	5	9
Al	8	5	10	5	12	9	1	1
Heating oil	7	4	5	12	13	13	11	11

commodities is the main risk exporter, and the research of many scholars is tenable [19, 20, 77]. However, the relationship between commodities changed. Taking Figure 12 for example, metal is the risk center, and its risk spillover further exceeds that of other commodities. When faced with more changes in state, we might as well put our perspective on the place where there is a change. Under this low-frequency sequence (IMF4), it can be seen that Al has always remained at the risk spillover center in both states, while the energy category has been overtaken by the commodity category, as can be seen from the strong risk spillovers of orange juice and lean hogs. Under IMF2 and IMF3, the boundaries between risks of different commodities are very clear. Although crude oil is still the risk center, there are a large number of other commodities surrounding it, which may eventually develop into a competition circle for three types of commodities. In other words, the joint volatility emerged [78]. Particularly, under IMF2, during the recession of geopolitical risks, cocoa surpassed heating oil to become the center of risk spillover, and the risk level of sliver and natural gas is equivalent. When focusing on oil, we can also find that, in the long run, geopolitical risk is more closely related to crude oil, which is inconsistent with the short-term view of Mei et al. [79]. From a vertical perspective, the network in different states maintains the position in a bigger picture, but there is a clear tendency of bigger risk degree [19].

When just concentrating on the net spillover (Table 7), we can observe that the changes in IMF1, IMF3, and IMF4 are delicate, and they are just fine-tuned under the same category. However, under IMF2, recession to expansion produced a large displacement change. When GPR is relatively strong and the sequence is under high frequency (E2), wheat is the center of risk spillover, followed by orange juice and then sliver, which is different from the risk aversion properties of oil and gold in the common perception [80–82]. However, in the period of geopolitical risk declining (R2), the risk spillover of energy commodities returned upward. It is worth noting that wheat only retreated to the third position, and the huge potential of risk in the near future may be deduced. However, during the expansion period at the same frequency, Figure 8 shows that cocoa is the risk center, which does not match the net risk spillover ranking of wheat in the table. Although it is still in the same category, this enlightens us on the path and dynamic changes analysis within the network [39, 42] to understand the risk transformation process in more detailed approaches.

Among the top five contagion paths that contribute to the entire commodity market (Table 8), the performances of recession and expansion are not the same. In the expansion period, the cumulative value continues to rise and reaches the highest value at low frequencies, while that of recession period presents an inverted “V” shape; that is, the medium-low frequency is the point in which the risk reaches the maximum, and then the risk gradually decreases. IMF3 has also become a key point for the exchange of the two states. However, the overall contribution of the recession period to the risk is greater than that of the expansion period, which is similar to the current situation reflected by oil, and the fact that the geopolitical crisis in the Middle East has made the world pay more attention to the import and export of oil is revelatory [77]. In the specific infection path, all regimes except for E2 are consistent with the net spillover risk ranking; that is, it is more reasonable to use the product with

Table 8: Infection path under all regimes and IMFs.

Rank	R1	R2	R4
1	Live cattle⟶cocoa	Natural gas⟶crude oil	Al⟶cocoa
2	Live cattle⟶wheat	Natural gas⟶heating oil	Al⟶natural gas
3	Live cattle⟶orange juice	Natural gas⟶Al	Al⟶orange juice
4	Live cattle⟶crude oil	Natural gas⟶wheat	Al⟶unleaded gas
5	Live cattle⟶Al	Natural gas⟶cocoa	Al⟶heating oil
Acc.	**48%**	53%	**50%**
Rank	R3	E1	E4
1	Crude oil⟶sliver	Crude oil⟶orange juice	Al⟶nickel
2	Crude oil⟶unleaded gas	Crude oil⟶wheat	Al⟶unleaded gas
3	Crude oil⟶live cattle	Crude oil⟶live cattle	Al⟶natural gas
4	Crude oil⟶lean hogs	Crude oil⟶cocoa	Al⟶lean hogs
5	Crude oil⟶wheat	Crude oil⟶natural gas	Al⟶sliver
Acc.	**59%**	42%	**78%**
Rank	E2	E3	
1	Nickel⟶wheat	Crude oil⟶sliver	
2	Orange juice⟶wheat	Crude oil⟶lean hogs	
3	Lean hogs⟶wheat	Crude oil⟶orange juice	
4	Sliver⟶wheat	Crude oil⟶Al	
5	Live cattle⟶wheat	Crude oil⟶live cattle	
Acc.	43%	51%	

the strongest spillover as the sender of the risk. The special performance of E2 echoes the above-mentioned contradiction. Although it is the product with the strongest net spillover, from the perspective of the relatively large risk transmission path, wheat is just only the receiver of risks, and three of them are transmitted by lean hogs, orange juice, and live cattle, which are also agricultural commodities, which explains this noncentral position in the weighted out-degree. As argued by Gardebroek et al. [13], strong volatility interactions across commodities reduce the effectiveness of diversifying price risk. This suggests that investors and risk managers should account not only for a commodity's own dynamics but also cross-commodity volatility connectedness when predicting the volatility behavior of commodity prices.

In recent years, many sudden surges in the commodity market have become a major cause of instability in systemic risk. Moreover, as time increases, the nonlinear characteristics of systemic risk become the focus of research. We combine commodity markets with geopolitical risk and enrich the current research on systemic risk contagion in the frequency domain through the STVAR model based on EMD. Extremum is composed of "continuous increase in amplitude" and "peak superposition," and positive correlation will produce extremum; otherwise, no extremum will appear. For investors, from the perspective of preventing risks, it will become an important concern in the long run. Under different frequencies, there are differences in the reaction of risk spillovers of commodities. In the medium-high term, energy commodities perform poorly, and their risk center position is shaken. This may provide guidance for investors to diversify their investment portfolios throughout time. Similarly, the joint volatility between different commodities cannot be ignored. In extremely unstable energy market, the agricultural commodity market may also be a risk aversion option.

5. Conclusion

The starting point of this research is to show the inherent characteristics of commodity changes and to provide investors with risk portfolio options. By combining empirical mode decomposition with the STVAR model, the nonlinear research on systemic risk has been enriched from theoretical and empirical perspectives. On the one hand, our research selects precursor data containing extreme value forming factors and eliminates the data with deviations. On the other hand, we continue to expand our research from the classic frequency domain perspective to the states' transformation brought by the state variables. Finally, we analyze the reasons for the formation of extreme values from a theoretical perspective; that is to say, the extreme value is composed of "continuous increase in amplitude" and "peak superposition." At the same time, we utilize the characteristics of macro variables to replace externally assigned one by quantiles. On the whole, risk spillover of energy commodities is stronger, especially in medium-low frequency. Only in the longest term, they are replaced by metals. Under different states of geopolitical risks, the joint fluctuations between three categories of commodities have emerged. Agricultural commodities become another place for gathering risks, and metal commodities are only behind. For the holding period and portfolio investments, the decision needs comprehensive consideration.

This research reveals the rationality of introducing the internal characteristics of macro variables to divide the state, that is, using the macroeconomic market itself to influence performances of commodity market. Whether the integration of state variables into systemic risk causes changes in risk centers and spillover channels is worth investigating. Applying different state variables, such as political uncertainty, is also worthy of expansion. However, in view of the differences between the overall and partial conditions, the internal transformation motivation of risk spillovers in commodity markets under different frequencies still needs further study.

Data Availability

Our original data were obtained from https://cn.investing.com and http://www.policyuncertainty.com/.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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Research Article

Understanding the Complexity of Business Information Dissemination in Social Media: A Meta-Analysis of Empirical Evidence from China

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With the development of social networks, the complexity of the factors affecting the users' information dissemination is increasing and the complexity of online social networks and influencing factors of individual behaviors and attitudes make the development of online public opinion present a dynamic, complex, and multifactor evolution. Analyzing the influencing factors of public opinion dissemination is conducive to optimize company management and information diffusion management. However, there has been no comprehensive analysis of the complex factors that influence the dissemination of information; this study focused on synthesizing 20 empirical studies on the influencing factors of China public opinion dissemination from the perspective of the user, and a meta-analysis was conducted. We establish the influencing factors of users' information adoption model from three aspects of information source reliability, perceived information quality, and the heat of public opinion events based on elaboration likelihood model. The results indicated that the main influencing factors of public opinion communication are authority, reliability, quality of information form, quality of information editing, quality of information utility, and event attendance preference. Among the factors, authority and quality of information editing have more significant impacts on users' information adoption behavior in the dissemination of public opinion. In addition, whether the type of event was a public emergency had a moderating effect. The results are helpful to explore the universality of the influencing factors so as to help related regulators better build a multiangle supervision mechanism and conduct early warning of information diffusion.

1. Introduction

With the rapid development of online social networks, various types of social media communication platforms and information dissemination platforms are constantly emerging, and people participate in public opinion discussions in a variety of ways. The development of the Internet has provided new platforms for the formation and dissemination of public opinion. Social networks have become the main channel for the dissemination of public opinion [1]. Users are no longer limited by time and space. Currently, they can participate in the discussion and dissemination of public opinions through social networks at anytime and anywhere.

While the growth of online social platforms can yield many benefits, some hidden dangers also exist. Online public opinion has a low threshold for participation and fast fermentation speed, which easily breeds false and harmful information. Once negative public opinion information is spread out of control or even evolves into a public opinion crisis, it will bring serious challenges to social security and stability. Therefore, how to effectively obtain public opinion and give full play to the role of media, opinion leaders, and the government on the basis of safeguarding citizens' freedom of speech and construct multiangle supervision mechanism to realize the maintenance and construction of benign public opinion ecology is an important issue that people should concerned about. In addition, in the commercial field, public opinion information provides an important reference for enterprise product research and development, marketing, brand building, and so on and plays an extremely important role in crisis management, creating economic value that cannot be ignored for enterprises.

For the past few years, compared with the traditional sociological perspective and communication perspective, the proportion of literature studies on public opinion studies using complex networks has significantly increased. A large number of empirical studies have shown that small-world networks and scale-free networks can reasonably and accurately describe the communication networks in the real world [2]. At the same time, the network groups that participate in the communication of public opinion are unstable. In the evolution process of public opinion, the change of microindividual attitude in the network is affected by a variety of factors. Therefore, the complexity of online social networks and the complexity of the influencing factors of individual behaviors and attitudes make the development of online public opinion present a dynamic, complex, and multifactor evolution.

In recent decades, there has been an increasing number of studies in the field of public opinion spread. These studies mainly involve the mechanisms, evolutionary mechanisms, governance, and characteristics of public opinion spread. Additionally, the influencing factors of public opinion dissemination have gradually become a hot topic. As early as the last century, Shannon pointed out in his information theory that the communication process of public opinion is affected by four elements, that is, the information source, trust, information, and channel [3]. In recent years, scholars in China have conducted abundant empirical studies on the influencing factors of public opinion dissemination. Researchers and organizations have sought the factors that influence public opinion dissemination, thereby ultimately provided a theoretical basis for the control of public opinion. Zhang et al. built a model from the perspective of information source characteristics and information form and studied the dissemination of public opinion on Sina Weibo [4]. It was concluded that the characteristics of information sources were the main influencing factor, the number of followers played a mediating role, and the related factors of information form had no significant influence. Yin conducted an empirical study on the influencing factors of WeChat public platform information dissemination, and the results showed that the heat of articles was correlated with the theme, push time, and title characteristics to a certain extent [5]. Based on the perspective of consumers, Zhang concluded that the professionalism of negative public opinion communicators and the network involvement of receivers influence the repurchase intention of passengers through the perceived usefulness and perceived risk of public opinion [6]. Liao et al. combined the 5W communication mode of Harold Lasswell and agenda-setting theory to propose hypotheses of information dissemination factors and found that opinion leaders had the greatest influence on the spread effect among communication groups, the attributes of Weibo publishers were positively correlated with the spread effect, and the amount of information was negatively correlated with the communication effect [7]. Gu et al. based on expectation confirmation theory, online trust theory, and immersion theory integrally proposed that users' perceived usefulness of public opinion, online trust, the convenience of link sharing, and other factors are related to users' willingness to spread public opinion [8]. In addition, according to the perspective of information ecology, Zhao concluded through relevant analysis that the information environmental heat, information preference, information technology preference, and the influence of microblog public opinion information personnel in the new media environment would positively influence the communication situation of microblog public opinion in the new media environment [9].

Although there have been numerous empirical studies on the influencing factors of public opinion dissemination over the past decade, most of them did not reach a consensus due to the complexity of the public opinion communication network and the complexity of the influencing factors of user behavior, and there are few comprehensive analyses of different research conclusions. This resulted in inconsistency among the existing independent empirical research results in this research direction. Therefore, we used meta-analysis to comprehensively analyze the results of previous empirical studies. Meta-analysis is a research method that forms a consistent conclusion and promotes the longitudinal development of research by summarizing and synthesizing existing multiple conclusions and further theoretical results [10]. Meta-analysis is a scientific research method used to summarize and evaluate existing research results. Compared with traditional literature reviews, a meta-analysis takes each research as a sample, and it can identify heterogeneity between multiple research results, integrate the research results, improve the accuracy of the test results, reduce the subjectivity of the research, and allow more objective conclusions to be drawn.

In view of this, using the meta-analysis method to synthetically analyze different research conclusions about factors affecting the spread of public opinion from the perspective of the user is of practical importance.

Therefore, to address their limitations and to the differences in the degree and direction of different research results, this article collects China and builds a users' public opinion information adoption behavior model based on the elaboration likelihood model to explore the general factors affecting public opinion dissemination and promote the in-depth development of research on the influencing factors of public opinion dissemination. A meta-analysis of the literature was conducted to comb and reanalyze the relevant empirical studies in this field and integrate a large volume of results to determine whether the research findings were homogeneous. We aimed to achieve the following goals:

(1) Propose relevant hypotheses about the influencing factors of users' information adoption behavior in public opinion spread based on the existing relevant literature, quantitatively combine the independent research results through a meta-analysis, and then qualitatively test the hypotheses.

(2) Examine the convergence or divergence of published research results by conducting a quantitative meta-analysis and try to analyze and explain the

controversial conclusions with large samples and universal adaptability. Discuss the factors influencing the universality of network public opinion communication from the perspective of quantitative research, discover the social and economic value of public opinion information, and provide valuable theoretical reference and practical reference for the government as well as enterprises to adjust and optimize the risk management mode of public opinion information.

(3) Explore the moderating variables that may influence the research results and provide new insights for future research.

2. Theoretical Background and Hypotheses

2.1. Definition of Information Adoption Behavior. The concept of information adoption comes from technology adoption theory, which has gradually become a hotspot in the field of library and information science. With the expansion and development of technology adoption theory, studies on users' information adoption behavior are gradually enriched. At present, there is no unified definition of information adoption behavior among scholars. Cheung et al. [11] gave a simple descriptive description of information adoption and information adoption behavior in their discussion; that is, "information adoption is a process in which people make purposeful use of information. Information adoption behavior is one of the main behaviors that users seek behavior guidance in virtual groups." Song believes that information adoption is a decision-making process in which users take the initiative to select and judge information based on their own needs and finally make a decision about whether to adopt the information [12]. Geng proposes that information adoption is the selection and evaluation of information as well as the absorption and utilization of information [13]. This paper holds that, in the field of public opinion spread, information adoption refers to the behavior that users make choices and judgments on complex and changeable public opinion information, and they adopt it based on the recognition of the utility of the information. Information adoption includes the following forms: information forwarding, comments, thumbs-ups, and so on.

2.2. Elaboration Likelihood Model. In empirical research on users' information adoption behavior, the theories include the technology acceptance model, rational behavior model, information adoption model (IAM), elaboration likelihood model, and others. The ELM is the most representative model for explaining the intention to adopt information, which has been supported by a large number of empirical studies. The elaboration likelihood model (ELM) originated from research in the field of social psychology. As a persuasion model, it has been widely used in research on attitude, social communication, and consumer behavior. The model assumes that there is a possibility interval of fine machining when information receivers process persuasive appeals, and one of the fundamental dimensions of information processing and attitudes is the depth and quantity of the information processing. In this paper, the ELM is used to analyze and explain the factors that affect users' information adoption behavior in public opinion dissemination. In the ELM, the process by which people change their attitude and behavior under the influence of an information source is described using two information processing paths, namely, the central route and peripheral route [14, 15]. The central path refers to the process in which the information receiver needs to change his or her attitude or behavior after thorough reading and high effort thinking about the characteristics of the information. Information traits are mainly related to a series of qualities of the information content such as its novelty and objectivity. For example, consumers carefully analyze and summarize the information content provided by product advertisements instead of forming purchase decisions based on the attractiveness of advertising spokespersons [16]. The marginal path refers to the process in which the information receiver changes his attitude or behavior by investing a little energy and time in the peripheral clues related to the problem and thinking with low effort. Information peripheral cues are mainly related to the characteristics of information sources, such as the reliability and authority of information sources, which can be used as peripheral cues to cause attitude changes under certain circumstances [11].

Based on the above, the elaboration likelihood model process is shown in Figure 1.

2.3. Models and Hypotheses. According to the ELM, users' information adoption behavior is jointly affected by the quality of the information content and the characteristics of the information sources [14]. In addition, research has suggested that people's motivation to forward popular microblogs is greater than that to forward ordinary microblogs and that the duration of the influence of popular microblogs is longer than that of ordinary microblogs [17]. Additionally, according to the research, the length of time that the microblog information spreads is related to the degree to which it is convenient for Internet users to obtain the information. If users can more easily obtain the information, this information can have a more continuous influence [18]. Therefore, public opinion events with high heat equivalent in the spotlight in the field of public opinion contain information that is easier for netizens to pay attention to and obtain. Based on this, we considered the heat angle of public opinion events to more comprehensively study the factors affecting users' information adoption behavior. Since people's attention preference for hot events is based on simple reasoning and judgment and they do not spend much time and energy on cognition and thinking, this variable is included in the edge path of the ELM.

2.3.1. The Influence of Information Source Reliability on Users' Information Adoption Behavior. Information source reliability refers to the degree of trust of information receivers in information sources [19], and it can be used as an

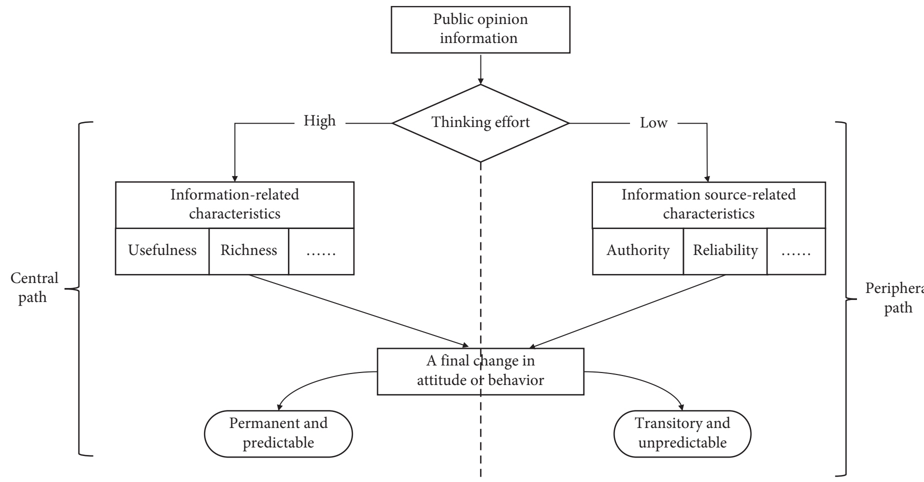

Figure 1: The elaboration likelihood model process.

important reference index of information persuasion. Research on source reliability mainly involves authority and reliability. According to existing studies, source reliability has a significant impact on the persuasion process. Under the condition of consistent information content, individuals are more likely to be persuaded when the source is highly reliable [20]. In addition, some studies have shown that authority and professionalism are important factors for celebrities to be more easily noticed and sought [21, 22]. The professionalism of bloggers is closely related to their reliability, which is an important screening mechanism for users for a large number of blog posts [15]. The authority of the information source includes authentication, identity type and the reliability of the information source. Authority refers to the trustworthiness of the information publisher perceived by the audience. Many scholars regard the number of followers as an important factor for representing the effect of information communication [23, 24], as well as the account level, which is mainly judged by the identity of an opinion leader. Therefore, we formulated the following hypotheses:

H1: the authority of the information source is positively related to the information adoption behavior of users

H2: the reliability of the information source is positively related to the information adoption behavior of users

2.3.2. The Influence of Perceived Information Quality on Users' Information Adoption Behavior. The central path in the ELM mainly involves the judgment of the information quality. Information quality is generally related to the characteristics of the information content itself, such as the novelty and objectivity of the information [11]. Previous studies have shown that perceived information quality positively influences users' willingness to communicate [25]. Information quality is generally related to the characteristics of the information content. This paper divides information quality into three categories: information form quality, information editing quality, and information utility quality. Information form quality refers to the information content features that can meet the information needs of the public and bring value to the public, including the richness of the information, such as whether there are videos, pictures, and microtopics. Studies have found that rich information forms contribute to readers' perception and memory of information [17], thus increasing the readability of information content and ultimately stimulating users' information adoption and sharing behavior. The information editing quality can be measured by the formality of the information editing format, and the professionalism of information editing and publishing can make the information more credible, including the integrity and reliability of the information. Information utility quality refers to the public's evaluation of whether event information can meet their needs and the information receivers' experience and perception of the information value. Specific measurement indexes include the usefulness (the gap between the information content and the public's expectations), timeliness, and relevance (the information is related to the public's purposes of use).

Consistent with this, our meta-analysis tested the following hypotheses:

H3: information form quality is positively related to users' information adoption behavior

H4: information editing quality is positively related to users' information adoption behavior

H5: information utility quality is positively related to users' information adoption behavior

2.3.3. Influence of the Heat of Public Opinion Events on Users' Information Adoption Behavior. The heat of a public opinion event refers to the overall attention to and degree of discussion of the event in the information environment. In this paper, the heat of public opinion events is divided into two dimensions: event attention preference and information environment heat. Research shows that microaffairs with different themes cause different scales of forwarding and attention [26]. In addition, through intercepting a week's microblogs and classifying their nature, some studies have found that fresh event information accounted for the highest proportion (33%) [27]. The extent to which the public prefers to pay attention to events often affects their behavior of expressing their opinions, thoughts, or emotions. The heat of the information environment refers to the heat of the social discussion on events. Hot events are more likely to arouse users' interest. For example, on microblogging platforms, hot microblogs and hot search topics are more likely to attract users' attention and participation [17].

Based on this, we tested the following hypotheses:

H6: event attention preference is positively related to users' information adoption behavior

H7: the heat of the information environment is positively related to the information adoption behavior of users

2.3.4. The Moderating Effect of the Types of Public Opinion Events. In the literature included in the meta-analysis, we noticed that the types of sample events in some studies were public emergencies, such as natural disasters, public health events, and social security events. According to the Emergency Response Law of the People's Republic of China, emergency events refer to natural disasters, accidents, disasters, public health events, and social security events that occur suddenly, cause or may cause serious social harm, and require emergency measures. Due to the particularity of public emergencies, users' adoption behaviors for public opinion information about these events may be different from those for public opinion information about ordinary events. Event type factors add a certain complexity to the study of users' information adoption behavior, while the occurrence of various emergencies brings severe challenges to the development of the country, society, and enterprises themselves. In the field of economics and business, the impact of public emergencies cannot be ignored. The response to emergencies is an important work that every enterprise should pay attention to, and it is also a problem about emergency management that should explore and solve. When an emergency occurs, the enterprise should timely understand the demands of users, effectively use diversified information communication channels to output information, do a good job in public opinion management of the emergency to control the impact and loss to a minimum, and provide public opinion guarantee for the high-quality development of the enterprise. Therefore, the study of this regulatory variable has a certain theoretical value for improving the emergency management level and crisis public relations level of enterprises. At present, there is generally a lack of studies investigating the effect of the type of public opinion event on users' information adoption. Thus, in this study, we considered the effect of the type of public opinion event and specifically addressed this moderator. We formulated an exploratory question:

Does the type of public opinion event (whether it is a public emergency or not) have an impact on the adoption of public opinion information?

Based on the above analysis and hypotheses, the influencing factors model of public opinion dissemination proposed in this study is shown in Figure 2.

3. Method

3.1. Meta-Analysis. Meta-analysis is a reanalysis of the results of multiple independent studies on the same issue to form a consistent conclusion by integrating the findings of these independent studies. Glass defined meta-analysis in 1976 as "a statistical method that systematically and quantitatively integrates previous research results" [28]. Meta-analysis is a research method that promotes the longitudinal development of research by summarizing and synthesizing existing conclusions and further theoretical results [10]. Meta-analysis was initially used in clinical research. As a scientific research method used to summarize and evaluate existing research results, it has been gradually applied to comprehensive research in all research directions because it allows integration of existing research and analysis of common characteristics.

Compared with traditional literature reviews, a meta-analysis takes each research as a sample, and it can identify heterogeneity between multiple research results, integrate the research results, improve the accuracy of the test results, reduce the subjectivity of the research, and allow more objective conclusions to be drawn.

3.2. Search Strategy. The research object of our study is the influencing factors of users' information adoption behavior in the dissemination of public opinion. To ensure the reliability and completeness of the research, two retrieval methods were used to identify eligible research. First, journal articles and doctoral dissertations, the subject and keywords of which include "public opinion spread," were included; additionally, we scanned the bibliographies of these journal articles and dissertations. A total of 936 core journal articles and CSSCI (Chinese Social Sciences Citation Index) papers and 1587 master's theses and doctoral dissertations were identified. Second, the key elements in the search and selection process were the following: "public opinion dissemination," "public opinion spread," and "information adoption." Wanfang Database (https://www.wanfangdata.com.cn/index.html) and CNKI (https://www.cnki.net) are the most professional academic databases in China, and they are the most important information sources for understanding the academic trends in China. So we searched the Wanfang and CNKI databases for any combination of these terms and the key elements and also scanned the bibliographies of the identified articles to find additional research. After a thorough screening of the titles, abstracts, and keywords, 41 articles that met the subject criteria were obtained.

The following guidelines were followed to select studies:

(1) Studies were chosen if they involved empirical research on users' information adoption behavior in the dissemination of public opinion

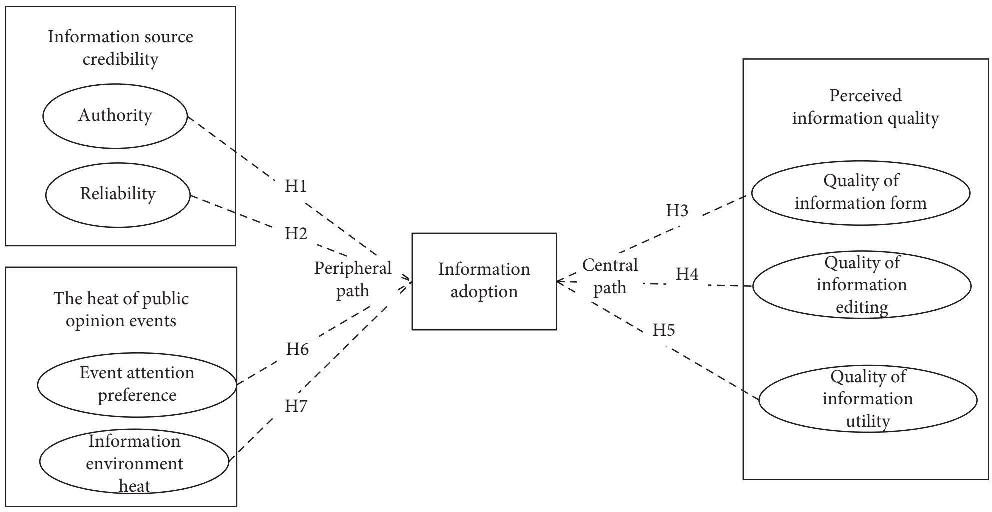

Figure 2: Influencing factor model of users' information adoption behavior in public opinion spread.

(2) To ensure the independence of each study, if two or more studies reported in different articles, proceedings papers, and dissertations were based on the exact data set, they were treated as one study, and only one article was selected

(3) Studies were chosen if users' information adoption behavior was the dependent variable of the research

(4) Studies were chosen if they reported correlations among influencing factors and sample size or correlation coefficients and p values or t-values and sample sizes, which can be converted to correlations

(5) We eliminated studies with unclear descriptions and unreasonable variable designs

After rigorous screening, 20 articles were selected for research. The sample included 9 academic journal articles and 11 master's theses and doctoral dissertations. We selected 20 independent studies that generated 20 samples and obtained the t-values and sample sizes from 3 studies. The correlation coefficients and sample sizes were obtained with formulas.

3.3. Coding. After 20 independent studies were obtained, the study was encoded in 7 aspects (code number, publication, literature resource, number of variables, sample size, effect size, and event type). In addition, there were differences in the results of different studies. In the coding process, we should note the following: (1) The generation of effect value is based on independent samples, and each independent sample is encoded once. If a study contains more than one independent sample, the corresponding multiple coding is carried out. (2) If only the upper or lower concepts of influencing factor variables and users' information adoption behaviors were listed in the literature, we obtained the required effect size by averaging the data [29]. In this study, the same authors were used to reencode all the coding literature studies at different time periods, and then the coding results at different time periods were compared, and it was found that there was no difference except for the deviation of some data. This indicates that the coding of this study has a high degree of consistency.

The detailed coding information is shown in Table 1.

3.4. Variable Design. In this study, through the analysis of variables in the selected 20 articles combined with analysis of relevant literature on information source reliability (authority and reliability), perceived information quality (information form quality, information editing quality, and information utility quality), and the heat of public opinion events (event attention preference and information environment heat), we identified variables with slight conceptual differences in the literature.

The description of the final relevant variables is shown in Table 2.

3.5. Meta-Analysis Procedures. For statistical analyses, we used Comprehensive Meta-Analysis software. We adopted the following procedure: (1) We used the correlation coefficients from the original literature as the effect size. For other pieces of literature, we extracted the t-value and the total number of individuals from the samples (N) to determine the final effect size. (2) We used the fixed effect model or random effect model to evaluate the correlation coefficients between the influencing factors of public opinion dissemination behavior and users' information adoption behavior. (3) We calculated confidence intervals. A significant correlation was one where the confidence interval did not include 0. (4) We used Egger's method to evaluate whether there was publication bias in the included literature. (5) Finally, in order to determine whether there was a moderator, we used the 75% rule, which holds that, after considering all statistical artifacts, if there is still a variance of 25% or an observed effect size, a moderator must exist.

4. Results

4.1. Heterogeneity Test. The heterogeneity test is an essential part of a meta-analysis. Heterogeneity refers to the

Table 1: A detailed overview.

Code number	Publication	Literature resource	Number of variables	Sample size	Effect size	Is it a public emergency?
1	Wei [30]	Master's thesis	4	480	Correlation coefficient and N	Yes
2	Han [31]	Master's thesis	10	700	Correlation coefficient	No
3	Zhang [6]	Master's thesis	5	182	N	Yes
4	Gu et al. [8]	Information science	7	616	Correlation coefficient	No
5	Zeng [32]	Information science	9	649	N	No
6	Wang [33]	China youth study	4	2745	Correlation coefficient	No
7	Zhao and Cheng [25]	Journal of the China Society for Scientific and Technical Information	8	420	N	No
8	Huang [34]	Master's thesis	11	170	Correlation coefficient	No
9	Zhang [35]	Master's thesis	4	343	N	Yes
10	Wu [36]	Master's thesis	9	148	Correlation coefficient	No
11	Zhao [9]	Master's thesis	4	235	N	Yes
12	Chen [37]	Master's thesis	8	420	Correlation coefficient	Yes
13	Hong [38]	China Population, Resources and Environment	6	10405	p value and N	No
14	Cao [39]	Chinese Journal of Computers	6	12284	Correlation coefficient and N	No
15	Zhang et al. [4]	Information and Documentation Services	7	598	T-value and N	Yes
16	Liao et al. [7]	Information and Documentation Services	2	24500	Correlation coefficient	Yes
17	Hou [40]	Discovering value	3	213	N	No
18	Wang [41]	Master's thesis	11	185	Correlation coefficient	No
19	Wu [42]	Master's thesis	4	291	N	No
20	Wang [43]	Master's thesis	10	295	Correlation coefficient	No

intergroup variance between groups of studies. The greater the proportion of intergroup variance to total variance, the greater the heterogeneity between studies. This study used the Q-test to determine whether the included literature was homogeneous. When $p < 0.05$, there was heterogeneity in the study [44]. If the research results were heterogeneous, the random effects model was adopted. The research results were homogeneous if the results obtained by the fixed effects model and the random effects model were consistent.

The results of this study are shown in Table 3. All the above assumptions have heterogeneity ($p < 0.001$). In summary, after the Q-test was performed, we adopted the random effects model analysis method.

4.2. Main Results. Table 4 reports the meta-analysis results of the factors influencing user public opinion spread behavior under the random effect model. First, H1 and H2 posit that authority and reliability, respectively, have a significant positive correlation with users' information adoption behavior in the dissemination of public opinion. These hypotheses are supported by the results (H1, $r = 0.484$, $p < 0.001$; H2, $r = 0.454$, $p < 0.01$). Authority (H1, $r = 0.484$) has the greatest impact on users' public opinion spread behavior. However, reliability (H2, $r = 0.454$) has little impact on user public opinion spread behavior, but its impact is significant. Therefore, H1 and H2 are verified.

Second, in terms of perceived information quality, the relationships between the quality of information form and quality of information editing and users' information adoption behavior in the dissemination of public opinion are stronger than the relationship between the quality of information utility and users' information adoption behavior (H3, $r = 0.472$, $p < 0.001$; H4, $r = 0.537$, $p < 0.001$; H5, $r = 0.459$, $p < 0.01$).

Finally, regarding the heat of public opinion events, H6 predicts that the impact of event attention preference and users' information adoption behavior will be greater in the spread of public opinion. The hypothesis is supported (H6, $r = 0.483$, $p < 0.01$). Conversely, H7 is not supported by sufficient evidence (H7, $r = 0.415$, $p = 0.117 > 0.05$). In the dissemination of public opinion, the information environment has no significant impact on users' information adoption behavior, and there is no relationship between

Table 2: The description of the relevant variables.

Information processing route based on the ELM	Second index	Third index	Variable explanation	Source documents
Peripheral route	Information source reliability	Authority	The authority of information sources, including identity authentication, identity type, and source reliability.	[45, 46]
		Reliability	Reliability of information publishers felt by the audience, including fans and account levels.	[45, 47]
Central route	Perceived information quality	Quality of information form	The characteristics of information content, including the richness of information such as videos, pictures, and microtopics, can meet public information needs and bring value to the public.	[48, 49]
		Quality of information editing	Measured by the formality of the information editing format. Professional information editing and publishing can make information more credible. It contains information integrity and reliability.	[49–51]
		Quality of information utility	The public's evaluation of whether their information needs are met. Specific measurement indicators include usefulness (the gap between information content and public expectations), timeliness, and relevance (information is related to the purpose of public use).	[50, 51]
Peripheral route	The heat of a public opinion event	Event attention preference	The public's preference for events can often affect their behaviors that express their opinions, ideas, or emotions.	[52, 53]
		Information environment heat	Social discussion of events. Hot events can arouse users' interest.	[49, 53, 54]

Table 3: *Q*-test.

	Variable	*K*	*N*	*Q*-test			Tau-squared			Egger regression intercept		
				Q value	*p* value	I^2	Tau-squared	SE	Variance	Tau	Coef.	*p*
H1	Authority	1	14721	1189.071	≤0.001	99.159	0.164	0.118	0.014	0.405	7.089	0.172
H2	Reliability	6	27212	3895.015	≤0.001	99.862	0.237	0.221	0.049	0.487	−20.618	0.378
H3	Quality of information form	3	11173	91.296	≤0.001	97.809	0.165	0.176	0.031	0.46	11.863	0.591
H4	Quality of information editing	4	1037	158.575	≤0.001	98.108	0.219	0.191	0.036	0.468	7.44812	0.7345
H5	Quality of information utility	8	2675	849.357	≤0.001	99.176	0.375	0.221	0.049	0.613	−27.679	0.089
H6	Event attention preference	2	840	44.137	≤0.001	97.734	0.103	0.150	0.022	0.322	—	—
H7	Information environment heat	3	678	268.885	≤0.001	99.256	0.621	0.640	0.409	0.788	12.953	0.877

Table 4: Results of the meta-analysis.

	Variable	*K*	*N*	Effect size and 95% CI			Two-tailed test	
				Point estimation	Lower	Upper	*Z* value	*p* value
H1	Authority	11	14721	0.484	0.243	0.624	3.978	≤0.001
H2	Reliability	2	27912	0.454	0.165	0.711	2.865	0.002
H3	Quality of information form	3	11173	0.472	0.150	0.553	2.324	≤0.001
H4	Quality of information editing	4	1037	0.537	0.135	0.787	2.536	≤0.001
H5	Quality of information utility	8	2675	0.459	0.070	0.727	2.281	0.003
H6	Event attention preference	2	840	0.483	0.075	0.752	2.288	0.002
H7	Information environment heat	3	678	0.415	−0.177	0.923	1.569	0.117

these factors. Therefore, it is assumed that the attention preference of H6 has verified the information adoption behavior of users in the spread of public opinion.

According to the degree of importance, the authority of the information source and the information editing quality have greater impacts on users' adoption behavior, and the effect of the information form quality and the incident on user attention preferences for users' information adoption behavior is moderate. In addition, the impacts on the reliability of information sources and information utility for public opinion spread have little effect on users' information behavior in the dissemination of public opinion.

Table 5: The results of the analysis.

	Correlative variable	Is it a public emergency?	K	Point estimation	95% CI	
					Lower	Upper
H1	Authority	Yes	5	0.368	0.330	0.405
		No	6	0.276	0.260	0.292
H2	Reliability	Yes	4	0.645	0.309	0.838
		No	2	0.247	−0.119	0.554
H3	Quality of information form	Yes	2	0.427	−0.188	0.802
		No	1	0.035	−0.045	0.115
H5	Quality of information utility	Yes	5	0.585	0.209	0.810
		No	3	−0.022	−0.772	0.754
H6	Event attention preference	Yes	1	0.510	0.284	0.450
		No	1	0.370	0.436	0.578
H7	Information environment heat	Yes	2	0.911	0.886	0.930
		No	1	0.295	−0.089	0.602

In summary, hypotheses H1 regarding authority, H2 regarding reliability, H3 regarding the quality of information form, H4 regarding the quality of information editing, H5 regarding the quality of information utility, and H6 regarding event attention preference are all verified. However, hypothesis H7 regarding information environment heat is not valid.

4.3. Moderator Analyses. According to the results in Table 3, since all the influencing factors are significant, the influence values of these variables come not only from the expected variables of sample error but also from the characteristics of different studies [55]; that is, there is a certain degree of heterogeneity between different studies. Heterogeneity is generally due to the different standards included in the studies and the different baseline levels and treatments of each research [26]. Considering the characteristics of the original literature, including the meta-analysis, this study took the type of event (whether it was a public emergency) as the moderator. The event types of different studies were divided into public emergencies and other events. Public emergencies refer to natural disasters, accident disasters, public health incidents, and social security incidents that occur suddenly, cause or may cause serious social harm, and require emergency response measures [56].

The results of the analysis of the effects of moderators are shown in Table 5.

When whether the event is a public emergency is used as a moderator variable, due to the small number of original studies, the event types of quality of information editing (H4) are nonpublic emergencies, so the variable is not included in the analysis results. The analysis results presented in Table 5 show that, among the other six variables, the point estimation when the event type is a public emergency is greater than the point estimation when the event type is not a public emergency. Therefore, we can infer that the event type has a moderating effect on users' information adoption behavior in the dissemination of public opinion. When the event type is a public emergency, the variable has a greater impact on users' information adoption behavior in public opinion spread.

4.4. Publication Bias. Publication bias refers to any situation that may lead to a systematic deviation between the accurate results and actual results in data collection, analysis, interpretation, publication, and review [57]. Publication bias may lead to inaccurate results. Therefore, it was necessary to test the publication bias of the collected literature. We used Egger's method to test the publication bias and judged the publication bias of the literature by identifying the significance between the regression intercept and 0. The results are shown in Table 3. Because of insufficient parameters, H6 was unable to complete the Egger test, and the p values for the other hypotheses were greater than 0.05, indicating that there was no significant difference. There was no publication bias in the study, and the meta-analysis results did not deviate from the real results due to publication bias.

5. Conclusions and Discussion

Taking the user's information adoption behavior as the starting point, this study explored a series of variables that affect adoption behavior through meta-analysis. More specifically, we focused on the factors that have different degrees of influence on users' information adoption behavior in public opinion information dissemination. Now, we will discuss the results of the meta-analysis related to each hypothesis.

The authority and reliability of the information source have a significant correlation with the influence on users' information adoption behavior in public opinion spread, which is consistent with the conclusions of most studies. In the field of information systems, Jing [57] believed that the more followers you have, the more retweets you receive. Our research results show that the number of followers has a significant effect on forwarding. From the direction of the results, if users believe the authority of the information source and the degree of trust is high, they are willing to recognize its information utility and adopt it. Opinion leaders with authority and reliability and other core users have a great influence on the spread of public opinion; and their emotional tendencies, behavior, and speech lead the trend of the spread of public opinion to a certain extent. Therefore, in the network public opinion control process, it is necessary to strengthen the guidance of core users and give full play to the role of influential information sources to effectively control the public opinion communication behavior of users. For example, build a multibody coordinated response mechanism led by the government, and let the Internet Society, industry associations, law-abiding online opinion leaders, and other nongovernmental organizations play their due roles. Besides, a public opinion monitoring system can be built by identifying opinion leaders to prevent the spread of rumors and control the temporal development of public opinion. In addition, our research data show that the number of followers has a significant effect on forwarding. The results show that the number of fans is also one of the decisive factors of the influence of the information source. The more fans a publisher of public opinion information has, the more potential public opinion receivers it has, and the more likely its published information is to be browsed, forwarded, and given a thumbs up and receive comments. Therefore, in the process of public opinion supervision and guidance, in addition to opinion leaders, users with a large number of followers should also be taken as the main objects because these users can also become opinion leaders. Additionally, studies have shown that news media users have a greater influence on information audiences, so the government and enterprises should also pay attention to the management of the media. As an important information source for netizens, the media has greater reliability and influence than individual users. The public opinion supervision department should strengthen the management of the media to prevent the media from reporting on events untruthfully; furthermore, we should make good use of the reliability of the media to accurately control the developmental trend of public opinion and guide users to have rational cognition of online public opinion.

The quality of information form, the quality of information editing, and the quality of information utility in the perceived information quality have positive impacts on users' information adoption behavior. As long as users believe that the information content features can meet their information needs, the information editing format is more formal and complete, and the information can meet their needs and is useful to them, the users will be willing to adopt the information and forward it, comment on it, give it a thumbs up, and so on. Therefore, all kinds of news media, enterprises, and governments should fully understand information about users' preferences, such as by being good at using pictures, video, and other forms of information; paying attention to the standardization of information editing formats; releasing information promptly; and making public opinion expression information richer, more attractive, and timelier, thereby expanding the scopes of their audiences. In terms of the dynamic grasp of public opinion, relevant government departments can also take this perspective to make use of the intelligent service platform to release accurate and reliable emergency description information in the first time, deal with false information in a timely manner, appease the public panic, improve the credibility of the government, and guard against false information damaging the normal network order.

Event attention preference in the heat of public opinion events has a positive influence on users' information adoption behavior. If the general attention to and degree of discussion on a public opinion event are high, users are more inclined to recognize the utility of its information and adopt it. Previous studies have shown that, in terms of event types, public opinion events related to the environment, culture, and sports have relatively high heat; however, public opinion events related to anticorruption have relatively low heat, and the proportion of such public opinion events has been decreasing year by year since 2016. In terms of the initial causes of public opinion, the average popularity of large-scale events and scientific and technological discoveries is relatively high. In different social environments, users' preferences for event attention are also different. The more attractive the features of public opinion events are, the more likely users will be to have the desire to participate. Therefore, to better address a public opinion crisis and the dynamic grasp of public opinion, the government public opinion supervision department should strengthen the ability to predict social security events, strengthen monitoring of events of a sensitive nature, and improve the control efficiency and crisis handling ability of online public opinion events based on understanding the attributes and characteristics of each event. A deep understanding of users' mentality and the trend of public opinion events, timely easing of the emotions of netizens, establishment of spread control and an early warning mechanism for crisis information in time, and avoidance of the explosion of public sentiment and the shock of the network public opinion field and other adverse effects can effectively promote the harmonious and healthy development of the network public opinion environment. However, the influence of information environment heat on users' information adoption behavior is not significant. It shows that the social discussion heat of the event can only affect users' information adoption behavior to some extent, but it cannot prove its usefulness. On the one hand, this proves that the relationship between information environment heat and users' information adoption behavior is not a simple linear relationship, which still needs further proof. On the other hand, it may be because the relevant pieces of literature and sample size were too small, and the reliability of the results needs to be tested by including more pieces of literature in a future study.

This study also has an important extended conclusion focusing on the moderating effect of the event type on users' information adoption behavior in the dissemination of public opinion. It was found that when the event type is a public emergency, the influence of various variables on users' information adoption behavior is more significant. That is, event types largely affect users' reception and adoption of public opinion information. Fully analyzing the types and characteristics of events and applying them to the source of public opinion information is a good strategy to solve the current dilemma of information dissemination.

5.1. Theoretical Implications. The purpose of this study is to summarize the influencing factors of users' information adoption behavior in the dissemination of public opinion through a comprehensive review and analysis of the relevant research on the dissemination of public opinion in China. At the theoretical level, the study revealed that the key influencing factors of users' information adoption behavior are the authority of information sources, reliability, quality of information form, quality of information form editing, quality of information form utility, event attention preference, information environment heat, and so on. This conclusion provides a new perspective and analysis method for studying users' information adoption behavior under the influence of public opinion information dissemination.

In addition, this study combines the effects of the existing literature to conduct quantitative research; uses the meta-analysis method to analyze the influencing factors of users' information adoption behavior in public opinion dissemination based on the ELM model; and proposes a model of the information adoption behavior of users in public opinion spread that combines information source reliability (authority and reliability), perceived information quality (quality of information form, quality of information form editing, and quality of information form utility), and the heat of public opinion event (event attention preference and information environment heat). This further enriches the ELM and reveals the path of users' information adoption behavior in public opinion spread, which is the innovation of our study. The study offers a new perspective for the study of users' information adoption behavior and expands the research scope of information adoption.

In addition, the theoretical framework of this study can provide good empirical support for the study of users' behavior in the spread of public opinion information based on a large number of empirical studies.

5.2. Practical Implications. The research conclusions can provide some support for the government management as well as the enterprise management and improve the decision-making capacity. If information publishers want to receive more attention and expand the scope of the content they publish, it is very important to improve their reliability and authority. Specifically, this can be achieved through identity verification, fan accumulation, and account level and reliability improvement. In addition, it is also necessary to pay attention to the information content, timing, and format. Reliable and rich information content, a formal information release format, and timely information release are more likely to be forwarded and spread by information recipients.

In addition, the continuous discussion, diffusion, and dissemination of public opinion information are inseparable from the leadership role of public opinion leaders. Information released by opinion leaders more easily spreads rapidly. If information cannot be controlled and managed in time, false information can be easily spread, and a public opinion crisis can even occur. In the management of public opinion information, after a public opinion incident breaks out, if opinion leaders make the correct judgments on the original incident or the truth of the incident and post it to social platforms, they can provide a large amount of correct guidance for a large number of network users. This can to some extent avoid unnecessary disputes about public opinion events. That is, by correctly guiding public opinion leaders to release content that has a significant impact on information, the development of public opinion information can move towards a benign direction. Therefore, in the identity authentication of opinion leaders, platform service providers should strictly control the authentication process during the identity authentication of opinion leaders to prevent some counterfeiters from passing authentication and breeding false information.

In addition, to maintain a good public opinion environment, the government can focus on fostering the sense of responsibility of social media users and severely crack down on fake news and harmful news to attract people's attention and improve the quality and the reliability of information. Users can be restrained through "education + law," and the behavior of information disseminators can be restrained through laws and regulations. In addition, humanized management can be achieved. Users can be referred to strategies to improve their information screening ability and information literacy, thereby preventing the secondary dissemination of passive information. Simultaneously, the government can use various means to expand the effect of positive topics. Before the dissemination of public opinion, standardized and reasonable topics can be set to actively guide public opinion in the correct direction. This can allow users to participate in the process of public opinion dissemination more reasonably.

The conclusions of this study also have economic value in the business field. On the one hand, enterprises can refer to the influencing factors of users' information adoption behavior to carry out network marketing and brand building. For example, be good at using pictures, videos, and other forms of information; pay attention to the standardization of information editing format. Enterprises can also combine the influence factors of the center path and the edge path to carry out product marketing and publicity and give full play to the role of media and opinion leaders, so as to better spread the corporate reputation. On the other hand, on the dynamic grasp of public opinion, the enterprise departments also may view this, using intelligent service platform, set up the media public opinion crisis early warning mechanism, strengthen the monitoring of sensitive events, improve the control efficiency of Internet public opinion events and crisis public relation capacity, and guard against potential threats, so as to ensure the stable development of the enterprise.

It is necessary to integrate multiple forces for the current network public opinion, and on the basis of maintaining the people's right to speak, give full play to the role of media, opinion leaders, and the government. Not only construct multiangle supervision mechanism to realize the construction of public opinion ecosystem, but also make full use of public opinion information, to create more economic and social benefits.

5.3. Limitations. After addressing the theoretical and practical implications of our meta-analysis, we also need to recognize some important limitations of our study.

First, in the process of the elimination and inclusion of meta-analysis literature, due to the insufficient number of relevant variables in the literature, unavailable data, or a lack of data that could be converted into effect variables, some pieces of literature and samples were lost, making the sample data incomplete and possibly leading to deviations caused by incomplete data.

Furthermore, although the 20 included pieces of literature met the requirements of the meta-analysis, the number of empirical research studies on the factors that affect the spread of public opinion after comprehensive screening is still limited. With the development of public opinion spread, the amount of research literature has increased. In the future, the literature can be further expanded to improve the analysis of the influencing factors of users' information adoption behavior in public opinion spread to obtain a more comprehensive and convincing universal conclusion.

Finally, in addition to the influencing factors of users' information adoption behavior in the dissemination of public opinion, the interaction between various influencing factors and their different action mechanisms on users' information adoption behavior is worthy of attention in the future.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Research Article

The Dynamic Effect of Public Information on Liquidity: From the Perspective of Limited Attention

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The financial system is a complex system. The heterogeneous behaviors of investors further increase the degree of its complexity. In this paper, we develop a rational expectations equilibrium model to analyze the effect of public information on market efficiency and liquidity, especially in the market in which investors monitor the market imperfectly. When public information is partly reflected in equilibrium price or the uncertainty about the asset value is great, market efficiency increases with the increase of the precision of public information and the investors holding it. However, when the uncertainty about the fundamental value is small, the increase of the precision of public information worsens market liquidity. And in this market, with the increase of the investors acquiring public information, market liquidity first decreases and then increases. Overall, our results suggest that listed companies should disclose their information accurately by different channels as much as possible, and the regulators should enhance the supervision of information disclosure to enhance market efficiency and liquidity.

1. Introduction

Regulation rules in most countries require listed companies to disclose their information accurately and timely to the public. And the news providers, such as Thomson Reuters and Bloomberg, and the securities companies, release every type of financial news and the relevant information about the asset value. However, the news arrives at unscheduled times, and its frequency differs a lot (Gross-Klussmann and Hautsch) [1]. Investors could not get the news instantaneously because of their limited attention. And they need time to analyze the news to make the right decision. Consequently, the public information is firstly used by part of investors. Then, all investors acquire it, and the public information is fully reflected in the price. How does the public information affect the market liquidity and efficiency in this process?

In fact, investors' information is asymmetry in this process. Thus, part of the investors will acquire the arbitrage using their information advantage. And the others will improve their limited attention and speed up their information processing capacity to capture the news as soon as possible. In recent years, lots of strategies and algorithms have been designed with the rapid development of computer technology, such as the High Frequency Trading specializing in trading extremely fast on financial news, and the strategies based on the public sentiment spread in the Twitter and microblog. How does investing affect the market liquidity and efficiency? And what should the regulators do to realize the positive effect of public information on enhancing liquidity and efficiency?

To address these questions, we develop a two-period rational expectations equilibrium model with one risky asset. Risk-averse investors and liquidity investors exist in the market. Risk-averse investors also differ in private information. And they trade based on their information to maximize expected utility. In period 1, because of the limited attention and the difference in processing news, only part of the risk-averse investors capture the public information instantaneously after it is disclosed. Then, all risk-averse investors observe it in period 2.

Focusing on period 1, we find that the price efficiency increases with the increase of the precision of public information and the investors capturing the public information. When the uncertainty of the asset value is great, the liquidity also increases with the two variables. However, when the uncertainty of the asset value is small, the liquidity decreases with the precision of public information. And when few investors capture the public information, the liquidity decreases with the increase of these investors; while more investors observe it, the liquidity increases with these investors. This is different with Han et al. [2]. The main reason is that the public information in this paper is firstly obtained by part of investors, while, in their paper, every investor could observe the public signal. Besides, since they endogenize the noise trading, the noise trading increases with the increase of the precision of public information, which worsens the price efficiency.

The,n we endogenize the public information acquisition. By comparing the benefit investing in the technology and the cost, investors choose to invest or not. The results show that the extra benefit of investing is higher for uninformed investors than for the investors with private signal. This is contradicting the learning complementarities in Easley et al. [3]. In fact, in their paper, the investors use the price signal, namely, the public signal, to predict the price, while, in this paper, investors use the public information to predict the fundamental value. Similar with their results, the four types of investors cannot coexist in the market. And the investors investing in the technology decrease with the increase of the cost.

At last, the results show that the regulators should require the listed companies to provide their information more accurately and timely to the public, especially disclosing their information by different channels as much as possible. And the regulators should give support to the companies investing in the technology and encourage more companies to develop the technology with the intent of decreasing the acquisition cost of investors.

This paper enriches the theoretical research on the implications of public signal for firm value, equilibrium price, market liquidity, and efficiency (see the surveys, Verrecchia [4] and Leuz and Wysocki [5]). In the framework of rational expectations equilibrium (REE), previous research has explored the implications of public signal for liquidity (Han et al. [2] and Chen et al. [6]), for price informativeness (Amador and Weill [7], Chen et al. [8], Han et al. [2]), and for information acquisition (Lundholm [9] and Easley et al. [3]). However, none of these studies pays attention to the process that public information is partly captured by the public. In their assumptions, all investors obtain the public information instantaneously. But with the development of financial markets, the process really plays an important role in market reactions to the public information (Dugast [10]). We investigate the implications of public information for liquidity and efficiency by considering this process.

2. Literature Review

Many theoretical studies have investigated the effect of public information on financial markets. Diamond and Verrecchia [11] show that releasing public information can improve market liquidity by reducing information asymmetry. Kim and Verrecchia [12] find that investors with heterogeneous information processing abilities have different reactions to public announcements. Then, the studies explore the effect of public information on other microstructure characteristics. For instance, Lambert et al. [13] show that the quality of public information can influence the cost of capital. Kondor [14] finds that when the correlation between the private information of different groups is sufficiently low, the public announcement can decrease the investors' disagreement about the fundamental value, but it increases the disagreement of the expected selling price among short-horizon traders. Han et al. [2] show that public information attracts more liquidity traders by reducing their expected trading loss. And this has a negative effect on information aggregation. When the information is endogenous, public information can crowd out the private information and attract more noise trading.

However, the public information in these studies is acquired by all investors once after it is released. Some empirical studies have documented that investors do not receive public information at the same time. For instance, Tetlock [15] uses a comprehensive data set on all type of news to investigate the effect of public information on stock returns. The research shows that public information plays a key role in informing certain traders in advance. DellaVigna and Pollet [16] show that the underreaction to public information caused by investors' limited attention could explain postearnings announcement drift.

In fact, the effect of limited attention on traders' decision-making has been a fairly new research topic. Johnston and Pashler [17] confirm that the central cognitive processing capacity of the human brain has its limits. Peng [18], Peng and Xiong [19], and Van Nieuwerburgh and Veldkamp [20, 21] build theories to explore traders' limit attention on portfolio diversification and asset prices. The intuition is straightforward. The more that investors pay attention to the asset, the more precise the investors' information about the future payoff. And several papers analyze the effect of limited attention on traders' strategy. For instance, Biais and Weill [22] describe the dynamic of order book after a liquidity shock in the market that investors cannot monitor markets continuously. Dugast [10] shows that prices reflect unscheduled news with delay because investors monitor the market imperfectly as a result of their limited attention. Following news arrival, the trading volume and price variability show a positive covariance. And this covariance declines with the news arrival frequency. This paper contributes to the literature by discussing the effect of public information on market dynamics in a market that both informed and uninformed investors monitor the market imperfectly.

3. The Model

3.1. The Model Assumptions. Consider a two-period market, in which a risky asset (of liquidation value $\tilde{v}$) is traded by a continuum of risk-averse investors and liquidity investors. $\tilde{v}$ is normally distributed $\tilde{v} \sim N(\bar{v}, (1/\rho_v))$, where $\bar{v} > 0$ and $\rho_v > 0$, and traded at a price $\tilde{p}_t$ $(t = 0, 1, 2, 3)$ with $\tilde{p}_0 = \bar{v}$ and $\tilde{p}_3 = v$.

The risk-averse investors have constant absolute risk aversion (CARA) utility with a risk-averse coefficient of $\gamma > 0$. Risk-averse investors are categorized into two groups according to whether they have the private signal on $\tilde{v}$ in the form of $\tilde{s}_i = \tilde{v} + \tilde{\epsilon}_i$ in period 1 with $\tilde{\epsilon}_i \sim N(0, (1/\rho_\epsilon))$ and $\rho_\epsilon > 0$. We call the investors acquiring private signal $\tilde{s}_i$ informed investors with a exogenous mass of μ, and the others private signal uninformed investors with a mass of $1 - \mu$. A private signal informed investor i recalls $\tilde{s}_i$ in period 2.

We further assume that, in period, 1 a signal $\tilde{y} = \tilde{v} + \tilde{\eta}$ is publicly disclosed to the market, where $\tilde{\eta} \sim N(0, (1/\rho_\eta))$, $\rho_\eta > 0$. However, because of the limited attention and the different information processing capacity, part of risk-averse investors could not acquire the public information in period 1. They can only acquire it in period 2. To improve their acquiring ability, they can invest in a technology at a cost c_L. We call the investors acquiring the technology public information informed investors, and the others public information uninformed investors.

According to the information type, the investors in period 1 could be defined to four groups: n-investors, l-investors, p-investors, and pl-investors (n: uninformed investors, l: technology of improving limited attention, p: private information) (n-investors are uninformed investors, and their information set is $I_{i1} = \{\tilde{p}_1\}$. l-investors acquire public news $\tilde{y}$, and their information set is $I_{i1} = \{\tilde{p}_1, \tilde{y}\}$. p-investors acquire private signal, and their information set is $I_{i1} = \{\tilde{p}_1, \tilde{s}_i\}$. And pl-investors acquire public news and private signal, and their information set is $I_{i1} = \{\tilde{p}_1, \tilde{y}, \tilde{s}_i\}$). The mass of each type of investors is μ_n, μ_l, μ_p and μ_{pl}, satisfying $\mu_n + \mu_l + \mu_p + \mu_{pl} = 1$, $\mu_n + \mu_l = 1 - \mu$ and $\mu_p + \mu_{pl} = \mu$. In Section 3.3, we endogenize the mass of investors investing in the technology (here, we do not endogenize the informed investors' private signal acquisition decision). In period 2, all the risk-averse investors get $\tilde{y}$, and they are distinguished by getting private signal or not. For simplicity, we call the investor with $\tilde{s}_i$ informed investors, and the other risk-averse investors uninformed investors (in period 2, the information set of informed traders is $I_{i2} = \{\tilde{p}_1, \tilde{p}_2, \tilde{y}, \tilde{s}_i\}$ and the information set of uninformed traders is $I_{i2} = \{\tilde{p}_1, \tilde{p}_2, \tilde{y}\}$). The mass of informed investors and uninformed investors is μ and $1 - \mu$.

In period t, the demand function of risk-averse investors i with information set I_{it} is $D_{it}(I_{it})$, and the net demand of liquidity investors is $\tilde{x}_t \sim N(0, (1/\rho_{x_t}))$. All variables in set $\{\tilde{v}, \{\tilde{x}_t\}_{t\in\{1,2\}}, \{\tilde{\epsilon}_i\}, \tilde{\eta}\}$ are mutually independent.

3.2. The Market Equilibrium. The equilibrium concept here is the rational expectations equilibrium [23] involving the optimal trading strategy. In a linear REE, investors conjecture about the following price function:

$$\tilde{p}_t = \alpha_{0t} + \alpha_{yt}\tilde{y} + \alpha_{vt}\tilde{v} + \alpha_{xt}\tilde{x}_t + \alpha_{p_{t-1}}\tilde{p}_{t-1}, \tag{1}$$

where the coefficients will be endogenously determined (in period 1, $\tilde{p}_0 = \bar{v}$ is included in the constant α_{01}). The market equilibrium in this paper is as follows.

Definition 1. Given the fractions of four type investors, the price information $\tilde{p}_t$ and investors' demand functions $D_{it}(I_{it})$ constitute an REE if (1) $D_{it}(I_{it})$ maximizes the expected utility of trader i conditional on their information given the price $\tilde{p}_t$ and (2) the market clearing by the total demand equals the total supply, i.e., $\int_0^1 D_{it} di + x_t = 0$.

By maximizing investors' conditional expected utility function, we could obtain that

$$D_{it}(I_{it}) = \frac{E(\tilde{v} - \tilde{p}_t | I_{it})}{\gamma \mathrm{Var}(\tilde{v} - \tilde{p}_t | I_{it})}. \tag{2}$$

Note that since part of investors does not get $\tilde{y}$ in period 1, the information in the price differs with the investor groups. For p-investors and n-investors, $\tilde{p}_1$ is equivalent to the signal $\tilde{s}_{p_{11}} = ((\tilde{p}_1 - \alpha_{01})/(\alpha_{v1} + \alpha_{y1})) = \tilde{v} + (\alpha_{x1}/(\alpha_{v1} + \alpha_{y1}))\tilde{x}_1 + (\alpha_{y1}/ (\alpha_{v1} + \alpha_{y1}))\tilde{\eta}$, which, conditional on $\tilde{v}$, is normally distributed with mean $\tilde{v}$ and precision $\rho_{s_{p_{11}}}^{-1}$, where $\rho_{s_{p_{11}}} = ((\alpha_{v1} + \alpha_{y1})^2 \rho_\eta \rho_{x_1})/(\alpha_{x1}^2 \rho_\eta + \alpha_{y1}^2 \rho_{x_1})$. And for pl-investors and l-investors, $\tilde{p}_1$ is equivalent to the signal $\tilde{s}_{p_{12}} = ((\tilde{p}_1 - \alpha_{01} - \alpha_{y1}\tilde{y})/\alpha_{v1}) = \tilde{v} + (\alpha_{x1}/\alpha_{v1})\tilde{x}_1$, which, conditional on $\tilde{v}$, is normally distributed with mean $\tilde{v}$ and precision $\rho_{s_{p_{12}}}^{-1}$, where $\rho_{s_{p_{12}}} = (\alpha_{v1}/\alpha_{x1})^2 \rho_{x_1}$. In period 2, all investors observe the public information, and then $\tilde{p}_2$ is equivalent to $\tilde{s}_{p_2} = ((\tilde{p}_2 - \alpha_{02} - \alpha_{p_1}\tilde{p}_1 - \alpha_{y2}\tilde{y})/\alpha_{v2}) = \tilde{v} + (\alpha_{x2}/\alpha_{v2})\tilde{x}_2$, which, conditional on $\tilde{v}$, is normally distributed with mean $\tilde{v}$ and precision $\rho_{s_{p_2}}^{-1}$, where $\rho_{s_{p_2}} = (\alpha_{v2}/\alpha_{x2})^2 \rho_{x_2}$.

Substituting $D_{it}(I_{it})$ in equation (2), we can determine the coefficients in equation (1), which is shown in Proposition 1.

Proposition 1. *There exists a unique linear equilibrium with the price function*

$$\tilde{p}_t = \alpha_{0t} + \alpha_{yt}\tilde{y} + \alpha_{vt}\tilde{v} + \alpha_{xt}\tilde{x}_t + \alpha_{p_{t-1}}\tilde{p}_{t-1}, \tag{3}$$

where the coefficients are endogenously determined and shown in the appendix.

Next, we analyze the effect of two public information variables, the precision of public information ρ_η and the mass of investors obtaining public information TB_2 (i.e., $TB_2 = \mu_l + \mu_{pl}$), on the price informativeness and liquidity.

In period 1, since n-investors and p-investors cannot observe $\tilde{y}$, the price informativeness is $I_1 = (\mathrm{var}(\tilde{v}|\tilde{p}_1))^{-1}$. Applying Bayes rules yields $I_1 = \rho_v + \rho_{s_{p_{11}}}$. In period 2, all investors observe $\tilde{y}$, and then the price informativeness is $I_2 = (\mathrm{var}(\tilde{v}|\tilde{p}_1, \tilde{p}_2, \tilde{y}))^{-1}$, and $I_2 = \rho_v + \rho_{s_{p_{12}}} + \rho_{s_{p_2}} + \rho_\eta$.

Corollary 1. $(\partial I_1/\partial\rho_\eta) > 0$, $(\partial I_1/\partial TB_2) > 0$, $(\partial I_2/\partial\rho_\eta) > 0$, $(\partial I_2/\partial TB_2) = 0$.

It is straightforward that, in period 1, as more investors get the public information, and the precision of the public information increases, more information is brought into the price by l and pl-investors. Thus, $(\partial I_1/\partial\rho_\eta) > 0$ and $(\partial I_1/\partial \mathrm{TB}_2) > 0$. Similarly, as ρ_η increases, I_2 increases. Since all investors obtain $\tilde{y}$ in period 2, TB_2 has no effect on I_2.

α_{xt} in Proposition 1 reflects how liquidity trading influences the equilibrium price; i.e., $1/\alpha_{xt}$ measures the market depth. A greater α_{xt} means that liquidity trading has a greater influence on price. Therefore, market liquidity LIQ is measured by $1/\alpha_{xt}$.

Computations show that market liquidity in period 1, LIQ_1, can be decomposed into two components: the direct effect and the indirect effect ($\mathrm{LIQ}_1 = (\alpha_{v1}/\alpha_{x1})[1+(\alpha_{y1}/\alpha_{v1})](1+(\rho_v/(\mathrm{WAP}-\rho_v)))$, where $\mathrm{WAP} = \mu_n \mathrm{var}^{-1}(\tilde{v}|\tilde{p}_1) + \mu_p \mathrm{var}^{-1}(\tilde{v}|\tilde{p}_1, \tilde{s}_i) + \mu_l \mathrm{var}^{-1}(\tilde{v}|\tilde{p}_1, \tilde{y}) + \mu_{pl} \mathrm{var}^{-1}(\tilde{v}|\tilde{p}_1, \tilde{s}_i, \tilde{y})$. α_{y1}/α_{v1} is the ratio of the effect of public news on equilibrium price and the effect of fundamental value on equilibrium price. The stronger the public news, the more the liquidity. We call the term $1 + (\alpha_{y1}/\alpha_{v1})$ the component of the public news direct effect. WAP is the weighted average of the precision that all investors' expectation to the fundamental value is based on their information, and it measures the rational traders' average market precision on asset. The greater it is, the greater the adverse risk faced by the investors without public news is. Thus, the liquidity provided by the public news uninformed traders decreases. We call it the component of the public news indirect effect). The direct component measures the positive effect of public information on liquidity due to the increase of the precision of public information and the investors with public information, whereas the indirect component mainly measures the adverse selection risk of public information on liquidity. In fact, as ρ_η increases, investors expect the fundamental value more precisely. Then, liquidity decreases because of the increase of adverse selection risk. When TB_2 increases, more investors trade based on the public information, and the price informativeness increases (as stated in Corollary 1). The adverse selection risk increases. However, the weight (the mass of n and p type investors decreases) of $\rho_{s_{p_{11}}}$ decreases. The adverse selection risk decreases. Therefore, the effect of TB_2 on liquidity is not determined. The total effect of public information variables on LIQ_1 is determined by the relative strength of the two effects.

As the public information is the new information, its effect on liquidity may be related to the previous uncertainty level of the asset fundamental. The next corollary shows the effect of ρ_η and TB_2 on liquidity.

Corollary 2. *(1) For sufficiently small ρ_v, $(\partial LIQ_1/\partial\rho_\eta) > 0$. And for sufficiently large ρ_v, $(\partial LIQ_1/\partial\rho_\eta) < 0$. (2) For sufficiently small ρ_v, $(\partial LIQ_1/\partial TB_2) > 0$. For sufficiently large ρ_v, when $TB_2 \in [0, TB_2^*]$, $(\partial LIQ_1/\partial TB_2) < 0$; while $TB_2 \in [TB_2^*, 1]$, $(\partial LIQ_1/\partial TB_2) > 0$.*

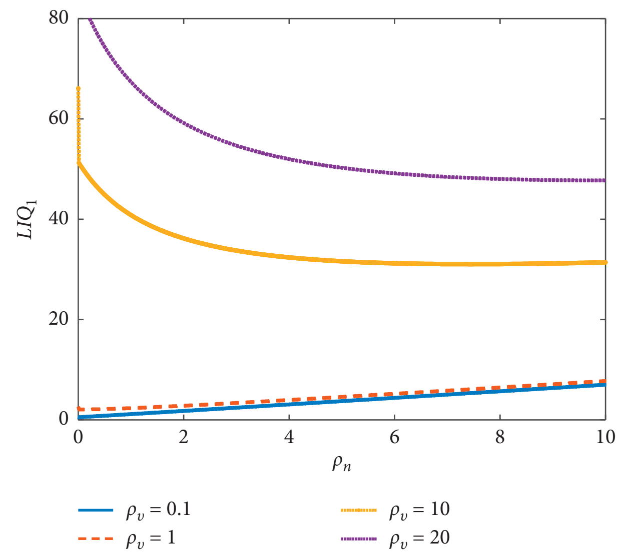

Figure 1: The relation between ρ_η and LIQ_1.

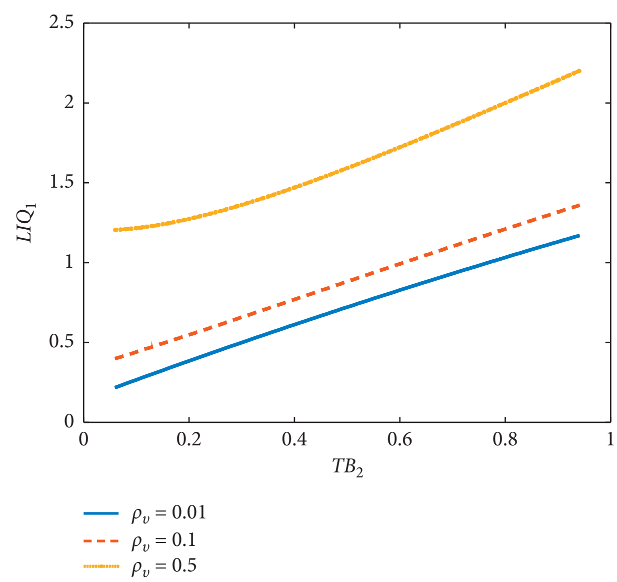

Figure 2: The relation between TB_2 and LIQ_1 when ρ_v is small.

Figure 1 describes the relation between ρ_η and LIQ_1 with different ρ_v. Figures 2 and 3 show the relation between TB_2 and LIQ_1 with different ρ_v. When ρ_v is sufficiently small, the uncertainty about the fundamental value is great. As ρ_η and TB_2 increase, trading based on public information transfers more information to the market. The public information direct effect dominates the public information indirect effect; thus, liquidity increases.

However, when ρ_v is sufficiently large, the effect of ρ_η and TB_2 on liquidity is different. When the uncertainty about the fundamental value is small, as ρ_η increases, the adverse selection risk becomes stronger. The public information indirect effect dominates the public information direct effect; thus, liquidity decreases. Since TB_2 affects $\rho_{s_{p_{11}}}$, the net weighted average of investors' expectation precision

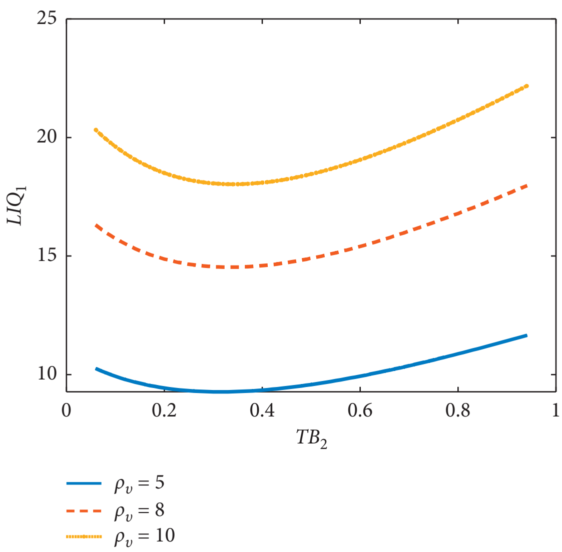

FIGURE 3: The relation between TB_2 and LIQ_1 when ρ_v is large.

increases with the increase of TB_2; i.e., the adverse selection risk increases. Thus, the liquidity decreases. While TB_2 is large, $\rho_{s_{p_{11}}}$ increases more, and then, the net weighted average of investors' expectation precision decreases with the increase of TB_2; i.e., the adverse selection risk decreases. Thus, liquidity increases. Besides, Figure 3 also shows that, with the increase of ρ_v, TB_2^* increases.

Since, in period 2, all investors obtain $\tilde{y}$, the liquidity increases with the increase of its precision. And the mass of investors acquiring $\tilde{y}$ is constant; thus, it does not affect the LIQ_2.

Corollary 3. *(1)* $(\partial LIQ_2/\partial \rho_\eta) > 0$. *(2)* $(\partial LIQ_2/\partial TB_2) = 0$.

3.3. Endogenous Public Information Acquisition. We now derive the equilibrium demand for the technology, namely, equilibrium masses, μ_l^* and μ_{pl}^*, of l-investors and pl-investors. Assume the cost c_L is constant (this assumption has its realistic foundation, and it has been modeled in some research. For example, some exchanges, such as NYSE, NASDAQ, and Deutsche Bourse, have sold their market data before public information appears. Easely et al. [3] model this practice and analyze its effect on price discovery and market quality. Biais and Weill [22] build an equilibrium model, in which fast traders have extremely rapid connections with the markets, and they can receive price information (namely, the public information) once it is disclosed. And slow traders could invest in fast trading technology to improve their information acquisition ability). Since all investors in period 2 will obtain the public information, the difference of the benefit between investors acquiring the public information or not is only reflected in period 1.

For an uninformed trader, the benefit, B_u, of investing in the technology is the difference between the indirect utility of a l-investor and his indirect utility. Calculations show that the benefit is

$$B_u = \frac{1}{2\gamma}\log\left(\frac{\mathrm{Var}(\tilde{v}-\tilde{p}_1|\tilde{p}_1)}{\mathrm{Var}(\tilde{v}-\tilde{p}_1|\tilde{p}_1,\tilde{y})}\right) = \frac{1}{2\gamma}\log\left(\frac{\rho_v+\rho_{s_{p_{12}}}+\rho_\eta}{\rho_v+\rho_{s_{p_{11}}}}\right). \tag{4}$$

Similarly, for an investor with private signal, the benefit, B_i, of investing in the technology is

$$B_i = \frac{1}{2\gamma}\log\left(\frac{\mathrm{Var}(\tilde{v}-\tilde{p}_1|\tilde{p}_1,\tilde{s}_i)}{\mathrm{Var}(\tilde{v}-\tilde{p}_1|\tilde{p}_1,\tilde{y},\tilde{s}_i)}\right) = \frac{1}{2\gamma}\log\left(\frac{\rho_v+\rho_{s_{p_{12}}}+\rho_\varepsilon+\rho_\eta}{\rho_v+\rho_{s_{p_{11}}}+\rho_\varepsilon}\right). \tag{5}$$

Direct computations show that $\rho_{s_{p_{12}}}+\rho_\eta > \rho_{s_{p_{11}}}$. In fact, investors with more information can expect the asset value with a higher precision $(\mathrm{Var}(\tilde{v}-\tilde{p}_1|\tilde{p}_1,\tilde{y}) < \mathrm{Var}(\tilde{v}-\tilde{p}_1|\tilde{p}_1)$ or $\mathrm{Var}(\tilde{v}-\tilde{p}_1|\tilde{p}_1,\tilde{y},\tilde{s}_i) < \mathrm{Var}(\tilde{v}-\tilde{p}_1|\tilde{p}_1,\tilde{s}_i))$. Then, $B_u > 0$ and $B_i > 0$.

By $\rho_{s_{p_{12}}}+\rho_\eta > \rho_{s_{p_{11}}}$, we also obtain that $B_u > B_i$. Thus, we have the following corollary.

Corollary 4. *The extra benefit of observing public information $\tilde{y}$ is higher for n-investors than for p-investors.*

$$\begin{aligned}
&\rho_{s_{p_{12}}}+\rho_\eta > \rho_{s_{p_{11}}}, \frac{1}{2\gamma}\log\left(\frac{\mathrm{Var}(\tilde{v}-\tilde{p}_1|\tilde{p}_1)}{\mathrm{Var}(\tilde{v}-\tilde{p}_1|\tilde{p}_1,\tilde{s}_i)}\right) > \frac{1}{2\gamma}\log\left(\frac{\mathrm{Var}(\tilde{v}-\tilde{p}_1|\tilde{p}_1,\tilde{y})}{\mathrm{Var}(\tilde{v}-\tilde{p}_1|\tilde{p}_1,\tilde{y},\tilde{s}_i)}\right)\\
&B_u - c_L, B_i - c_L, B_i(\mu_l,\mu_{pl}), B_u(\mu_l,\mu_{pl}), \mu_l^*, \mu_{pl}^*, B_u(\mu_l^*,\mu_{pl}^*) - c_L = 0\\
&B_i(\mu_l^*,\mu_{pl}^*) - c_L = 0, \quad 0<\mu_l^*<1-\mu, 0<\mu_{pl}^*<\mu, B_u(\mu_l^*,\mu_{pl}^*) = c_L = B_i(\mu_l^*,\mu_{pl}^*)\\
&B_u(\mu_l,\mu_{pl}) > B_i(\mu_l,\mu_{pl}).
\end{aligned} \tag{6}$$

Remark 1. Assume that investors can also choose to acquire private signal. Then, by $\rho_{s_{p_{12}}}+\rho_\eta > \rho_{s_{p_{11}}}$, we have $1/2\gamma\log(\mathrm{Var}(\tilde{v}-\tilde{p}_1|\tilde{p}_1)/\mathrm{Var}(\tilde{v}-\tilde{p}_1|\tilde{p}_1,\tilde{s}_i)) > 1/2\gamma\log(\mathrm{Var}(\tilde{v}-\tilde{p}_1|\tilde{p}_1,\tilde{y})/\mathrm{Var}(\tilde{v}-\tilde{p}_1|\tilde{p}_1,\tilde{y},\tilde{s}_i))$, which shows that the extra benefit of acquiring private information $\tilde{s}_i$ is higher for n-investors than for l-investors. Thus, the marginal benefit of acquiring an additional form of information is smaller for investors who have already obtained some information than for those who have not. In other words, the two pieces of information $\tilde{s}_i$ and $\tilde{y}$ are substitutable. Investors without information have a great incentive to acquire additional information than those with some information. This occurs because both $\tilde{s}_i$ and $\tilde{y}$ include the same information about the fundamental value $\tilde{v}$.

An n-investor (p-investor) investing in the technology obtains a net expected profit of $B_u - c_L$ $(B_i - c_L)$. No investors will choose to invest if $B_u - c_L < 0$ and $B_i - c_L < 0$. Computations show that B_u and B_i decrease with μ_l and μ_{pl} (in the following, regard B_u and B_i as the function of μ_{pl} and μ_l to determine the equilibrium mass, i.e., $B_i(\mu_l, \mu_{pl})$ and $B_u(\mu_l, \mu_{pl})$). Because of the monotone decreasing, μ_l^* and μ_{pl}^* can be determined by solving $B_u(\mu_l^*, \mu_{pl}^*) - c_L = 0$ and $B_i(\mu_l^*, \mu_{pl}^*) - c_L = 0$.

Note that, in equilibrium, the four investor types cannot be in the market at the same time. In fact, assume there are four types of investors in the market; i.e., there exist μ_l^* and μ_{pl}^* satisfying $0 < \mu_l^* < 1 - \mu$ and $0 < \mu_{pl}^* < \mu$. Then, we have $B_u(\mu_l^*, \mu_{pl}^*) = c_L = B_i(\mu_l^*, \mu_{pl}^*)$. However, this is contradicting with $B_u(\mu_l, \mu_{pl}) > B_i(\mu_l, \mu_{pl})$, for any μ_l and μ_{pl}. Hence, we have the following corollary.

Corollary 5. *In the market, all four groups of investors cannot coexist.*

Using the above corollary and the equilibrium condition, we have the following results based on the different level of c_L:

Proposition 2. *The equilibrium mass of each type of investors is as follows:*

(1) When $c_L < B_i(\mu_l, \mu_{pl})|_{\mu_{pl}=\mu, \mu_l=1-\mu}$, all n-investors and p-investors invest in the technology

(2) When $B_i(\mu_l, \mu_{pl})|_{\mu_{pl}=\mu, \mu_l=1-\mu} < c_L < B_i(\mu_l, \mu_{pl})|_{\mu_{pl}=0, \mu_l=1-\mu}$, all c-investors invest in the technology, whereas a μ_{pl}^* fraction of p-investors invest in the technology (the details of μ_{pl}^* in case (2) and μ_l^* in case (4) are given in Appendix)

(3) When $B_i(\mu_l, \mu_{pl})|_{\mu_{pl}=0, \mu_l=1-\mu} < c_L < B_u(\mu_l, \mu_{pl})|_{\mu_{pl}=0, \mu_l=1-\mu}$, all n-investors invest in the technology, whereas all p-investors do not invest in the technology

(4) When $B_u(\mu_l, \mu_{pl})|_{\mu_{pl}=0, \mu_l=1-\mu} < c_L < B_u(\mu_l, \mu_{pl})|_{\mu_{pl}=0, \mu_l=0}$, all p-investors do not invest in the technology, whereas a μ_l^* fraction of n-investors invest in the technology

(5) When $B_u(\mu_l, \mu_{pl})|_{\mu_{pl}=0, \mu_l=0} < c_L$, all n-investors and p-investors do not invest in the technology

Proposition 2 implies that the population of investors investing in the technology is negatively related to the cost. Trivially, when c_L is equal to 0 or smaller than $B_i(\mu_l, \mu_{pl})|_{\mu_{pl}=0, \mu_l=1-\mu}$, every investor invests to acquire the public information immediately. There are only two types of investors: l-investors and pl-investors.

Since $B_u > B_i$, n-investors have more incentive to invest in the technology compared with p-investors. When c_L increases above $B_i(\mu_l, \mu_{pl})|_{\mu_{pl}=0, \mu_l=1-\mu}$, part of p-investors first choose not to invest. As c_L increases, more p-investors will keep their current steady. And there are three types of investors in the market: p-investors, p-investors, and l-investors. Then, when c_L increases to $B_i(\mu_l, \mu_{pl})|_{\mu_{pl}=0, \mu_l=1-\mu}$, all p-investors will choose not to invest. However, in this interval of c_L, all n-investors become l-investors. Note that when c_L belongs to $[B_i(\mu_l, \mu_{pl})|_{\mu_{pl}=0, \mu_l=1-\mu}, B_u(\mu_l, \mu_{pl})|_{\mu_{pl}=0, \mu_l=1-\mu}]$, all p-investors will choose not to invest, and all n-investors will invest. Now, there are only p-investors and l-investors in the market.

Once c_L increases above $B_u(\mu_l, \mu_{pl})|_{\mu_{pl}=0, \mu_l=1-\mu}$, part of n-investors will choose to not invest, and all p-investors do not invest. And there are three types of investors in the market: n-investors, l-investors, and p-investors. After c_L reaches $B_u(\mu_l, \mu_{pl})|_{\mu_{pl}=0, \mu_l=0}$, no investors will invest in the technology. And there are only n-investors and p-investors in the market.

3.4. Policy Implications. Our results show that, with the increase of the precision of public information, the liquidity increases (the underlying hypothesis is that public information is acquired by most investors. This is true in r reality). In fact, the public information can be divided into two parts: the trading information from exchange, such as the volume and price, and the information from the listed companies, such as the accounting information and management information. We will give some policy suggestions from these two aspects. For the trading information, some exchanges such as US exchanges require trades, and amounts must be reported in real time. Our results show that the price informativeness increases with the increase of the precision of public information and the quantities of traders acquiring public information. Therefore, it is necessary to disclose more trading information to enhance price discovery.

For the public information related to the business of listed companies, the regulation rules in many countries, such as the Measures for the Administration of Information Disclosure of Listed Companies (Revised) (2020) in China, the Sarbanes-Oxley Act (2002), and the Dodd-Frank Act (2010) in the United States, have required the listed companies to strengthen information disclosure truthfully, accurately, completely, and timely to the public. The main purpose of these rules' intent is to improve market transparency and enhance market efficiency and liquidity. However, the results in this paper show that when the public information is just disclosed, these goals may not be achieved simultaneously. The news needs time to be fully reflected in equilibrium price. The regulators should be patient with the process. As stated in Corollary 2, sometimes the realization of these goals is affected by the variables related to the asset, such as the precision of the fundamental value. For the asset with small uncertainty about its value, the liquidity decreases with more precise public information. However, it is temporary. When all investors acquire the public information, the liquidity increases with the precision of public information. Hence, the regulators should require the listed companies to provide more accurate public information.

Furthermore, by endogenizing the public information acquisition, more investors could acquire the public information in period 1 when the cost is low. When the uncertainty about the asset value is small and few investors observe the public information, decreasing the cost harms liquidity. However, if the cost is low enough, there are more investors acquiring the public information (more than TB_2^* as stated in Corollary 2). The liquidity will increase. Therefore, the regulators should require the listed companies to disclose their information in more channels, such as newspaper, TV, and Internet to make the public information available to most investors. To achieve this goal, on the one hand, the information should be clear and easy to understand. On the other hand, the regulators should give support, such as tax benefit and loans with no or low interest, to the data companies to make their price lower and encourage more companies to develop this technology.

4. Conclusion

We construct a tractable REE model, in which investors have limited attention capacity to endogenize the public information acquisition and examine the implications of public information. Because of limited attention, only part of investors could acquire the public information after it is disclosed. And when public information is partly reflected in equilibrium price, it has different effect to market liquidity. When the uncertainty about the asset value is great, liquidity increases with the increase of the precision of public information and the investors acquiring public information. However, when the uncertainty about the asset value is small, the effect of public information on liquidity is different. For the precision of public information, its increase harms liquidity. With the increase of investors acquiring public information, liquidity first decreases and then increases. Endogenizing the public information acquisition shows that the mass of investors acquiring public information is negatively related to the cost. To enhance market efficiency and liquidity, the regulators should require the listed companies to disclose their information accurately by different channels as much as possible.

Appendix

A. Proof of Proposition 1

In period 1, for n-investors, using the expressions of $\tilde{v}$ and $\tilde{s}_{p_{11}}$, we apply Bayes' rule and compute $E(\tilde{v}|\tilde{p}_1) = (\rho_v\overline{v} + \rho_{s_{p_{11}}}\tilde{s}_{p_{11}})/(\rho_v + \rho_{s_{p_{11}}})$ and $\text{Var}(\tilde{v}|\tilde{p}_1) = 1/(\rho_v + \rho_{s_{p_{11}}})$. Plugging these expressions into demand function $D_{1i}(I_{1i})$ yields the demand function $D_{1i}(\tilde{p}_1) = (\rho_v\overline{v} + \rho_{s_{p_{11}}}\tilde{s}_{p_{11}} - (\rho_v + \rho_{s_{p_{11}}})\tilde{p}_1)/\gamma$, where $I_{1i} = \{\tilde{p}_1\}$. Similarly, for p-investors, we obtain $E(\tilde{v}|\tilde{p}_1, \tilde{s}_i) = (\rho_v\overline{v} + \rho_{s_{p_{11}}}\tilde{s}_{p_{11}} + \rho_\epsilon\tilde{s}_i)/(\rho_v + \rho_{s_{p_{11}}} + \rho_\epsilon)$, $\text{Var}(\tilde{v}|\tilde{p}_1, \tilde{s}_i) = 1/(\rho_v + \rho_{s_{p_{11}}} + \rho_\epsilon)$, and $D_{1i}(\tilde{p}_1, \tilde{s}_i) = (\rho_v\overline{v} + \rho_{s_{p_{11}}}\tilde{s}_{p_{11}} + \rho_{\epsilon_1}\tilde{s}_i - (\rho_v + \rho_{s_{p_{11}}} + \rho_{\epsilon_1})\tilde{p}_1)/\gamma$. For l-investors, $E(\tilde{v}|\tilde{p}_1, \tilde{y}) = (\rho_v\overline{v} + \rho_{s_{p_{12}}}\tilde{s}_{p_{12}} + \rho_\eta\tilde{y})/(\rho_v + \rho_{s_{p_{12}}} + \rho_\eta)$, $\text{Var}(\tilde{v}|\tilde{p}_1, \tilde{y}) = 1/(\rho_v + \rho_{s_{p_{12}}} + \rho_\eta)$, and $D_{1i}(\tilde{p}_1, \tilde{y}) = (\rho_v\overline{v} + \rho_{s_{p_{12}}}\tilde{s}_{p_{12}} + \rho_\eta\tilde{y} - (\rho_v + \rho_{s_{p_{12}}} + \rho_\eta)\tilde{p}_1)/\gamma$. And for pl-investors $E(\tilde{v}|\tilde{p}_1, \tilde{y}, \tilde{s}_i) = (\rho_v\overline{v} + \rho_{s_{p_{12}}}\tilde{s}_{p_{12}} + \rho_\eta\tilde{y} + \rho_\epsilon\tilde{s}_i)/(\rho_v + \rho_{s_{p_{12}}} + \rho_\epsilon + \rho_\eta)$, $\text{Var}(\tilde{v}|\tilde{p}_1, \tilde{y}, \tilde{s}_i) = 1/(\rho_v + \rho_{s_{p_{12}}} + \rho_\epsilon + \rho_\eta)$, and $D_{1i}(\tilde{p}_1, \tilde{y}, \tilde{s}_i) = (\rho_v\overline{v} + \rho_{s_{p_{12}}}\tilde{s}_{p_{12}} + \rho_\eta\tilde{y} + \rho_\epsilon\tilde{s}_i - (\rho_v + \rho_{s_{p_{12}}} + \rho_\eta + \rho_\epsilon)\tilde{p}_1)/\gamma$.

Then, substituting the above demand function, $\tilde{s}_{p_{11}}$ and $\tilde{s}_{p_{12}}$ in the market-clearing condition in equation (2), we get the price function as the form of equation (1), which yields the coefficients in $\tilde{p}_1 = \alpha_{01} + \alpha_{y1}\tilde{y} + \alpha_{v1}\tilde{v} + \alpha_{x1}\tilde{x}_1$. Similarly, we obtain the detail price function in period 2.

The coefficients are as follows: $\alpha_{01} = \rho_v\overline{v}/[\rho_v + (\mu_l + \mu_{pl})\rho_\eta + (\mu_p + \mu_{pl})\rho_\epsilon + (\mu_n + \mu_p)\rho_{s_{p_{11}}} + (\mu_l + \mu_{pl})\rho_{s_{p_{12}}}]$, $\alpha_{v1} = [(\mu_p + \mu_{pl})\rho_\epsilon + (\mu_l + \mu_{pl})\rho_{s_{p_{12}}} + (\mu_n + \mu_p)(\rho_{s_{p_{11}}}/(1 + (\alpha_{y1}/\alpha_{v1})))]/[\rho_v + \text{MP}]$, $\text{MP} = (\mu_l + \mu_{pl})\rho_\eta + (\mu_p + \mu_{pl})\rho_\epsilon + (\mu_n + \mu_p)\rho_{s_{p_{11}}} + (\mu_l + \mu_{pl})\rho_{s_{p_{12}}}$, $\alpha_{y1}/\alpha_{v1} = (\mu_l + \mu_{pl})\rho_\eta/[(\mu_p + \mu_{pl})\rho_\epsilon + (\mu_l + \mu_{pl})\rho_{s_{p_{12}}}]$, $\alpha_{x1}/\alpha_{v1} = \gamma/(\mu_p + \mu_{pl})\rho_\epsilon$, $\alpha_{02} = (\rho_v\overline{v} - (\alpha_{01}/\alpha_{v1})\rho_{s_{p_{12}}})/(\rho_v + \rho_\eta + \rho_{s_{p_{12}}} + \rho_{s_{p_2}} + \mu_i\rho_\epsilon)$, $\alpha_{v2} = (\mu_i\rho_\epsilon + \rho_{s_{p_2}})/(\rho_v + \rho_\eta + \rho_{s_{p_{12}}} + \rho_{s_{p_2}} + \mu_i\rho_\epsilon)$, $\alpha_{y2} = (\rho_\eta - (\alpha_{y1}/\alpha_{v1})\rho_{s_{p_{12}}})/(\rho_v + \rho_\eta + \rho_{s_{p_{12}}} + \rho_{s_{p_2}} + \mu_i\rho_\epsilon)$, $\alpha_{x2}/\alpha_{v2} = \gamma/\mu_i\rho_\epsilon$, and $\alpha_{p1} = (\rho_{s_{p_{12}}}/\alpha_{v1})/(\rho_v + \rho_\eta + \rho_{s_{p_{12}}} + \rho_{s_{p_2}} + \mu_i\rho_\epsilon)$.

B. Proof of Corollary 1

$I_1 = (\text{var}(\tilde{v}|\tilde{p}_1))^{-1}$ is positively related to $\rho_{s_{p_{11}}}$. Since $\partial\rho_{s_{p_{11}}}/\partial\rho_\eta = FZ_1/((\alpha_{x1}/\alpha_{v1})^2\rho_\eta + (\alpha_{y1}/\alpha_{v1})^2\rho_{x_1})^2$, where $FZ_1 = (1 + (\alpha_{y1}/\alpha_{v1}))\rho_{x_1}(\rho_\eta\rho_{x_1}/((\mu\rho_\epsilon/\text{TB}_2) + \rho_{s_{p_{12}}})^2)[\rho_\eta - ((\mu\rho_\epsilon/\text{TB}_2) + \rho_{s_{p_{12}}}) + (2/\rho_{s_{p_{12}}})((\mu\rho_\epsilon/\text{TB}_2) + \rho_{s_{p_{12}}})^2] > 0$, $\text{TB}_1 = \mu_n + \mu_p = 1 - \text{TB}_2$, $\text{TB}_2 = \mu_l + \mu_{pl}$, $A = \mu\rho_\epsilon + \text{TB}_2\rho_{s_{p_{12}}}$ and $B = A + \text{TB}_2\rho_\eta + (1 - \text{TB}_2)\rho_{s_{p_{11}}}$. Hence, $(\partial I_1/\partial\rho_\eta) > 0$. Besides, since $\partial\rho_{s_{p_{11}}}/\partial\text{TB}_2 = (2\rho_{s_{p_{11}}}\mu^2\rho_\epsilon^2\rho_\eta/([A^2 + (\text{TB}_2)^2\rho_\eta\rho_{s_{p_{12}}}][A + \text{TB}_2\rho_\eta])) > 0$, where $A = (\mu_p + \mu_{pl})\rho_\epsilon + (\mu_l + \mu_{pl})\rho_{s_{p_{12}}}$, $(\partial I_1/\partial\text{TB}_2) > 0$.

Since $\rho_{s_{p_{12}}} = ((\mu/\gamma)\rho_\epsilon)^2\rho_{x_1}$ and $\rho_{s_{p_2}} = ((\mu/\gamma)\rho_\epsilon)^2\rho_{x_2}$, ρ_η and TB_2 donot affect $\rho_{s_{p_{12}}}$ and $\rho_{s_{p_2}}$. Then $(\partial I_2/\partial\rho_\eta) > 0$ and $(\partial I_2/\partial\text{TB}_2) = 0$.

C. Proof of Corollary 2

For case (1), taking the differentiation with respect to ρ_η yields that $\partial\text{LIQ}_1/\partial\rho_\eta$ is positive related to $\text{TB}_2^2\rho_{s_{p_{12}}}^2\rho_\eta^2 + 2A[A + \text{TB}_1\rho_{s_{p_{12}}}]\text{TB}_2\rho_{s_{p_{12}}}\rho_\eta + A^2[A + \text{TB}_1\rho_{s_{p_{12}}}]^2 - \rho_v\text{TB}_1\mu\rho_\epsilon A\rho_{s_{p_{12}}}$. Hence, when ρ_v is sufficiently small, $(\partial\text{LIQ}_1/\partial\rho_\eta) > 0$; while ρ_v is sufficiently large, $(\partial\text{LIQ}_1/\partial\rho_\eta) < 0$.

For case (2), taking the differentiation with respect to TB_2 yields that $(\partial\text{LIQ}_1/\partial\text{TB}_2)$ is positive related to $[A^2 + (\text{TB}_2)^2\rho_\eta\rho_{s_{p_{12}}} + (1 - \text{TB}_2)\rho_{s_{p_{12}}}(A + \text{TB}_2\rho_\eta)]^2 + \rho_v\rho_{s_{p_{12}}}[A^2 + (\text{TB}_2)^2\rho_\eta\rho_{s_{p_{12}}} - 2\mu\rho_\epsilon(1 - \text{TB}_2)A]$. Therefore, when ρ_v

is sufficiently small, $(\partial \mathrm{LIQ}_1/\partial \mathrm{TB}_2) > 0$; while ρ_v is sufficiently large, $(\partial \mathrm{LIQ}_1/\partial \mathrm{TB}_2) > 0$ is positively related to $A^2 + (\mathrm{TB}_2)^2 \rho_\eta \rho_{s_{p12}} - 2\mu\rho_\epsilon (1 - \mathrm{TB}_2)A$, which can be written as $(\mathrm{TB}_2)^2 \rho_{s_{p12}} (\rho_\eta + \rho_{s_{p12}} + 2\mathrm{TB}_3\rho_\varepsilon) + 2(\mu\rho_\epsilon)^2 \mathrm{TB}_2 - (\mu\rho_\epsilon)^2$. Then when $\mathrm{TB}_2 \in [0, \mathrm{TB}_2^*)$, $(\mathrm{dLIQ}_1/\mathrm{dTB}_2) < 0$; otherwise, when $\mathrm{TB}_2 \in [\mathrm{TB}_2^*, 1]$, $(\mathrm{dLIQ}_1/\mathrm{dTB}_2) > 0$, where TB_2^* is the bigger solution to the above quadratic equation.

D. Proof of Proposition 2

For case (2), when $B_i(\mu_l, \mu_{pl})|_{\mu_{pl}=\mu, \mu_l = 1-\mu} < c_L < B_i(\mu_l, \mu_{pl})|_{\mu_{pl}=0, \mu_l=1-\mu}$, using Corollary 5 we have $\mu_l^* = 1 - \mu$. $B_i(\mu_l^*, \mu_{pl}^*)|_{\mu_l^* = 1-\mu} - c_L = 0$ yields $(\mathrm{TB}_2)^2 \rho_{s_{p12}} (\rho_\eta + \rho_{s_{p12}})(\rho_\eta + \rho_{s_{p12}} - C_1) + \mathrm{TB}_2 2\mathrm{TB}_3 \rho_\epsilon \rho_{s_{p12}} (\rho_\eta + \rho_{s_{p12}} - C_1) + (\mathrm{TB}_3\rho_\epsilon)^2 (\rho_{s_{p12}} - C_1) = 0$, where $C_1 = \exp\{-2\gamma c_L\}(\rho_v + \rho_\eta + \rho_{s_{p12}} + \rho_\epsilon) - \rho_v - \rho_\epsilon$. Since $\rho_\eta + \rho_{s_{p12}} - C_1 = (\rho_v + \rho_\eta + \rho_{s_{p12}} + \rho_\epsilon)(1 - \exp\{-2\gamma c_L\}) > 0$, the discriminant of above quadratic equation is $4(\mathrm{TB}_3\rho_\epsilon)^2 \rho_{s_{p12}} (\rho_\eta + \rho_{s_{p12}} - C_1) C_1 \rho_\eta$, which is greater than 0. Besides, since $-(b/2a) = ((\mathrm{TB}_3\rho_\epsilon)/(\rho_\eta + \rho_{s_{p12}})) < 0$, $\mathrm{TB}_{2*} = \mu_l^* + \mu_{pl}^* = (-2TB_3\rho_\epsilon\rho_{s_{p12}}(\rho_\eta + \rho_{s_{p12}} - C_1) + \sqrt{\Delta})/(2\rho_{s_{p12}}(\rho_\eta + \rho_{s_{p12}})(\rho_\eta + \rho_{s_{p12}} - C_1))$ is the equilibrium mass of investors investing in the technology, where $\Delta = 4(\mathrm{TB}_3\rho_\epsilon)^2 \rho_{s_{p12}} (\rho_\eta + \rho_{s_{p12}} - C_1) C_1 \rho_\eta > 0$. And $\mu_{pl}^* = \mathrm{TB}_{2*} - \mu_l^*$ is the equilibrium mass of p-investors investing in the technology, where $\mu_l^* = 1 - \mu$.

Similarly, for case (4), $\mu_{pl}^* = 0$. $B_u(\mu_l^*, \mu_{pl}^*)|_{\mu_{pl}^*=0} - c_L = 0$ yields $\mathrm{TB}_{2*} = \mu_l^* + \mu_{pl}^* = (-2TB_3\rho_\epsilon\rho_{s_{p12}}(\rho_\eta + \rho_{s_{p12}} - C_2) + \sqrt{\Delta})/(2\rho_{s_{p12}}(\rho_\eta + \rho_{s_{p12}})(\rho_\eta + \rho_{s_{p12}} - C_2))$, where $\Delta = 4(\mathrm{TB}_3\rho_\epsilon)^2 \rho_{s_{p12}} (\rho_\eta + \rho_{s_{p12}} - C_2) C_2 \rho_\eta$, and $C_2 = \exp\{-2\gamma c_L\}(\rho_v + \rho_\eta + \rho_{s_{p12}}) - \rho_v$. Since $\mu_{pl}^* = 0$, $\mu_l^* = \mathrm{TB}_{2*}$ is the equilibrium mass of n -investors investing in the technology.

Data Availability

No data were used to support this study.

Disclosure

The views expressed in this paper are those of the authors and do not necessarily represent the views of the Shenzhen Stock Exchange.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Chaotic Dynamics Analysis Based on Financial Time Series

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It is a common phenomenon in the field of financial research to study the dynamic of financial market and explore the complexity of financial system by using various complex scientific methods. In this paper, the chaotic dynamic properties of financial time series are analyzed. Firstly, the nonlinear characteristics of the data are discussed through the empirical analysis of agriculture index data; the daily agriculture index returns can be decomposed into the different scales based on wavelet analysis. Secondly, the dynamic system of some nonlinear characteristic data is established according to the Taylor series expansion form, and the corresponding dynamic characteristics are analyzed. Finally, the bifurcation diagram of the system shows complicated bifurcation phenomena, which provides a perspective for the analysis of chaotic phenomena of economic data.

1. Introduction

With the development and progress of the society, the financial system we are facing is becoming more and more complex, and the fundamental reason for this complexity is the nonlinearity of the financial system. For financial data, it is usually difficult to establish mathematical models. It is a common phenomenon in the field of financial research to study the dynamics of financial market and explore the complexity of financial system with various complex scientific methods [1–4]. In the past, there have been some different research directions through different methods to study financial problems, such as economic physics, chaos economics, and dynamic economics [5–9]. For many years, researchers have devoted themselves to the study of the relationship between dynamics and time data [10–12]. In 1996, Chen et al. used the Hankel matrix method to discuss dynamic system identification of time data [13, 14]. In 2003, Lu et al. used the least square method to reconstruct the dynamic system, based on noise observation data [15]. In 2007, Yu et al. discussed dynamic system synchronization and parameter identification of time data [16]. In 2013, Liu et al. reconstructed time series data through recursive graph of power system [17]. In [18], the authors discussed the evolution process of the dynamic system through feedback control method.

Most of the existing research studies about the identification methods of nonlinear dynamic characteristics of data mainly analyze some properties of data from the macro level. The hidden economic relations (regression, cointegration, causality, etc.) in financial data are a dynamic evolution process. Once the dynamic mechanism of financial data evolution is established, it is of great significance to understand and predict the evolution of financial data.

As far as we know, there are few studies on the internal structure of financial data from the micro scale of complex dynamic system, and financial data in the index market have also not been tested by chaotic dynamics at different time scales. In this paper, we firstly analyze the nonlinear characteristics of the data; then the dynamic system is established according to the Taylor series expansion form, and the dynamic properties of the data are also analyzed.

The remainder of the paper is organized as follows: Section 2 describes the data and empirical analysis. In Section 3, the nonlinear dynamic characteristics of the data are verified. Finally, the conclusion is given in Section 4.

2. Data and Empirical Analysis

The Shanghai Stock Exchange and Shenzhen Stock Exchange are two stock exchanges in China. Agriculture listed companies is the representative of the advanced agriculture productivity. The agricultural products index is issued by Shenzhen Stock Exchange, which is composed of 26 index components. It is a very liquid component of China's agricultural stock market. The index reflects the average value of the stock price of the listed agricultural companies in the Shenzhen stock market.

The data, daily observation on returns to the agriculture index from February 2, 2009 to December 24, 2015 (a total of 1680 observations) were collected from the Wind database in our empirical study.

Let p_t be the closing price of index on day t. As known to all, historical prices are nonstationary, which can be solved by calculating the returns. The daily price return r_t can be calculated as its logarithmic difference; that is,

$$r_t = \log\left(\frac{p_{t+1}}{p_t}\right). \quad (1)$$

The agriculture index is displayed in Figure 1. The graphical representation of returns is illustrated as Figure 2.

To decompose a given time series on a scale-by-scale basis, the wavelet analysis is introduced. The early research on the application of wavelet method in economics and finance was carried out by Ramsey and Usikov [19] and Ramsey and Zhang [20]. More recent contributions, among others, are Lee [21, 22], Lin and Stevenson [23], Gencay and Selcuk [24–27], Hong and Kao [28], and In and Kim [29]. In recent years, wavelet has been applied more and more in the field of economy and finance [30–32].

Wavelet analysis is an improvement of Fourier analysis. It provides a powerful method to analyze the time series of signals, images, and other types of data, which contain different powers at different frequencies. This method is called the wavelet multiscale method, which means to decompose the given time series scale-by-scale. The main advantage of wavelet analysis is that it can decompose data into multiple time scales, and it can process nonstationary data, locate in time, and distinguish signals based on the time scale of analysis.

Krishnan et al. proposed the use of the continuous Wavelet transform with a Daubechies mother wavelet of order 4 (DB4) as the mother wavelet and showed its efficacy using simulated data from the ASCE benchmark structure [33]. They also noted that the DB4 wavelet was a good choice as it has a Discrete Wavelet Transform (DWT) counterpart, which would be more suitable for sensor level processing. It is implemented using the DB4 mother wavelet in this study, and the DWT appears to be better suited to smart sensing applications.

Considering the sample size and the length of the wavelet filter, we settle on the MODWT based on the Daubechies external phase wavelet filter of lenghth 4 (Db (4)). As we take advantage of the daily return on data, the daily price returns can be divided into 1–6 scales.

$$r = A_6 + D_6 + D_5 + D_4 + D_3 + D_2 + D_1. \quad (2)$$

Wavelet scale 1 means 2–4 day dynamics, scale 2 means 4 to 8 days of dynamic, scale 3 means 8 to 16 days of dynamics, and scale 4 means 16 to 32 days of dynamic. Also scale 5 is associated with 32–64 day dynamics, scale 6 is associated with 64–128 day dynamics, and scale 7 corresponds with 128–256 day dynamics, that is, approximately 1 year. The recomposed crystals D_1 and D_6 mean the return on the market portfolio at scales 1 and 6, respectively. As we see, D_1 depicts the high frequency fluctuations of the market portfolio, whereas D_6 depicts its long-term behavior (see Figure 3).

Descriptive statistics of the returns in different scales are presented in Table 1.

Chaotic dynamics are surveyed in different scales by the Lyapunov exponent λ.

Shintani and Linton obtained the asymptotic distribution of λ based on a central limit theorem from a functional Markov process [34]. Ahmed [35] approximated the variance of the largest Lyapunov exponent as

$$\widehat{\Sigma} = \frac{1}{M}\sum_{j=-M+1}^{j=M-1}\left[\xi\left(\frac{j}{1.3221 \cdot M^{0.2}}\right)\sum_{t=|j|+1}^{M}\widehat{\eta}_t\widehat{\eta}_{t-|j|}\right]. \quad (3)$$

The test statistic is asymptotically normal:

$$\widehat{W} = \sqrt{M} \cdot \widehat{\lambda}_M \xrightarrow{\text{Asymptotically}} N(0, \widehat{\Sigma}). \quad (4)$$

Let null hypothesis be H_0: $\lambda \geq 0$, and its rejection H_1: $\lambda < 0$. The rejection of the null hypothesis provides a strong evidence of no chaotic dynamics. The details are omitted here.

The results are summarized in Table 2. In fact, we may not accept chaos at a certain level of significance (for example, p is equal to 0.05) for negative λ.

As to the raw signal for the Chinese agriculture index, we can see that lambda is −0.4649 and the p value is almost equal to zero. The test has rejected the null hypothesis of chaotic dynamics for the Chinese agriculture index. Result has shown that returns are stochastic and not chaotic.

When we decompose a given agriculture index time series on a scale-by-scale basis, different chaos properties can be found. Lambda is negative and equal to −0.1264, −0.0326, and −0.0046 in D_1, D_3, and D_4, respectively. Associated to the p value, the test has rejected the null hypothesis of chaotic dynamics at the shortest scale (2–4 day dynamics). The test cannot reject the null hypothesis in the case D_3 and D_4. Lambda is positive and equal to 0.0213, 0.0025, 0.0199, and 0.4725 in D_2, D_5, D_6, and A_6. So at the intermediate time scale and long time scale, the test cannot reject the null hypothesis.

3. Chaos Dynamic Characteristics of Agriculture Index Time Series

Generally, when Lyapunov exponent is positive, the system exhibits chaotic behavior. In this section, we use scale 2, that is, D_2, data as an example to further verify the nonlinear

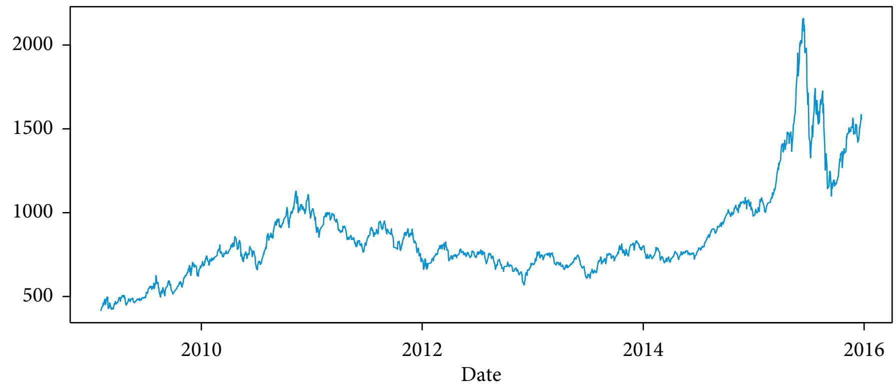

Figure 1: The Chinese agriculture index from February 2, 2009 to December 24, 2015.

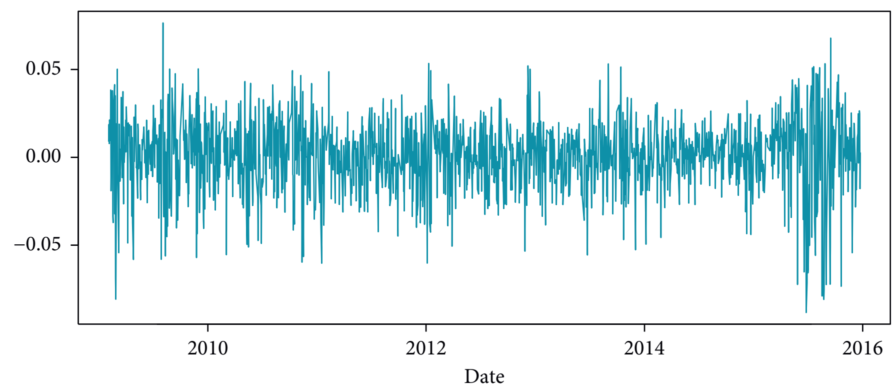

Figure 2: The Chinese daily agriculture index returns from February 2, 2009 to December 24, 2015.

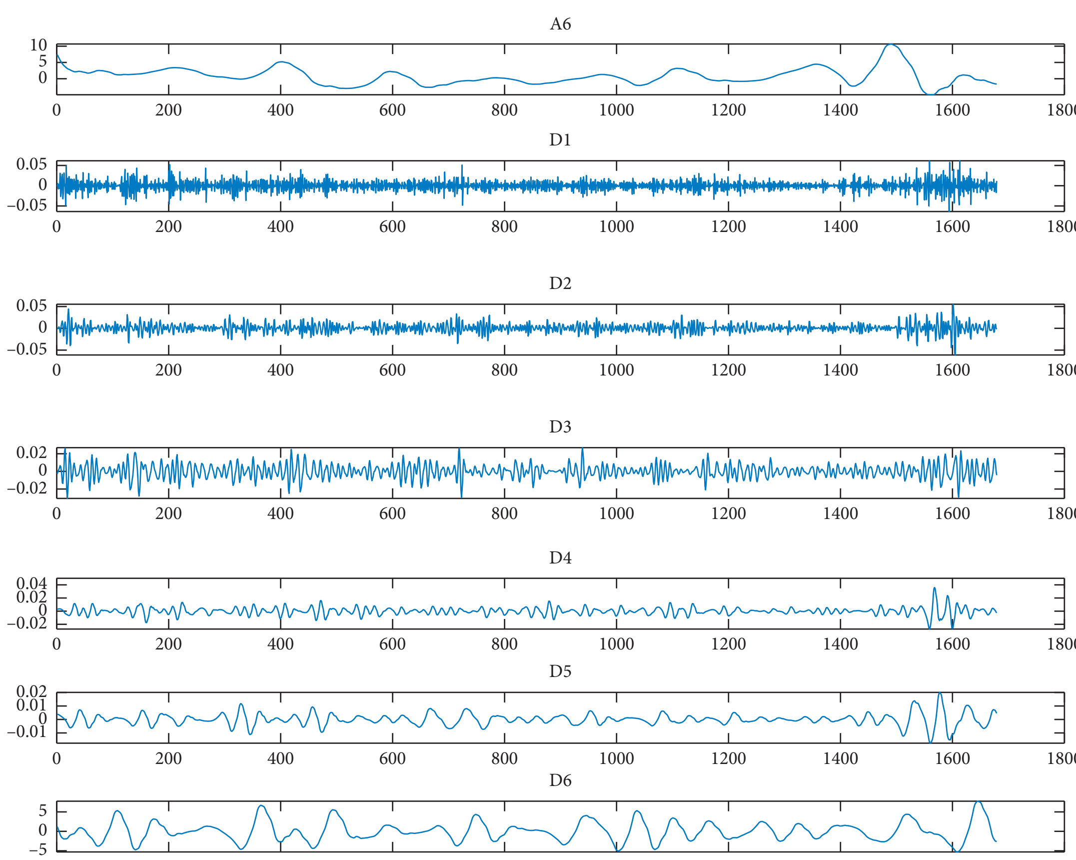

Figure 3: Six-level decomposition of the agriculture index return.

Table 1: Descriptive statistics of the agriculture index returns in different scales.

	Mean	Median	Std. Dev	Minimum	Maximum	Skewness	Kurtosis
Raw data	0.000867	0.002197	0.020333	−0.088357	0.076517	−0.55123	4.49416
D_1	$-2.82e-7$	−0.000103	0.013506	−0.063764	0.061599	−0.002917	4.885629
D_2	$5.69e-06$	−0.000110	0.010536	−0.0612	0.05534	−0.09167	5.685012
D_3	$1.3e-05$	$-5.71e-05$	0.007542	−0.030437	0.026891	−0.07229	3.990095
D_4	$-2.15e-06$	0.000101	0.005675	−0.027223	0.035903	0.218073	7.956299
D_5	$3.23e-07$	−0.000139	0.00411	−0.018213	0.024713	0.588429	8.929143
D_6	$5.77e-05$	$5.52e-05$	0.002842	−0.008262	0.0011984	0.512385	6.170815
A_6	0.00792	0.000644	0.002436	−0.004763	0.008983	0.323109	0.758442

Table 2: Chaos test results for the agriculture indexes returns.

	(L, m, q)	λ	p value	Accepted hypothesis
Raw data	(4, 6, 4)	−0.4649	$1.575e-88$	H_1
D_1	(1, 5, 2)	−0.1264	$9.7346e-19$	H_1
D_2	(1, 2, 1)	0.0213	1	Can not reject H_0
D_3	(1, 6, 3)	−0.0326	0.0523	Can not reject H_0
D_4	(1, 6, 1)	−0.0046	0.4028	Can not reject H_0
D_5	(1, 6, 5)	0.0025	0.5334	Can not reject H_0
D_6	(1, 6, 1)	0.0199	0.7369	Can not reject H_0
A_6	(3, 5, 1)	0.4725	1	Can not reject H_0

dynamic characteristics of the data. Of course, a similar analysis can be made for that the other Lyapunov exponents is positive.

In the following, we discuss the growth and change of agricultural index, and set its simplest Taylor series expansion form as

$$\frac{\mathrm{d}x}{\mathrm{d}t} = a_0 + a_1 x + a_2 x^2. \quad (5)$$

When $x = 0$, $(\mathrm{d}x/\mathrm{d}t) = 0$, so, equation (5) can be rewritten as

$$\frac{\mathrm{d}x}{\mathrm{d}t} = a_1 x + a_2 x^2 = a_1 x\left(1 - \left(-\frac{a_2}{a_1}\right)x\right). \quad (6)$$

Equation (6) is a typical Logistic equation, which is a nonlinear feedback system, and it can be expressed by the following difference equation:

$$x_i = a_3 x_{i-1}\left(1 - a_4 x_{i-1}\right). \quad (7)$$

In the paper, the evolution process of agricultural index market is analyzed based on Logistic dynamic model. Also, the time series data scale 2, that is, D_2, is regarded as a series of discrete values of the logistic dynamic model, and the differential equation model is obtained:

$$x_i = 0.6584 x_{i-1} - 0.1765 x_{i-1}^2. \quad (8)$$

If equation (8) has only one parameter to change,

$$x_i = a x_{i-1} - 0.1765 x_{i-1}^2. \quad (9)$$

Equation (9) will show the complicated nonlinear phenomena.

According to the stability criterion of the fixed point of the difference equation, if the critical state of equation (9)

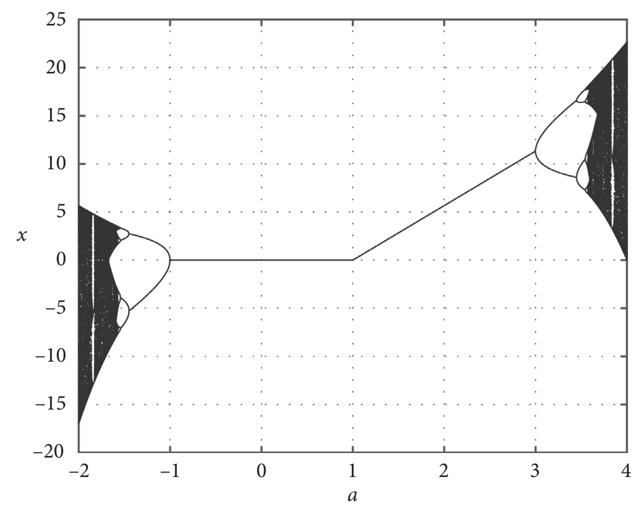

Figure 4: Bifurcation diagram of system states versus parameter.

exists, that is, $|\lambda| = |f'(x)| = 1$, there are two states happening. On one hand, if $|\lambda| = |f'(x)| < 1$, the trend will be stable. On the other hand, if $|\lambda| = |f'(x)| > 1$, the trend will be unstable.

For equation (9), when $x = ax - 0.1765x^2$, there are two fixed points, $x_1 = 0$, $x_2 = (a - 1/0.1765)$.

Obviously, $x_1 = 0$ is a vanishing fixed point, and it does not make any sense.

From $\lambda = f'(x) = 2 - a$, if $|2 - a| = 1$, that is, $a = 1$ or $a = 3$, the system is in the critical state. If $|2 - a| > 1$, $a < 1$ or $a > 3$, the system is in unstable and monotonous divergent. In equation (8), $a = 0.6584 < 1$, so system (8) is unstable. Instability is a prerequisite for the generation of chaos in the system, which is exactly consistent with D_2 data's Lyapunov positive exponent.

The bifurcation diagram would be far better to summarize all of the possible behaviors as the parameter varies on one diagram. For $a \in [-2, 4]$, the bifurcation diagram of system (9) shows the complicated bifurcation phenomena (see Figure 4).

From Figure 4, when the parameter a lies in $[-1.57, -1] \cup [3, 3.57]$, the trajectory of ordinate fluctuates greatly with the increase of parameters, and the system undergoes period doubling evolution. If the parameter a lies in the range $[-2, -1.57t \cup n(3.57, 4]$, the system shows chaotic properties.

4. Conclusion

In recent decades, chaos theory has attracted the attention of many financial analysts and economists. Multiscale wavelet decomposition decomposition can analyze time and frequency at the same time. It is a valuable method to study and forecast the complex dynamics of economic time series. In this paper, daily price returns have been decomposed into different scales based on the wavelet method. Chaos test has shown that the rate of return is random and not chaotic in the shortest scale, but in the medium- and long-term scales, the test cannot reject the null hypothesis, and the financial data have shown some chaotic characteristics. We have taken scale 2 with 4–8 day dynamics as an example to further verify the nonlinear dynamic characteristics of the data. Based on the logistic model to describe the evolution of the index, the bifurcation diagram of the system has been done and shown the complicated bifurcation phenomena. As the bifurcation behavior in the economic system will increase the instability of the system. Therefore, the control of the bifurcation of the economic system will help to reduce the risk of the system, which will be our next research topic.

Data Availability

The data used to support the results of this study can be obtained from the first author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Research Article

Customer Knowledge Enabled Innovation: Analyzing Pricing-Promotion Coordination Mechanism

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Pricing and promotion are two important decisions during the market launch of new consumer electronics products. Nowadays, the pricing and promotion of consumer electronic products are often not made separately but at the same time. This study focuses on the pricing-promotion coordination mechanism of a secondary supply chain of new consumer electronics products (which consists of a manufacturer and a seller). Price and the degree of promotion together affect the demand for products. Manufacturers give sellers a sales target. Manufacturers and sellers set prices and promotions separately, introduce repurchase penalty joint contracts, and establish supply chain profit models to compare and analyze optimal pricing, promotion efforts, and maximum profit of supply chains under different decision-making situations. We prove that the repurchase penalty joint contract can coordinate the supply chain under the assumptions of a single-period game and a multiperiod repeated game. The results show that under the repurchase penalty joint contract, when manufacturers and sellers choose high prices and high promotions at the same time, the supply chain of new consumer electronics products has the largest profit. Finally, numerical experiments are conducted to study the influence of parameters on optimal decision-making and supply chain profits.

1. Introduction

China is the world's largest consumer, producer, and exporter of consumer electronic products. With the continuous escalation of Sino-US trade frictions, as the world's largest producer and exporter of consumer electronics products, China's export of consumer electronics products will inevitably be affected. According to statistics from China International Capital Corporation, China's exports to the United States are mainly machinery, equipment, and instruments, which are mainly home appliances, electronics, and other categories according to classification, accounting for 48% of the total exports [1]. On the one hand, in the process of Sino-US trade frictions, consumer electronic products are bound to become part of the US high tariffs. On the other hand, the rapid iteration speed of consumer electronics products has intensified competition in the domestic market, such as the double launch of new models of Apple mobile phones a year. China's consumer electronics industry is struggling to survive under the dual squeeze of fierce competition in the domestic market and constant external Sino-US trade frictions. Therefore, designing an effective pricing and promotion coordination mechanism in the early stage of the advent of new consumer electronics products can effectively reduce the impact of Sino-US trade frictions and enable new consumer electronics products to increase revenue steadily, which is of great significance to upstream and downstream enterprises in the supply chain.

Existing new product supply chain research mainly focuses on the allocation of new product supply chain, risk assessment, new product development performance, and channel efficiency, but few scholars have specifically studied the issue of the new product pricing-promotion mechanism. For example, Clark et al. [1] and Handfield and Ragatz [2] studied the selection of suppliers and the development of new products. There are also some scholars studying the diffusion of new products. Amini et al. [3] used agent modeling, and simulation methods are based on three different supply chain production-sales strategies to study their impact on the diffusion of new products. Scholars like Gutierrez and Xiuli [4] studied the interaction between manufacturers and sellers in the innovative durable goods supply chain. Chiang [5] studied the impact of dynamic pricing strategies on the efficiency of supply chain channels in both the centralization and decentralization of the new product supply chain. Considering that, it is more appropriate to the demand form of the new products expected in this article. I specially refer to the demand form of new products in study by Lariviere and Padmanabhan [6] and Ray [7], that is, prices and promotion efforts jointly affect the demand for new products.

In the consumer electronics industry, new products are the key to a company's market leadership; in addition, pricing and promotion are key factors for new products to enter the market successfully. Appropriate pricing directly affects product demand. For example, Apple's iPhone7 Red Special Edition has become the shortest-lived mobile phone in Apple's series of mobile phones because of its high pricing and poor sales. In addition, under the premise that there is no substantial breakthrough in new consumer electronics technology, some effective promotions that do not affect the selling price also have a great impact on the demand for new products, such as the hunger marketing strategies of Apple and Xiaomi and various advertising of consumer electronics manufacturers. From the perspective of new product pricing and promotion decision-making research, domestic and foreign research mainly focuses on two aspects. First, research on the optimal pricing and promotion strategies of new products when there are different market segments [8–11] studied the decision-making of pricing and promotion efforts in a multistage supply chain. Liu et al. [12] studied the impact of promotion efforts under dual channels on the profits of manufacturers and retailers and concluded that only synergy between the upstream and downstream of the supply chain can improve promotion efficiency. Game theory has been very successfully applied in many fields [13, 14]. In supply chain research, game theory methods are widely used. Zamarripa et al. [15] applied game theory to industrial SCs and study solutions to maximize total profit under Nash equilibrium.

In the early stage of new consumer electronics products entering the market, this study proves that the repurchase penalty joint contract can effectively coordinate the secondary supply chain and proposes the optimal pricing-promotion strategy of the supply chain manufacturer-seller. The remaining content of the article is arranged as follows: Section 2 describes the problem and establishes basic models under different propositions and obtains the optimal price and optimal promotion degree in different situations. Third section presents the empirical analysis of the study, and fourth section further analyzes the influence of parameters on decision-making and the overall profit of the supply chain through numerical experiments. The last section concludes the study and presents future research directions.

2. Model Construction

2.1. Problem Statement. This article considers a secondary supply chain composed of a manufacturer and a seller. The manufacturer supplies a new consumer electronics product to the seller. Assuming that both parties are independent decision makers, the decision goal is to maximize the overall profit of the supply chain. Due to the short life cycle and single periodicity of consumer electronic products, inventory-related costs are less dependent on product output, order quantity, and order frequency, while pricing and promotional efforts have seriously affected demand. Therefore, in order to quickly open the market and increase the overall profit of the new product supply chain to maximize the profit, it is particularly important for manufacturers and sellers of the new product supply chain to make a strong pricing-promotion coordinated combination decision.

2.2. Basic Assumptions

(1) This type of new products is no different from traditional consumer electronic products in terms of supply, sales channels, and target groups. There are innovations in functions, but there is no essential difference.

(2) Both manufacturers and sellers are rational economic people

(3) All new products of this type produced by the manufacturer are distributed to the seller, and the manufacturer's own production capacity can cope with emergencies such as a surge in demand.

2.3. Related Symbols

P_1: unit wholesale price, which is the manufacturer's decision variable and the seller's acquisition cost

P_2: unit retail price, that is, the seller's decision variable

P_3: the seller has not reached the sales target to reduce the price for promotion

C_1: manufacturer unit production cost

C_2: manufacturer's overall R&D cost

e_1: manufacturer's promotion effort level

e_2: sales promotion effort level

The manufacturer wholesales to the seller at the price P_1, and the seller sells it at the retail price P_2 ($P_2 \geq P_1$). The manufacturer's unit production cost is C_1, and the overall R&D cost $C_2 = (q * R^2)/2$ (q is the R&D cost elasticity and R is the innovation level). The manufacturer determines the unit promotion cost h_1, and the seller determines the unit promotion cost h_2 (h_1, $h_2 \geq 0$), and the price reduction promotion price is P_3 ($P_2 \geq P_3 \geq P_1$). The demand for new products is related to wholesale prices, retail prices, and promotion costs. This article uses the market demand function: $f(x) = a - k_1P_1 - k_2P_2 + e_1 + e_2$, where a represents the predicted sales scale of new electronic products, K_1 ($K_1 > 1$) represents the wholesale price elasticity, and K_2 ($K_2 > 1$) is the retail price elasticity of commodities. The cost required for the promotion effort level of manufacturers and sellers is expressed by the following quadratic function:

$$\begin{aligned} h_1 &= \frac{\varphi e_1^2}{2}, \\ h_2 &= \frac{\varphi e_1^2}{2}, \quad \varphi > 0. \end{aligned} \tag{1}$$

Suppose $f(x)$ is the sales target given by the manufacturer. Assuming the manufacturer's profit is Π_1 and the seller's profit is Π_2, the expression is as follows:

$$\begin{aligned} \Pi_1 &= f(x) * (P_1 - C_1) - h_1 - C_2, \\ \Pi_2 &= f(x) * (P_2 - P_1) - h_2. \end{aligned} \tag{2}$$

The expression of the total profit of the supply chain, which is the sum of the profit of the manufacturer and the seller, is

$$\Pi = (P_2 - C_1) * f(x) - h_1 - h_2 - C_2. \tag{3}$$

It is assumed here that $K_2 * \varphi > 0$, that is, market demand is more sensitive to retail price or promotion effort cost. For consumer electronic products, retail prices or promotions are bound to affect market demand.

2.4. Model Construction and Model Resolution. In order to find the best supply chain pricing-promotion combination strategy, considering that the repurchase penalty joint contract can effectively coordinate the supply chain under the situation of uncertain market demand, this section specially proposes the repurchase penalty joint contract and introduces that the unit penalty price is m and the unit reward price is n (under the contract, the manufacturer sets a sales target a according to the forecast (requires the seller to sell out) and sells the product to the seller at the wholesale price P_1, and the seller sets the retail price P_2 by himself. If the seller cannot achieve the sales target, the manufacturer will repurchase the part that exceeds the market demand at the wholesale price P_1 and punish it; if the sales target is achieved, the difference will be rewarded according to the amount of the difference). The specific decision is made according to the game behavior and actual situation of the manufacturer and the seller.

Case 1. $a < f(x)$

(1) The seller follows the repurchase penalty contract. At this time, the profits of the manufacturer, seller, and supply chain are as follows:

$$\begin{aligned} \Pi_1 &= a * (P_1 - C_1) + [f(x) - a] * (P_1 - m) - C_2 - h_1, \\ \Pi_2 &= a * (P_2 - P_1) + [f(x) - a] * m - h_2, \\ \Pi_A^* &= a * (P_2 - C_1) - P_1[f(x) - a] - C_2 - h_1 - h_2. \end{aligned} \tag{4}$$

Then, the optimal decision problem under this condition is that manufacturers and sellers choose appropriate P_1, P_2 and promotion efforts e_1, e_2 to maximize the overall return of the supply chain, that is, the optimal decision is the optimal solution of the following optimization model:

$$\text{Max}\, P_2 \geq P_1 \Pi(P_2, e_1, e_2). \tag{5}$$

Proposition 1. *The optimal solution for the seller to follow the repurchase penalty contract is* $\begin{cases} P_{1(A)}^* = (a/k_2), \\ P_{2(A)}^* = (a/k_2\varphi), \\ e_{1(A)}^* = (-2a(k_1\varphi - 1)/k_2^2\varphi), \\ e_{2(A)}^* = (a/k_2\varphi). \end{cases}$

Proof. In order to verify whether the total profit $\prod$ of the supply chain can achieve the maximum value, a Hessian matrix G_1 is established:

$$G_1 = \begin{bmatrix} -2k_1 & -k_2 & 1 & 1 \\ -k_2 & 0 & 0 & 0 \\ 1 & 0 & -\varphi & 0 \\ 1 & 0 & 0 & -\varphi \end{bmatrix}. \tag{6}$$

From the value of matrix $G_1 = -K_2^2\varphi^2 < 0$, it is easy to verify that Π (P_1, P_2, e_1, e_2) is a strictly concave function, so the optimal solution of problem (5) satisfies $\begin{cases} (\partial\Pi/\partial P_1) = 0, \\ (\partial\Pi/\partial P_2) = 0, \\ (\partial\Pi/\partial e_1) = 0, \\ (\partial\Pi/\partial e_2) = 0. \end{cases}$ Thus, the optimal $P_1^*, P_2^*, e_1^*, e_2^*$ can be obtained as

$$\begin{cases} P_{1(A)}^* = \dfrac{a}{k_2}, \\ P_{2(A)}^* = \dfrac{a}{k_2\varphi}, \\ e_{1(A)}^* = \dfrac{-2a(k_1\varphi - 1)}{k_2^2\varphi}, \\ e_{2(A)}^* = \dfrac{a}{k_2\varphi}. \end{cases} \tag{7}$$

Substituting (7) into (5), the maximum profit of the supply chain based on the repurchase penalty contract is

$$\Pi_A^* = \frac{8k_1a^2\phi + k_2^2a^2 + 4k_2a^2 - 4a^2 - 4k_1^2a^2\phi^2 - 2k_1k_2^2a^2\phi - 4k_1k_2a^2\phi}{2k_2^4\phi}. \quad (8)$$

(2) The seller does not follow the repurchase penalty contract; the seller does not return the product and reduces the price by themself. At this time, the profit of the manufacturer, seller, and supply chain is as follows:

$$\Pi_1 = a * (P_1 - C_1) - h_1 - C_2, \quad (9)$$

$$\begin{aligned}\Pi_2 &= a * (P_2 - P_1) + [a - f(x)] * (P_1 - P_3) - h_2,\\ \Pi_B^* &= a * (P_2 - C_1) + [a - f(x)] * (P_1 - P_3) - h_1 - h_2 - C_2.\end{aligned} \quad (10)$$

Then, the optimal decision problem under this condition is that manufacturers and sellers choose appropriate P_1, P_2 and promotion efforts e_1, e_2 to maximize the total revenue of the supply chain, that is, the optimal decision is the optimal solution of the following optimization model:

$$\text{Max}\, P_2 \geq P_1 \Pi(P_2, e_1, e_2). \quad (11)$$

□

Proposition 2. *The optimal solution for the seller to follow the repurchase penalty contract is* $\begin{cases} P_{1(B)}^* = (k_2P_3 - a/k_2),\\ P_{2(B)}^* = (a/k_2\varphi),\\ e_{1(B)}^* = (2a + 2ak_1\varphi - k_1k_2P_3\varphi/k_2^2\varphi),\\ e_{2(B)}^* = (a/k_2^2\varphi).\end{cases}$

Proof. In order to verify whether the total profit $\prod$ of the supply chain can achieve the maximum value, a Hessian matrix G_2 is established:

$$G_2 = \begin{bmatrix} 2k_1 & k_2 & -1 & -1\\ 0 & k_2 & 0 & 0\\ -1 & & -\varphi & 0\\ -1 & & 0 & -\varphi \end{bmatrix}. \quad (12)$$

From the value of matrix $G_2 = -K_2^2\varphi^2 < 0$, it is easy to verify that Π (P_1, P_2, e_1, e_2) is a strictly concave function, so the optimal solution of problem (9) satisfies

$$\begin{cases} \dfrac{\partial \Pi}{\partial P_1} = 0,\\[2mm] \dfrac{\partial \Pi}{\partial P_2} = 0,\\[2mm] \dfrac{\partial \Pi}{\partial e_1} = 0,\\[2mm] \dfrac{\partial \Pi}{\partial e_2} = 0. \end{cases} \quad (13)$$

Thus, the optimal $P_1^*, P_2^*, e_1^*, e_2^*$ can be obtained as

$$\begin{cases} P_{1(B)}^* = \dfrac{k_2P_3 - a}{k_2},\\[2mm] P_{2(B)}^* = \dfrac{a}{k_2\varphi},\\[2mm] e_{1(B)}^* = \dfrac{2a + 2ak_1\varphi - k_1k_2P_3\varphi}{k_2^2\varphi},\\[2mm] e_{2(B)}^* = \dfrac{a}{k_2^2\varphi}. \end{cases} \quad (14)$$

The maximum profit of the supply chain at this time is

$$\begin{aligned}\Pi_B^* = {} & \frac{4k_1^2k_2\varphi^2P_3 + 4ak_1k_2\varphi P_3 + 2a^2k_1k_2^2\varphi + 4a^2k_1k_2\varphi + a^2k_2^2 + 4a^2k_2}{2k_2^4\varphi}\\ & - \frac{k_1^2k_2^2\varphi^2P_3^2 + 4k_1^2a^2\varphi^2 + 2k_1k_2^3P_3\varphi + 2k_1k_2^2P_3\varphi}{2k_2^4\varphi} + \frac{8a^2k_1\varphi + 4a^2 + 2C_1ak_2^4\varphi + 2C_2k_2^4}{2k_2^4\varphi}.\end{aligned} \quad (15)$$

(3) In order to ensure that the sales price will not fluctuate significantly in the next cycle, the seller will make a decision of neither returning the product nor reducing the price. At this time, the profit of the manufacturer, seller, and supply chain is as follows:

$$\begin{aligned}\Pi_1 &= a * (P_1 - C_1) - h_1 - C_2,\\ \Pi_2 &= a * (P_2 - P_1) - [a - f(x)] * P_1 - h_2,\\ \Pi_C^* &= a * (P_2 - C_1) - [a - f(x)] * P_1 - C_2 - h_1 - h_2.\end{aligned} \quad (16)$$

Under the same conditions, the optimal decision problem is that manufacturers and sellers choose appropriate P_1, P_2 and promotion efforts e_1, e_2 to maximize the overall revenue of the supply chain, that is, the optimal decision is the optimal solution of the following optimization model:

$$\text{Max}\, P_2 \geq P_1 \Pi (P_2, e_1, e_2). \tag{17}$$

□

Proposition 3. *The optimal solution for the seller to follow the repurchase penalty contract is* $\begin{cases} P^*_{1(C)} = (a/k_2), \\ P^*_{2(C)} = (a/k_2\varphi), \\ e^*_{1(C)} = (-2a(K_1\varphi - 1)/k_2^2\varphi), \\ e^*_{2(C)} = (a/k_2\varphi). \end{cases}$

Proof. In order to verify whether the total profit $\prod$ of the supply chain can achieve the maximum value, a Hessian matrix G_3 is established:

$$G_3 = \begin{bmatrix} -2k_1 & k_2 & 1 & 1 \\ 0 & -k_2 & 0 & 0 \\ 1 & 0 & -\varphi & 0 \\ 1 & 0 & & -\varphi \end{bmatrix}. \tag{18}$$

From the value of matrix $G_3 = K_2^2 \varphi^2 < 0$, it is easy to verify that $\Pi(P_1, P_2, e_1, e_2)$ is a strictly concave function, so the optimal solution of problem (17) satisfies

$$\begin{cases} \dfrac{\partial \Pi}{\partial P_1} = 0, \\ \dfrac{\partial \Pi}{\partial P_2} = 0, \\ \dfrac{\partial \Pi}{\partial e_1} = 0, \\ \dfrac{\partial \Pi}{\partial e_2} = 0. \end{cases} \tag{19}$$

Thus, the optimal $P_1^*, P_2^*, e_1^*, e_2^*$ can be obtained as

$$\begin{cases} P^*_{1(C)} = \dfrac{a}{k_2}, \\ P^*_{2(C)} = \dfrac{a}{k_2\varphi}, \\ e^*_{1(C)} = \dfrac{-2a(K_1\varphi - 1)}{k_2^2\varphi}, \\ e^*_{2(C)} = \dfrac{a}{k_2\varphi}. \end{cases} \tag{20}$$

At this time, the maximum profit of the supply chain is

$$\Pi_C^* = \frac{8k_1a^2\phi + k_2^2a^2 + 4k_2a^2 - 4a^2 - 4k_1^2a^2\phi^2 - 2k_1k_2^2a^2\phi - 4k_1k_2a^2\phi - 2k_2^4a\phi(C_1 + C_2)}{2k_2^4\phi}. \tag{21}$$

Proposition 4. *In Case 1,* $\Pi_A^* > \Pi_B^* > \Pi_C^*$.

Proof. Judging from the expressions of Π_A^* and Π_B^*, $\Pi_A^* - \Pi_B^* = [a - f(x)] * P_3 > 0$ always holds according to the conditions. Judging from the expressions of Π_B^* and Π_C^*, $\Pi_B^* - \Pi_C^* = [a - f(x)] * (2P_1 - P_3) > 0$ always holds according to the conditions. It can be concluded that when the sales target set by the manufacturer is less than the final sales volume, $\Pi_A^* > \Pi_B^* > \Pi_C^*$. □

Case 2. $a > f(x)$, that is, when the final sales volume is greater than the predicted market demand, regardless of whether the initial seller chooses to comply with the repurchase penalty joint contract, the profit change only exists in the manufacturer and the seller, and has no impact on the profit of the supply chain. Supply chain profits are as follows:

$$\begin{aligned}\Pi_1 &= a*(P_1 - C_1) - [f(x) - a]*n - h_1 - C_2,\\ \Pi_2 &= a*(P_2 - P_1) + [f(x) - a]*n - h_2,\\ \Pi_D^* &= f(x)*(P_2 - C_1) - C_2 - h_1 - h_2.\end{aligned} \tag{22}$$

At this time, under this condition, P_1 has no substantial impact on the profit of the supply chain and $k_1 > 1$ which is regarded as a constant. Then, the optimal decision-making problem becomes that the manufacturer chooses the appropriate e_1 and the seller chooses the appropriate P_2 and the promotion effort e_2 to maximize the overall return of the supply chain, that is, the optimal decision is the optimal solution of the following optimization model:

$$\operatorname{Max} P_2 \geq P_1 \Pi(P_2, e_1, e_2). \tag{23}$$

Proposition 5. *The optimal P_2^*, e_1^*, e_2^* in Case 2 are*

$$\begin{cases} P_{2(D)}^* = \dfrac{a - C_1K_2 - K_1P_1}{2(k_2\varphi - 1)},\\ e_{1(D)}^* = \dfrac{a\varphi + C_1K_2\varphi - 2C_1 - K_1P_1\varphi}{2(k_2\varphi - 1)},\\ e_{2(D)}^* = \dfrac{a - C_1K_2 - K_1P_1}{2(k_2\varphi - 1)}.\end{cases} \tag{24}$$

Proof. In order to verify whether the total profit $\prod$ of the supply chain can achieve the maximum value, a Hessian matrix G_4 is established:

$$G_4 = \begin{bmatrix} -2K_2 & 1 & 1\\ 1 & -\phi & 0\\ 1 & 0 & -\phi\end{bmatrix}. \tag{25}$$

From the value of matrix $G_4 = 2\phi - 2K_2\varphi^2$, it is easy to verify that $\Pi(P_1, P_2, e_1, e_2)$ is a strictly concave function, so the optimal solution of problem (26) satisfies $\begin{cases}(\partial\Pi/\partial P_2) = 0,\\ (\partial\Pi/\partial e_1) = 0,\\ (\partial\Pi/\partial e_2) = 0.\end{cases}$ Thus, the optimal P_2^*, e_1^*, e_2^* can be obtained as

$$\begin{cases} P_{2(D)}^* = \dfrac{a - C_1K_2 - K_1P_1}{2(k_2\varphi - 1)},\\ e_{1(D)}^* = \dfrac{a\varphi + C_1K_2\varphi - 2C_1 - K_1P_1\varphi}{2(k_2\varphi - 1)},\\ e_{2(D)}^* = \dfrac{a - C_1K_2 - K_1P_1}{2(k_2\varphi - 1)}.\end{cases} \tag{26}$$

Substituting (8) into (23), the maximum profit of the supply chain at this time is

$$\begin{aligned}\Pi_D^* = {}& \frac{C_1K_2^3\big(4\varphi - 2C_1^2K_2^3 - C_1^2K_2^2\varphi^3 - 4C_1^2K_2^2 + C_1^2K_2^2\varphi + 6C_1^2K_2^2 + 4C_1^2K_2\varphi^2 + 12C_1^2K_2\varphi}{8(K_2\varphi - 1)^2}\\ &+ \frac{8C_1K_1K_2^2P_1\varphi^2 - 4C_1^2\varphi - 8C_1^2 - 4C_1K_1K_2^2P_1 + 2C_1K_1K_2P_1\varphi^3 + 4C_1K_1K_2P_1\varphi^2 - 14C_1K_1K_2P_1\varphi}{8(K_2\varphi - 1)^2}\\ &+ \frac{4C_1K_1K_2P_1 - 4C_1K_1P_1\varphi^2 - 4C_1K_1P_1\varphi + 8C_1K_1P_1 - 8C_1aK_2^2\varphi^2 + 4C_1aK_2^2 - 2C_1aK_2\varphi^3}{8(K_2\varphi - 1)^2}\\ &+ \frac{14C_1aK_2\varphi - 4C_1aK_2\varphi^2 - 4C_1aK_2 + 4C_1a\varphi^2 + 4C_1a\varphi - 8C_1a + 4K_1^2P_1^2K_2\varphi - 24K_1^2P_1^2K_2}{8(K_2\varphi - 1)^2}\\ &+ \frac{K_1^2P_1^2\varphi - K_1^2P_1^2\varphi^3 - 2K_1^2P_1^2 - 8K_1P_1aK_2\varphi + 4K_1P_1aK_2 + 2K_1P_1a\phi^3 - 2K_1P_1a\phi + 4K_1P_1a}{8(K_2\varphi - 1)^2}\\ &+ \frac{4a^2K_2\varphi - 2a^2K_2 - a^2\varphi^3 + a^2\varphi - 2a^2 - 8C_2K_2^2\varphi^2 + 16C_2K_2 - 8C_2}{8(K_2\varphi - 1)^2}.\end{aligned} \tag{27}$$

Proposition 6. *When the sales target set by the manufacturer is greater than the final sales volume, the supply chain profit under the repurchase penalty contract and the profit in the noncompliance contract are the same as Π_D^*, but for the manufacturer and the seller as a whole, it increases profits and enhances promotion enthusiasm, which is conducive to the manufacturer's next cycle of new product demand forecasts and promotion cost input by both parties, improves the success* *rate of new products on the market, and thereby increases the profit level of the entire supply chain.*

3. Numerical Analysis

In the previous section, we obtained the comparison results of supply chain profits under different pricing and promotion orders through theoretical analysis. In this section, we will use numerical analysis to explore the influence of wholesale price sensitivity coefficient K_1, retail price sensitivity coefficient K_2, and promotion effort cost coefficient φ on optimal decision-making and the impact of supply chain profit Π_A^*. Here, the parameters of the new product supply chain are set as follows: $a = 1450$, $C_1 = 400$, and $C_2 = 30$.

3.1. Wholesale Price Elasticity Coefficient K_2. We set $K_1 = 4$, $\varphi = 0.1$, and K_2 to be 1, 2, 3, 4, 5, and 6, respectively. According to Figure 1, as K_2 increases, the wholesale price P_1, retail price P_2, promotion efforts, and supply chain profits are lower, and manufacturers and sellers are less willing to promote sales. The smaller K_2, the lower the wholesale price and retail price and the higher the promotion level. While manufacturers are adopting high-pricing and high-promotion decisions, sellers should also adopt higher-pricing and higher-promotion decision-making strategies to improve supply chain profits. The larger K_2 is, it is not good for the supply chain of new consumer electronics products.

3.2. Promotional Effort Cost Coefficient φ. We set $K_1 = 4$, $K_2 = 6$, and φ takes 0.1, 0.2, 0.3, and 0.5, respectively. According to Figure 2 the larger φ, the lower the retail price and the promotion efforts of manufacturers and sellers because the higher the promotion cost, the less willing are manufacturers and sellers to promote sales, and sellers can only expand market demand by lowering retail prices. At the same time, as φ increases, the optimal retail price P_2 under the repurchase penalty contract, the optimal promotion effort levels e_1 and e_2, and the profit of the entire supply chain will all become lower. This means that the larger φ, the more unfavorable the supply chain of new consumer electronics products.

In order to ensure the maximum profit of the new consumer electronics product supply chain, both parties in the supply chain should abide by the repurchase penalty joint contract and make both manufacturers and sellers adopt a coordination mechanism of high pricing and high promotion.

4. Long-Term Repeated Game Pricing-Promotion Decision Game

The above discussion only considers the situation of a single game. However, in the actual supply chain, there are multiple repeated games between manufacturers and sellers. The strategic choices of both parties in the supply chain are based on the results of the previous game. From a long-term perspective, in order for both parties in the supply chain to choose a pricing-promotion mechanism with high pricing and high promotion each time the game results, both manufacturers and retailers must have a certain spirit of contract while introducing a reasonable form of profit distribution. Assuming that the undistributed profit before the manufacturer's profit will be more than the profit after the distribution, it is very likely that the seller will choose not to comply with the contract in the second game stage, which will damage the overall profit of the supply chain. If the seller predicts this before the transaction, they will not choose to comply with the contract in the first game stage. At this time, both the manufacturer and the retailer will choose not to comply with the previously agreed contract. It can be seen that if there is a long-term lack of control measures, the profit of the supply chain will fluctuate greatly.

Considering that in a competitive market environment, the relationship between manufacturers and sellers in the supply chain is equal, so in order to seek the problem of maximizing the profits of the new product supply chain under the long-term repeated game (that is, both manufacturers and sellers choose high price and high promotion decision), we assume that the loss value of the party who does not comply with the contract is M (including loss of reputation and increase in collective costs caused by work stoppage). The value of M is much greater than the profit obtained by any party in the one-time game. Get a profit distribution plan that is acceptable to both parties and has a certain contractual nature; then, the distribution of profits is

$$\begin{aligned} a > f(x)t, \quad & \Pi_1 = \rho * \Pi_A^*, \\ & \Pi_2 = (1-\rho) * \Pi_A^*, \\ a < f(x)t, \quad & \Pi_1 = \rho * \Pi_D^*, \\ & \Pi_2 = (1-\rho) * \Pi_D^*. \end{aligned} \tag{28}$$

Let i represent the number of stages in the repeated game between the two parties, and set the profit distribution factor of the i^{th} stage as ρ_i. If the manufacturer chooses not to comply with the contract in the $n+1$ stage, considering the time value of funds, the manufacturer's discount rate for each stage is j_1. The discount rate of each stage of the seller is j_2, and the present value of the manufacturer's mincome at stage n is

$$\Pi_1 = \sum_{i=1}^{n} \rho_i, \Pi_A^*\left(P_{1(A)}^*\right)\mu_1^j. \tag{29}$$

If the repurchase penalty contract is not complied with in the $n+1$ stage, then

$$\Pi_1^F = \sum_{i=1}^{n} \rho_i, \Pi_A^*\left(P_{1(A)}^*\right)\mu_1^j - M. \tag{30}$$

Present value of seller's earnings is

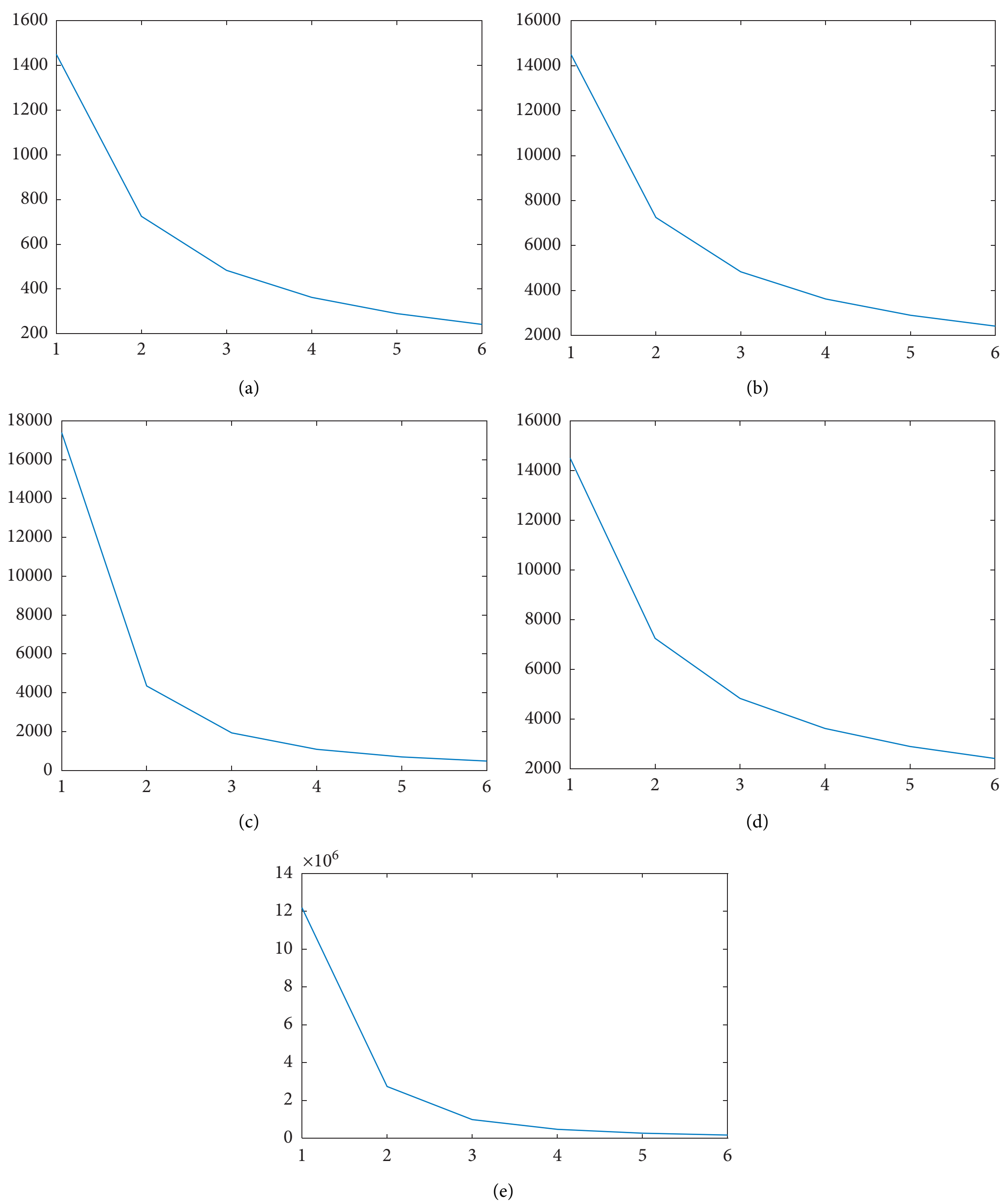

FIGURE 1: The influence of K_2 on optimal decision and optimal profit. (a) The influence of K_2 on the wholesale price P_1. (b) The influence of K_2 on the wholesale price P_2. (c) The influence of K_2 on the wholesale price e_1. (d) The influence of K_2 on the wholesale price e_2. (e) The influence of K_2 on optimal profit.

$$\Pi_2 = \sum_{i=1}^{n} \rho_i, \Pi_A^* \left(P_{2(A)}^*\right) \mu_2^j. \tag{31}$$

If the repurchase penalty contract is not complied with in the $n+1$ stage, then

$$\Pi_2^F = \sum_{i=1}^{n} \rho_i, \Pi_A^* \left(P_{2(A)}^*\right) \mu_2^j - M. \tag{32}$$

Obviously, once the manufacturer decides not to comply with the repurchase penalty joint contract, the manufacturer's profit will eventually be negative. Similarly, if the seller decides not to comply with the repurchase penalty joint contract for a certain period, the profit will eventually be negative. Therefore, in the repeated game, manufacturers and sellers need to comply with the repurchase penalty joint contract at each game stage is the only equilibrium result.

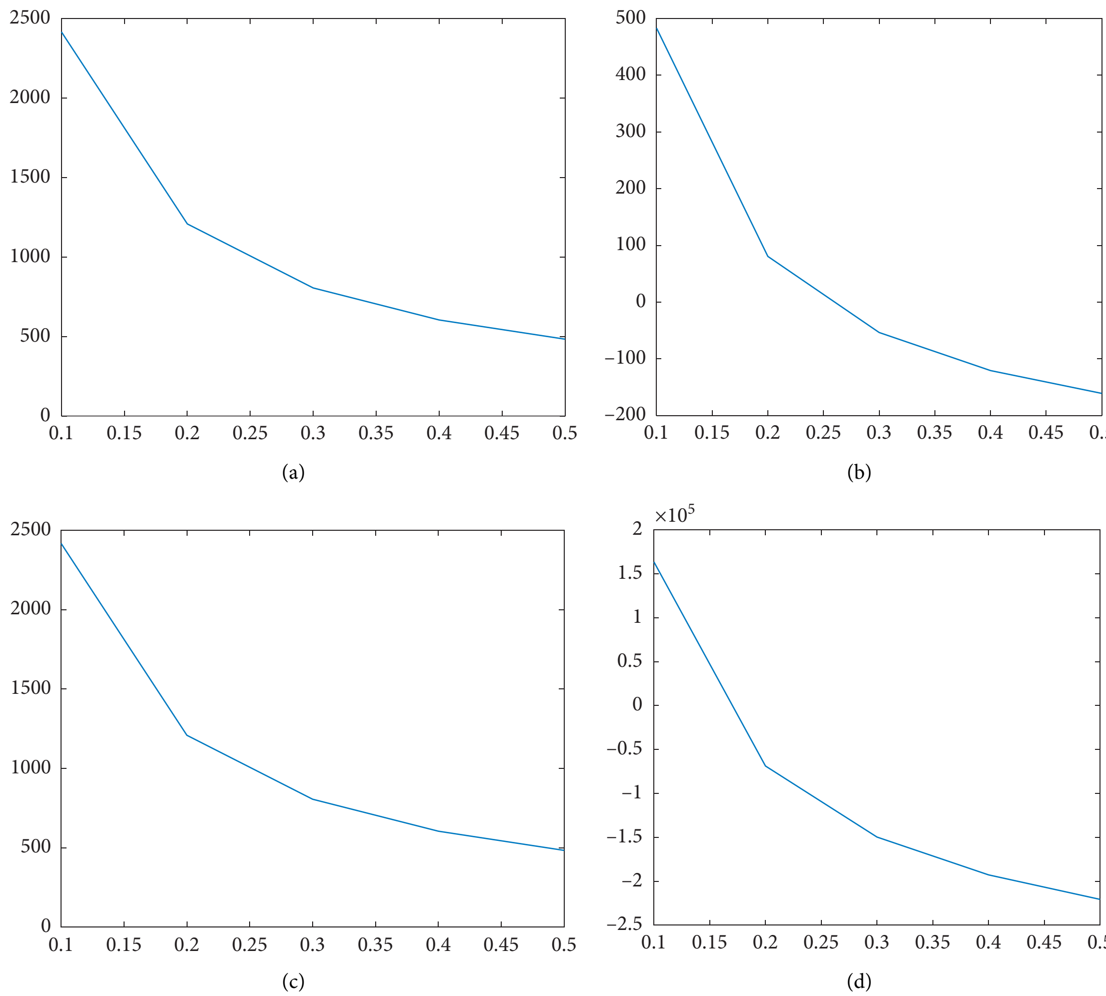

Figure 2: The influence of φ on the optimal decision and optimal profit. (a) The influence of φ on the retail price P_2. (b) The influence of φ on the promotion effort level e_1. (c) The influence of φ on the retail price e_2 (d) The influence of φ on optimal profit.

5. Conclusion

The rapid rise of electronic technology with the development of social science and technology has greatly improved people's living standards. At present, consumer electronics products are lacking in innovation, and products are becoming more and more homogeneous. With the advent of the 5G era, a large number of homogenized new products have swarmed into the consumer electronics market. In order to compete for market share, competition between enterprises and even the supply chain is bound to be fierce. Price wars and sales promotion wars will emerge in endlessly, flooding every game cycle of sales. At this time, only by implementing appropriate pricing-promotion coordination strategies can companies gain a foothold in market competition. In the postepidemic era, in the case of different damages to the global supply chain, in order to ensure that the overall profit of the consumer electronics new product supply chain is optimal, adopting appropriate pricing-promotion coordination strategies and appropriate contracts have become the research focus.

This article mainly studies the coordination of the supply chain of new consumer electronics products and tries to explore a contract that can coordinate the supply chain of new consumer electronics products, introduces a repurchase penalty contract and seeks the most effective pricing-promotion mechanism under this contract, and finally maximizes the profits of the supply chain. In this article, demand is not only related to price but also affected by promotional efforts. We also compared the profit situation of the new consumer electronics product supply chain under the joint repurchase penalty under different decision-making situations and derived the profit function of the supply chain manufacturers and sellers under the long-term game, indicating that whether it is in the optimal equilibrium is a single-period game or a long-term game where manufacturers and sellers comply with the repurchase penalty joint contract. Finally, through numerical experiments, the influence of some parameters of the supply chain on decision-making and profit is analyzed. Through research, the results of this article are as follows:

(1) In situation 1, when the sales target set by the manufacturer is less than the final sales volume, Proposition 1, the supply chain profit of the seller under the repurchase penalty joint contract, is the largest, which is also in line with the seller's decision-making choice under actual circumstances. In situation 2, when the sales target set by the manufacturer is greater than the final sales volume, the supply chain profit under the supplier's compliance with the repurchase penalty contract and the profit under the noncompliance contract are both Π_D^*; but for both the manufacturer and the seller as a whole, it increases profits and enhances the enthusiasm for promotion, which is conducive to the manufacturer's next cycle of new product demand forecasts and promotion cost input by both parties, and improves the success rate of new products on the market, thereby increasing the profit level of the entire supply chain.

(2) When the contract parameters meet the given conditions and are within a certain range, the repurchase reward and punishment joint contract can realize the coordination of the new consumer electronics product supply chain. When repurchase rewards and punishments are based on joint contracts, both manufacturers and sellers should adopt a high-pricing and high-promotion strategy.

(3) Under the model of joint promotion by manufacturers and sellers, with the increase in production costs, manufacturers' promotion levels, and sellers' promotion efforts, wholesale and retail prices will rise accordingly. The relationship between the manufacturer's promotion level, seller's promotion effort level, and retail price depends on the value of K_1 and K_2.

5.1. Future Research Direction. On the basis of this article, future research can also be carried out from the following perspectives: (1) research on the coordination of the pricing-promotion mechanism of new consumer electronic products under other contracts. This article considers the repurchase penalty joint contract. In real life, companies may sign other contracts. Therefore, it is an interesting research topic to study the decision sequence under other contracts. (2) This article assumes that promotion is verifiable. In real life, sometimes promotion is not verifiable. It is an important topic to study the problem of new product supply chain coordination when promotion is not verifiable.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Credit Risk Assessment of Supply Chain Financing with a Grey Correlation Model: An Empirical Study on China's Home Appliance Industry

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Supply chain finance (SCF) plays an increasingly important role in global enterprise competition. The credit risk accompanying SCF has attracted the attention of the government, enterprises, and academia. However, with the absence of data and inaccurate information, traditional risk assessment methods are frequently failed to assess the credit risk in SCF, especially for small- and medium-sized enterprises (SMEs). In this study, a grey correlation model is introduced and applied to the SCF risk assessment process for 15 firms in the Chinese home appliance industry with 15 performance indicators that represent profitability, solvency, operational capability, and development capability. The empirical study displays the operability and effectiveness of the grey correlation model, which is superior to traditional methods in the supply chain financial risk assessment.

1. Research Background and Significance

At the beginning of the 20th century, supply chain finance (SCF) gradually developed in China and established a certain scale after nearly 20 years of development. The SCF business initiated by Shenzhen Development Bank not only provides all-round financial services for enterprises of all sizes in the supply chain but also greatly boosts the efficiency of core enterprises, accelerates their capital flow, and secures substantial profits for them. At the same time, the service has eased the funding gap of other small- and medium-sized enterprises (SMEs) in the upstream and downstream activities and contributed to their rapid growth. As of 2018, it reached a market size of 17.5 trillion and had been expected to reach 27 trillion by 2020. On January 19, 2017, the Ministry of Commerce, the National Development and Reform Commission, the Ministry of Land and Resources, the Ministry of Transport, and the State Post Bureau jointly issued the "13th Five-Year Plan for Trade and Logistics Development," which was aimed, as stated in the planning area, at expanding financing channels and promote SCF, encouraging commercial and logistics enterprises to finance directly through equity investment, and undertaking bond financing and other mechanisms. It is aligned with assisting small- and medium-sized enterprises in obtaining funds, optimizing resource allocation in the supply chain, and improving the quality of supply chain financial services. The General Office of the State Council issued the "Guiding Opinions on Actively Promoting Supply Chain Innovation and Application" in January 2020. The "Opinions" proposes that, by the end of 2020, a batch of new technologies and new models of supply chain development suitable for my country's national conditions will be formed, and a smart supply chain system covering my country's key industries will basically be formed to make China an important center of innovation and application in the global supply chain.

The current COVID-19 and the previous global financial crisis have caused millions of companies to go bankrupt. The main reason is that the capital chain is broken. This has caused all sectors of society to pay attention to risk management issues, especially between banks, between enterprises, and between banks and enterprises. The credit risk between the government, banks, and many enterprises should pay attention to it. In the context of the "Internet+" economy, SCF is a relatively new research field. The relationships among commercial banks, core enterprises, and small- and medium-sized enterprises in the supply chain are becoming increasingly complex and intertwined more closely, forming a huge complex supply chain finance network.

While SCF is widely recognized and valued by the global industry, it has also encountered significant challenges and obstacles, one of which is how to control or avoid the credit risk of SCF that has resulted in many financial risks in reality, such as the Greensill incident (2021) in the USA (On March 8, 2021, Greensill, a well-known supply chain financial service provider founded in the United Kingdom, filed for bankruptcy protection, mainly because major insurers stopped providing credit insurance for $4.1 billion of debt in its portfolio created for clients including Credit Suisse due to questions about the quality of its debt receivable assets. The incident has caused a global rethink on supply chain finance business, especially on how to control asset quality and capital security in supply chain finance.); Noah Wealth stampede (2020), Minxing Pharmaceutical fraudulent loan case (2020), and the 83-ton fake gold case of Wuhan Jinhuang Jewelry (2019) in China. These incidents are forcing many financial institutions to shift to a cautious attitude towards the supply chain finance business and an increased focus on risk assessment. However, it is very difficult for companies, especially for small- and medium-sized companies, to carry out supply chain financial risk assessment since relevant information, including data, is commercial secret for individual companies and is difficult to obtain. Under this circumstance, this study introduces a grey correlation model to assess supply chain financial risk, which is exactly in line with the basic characteristics of grey systems, to overcome the difficulty of missing data to the maximum extent. For demonstrating the convenience and effectiveness of the model, 15 firms are selected as samples in the SCF of the Chinese home appliance industry for an empirical study.

The purpose of this study is to introduce a grey correlation model in supply chain financial risk assessment, firstly, which is no longer limited to the asset operation status and financial data of individual enterprises, but highlights the overall strength of the supply chain and the real transaction background between upstream and downstream enterprises, which is conducive to promoting the cooperation and coordinated development of core enterprises and upstream and downstream enterprises in the supply chain, improving the operation relationship, and realizing the value maximization and cost minimization of the supply chain. Secondly, in the SCF system, the small and medium enterprises can improve the situation of low credit rating and small capital scale with the commercial credit of core enterprises and obtain financing in a timely and effective manner, thus solving the problem of difficult and expensive financing. Finally, the study of the credit risk of enterprise SCF can reduce the financing risk of financial institutions and bring them more lucrative income.

The rest of the paper is organized as follows. Section 2 presents the previous studies. Section 3 provides the mechanism of supply chain financial credit risk. Then the model of grey relational analysis has been introduced in Section 4. Section 5 carries out the empirical study on supply chain finance credit risk. The final conclusions are drawn in Section 6.

2. Literature Review

The theory of SCF has been continuously developed and enhanced since it was put forward to the state of being a systematic and mature system. Timme and Williams-Timme [1] first proposed the concept of SCF, exploring and explaining its meaning. It is believed that SCF is a new business model created by the cooperation among enterprises in the supply chain and financial service companies outside the supply chain to achieve the goals of the supply chain. Lamoureux [2] summarized the meaning of SCF based on previous studies. He believes that SCF can systematically optimize the availability of funds and reduce costs in the enterprise ecosystem dominated by core enterprises. Gupta and Dutta [3] studied currency flows in the supply chain from the perspective of supply chain partners and established an integer programming model to solve the measurement of the dynamic level of static problems. Guided by SCF, Gelsomino et al. [4] highlighted the four key factors of accounts payable, accounts receivable, inventory, and working capital optimization for fixed asset financing and identified the most important issues to be addressed in future research. Xie and He [5] summarized and analyzed three typical models of international SCF: the leading model of logistics enterprises, the cooperation model of enterprise groups, and the service model of commercial banks and performed a comparative analysis of the three models. Finally, they posited a vision for China to develop their SCF business better. Tseng et al. [6] established a fuzzy interpretation structure model, with the help of a hierarchical model, and applied fuzzy TODIM to determine language preferences, benefits, and costs. The results show that sustainable supply chain financing improves the competitive advantage of enterprises through multiple attributes, which means that collaborative value innovation, strategic competitive advantage, and financial attributes are the most important aspects to improve enterprise performance.

The change in the credit risk of upstream and downstream enterprises in the supply chain has a direct impact on the business status and future development trends. According to the characteristics of SMEs, Liu and Cui [7] used the structural equation model (SEM) and the grey relation analysis models to evaluate the credit risk of SCF. With the development of the Internet, the combination of SCF and the Internet has gradually developed online, and its credit risk challenges have become more complicated. Fan et al. [8] combined the thinking and data mining direction of financial big data on the Internet to screen the financial risk evaluation indicators of the supply chain and established a credit risk evaluation system and a three-party game model. It used qualitative and quantitative methods to analyze the principle of risk-sharing among the participants of SCF and evaluated the credit risk of SMEs. Under the innovative mode of combining online and traditional SCF, He and Shen [9] extracted the influencing factors of risks, constructed a risk evaluation system for online SCF, and evaluated these risks through the analytic hierarchy process and fuzzy comprehensive evaluation method. Li and Zhao [10] analyzed the influence factors of supply chain finance credit risk based on the systems science perspective. They built a structural equation model to explore the basic path of supply chain financial credit risk formation and established a system dynamics model to study the mechanism of system elements in the evolution of supply chain financial credit risk. Tian et al. [11] constructed a credit risk assessment model for SMEs in the supply chain financing model. The empirical results show that the model is more accurate in predicting the financing risks of SMEs in the automobile manufacturing industry and provides suggestions for commercial banks, core supply chain enterprises, and SMEs to improve the supply chain financing dilemma.

Commercial banks provide the main impetus for capital circulation in SCF and play a vital role in its development. Diercks [12] noted that commercial banks should strictly monitor and mitigate SCF business risks and introduce multiple monitoring methods. Sheng [13] explained the credit risk assessment of commercial banks in SCF and proposed suggestions and measures by taking the example of the Hunan branch of the Bank of China, supported by Lu [14] also by taking a bank as an example. Zhang [15] analyzed the risk of SCF in China from the perspective of game theory.

As the application of grey relation analysis, Deng [16] systematically expounded the grey theory in the book *Grey System* and proposed the grey correlation analysis model as one of the main components of the grey theory. Liu et al. [17] explained the grey relation analysis model in detail in the *Grey System: Theory and Its Application* including its meaning, types, formulas, and application. Wang et al. [18] improved the analytic hierarchy process and proposed an analysis method to solve the problem whereby the grey relational analysis method is not sufficiently objective to calculate the relational degree. They summed up the advantages and disadvantages of both approaches and confirmed it through empirical research. Cao et al. [19] improved the calculation method of the grey relation analysis model and overcame the limitations of specific calculation methods. He redefined the similarity of the curve and grey relational space so that the result of the calculation more reasonably reflected the essence of the grey relational degree. Tian et al. [20] carried out a classification review and evaluation of the existing grey relational degree algorithm model and found that there is no grey correlation degree algorithm that satisfies both normative and order-preserving performance and analyzed the reason. The research conclusion makes it more objective, accurate, and precise and promotes the development of the grey relation analysis model. Dagdevir and Ozceyhan [21] present an optimization of the water-based TiO_2 nanofluid preparation process for thermal conductivity and zeta potential using the Taguchi method for single-objective and grey relation analyses for multi-objective optimization. Huang et al. [22] used the grey relational analysis method to study the correlation between energy consumption and economic growth in Fujian Province. The results show that Fujian's GDP is significantly correlated with energy consumption products. The correlation degree is greater than 0.7, indicating that the economic growth of Fujian Province is highly dependent on energy consumption.

From the existing studies of Chinese and international scholars, we have gained a profound understanding of SCF. The analysis of the SCF theory and financing mode is becoming mature. However, most of the literature studies have analyzed supply chain financial risks from the perspective of individual institutions, such as companies, banks, financial institutions, or the like. Instead, it is pertinent to understand and analyze the financial risks from the industrial perspective since the cooperation between upstream and downstream enterprises in the supply chain frequently occurs in the same industry. As for the methods, many existing studies use logistic regression or principal component analysis to study the credit risk of supply chain finance, which is difficult to carry out in reality due to the unavailability of data. This study adopts the grey correlation analysis model to overcome the uncertainty of information required in the risk assessment in the traditional methods and analyze the credit risk of the supply chain finance from a perspective of the industry.

3. Mechanism of Supply Chain Financial Credit Risk

The credit risk of SCF is evident when commercial banks and upstream and downstream enterprises carry out financing activities. Due to the negative effects of immeasurable uncertainty, their products cannot achieve the expected earnings, or the capital cannot be recovered, and there is a certain probability of economic losses. The mechanism includes the following aspects.

3.1. Principal-Agent Theory Analysis of Credit Risk in SCF.

The principal-agent theory, which advocates the separation of ownership and management rights, was put forward by American economists Berles and Means in the 1930s [23] The principal-agent relationship originates from the existence of "specialization." The "grantor" acts as the "principal," and the "authorized person" acts as the "agent." Professional agents have a comparative advantage over principals. A principal-agent relationship means that one or more behavioral subjects, according to an express or implied contract, designate and hire some other behavioral subjects to serve them, while granting the latter certain decision-making rights and paying them corresponding remuneration according to the quantity and quality of the services provided by the latter.

In SCF, each enterprise in the supply chain is different from financial institutions, logistics enterprises, and other majors, and the division of labor is differentiated and clear, resulting in a principal-agent relationship.

Figure 1 shows a principal-agent relationship among commercial banks, core enterprises, and financing enterprises as well as between logistics, core, and financing enterprises. The information of the principal and agent is asymmetric. The principal aims to obtain the maximum profit from the capital, and the agent is concerned about whether his interests can be met. The two parties have different goals. From the perspective of measuring their interests, core enterprises may choose to help banks supervise financing enterprises or assist financing enterprises in cheating commercial bank loans. When core enterprises have a low position in the supply chain and rely on financing enterprises, they may choose to help finance enterprises cheat commercial banks of loans to ensure their own interests, thus increasing the credit risk of SCF.

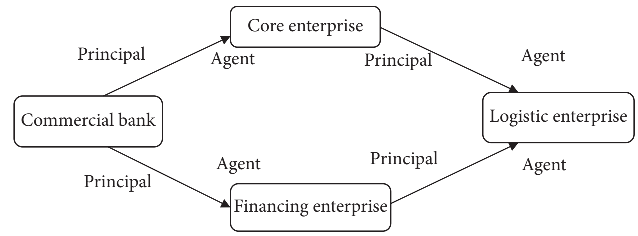

Figure 1: Principal-agent relationship in SCF.

3.2. Systematic Analysis of Financial Credit Risk in Supply Chain. System theory is one of the components of the three extant theories (system theory, information theory, and cybernetics). It is generally recognized in academic circles that system theory was founded by L.V. Bertalanffy, an Austrian American theoretical biologist. In 1932, he published the antibody system theory and put forward the idea of system theory. In 1937, the framework of general system theory was proposed, which laid the theoretical foundation for this science. It has the characteristics of interdisciplinary research and horizontally links various disciplines. It is the study of the general model, structure, and law of the system. System theory studies the common characteristics of various systems, quantitative descriptions of their functions using mathematical methods, and establishes the principles and mathematical models applicable to all systems—the logic and mathematical nature of new science.

Research and analysis of the SCF model indicate how it organically combines upstream and downstream enterprises through the supply chain to form a whole. In the SCF system, every enterprise is dynamically changing capital, goods, and information flow between them. At the same time, enterprises influence and correlate with each other, and each node may generate risks. By using system theory to study the financial credit risk of SCF, we can explore the causes of its production in detail and improve the management capabilities of enterprises in SCF.

3.3. Information Asymmetry Theory Analysis of SCF Credit Risk. In the 1970s, three economists, George Akerlof, Michael Spence, and Joseph Stiglitz, proposed the theory of information asymmetry. The theory indicates that, in market economy activities, there is information asymmetry. Each party has different amounts and content of information. Relatively speaking, the information-dominant party is in a favorable position, and the information-disadvantaged party is in a weaker position. The advantaged parties can gain benefits in the market by communicating reliable information with those having less information—the poorly performing party in the transaction will try to obtain the information they need from the other party. Market signals indicate that the problem of information asymmetry can be compensated to a certain extent. According to the theory of information economics, information asymmetry is divided into an adverse selection and a moral hazard.

In SCF, there is information asymmetry when financing companies intentionally conceal negative information from commercial banks to obtain bank loans. In the process of approving enterprises' financing requests, commercial banks may make misjudgments that may, according to the theory of information asymmetry, lead to adverse selection. Conversely, when the financing company obtains financing, if the relevant information is concealed to the commercial bank in the production and operation process, the account is inconsistent, and the credit risk of the commercial bank is increased, which generates a moral hazard. Logistics companies may also collude with companies in the supply chain to conceal warehousing and logistics information. In the supply chain, both financing and core enterprises are likely to conceal their operating conditions, financial information, and management information, resulting in information asymmetry.

Grey system theory can partially mitigate the lack of, or fuzzy, information due to information asymmetry; thus, it is more accurate to analyze the credit risk of SCF by using the grey relation model, and the analysis results are more significant for referencing.

3.4. Supply Chain Financial Analysis of Household Appliance Industry. China's household electrical appliance industry began in the late 1970s and early 1980s. Since its development, the industry has become one of the pillars of China's manufacturing industry and is an important part of China's national economy. From the perspectives of profitability, debt repayment, operation, and development capabilities, the home appliance industry is developing well in SCF.

When the 2008 financial crisis broke, China implemented the fiscal policy of "home appliances going rural to expand domestic demand" (Ministry of Finance, the Ministry of Commerce and the Ministry of Industry and Information Technology, "Notice on the National Promotion of Home Appliances to the Countryside," 2008. http://www.gov.cn/gzdt/2008-12/05/content_1169347.htm). Nonurban residents who bought color TV sets, refrigerators, mobile phones, and washing machines received a 13% subsidy on the product price, which quickly stimulated the consumption of domestic electrical appliances. However, by the end of the policy, the consumption of household appliances fell sharply. In May 2012, the state council decided to implement a new policy to subsidize energy-efficient home appliances. During the 11th and 12th five-year plans, the rapid development of the world economy created much demand for China's home appliance industry both domestically and internationally, despite China's industry having suffered from the impact of the economic crisis. Due to the rapid development of China's domestic economic conditions and the government's strong policy support, such as "home appliance energy subsidies," "home appliances to the countryside," and "home appliances trade-in," China's home appliance industry developed rapidly along with its reputation in the international market. Currently, China's home appliance industry is competitive in the international market and has established a strong market share; its scale of production ranks first worldwide. According to a report by the National Bureau of Statistics, China's home appliance industry has been growing rapidly and stable in recent years. In 2016, operating revenue and total profit reached 820.8 and 119.69 billion yuan and cumulative yearly increases of 13.4% and 20.4%, respectively.

With the rapid development and growth of the Internet and online shopping consumer groups in China, the number of online sales of household appliances has increased. The major home appliance companies have also established their own online sales channels. In 2010, Suning Appliance, GOME Electrical Appliances, Chunlan Group, Haier Electric, Midea Group, and other leading enterprises in the home appliance industry entered the online sales market using bespoke online sales platforms, e-commerce companies, and online shopping websites. These new sales channels ushered in a new round of sales growth in the home appliance industry with online shopping fast becoming the most promising market. The 2016 China National Grid Purchase Analysis Report jointly released by the CCID Research Institute and the China Electronics News Agency shows the following data.

In 2016, China's B2C home grid purchase market, including mobile terminals, reached 384.6 billion yuan, a year-on-year increase of 27.9%. Regardless of mobile terminal products, the online market size of pure household electrical and electronic products was 179.6 billion yuan, an increase of 35.3%. In 2016, the penetration rate of online shopping in the home appliance market reached 19.95%. The three giants, Jingdong, Tmall, and Suning Tesco, have occupied most of the market, and the channel pattern of the online shopping market of home appliances is stable (CCID Research Institute, China Electronics News 2016; China National Grid Purchase Analysis Report 2016).

As of the end of 2017, there were 67 listed companies in China's home appliance industry, of which 20 were listed on the Shanghai Stock Exchange and 47 on the Shenzhen Stock Exchange. Of those listed on the Shenzhen Stock Exchange, the small- and medium-sized sectors accounted for 28 listings. According to relevant statistics, in 2017, China's household appliance industry grew rapidly, and its output value reached 1.70 billion yuan, an increase of 9.8% over the same period of the previous year (data from Zhongyikang Data). With the advancement of supply-side structural reform, the innovation capability of China's home appliance industry has increased, and production technology has clearly shown an upward trend. Research and development progress appear endless.

4. Establishment of the Grey Relational Analysis Model

The basic idea of the Grey correlation analysis is to determine whether the relationship between two factors is close based on the similarity of the geometry of the sequence curve; a more similar curve indicates a greater correlation. There is no specific requirement for the sample size. The sample is irregular, and there is no situation whereby the quantitative result does not match the qualitative analysis result. This method compensates for deficiencies arising from systematic analysis using mathematical-statistical methods [24].

4.1. Calculation of the Grey Absolute Degree of Incidence. We establish the material steps of our grey incidence analysis.

Assuming $X_0 = (x_0(1), x_0(2), \ldots, x_0(n))$ as a sequence of system characteristic behaviors, we define

$$X_i = (x_i(1), x_i(2), \ldots, x_i(n)), \quad i = 1, 2, \ldots, m, \tag{1}$$

as a related factor sequence.

4.1.1. Calculation of Initial Point Annihilation Image. Assuming D as sequence operator and

$$X_i D = (x_i(1)d, x_i(2)d, \ldots, x_i(n)d). \tag{2}$$

Therefore, $x_i(k)d = x_i(k) - x_i(1)$ $(k = 1, 2, \ldots, n)$; we define D as the initial point annihilation operator and $X_i D$ as the initial point annihilation image of X_i, denoted as:

$$X_i D = X_i^0 = \left(x_i^0(1), x_i^0(2), \ldots, x_i^0(n)\right). \tag{3}$$

4.1.2. Calculation of $|s_0|$, $|s_i|$, and $|s_i - s_0|$.

$$\begin{aligned} |s_0| &= \left|\sum_{k=2}^{n-1} x_0^0(k) + \frac{1}{2}x_0^0(n)\right|, \\ |s_i| &= \left|\sum_{k=2}^{n-1} x_i^0(k) + \frac{1}{2}x_i^0(n)\right|, \\ |s_i - s_0| &= \left|\sum_{k=2}^{n-1}\left(x_i^0(k) - x_0^0(k)\right) + \frac{1}{2}\left(x_i^0(n) - x_0^0(n)\right)\right|. \end{aligned} \tag{4}$$

4.1.3. Calculation of the Grey Absolute Degree of Incidence: ε_{0i}.

$$\varepsilon_{0i} = \frac{1 + |s_0| + |s_i|}{1 + |s_0| + |s_i| + |s_i - s_0|}. \quad (5)$$

4.2. Calculation of the Grey Relative Degree of Incidence

(1) To calculate the initial point annihilation image of $X_i{}'$, we define

$$X_i' D = \left(x_i'(1)d, x_i'(2)d, \ldots, x_i'(n)d\right). \quad (6)$$

Substituting $x_i'(k)d = x_i'(k) - x_i'(1)\,(k = 1, 2, \ldots, n)$, $X_i' D$ is the initial point annihilation image of X_i', obtaining

$$X_i' D = X_i^{0'} = \left(x_i^{0'}(1), x_i^{0'}(2), \ldots, x_i^{0'}(n)\right). \quad (7)$$

(2) Calculate $|s_0'|$, $|s_i'|$, and $|s_i' - s_0'|$:

$$|s_0'| = \left|\sum_{k=2}^{n-1} x_0^{0'}(k) + \frac{1}{2}x_0^{0'}(n)\right|,$$

$$|s_i'| = \left|\sum_{k=2}^{n-1} x_i^{0'}(k) + \frac{1}{2}x_i^{0'}(n)\right|,$$

$$|s_i' - s_0'| = \left|\sum_{k=2}^{n-1}\left(x_i^{0'}(k) - x_0^{0'}(k)\right) + \frac{1}{2}\left(x_i^{0'}(n) - x_0^{0'}(n)\right)\right|. \quad (8)$$

(3) Calculate the grey relative degree of incidence: γ_{0i}

$$\gamma_{0i} = \frac{1 + |s_0'| + |s_i'|}{1 + |s_0'| + |s_i'| + |s_i' - s_0'|}. \quad (9)$$

4.3. Calculation of the Grey Synthetic Degree of Incidence

$$\rho_{0i} = \theta\varepsilon_{0i} + (1 - \theta)\gamma_{0i}, \quad \theta \in [0, 1]. \quad (10)$$

Generally, $\theta = 0.5$. ρ_{0i} not only shows the similarity between the fold lines X_0 and X_i but also reflects the closeness of the rate of change of X_0 and X_i relative to the starting point. It is a quantitative index to show in a more comprehensive way whether the links between sequences are similar (Liu Sifeng, Yang Yingjie, Wu Lifeng. Grey System Theory and Its Application. Bejing: Science Press:85, 2014).

5. Empirical Analysis of SCF Credit Risk

The credit risk evaluation index system was constructed; the degree of correlation between 2012 and 2016 was calculated using the grey correlation model; and the ranking and changes of each enterprise were obtained.

5.1. Data Sources. Sixty-seven home appliance companies—listed on the Shanghai Stock Exchange and the Shenzhen Stock Exchange—are selected as research samples, with ten upstream appliance parts companies and five downstream distribution and service enterprises, of which eleven came from the Shanghai and Shenzhen sectors, and four from the small- and medium-sized sectors. The sample companies are listed in Table 1.

In this study, 15 listed companies in the home appliance industry with business connections were selected. The supply relationships and products are shown in Figure 2. The five companies on the left side of the picture are downstream in the supply chain, offering distribution and enterprises, with most products being sold directly to consumers. The ten companies on the right are upstream in the supply chain and provide various home appliance parts to the five companies on the left. Zhejiang Sanhua Intelligent Controls, Zhejiang Kangsheng, Suzhou China Create Special Material, and Guangzhou Echom Sci. & Tech. are classified as medium-sized. As a relatively mature SCF industry, the home appliance industry has a complicated supply relationship, which is not limited to Figure 2.

According to the analysis of corporate financial capability, this study selected 15 indicators grouped by profitability, solvency, operational capability, and development capability to form a risk indicator system. The data are obtained from the company's annual financial reports. The specific indicators are shown in Table 2.

5.2. The Empirical Analysis. The home appliance industry is one of the traditional advantageous industries in supply chain finance. Among them, Qingdao Haier (600690) achieved a global turnover of 241.9 billion yuan in 2017. On December 21 of the same year, Qingdao Haier ranked 50th in the 2017 "Top 500 Global Brands" (14th), ranking compiled by the World Brand Lab in the United States, compared with 76th in the previous year. It has risen 26 places and since then Haier has entered the world's top 50 brands. At the same time, Haier Group seized the opportunity of the "Internet+" era to create business models such as "Internet + industry," "Internet + commerce," "Internet + finance," "Internet + residence," and "Internet + culture." It owns Haier Industrial Finance Company, which provides supply chain financial services, and is involved in food and agriculture, medical and health, green finance, intelligent manufacturing, and shared consumption industries. At the same time, it also has its own e-commerce platforms, including Haimao Yunshang cross-border e-commerce, Jushanghui, Goodaymart, and Haier Mall. It has been transformed and upgraded from traditional commercial distribution channels to a bilateral platform for value interaction and constructed an open platform led by user experience in the Internet era with the Internet of Things and logistics services as the core. Because Qingdao Haier has a mature supply chain financial system, Qingdao Haier is selected as the characteristic behavior sequence.

Through the index set determined above, the original sequence set determines the characteristic behavior sequence, namely, Qingdao Haier, and the related factor sequence, namely, the other 14 companies. In this paper, the sample data of 15 listed companies in the household

Table 1: Sample company code.

Company code	Company short name
000651.SZ	Gree Electric
000333.SZ	Midea Group
600690.SS	Qingdao Haier
600060.SS	Hisense Electric
600839.SS	Sichuan Changhong
002050.SZ	Zhejiang Sanhua Intelligent Controls
603578.SS	Zhejiang Three Stars New Materials
603677.SS	Qijing Machinery
002418.SZ	Zhejiang Kangsheng
603519.SS	Jiangsu Liba Enterprise Joint-Stock
300475.SZ	Anhui Julong Transmission Technology
002290.SZ	Suzhou China Create Special Material
300217.SZ	Zhenjiang Dongfang Electric Heating Technology
002420.SZ	Guangzhou Echom Sci. & Tech.
603311.SS	Zhejiang Goldensea Environment Technology

appliance industry from 2012 to 2016 were imported into the grey correlation analysis model for empirical research, and the results were analyzed and discussed.

5.2.1. Determine Characteristic Behavior Sequence and Related Factor Sequence. In this study, Qingdao Haier (600690) is used as the characteristic behavior sequence. The other 14 companies are Gree Electric (000651.SZ), the Midea Group (000333.SZ), Hisense Electric (600060.SS), Sichuan Changhong (600839.SS), Zhejiang Sanhua Intelligent Control (002050.SZ), Zhejiang Three Star New Materials (603578.SS), Qijing Machinery (603677.SS), Zhejiang Kangsheng (002418.SZ), Jiangsu Liba Enterprise Joint-Stock (603519.SS), Anhui Julong Transmission Technology (300475.SZ), Suzhou China Create Special Material (002290.SZ), Zhenjiang Dongfang Electric Heating Technology (300217.SZ), Guangzhou Echom Sci. & Tech (002420.SZ), and Zhejiang Goldensea Environment Technology (603311.SS) as the related factor sequence. These are recorded as X_1 to X_{14}. We establish a behavior indicator matrix for 15 companies and the previously determined indicator set. First, 2016 is taken as an example to calculate the grey degree of incidence of each enterprise.

5.2.2. Calculation of Grey Absolute Degree of Incidence. The behavior indicator matrix has to be substituted into Formula (3) to obtain the initial point annihilation image of the sequence, denoted as x_i^0.

$x_0^0 = (0.0000, 22.6700, 10.7500, -2.7300, -7.4000, -7.6100, 63.0200, 180.7100, -1.4500, 4.6000, 1.5900, -7.2000, 24.2400, 7.6200, 8.8700)$

$x_1^0 = (0.0000, 22.6100, 18.5400, 4.2400, -8.9600, -9.0300, 59.7900, 276.4200, -2.2100, 27.0000, -3.4400, -9.4500, 0.7100, 3.2600, 14.2000)$

$x_2^0 = (0.0000, 11.5900, 1.7100, -0.9600, -1.5600, -1.8800, 63.8500, 251.7900, 2.1500, 5.8000, 9.0300, -1.5300, 0.9000, 1.4600, 197.5700)$

$x_3^0 = (0.0000, 15.1000, 11.8100, -2.2400, -10.8600, -11.0300, 47.3600, 256.3400, -3.3400, 1.1400, -4.1800, -11.1400, 2.6700, 12.0300, 5.6300)$

$x_4^0 = (0.0000, 7.0800, 3.8400, -3.8800, -7.2300, -7.6500, 30.5200, 959.0700, -1.3800, 4.9100, 14.8500, -8.0400, -4.0600, 1.4400, 6.3100)$

$x_5^0 = (0.0000, 17.0600, 3.4000, 0.0200, -10.5600, -11.0300, 23.3900, 246.4600, -8.7300, -6.6800, -9.5500, -11.8900, -2.8300, 1.7100, 27.1600)$

$x_6^0 = (0.0000, 15.0200, 3.3400, 1.9700, -4.8900, -4.9700, 63.9900, 229.1100, 1.4900, -2.6100, -3.0000, -5.3700, 22.9100, 2.1400, 140.2700)$

$x_7^0 = (0.0000, 21.6700, 0.2700, 2.6700, 0.6700, 0.0700, 23.6100, 358.6300, -0.0400, 0.2200, -0.3800, -1.9000, -3.6000, -1.9900, -38.6900)$

$x_8^0 = (0.0000, 6.7300, 0.7200, -1.4200, -6.2200, -6.8600, 14.2300, 852.3700, -3.4800, -5.6500, 0.5300, -8.7800, -0.1600, -4.8600, 3.6400)$

$x_9^0 = (0.0000, 6.6700, 5.0400, -6.3600, -12.9300, -13.3600, 204.8600, 35.3300, -9.5200, -10.0900, -8.8400, -13.0100, -25.5700, 4.6900, -3.7300)$

$x_{10}^0 = (0.0000, 23.9800, 0.3500, 4.0600, -6.4800, -7.0800, 8.1000, -6.7500, -6.4400, -6.9500, -9.8000, 6.2000, 1.1400, 23.8400, 469.9000)$

$x_{11}^0 = (0.0000, 13.9600, -0.2800, 0.0600, -0.5200, -0.9500, 35.7200, 379.1100, 0.2400, 0.0300, 1.6600, -1.9600, -5.5600, 41.5300, -2.7800)$

$x_{12}^0 = (0.0000, 26.7700, 0.7500, 12.3000, -3.0500, -3.2000, 13.4700, 1803.0200, -0.3300, -2.4100, 1.0000, -7.3900, 17.4300, -0.6500, -15.1400)$

$x_{13}^0 = (0.0000, 9.8600, 2.9700, -1.1800, -16.0400, -16.4700, 7.4800, 285.7300, -12.7400, -15.4700, -14.9300, -17.6900, -3.9000, -20.8700, 6.8000)$

$x_{14}^0 = (0.0000, 6.6800, 0.0400, -0.8600, 0.0900, -0.2500, 58.4600, 176.9400, 5.0900, 4.0300, 5.2100, 0.2800, 53.7300, -0.1600, -81.3400)$

The Grey absolute degree of incidence of 14 enterprises was calculated and sorted into Table 3.

5.2.3. Grey Relative Degree of Incidence. When calculating the grey relative degree of incidence, first, the behavior index matrix should be initialized and introduced into Formula (7) to obtain the initial image of the sequence, denoted as x_i'.

$x_0' = (1.0000, 3.7150, 2.2874, 0.6731, 0.1138, 0.0886, 8.5473, 22.6419, 0.8263, 1.5509, 1.1904, 0.1377, 3.9030, 1.9126, 2.0623)$

$x_1' = (1.0000, 3.2408, 2.8375, 1.4202, 0.1120, 0.1051, 6.9257, 28.3954, 0.7810, 3.6759, 0.6591, 0.0634, 1.0704, 1.3231, 2.4073)$

$x_2' = (1.0000, 5.3086, 1.6357, 0.6431, 0.4201, 0.3011, 24.7361, 94.6022, 1.7993, 3.1561, 4.3569, 0.4312, 1.3346, 1.5428, 74.4461)$

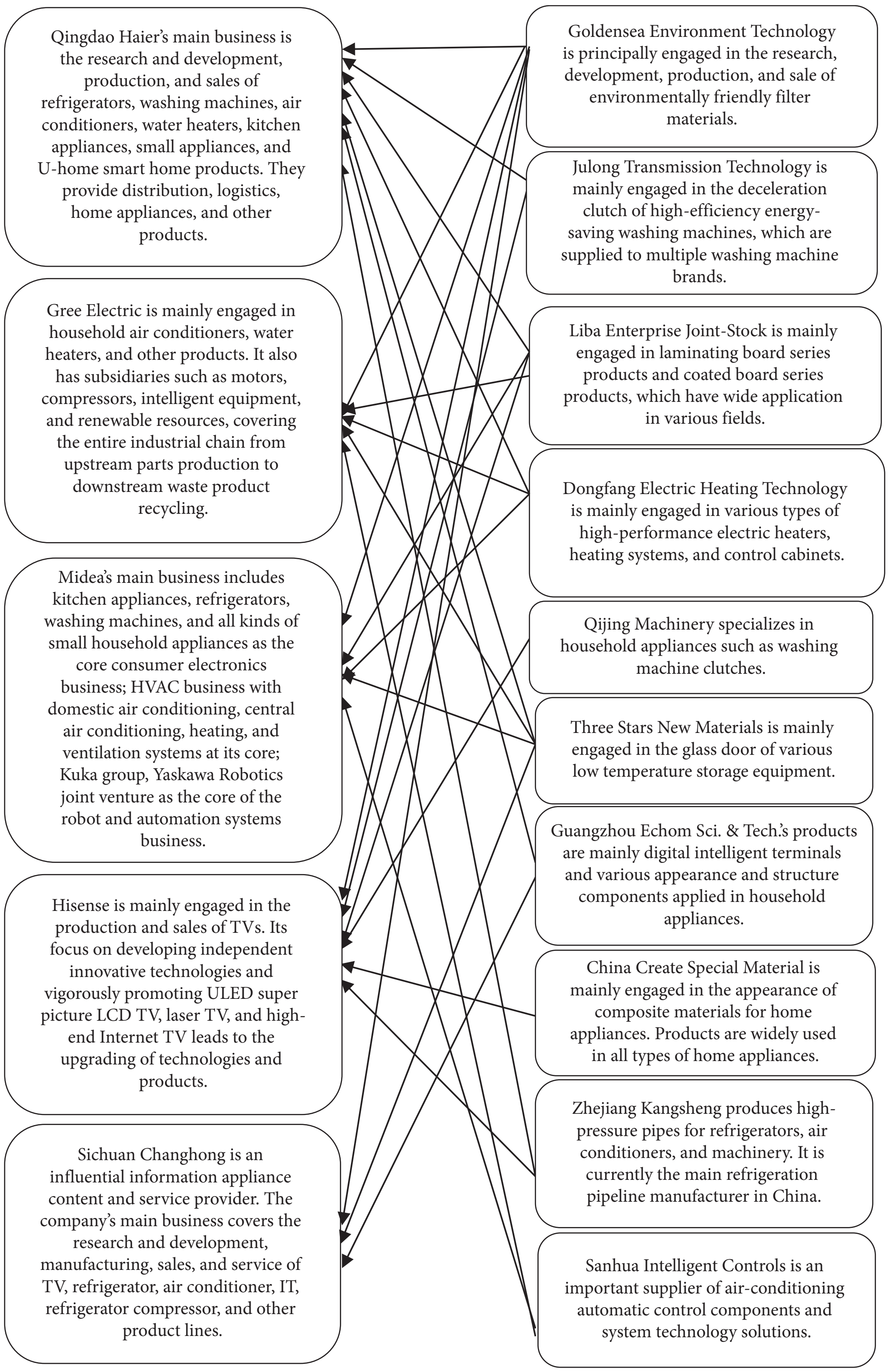

Figure 2: Supply relationship of sample companies.

$x_3' = (1.0000,\ 2.2367,\ 1.9672,\ 0.8165,\ 0.1106,\ 0.0966,\ 4.8788,\ 21.9943,\ 0.7265,\ 1.0934,\ 0.6577,\ 0.0876,\ 1.2187,\ 1.9853,\ 1.4611)$

$x_4' = (1.0000,\ 1.7453,\ 1.4042,\ 0.5916,\ 0.2389,\ 0.1947,\ 4.2126,\ 101.9547,\ 0.8547,\ 1.5168,\ 2.5632,\ 0.1537,\ 0.5726,\ 1.1516,\ 1.6642)$

Table 2: SCF credit risk index system.

Indicator	Metric	Calculation
Profitability	Return on assets (U1)	Net profit/average asset total * 100%
	Sales gross margin (U2)	(Net operating income – operating costs)/net operating income * 100%
	Return on equity (U3)	Net profit/average shareholder equity * 100%
	Net sales margin (U4)	Net profit/net operating income * 100%
Solvency	Flow ratio (U5)	Current assets/current liabilities
	Quick ratio (U6)	Quick-moving assets/current liabilities
	Asset-liability ratio (U7)	Total liabilities/total assets * 100%
	Long-term asset suitability rate (U8)	(Total shareholders' equity + total long-term liabilities)/(total fixed assets/long-term investment) * 100%
Operating capacity	Inventory turnover rate (U9)	Cost of sales/average inventory balance
	Accounts receivable turnover rate (U10)	Net sales revenue/average balance of accounts receivable
	Fixed asset turnover rate (U11)	Sales revenue/average net value of fixed assets
	Total asset turnover rate (U12)	Sales revenue/average asset total
Development ability	Yearly growth rate of operating income (U13)	The increase in operating income this year/the total operating income in the previous year * 100%
	Capital accumulation rate (U14)	The increase in shareholders' equity this year/shareholders' equity at the beginning of the year * 100%
	Profit growth rate (U15)	Total profit growth this year/total profit of the previous year * 100%

Table 3: Grey absolute degree of incidence.

Company code	Grey absolute degree of incidence	
000651.SZ	ε_{01}	0.8794
600839.SS	ε_{02}	0.8326
000333.SZ	ε_{03}	0.9785
600060.SS	ε_{04}	0.6479
002050.SZ	ε_{05}	0.9168
002418.SZ	ε_{06}	0.8768
300217.SZ	ε_{07}	0.8854
603519.SS	ε_{08}	0.6750
603677.SS	ε_{09}	0.7648
603311.SS	ε_{10}	0.9419
002290.SZ	ε_{11}	0.8178
300475.SZ	ε_{12}	0.5794
603578.SS	ε_{13}	0.8245
002420.SZ	ε_{14}	0.9581

$x_5' = (1.0000, 2.3423, 1.2675, 1.0016, 0.1692, 0.1322, 2.8403, 20.3910, 0.3131, 0.4744, 0.2486, 0.0645, 0.7773, 1.1345, 3.1369)$

$x_6' = (1.0000, 3.5631, 1.5700, 1.3362, 0.1655, 0.1519, 11.9198, 40.0973, 1.2543, 0.5546, 0.4881, 0.0836, 4.9096, 1.3652, 24.9369)$

$x_7' = (1.0000, 10.5463, 1.1189, 2.1762, 1.2952, 1.0308, 11.4009, 158.9868, 0.9824, 1.0969, 0.8326, 0.1630, -0.5859, 0.1233, -16.0441)$

$x_8' = (1.0000, 1.6846, 1.0732, 0.8555, 0.3672, 0.3021, 2.4476, 87.7111, 0.6460, 0.4252, 1.0539, 0.1068, 0.9837, 0.5056, 1.3703)$

$x_9' = (1.0000, 1.4681, 1.3537, 0.5537, 0.0926, 0.0625, 15.3761, 3.4793, 0.3319, 0.2919, 0.3796, 0.0870, -0.7944, 1.3291, 0.7382)$

$x_{10}' = (1.0000, 3.3102, 1.0337, 1.3911, 0.3757, 0.3179, 1.7803, 0.3497, 0.3796, 0.3304, 0.0559, 1.5973, 1.1098, 3.2967, 46.2697)$

$x_{11}' = (1.0000, 6.3692, 0.8923, 1.0231, 0.8000, 0.6346, 14.7385, 146.8115, 1.0923, 1.0115, 1.6385, 0.2462, -1.1385, 16.9731, -0.0692)$

$x_{12}' = (1.0000, 4.4542, 1.0968, 2.5871, 0.6065, 0.5871, 2.7381, 233.6477, 0.9574, 0.6890, 1.1290, 0.0465, 3.2490, 0.9161, -0.9535)$

$x_{13}' = (1.0000, 1.5295, 1.1595, 0.9366, 0.1386, 0.1155, 1.4017, 16.3453, 0.3158, 0.1692, 0.1982, 0.0499, 0.7905, -0.1208, 1.3652)$

$x_{14}' = (1.0000, 6.9643, 1.0357, 0.2321, 1.0804, 0.7768, 53.1964, 158.9821, 5.5446, 4.5982, 5.6518, 1.2500, 48.9732, 0.8571, -71.6250)$

The grey relative degree of incidence of 14 enterprises was calculated and sorted in Table 4.

5.2.4. Calculation of Grey Synthetic Degree of Incidence. The grey absolute ε_{0i} and grey relative degree of incidence γ_{0i} are substituted into Formula (10):

$$\rho_{0i} = \theta\varepsilon_{0i} + (1-\theta)\gamma_{0i}, \quad \theta \in [0,1]. \tag{11}$$

Generally, $\theta = 0.5$. We calculate the grey synthetic degree of incidence and rank in Table 5 for 2016.

5.3. Evaluation Result. The grey degree of incidence of 14 listed companies in the household appliance industry from 2012 to 2016 is calculated and ranked (Table 5).

The higher the degree of association and the stronger the correlation between the evaluated listed and ideal companies, the lower the credit risk degree of the listed company. The higher the risk ranking, the higher the correlation

Table 4: Grey relative degree of incidence of 14 enterprises.

Company code	Grey relative degree of incidence	
000651.SZ	γ_{01}	0.9589
600839.SS	γ_{02}	0.6083
000333.SZ	γ_{03}	0.8594
600060.SS	γ_{04}	0.6696
002050.SZ	γ_{05}	0.7769
002418.SZ	γ_{06}	0.7661
300217.SZ	γ_{07}	0.6059
603519.SS	γ_{08}	0.7075
603677.SS	γ_{09}	0.6597
603311.SS	γ_{10}	0.8574
002290.SZ	γ_{11}	0.6000
300475.SZ	γ_{12}	0.5744
603578.SS	γ_{13}	0.6504
002420.SZ	γ_{14}	0.5741

Table 5: Grey degree of incidence and ranking from 2012 to 2016.

Company code	2016		2015		2014		2013		2012	
	ρ_{0i}	Rank	ρ_{0i}	Rank	ρ_{0i}	Rank	ρ_{0i}	Rank	ρ_{0i}	Rank
000651.SZ	0.9191	1	0.8533	3	0.8925	3	0.8605	4	0.8003	7
600839.SS	0.7204	9	0.8154	5	0.7364	11	0.7371	9	0.7408	10
000333.SZ	0.9189	2	0.9185	2	0.8570	4	0.9493	2	0.8332	6
600060.SS	0.6588	13	0.6229	13	0.7071	13	0.7328	11	0.8516	4
002050.SZ	0.8468	3	0.9590	1	0.8399	5	0.9183	3	0.9133	1
002418.SZ	0.8215	5	0.6464	12	0.7691	8	0.8103	6	0.8712	2
300217.SZ	0.7457	7	0.6691	10	0.8176	7	0.7717	8	0.7118	12
603519.SS	0.6912	12	0.6574	11	0.9312	1	0.9630	1	0.8664	3
603677.SS	0.7123	10	0.7884	6	0.6970	14	0.7988	7	0.7677	8
603311.SS	0.8418	4	0.7269	8	0.8234	6	0.8261	5	0.8478	5
002290.SZ	0.7089	11	0.7067	9	0.9022	2	0.6793	13	0.6632	13
300475.SZ	0.5769	14	0.5538	14	0.7421	10	0.7330	10	0.7267	11
603578.SS	0.7374	8	0.8387	4	0.7134	12	0.6645	14	0.6589	14
002420.SZ	0.7661	6	0.7568	7	0.7525	9	0.6998	12	0.7655	9

between the evaluated listed company and the ideal company. Companies with more stable operations carry a lower credit risk.

From the empirical results, the listed companies ranking high in the household appliance industry include Gree Electric, Midea Group, and Sanhua Intelligent Controls, and their credit risks are relatively small. Gree Electric has steadily improved its ranking from 7th place in 2012 to first place in 2016. In 2016, Gree Electric achieved a total operating income of 110.113 billion yuan, a net profit of 15.421 billion yuan, and tax payments of 13.075 billion yuan. Gree Electric has holdings in 59 companies that constitute its own supply chain. There are 48 industrial manufacturing companies and 5 sales companies, as well as companies responsible for technology research and development, information technology, and financial services. Zhuhai Gree Group Finance Co., Ltd. plays the role of the supply chain's financial funder. Since the launch of financial services for enterprises in the industrial chain until the end of 2014, it has provided more than 25 billion yuan of financial support to enterprises in the industrial chain, including more than 8 billion yuan of financial support for small- and medium-sized enterprises (30% of total financing). The Midea Group was ranked relatively high over the past 5 years. Although fluctuating slightly, it advanced from sixth place in 2012 to second in 2016. It has consolidated its leading position in the SCF of the home appliance industry and enjoys strong development. Sanhua Intelligent Controls is a global leader in refrigeration control components and is located downstream of the home appliance industry chain. It was listed in the Shenzhen SME sector in 2005. From 2012 to 2016, its ranking has remained in the top five, indicating that the company has strong credit.

Companies with more stable rankings are Goldensea Environment Technology, Dongfang Electric Heating Technology, and Echom Sci. & Tech. Goldensea Environment Technology is a professional manufacturer of well-known environmental protection filtration materials in China. The company set up factories in Zhejiang, Zhuhai, Tianjin, Suzhou, and other places. At the same time, sales networks have been established in Sichuan, Shandong, and Jiangsu. It has established long-term cooperative relationships with Gree, LG, Midea, Samsung, Mitsubishi Heavy Industries, Haier, Hisense, Changhong, Chunlan, and other domestic, commercial, and automotive air-conditioning manufacturing enterprises. It ranks between 4th and 8th and is relatively stable while carrying relatively low credit risk. The ranking of Dongfang Electric Heating Technology in the past five years has been in the middle position, and its overall situation is relatively stable, with minimal fluctuations and low credit risk. Echom Sci. & Tech. ranked lower in 2013 than in 2012, but after 2013, its ranking has steadily improved, rising to sixth place in 2016, which indicates that Echom Sci. & Tech. has developed rapidly in recent years, and its credit risk has been steadily reduced.

The rankings of enterprises such as Qijing Machinery, Three Stars New Materials, Kangsheng, and Sichuan Changhong have changed greatly, indicating that the operating conditions of these enterprises are highly volatile, and more attention should be paid to their credit risks.

The lower-ranked enterprises are Julong Transmission Technology, Hisense Electric, Liba Enterprise Joint-Stock, and China Create Special Material. Julong Transmission Technology is mainly engaged in the research and development, production, and sales of new and high-efficiency energy-saving washing machine deceleration clutches. Several products are nonbidding procurement products of leading enterprises in the washing machine industry, such as Haier and Midea. The ranking in the past five years is outside the top 10, indicating an overall weakness and high credit risk. Hisense Electric ranked 4th in 2012, 11th in 2013, and 13th in the following years. Most of its subsidiaries are manufacturing companies, which indicates that its SCF suffers from poor development high credit risk. Liba Enterprise Joint Stock was ranked third in 2012, and first from 2013 to 2014; in 2015, however, its rank quickly fell to 11th place, before falling further in 2016. The reason is that although the absolute financial value of the enterprise still shows an upward trend, its operating income growth rate, gross profit margin of sales, return on investment, and cash income ratio have all decreased to varying degrees since 2014. This shows that the development momentum of the enterprise is insufficient, and thus, its credit risk gradually increases. Although China Create Special Material rose to second place in 2014, it ranked relatively low in other years and ultimately ranked 11th in 2016. This shows that the credit status of the company is not satisfactory, although it does indicate great development prospects.

6. Conclusion

Supply chain financial risks are increasingly attracting attention, especially in the period of the COVID-19. The disclosure of financial risk level in the supply chain enhances the transparency of supply chain finance information and helps reduce the risk level of supply chain finance in this industry. In addition, a clear risk level of supply chain finance of major listed companies contributes to strengthening the cooperation between upstream and downstream enterprises and financial institutions in this supply chain, which has important practical significance for the development of the whole industry. However, with the absence of data and inaccurate information, traditional risk assessment methods are difficult to implement for enterprises. In this study, a grey correlation model is introduced and applied to the supply chain financial risk assessment process for 14 firms in the Chinese home appliance industry. The empirical study measures the financial risk level of each firm, which is highly consistent with reality. The operability and effectiveness of the model reflect the superiority of the grey correlation model in the supply chain financial risk assessment. It is highly recommended that the model can be used as an effective risk assessment tool in corporate supply chain financial services in the future.

The sample companies selected in the empirical analysis are representative, but the size of the sample is small, which may have a certain impact on the accuracy of the model results. In addition, in the grey correlation model, the selection of risk indicators also indirectly affects the system behavior, which affects the accuracy of the empirical analysis results. Therefore, the size of the sample and the selection of risk indicators make the empirical analysis of this study subject to certain errors. Accordingly, in the future, the sample size and risk indicators can be expanded to characterize the system behavior more comprehensively and improve the accuracy of the grey model in the process of assessing the risk level of supply chain finance.

Data Availability

The data used to support the findings of this study are included in the annual financial report of the company and is available in the database of the Shanghai Stock Exchange (http://www.sse.com.cn/disclosure/listedinfo/regular/) and Shenzhen Stock Exchange (http://www.szse.cn/disclosure/listed/fixed/index.html).

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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Research Article

Restrain Price Collusion in Trade-Based Supply Chain Finance

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Collusion can increase the transaction value among supply chain members to obtain higher loans from supply chain finance (SCF) service provider, which will bring some serious risks for SCF. However, it is difficult to be identified and restrain the SCF service provider due to its stability and hiddenness. Different SCF transaction structures will affect the profits of supply chain members from collusion. This paper develops various game models for collusion and not collusion for different SCF transaction structures and investigates the impact of SCF transaction structures on the boundary conditions of collusion. Through comparative analysis, the findings of models are as follows: (1) in a two-echelon supply chain, the supplier and retailer are more likely to conduct collusion under the sequential game than under the simultaneous game; (2) collusion in the two-echelon supply chain can obtain higher loans than that in the three-echelon supply chain, so it has more serious hidden danger; (3) in the two-echelon supply chain, collusion is easier to form than in the three-echelon SCF supply chain that has spontaneous endogenous constraints. We also develop two types of mechanisms to restrain collusion behavior from profit sharing and incomplete information perspectives. Finally, we summarize the theoretical implications and analyze the management implications through a case study.

1. Introduction

Collusion refers to the behavior that some firms reach a secret agreement on the price or volume of the products or services they provided and use the agreed price to replace the market price, so as to obtain more profits [1, 2]. Once collusion is implemented, it will inevitably lead to the loss of the profits of consumers and other firms, that is, they will pay higher prices for products and services. Although governments have enacted antitrust laws (such as the antitrust law of China in 2007) to limit the formation of cartels and other collusions in determining market price, collusion is still frequently appeared in the market [1, 3]. One reason is that it is very difficult to obtain concrete evidence to prove collusion behavior between firms [4]. Another reason is that firms of collusion can achieve extra profits, such as high financial loans.

The rapid development of supply chain finance (SCF) has effectively solved the problem of the capital shortage of supply chain firms and promoted the development of real economic and financial services [5]. Although the SCF system has set up many mechanisms to prevent various financial risks, collusion brings great risks to SCF service provider because of its hiddenness. For example, more than 20 steel traders increased the price and amount of transactions through collusion in China to obtain higher financial loans based on the transaction value and were sued by the bank to the court (see [6]). The amount of cash and the number of companies involved are unprecedented. For another example, on April 2, 2020, Luckin Coffee Inc. (NASDAQ: LK) announced that the COO and several other executives engaged in certain misconduct, including fabricating certain transactions amounting to roughly RMB 2.2 billion, resulting in the stock plunging by 80% in one day [7]. Then, SCF service providers, such as banks, funds, and trusts, generally worry that there is no effective way to identify and prevent collusion in the financial industry. Collusion against the real trading bottom line has become a stumbling block for SCF [8]. As far as we know, there is no research on collusion in the field of SCF.

The collusion agreement is not always unbreakable and stable. When the profit of collusion is less than that of noncollusion, the collusion agreement will be broken. SCF service providers can effectively control the profit of collusion and noncollusion through the discount factor of loans. Then, we will investigate the discount factor of loans to determine the boundary condition of collusion.

Transaction structure plays an important role in all kinds of supply chain financial loans. Previous research on SCF focuses on the design of SCF transaction structures to prevent various risks [9, 10]. However, the impact of SCF transaction structures on the boundary condition of collusion is unclear. This paper focuses on two types of trade-based SCF transaction structures. The first is the hierarchical transaction structures, which are often divided into two-echelon supply chain and three-echelon supply chain [11]. The second is the relation structures, which are often divided into master-slave relation and equivalent relation [12]. The objective of this paper is to investigate the boundary conditions of collusion between the supply chain members in different trade-based SCF transaction structures. We mainly address the following issues:

(1) What are the boundary conditions (discount factor) (according to collusion theory in microeconomics, the boundary condition is when the discount factor is greater than a threshold, the collusion can be conducted and will be stable; otherwise, the collusion cannot be conducted and will be unstable (similar to [13]) of price collusion in these different trade-based SCF transaction structures?

(2) Which trade-based SCF transaction structure has a spontaneous endogenous constraint on collusion that is called self-restraint (not easy to collusion)? Which trade-based SCF transaction structure has hidden, unidentifiable collusion that is called hidden vulnerability (easy to collusion)?

(3) How to develop a mechanism to restrain price collusion in trade-based SCF transaction structure with hidden vulnerability from the profit sharing and incomplete information perspectives?

To answer these questions, we develop different game models for different trade-based SCF transaction structures to identify the boundary condition of collusion. We then compare and analyze the results of these boundary conditions to confirm the advantages and disadvantages of different trade-based SCF transaction structures on restraining price collusion. We look forward to providing reference values for the design of trade-based SCF transaction structure. SCFWG also points out that financial institutions are risk-averse and lack resources to evaluate numerous and varied trade-based SCF structures. In current SCF market conditions where loan quality has become a key issue, this study can provide new solutions for trade-based SCF service providers in preventing collusion and making loan decisions.

This study contributes to the operation management literature studies in the following respects. First, as far as we know, this study is the first focus on the impact of trade-based SCF transaction structures on collusion in the supply chain. Few studies have integrated collusion [14] and SCF [15] to design an effective trade-based SCF transaction structure to prevent collusion from the perspective of supply chain financial risk. Second, we also investigate the impact of the different relation structures on the collusion, such as master-slave relationship and equivalent relationship. Finally, we develop two mechanisms to restrain price collusion from profit sharing and incomplete information perspectives.

The rest of this paper is organized as follows. Section 2 reviews relevant research streams. Section 3 describes the problems. Section 4 discusses the collusion in the two-echelon supply chain, and Section 5 discusses that in the three-echelon supply chain. Section 6 conducts a comparative analysis, and Section 7 tries to extend the research, for example, profit sharing and incomplete information. Section 8 further discusses the theoretical and managerial implications. Finally, Section 9 highlights the main conclusions, limitations, and future research directions.

2. Literature Review

To provide research background and highlight our contributions, we mainly review two related research fields: (1) collusion in the field of economy and management and (2) SCF transaction structure.

2.1. Collusion in Economics and Management. Collusion is a kind of risk behavior in the economic field, which widely exists in insurance, financing, and other financial fields [16]. According to existing research, many different types of collusion exist, and they can be divided into two major categories, namely, management collusion and business collusion. Management collusion mainly refers to the collusion between the company's stakeholders, managers, and employees [17]. On the contrary, business collusion is complex and diverse, such as the market collusion, production collusion, and price collusion [18].

In recent years, some scholars have paid attention to collusion research in the field of operation management [11, 19, 20]. Piccolo and Reisinger. [21] analyze the impact of exclusive territories on manufacturers' incentives to sustain tacit collusion between competing supply chains. Melkonyan et al. [22] develop a formal account of virtual bargaining and demonstrate that it leads to collusion in Bertrand, but not in Cournot, competition. Zheng et al. [23] establish an infinitely repeated game to examine the interaction between the manufacturer's channel strategy and the downstream retailers' collusion behavior. Bian et al. [13] find that upstream collusion in a two-echelon supply chain is easier to sustain under Cournot competition than Bertrand competition, and it is least likely to be sustained under mixed Bertrand–Cournot competition. Miklós-Thal and Tucker [14] build a game-theoretic model to examine how better demand forecasting resulting from algorithms, machine learning, and artificial intelligence affects the sustainability of collusion in an industry. Wang et al. [24] built three twotier game models: Stackelberg-collusion model, Stackelberg-Nash model, and Stackelberg-Stackelberg model, to consider the retailers' potential collusive behavior and the upstream manufacturer's interactive decisions.

Collusion price, which differs from false price, is a collusion agreement that increases the real price consumers pay for a product and then obtains high loans from SCF service providers through the increased transaction value. Collusion also differs from the supply chain integration which realizes the maximization of supply chain benefits by positive practices, such as improving production efficiency, increasing product quality, reducing production costs, or other means [25, 26]. However, collusion realizes the maximization of supply chain benefits by negative practices, such as increasing product price and limiting production. Then, it not only damages the benefits of consumers but also reduces the benefits of financial institutions. Supply chain integration denotes Pareto optimization, whereas collusion is the opposite [27]. Supply chain members easily make short-sighted successful decisions in collusion, thus shaking the development foundation of strategic and stable supply chain.

Collusion can increase the transaction value among supply chain members to obtain higher loans from supply chain finance (SCF) service provider, which will bring some serious risks for SCF. As collusion is very common in supply chain transactions, identifying and preventing this kind of behavior is difficult by means of policy. However, the research of price collusion in supply chain finance has not been effectively analyzed, especially in order to obtain high loans.

2.2. Supply Chain Finance and Transaction Structure. SCF has evolved from the original trade finance, which plays an increasingly important role in solving the financing problems of SMEs [28]. Therefore, most of the existing literature mainly studies how to design an SCF solution that can not only meet the requirements of financial institutions but also effectively solve the financing problem of SMEs, such as bill discount business [29], inventory and receivables finance [30], purchase order finance [9], supply chain inventory finance [10] and trade credit [31].

Trade finance is a very important form of SCF. Lee and Rhee [32] explain trade finance from a supplier perspective and use it as a tool for supply chain coordination. Seifert et al. [33] summarize the relevant literature of trade finance from the aspects of motivation, order quantity decision, credit period decision, and settlement period decision. They hold that trade finance can increase the number of economic orders and serve as the coordination mechanism of the supply chain. Supply chain structure and SCF have a very close relationship. Lee et al. [34] study how trade finance responds to various kinds of competition in the supply chain and the impact of trade finance on firm performance. Peura et al. [35] study whether trade finance is beneficial to suppliers in the horizontal supply chain structure.

Only when more than 20 SCF cases were heard [6] that scholars began to realize the seriousness of the SCF risk. However, at that time, few studies are about the risk management of SCF. Zhao et al. [20] use the external big dataset to establish a forecasting model from the perspective of risk management, and they predict the failures of SCF customers aiming to reduce the risk of financial institutions. They find that cooperation between logistics service providers and financial service providers seems to be a feasible method to solve the financing problem through the case analysis of Swiss Post Logistics in Hofmann's study. Martin and Hofmann [36] conduct a survey of 62 companies from Switzerland and 10 expert interviews to analyze the reasons financial service providers participate in the integrated management of the supply chain processes.

The study of SCF has three limitations though. First, collusion risk in SCF is not well studied. In recent years, the transition from the traditional rational economic man hypothesis to the behavioral economic man hypothesis has become increasingly obvious. Behavioral operation management (BOM) and behavioral finance have become new research hotspots. Therefore, SCF risk management research, as a cross-research issue of operation management and finance (OM-finance), must consider this important research foundation change. This trend has been exacerbated by the outbreak of collusion among steel traders. Second, the SCF structure has positive significance for financial loans, but the impact on collusion risk is unclear. Particularly important is the research on SCF risk management based on the behavior of all parties in the SCF transaction structure. Third, what mechanisms can prevent collusion has not been studied in detail. Song et al. [37] indicate that information sharing in supply chain and other related attributes of SMEs' supply chain network are the key factors that affect the credit quality of SMEs and influence the financing of SMEs.

3. Problem Description

The motivation of collusion among supply chain members is to obtain higher long profits in this paper. If the profits of collusion are high enough, supply chain members will continue to collusion. If the profits of collusion is not higher than the profits of noncollusion, then one member may form cheat behavior in collusion to obtain short-term profit of itself, thus destroying collusion agreement and returning to normal market price trading. Therefore, we need to compare the profits of collusion with the profits of cheat behavior and normal market transaction. When the profits of collusion are higher, supply chain members will choose price collusion. When the profits of price collusion are lower, supply chain members will generate cheat behavior to destroy the current collusion. As financial loans will span multiple stages of sales and production, we need to consider the profits of multiple stages and the discount value of profits. Clearly, the discount factor is the most important factor affecting the profits of collusion and noncollusion. We investigate the discount factor to determine the boundary conditions of collusion. We solve the model according to this idea.

To systematically reveal the impact of SCF transaction structures on the boundary conditions of collusion behavior, we mainly study two kinds of trade-based SCF transaction structures: hierarchical and relation transaction structures. The hierarchical transaction structures are often divided into a two-echelon supply chain with one supplier and one retailer (see Figure 1) and a three-echelon supply chain with one supplier, one distributor, and one retailer (see Figure 2). The relation transaction structures are often divided into master-slave relation and equivalent relation.

In the two-echelon supply chain, the retailer signs a purchase contract (p, q) with the supplier. p represents the unit price of the order product, whereas the q represents the quantity of the order product. First, the retailer signs the financial loan contract with SCF service provider and releases the purchase order to the supplier according to the purchase contract, which is the trade flow. Second, the retailer makes a certain proportion $\hat{r}$ of loans to SCF service provider based on the value of order product between the supplier and the retailer. Third, the retailer should pay the percentage $(1-\hat{r})$ of payments to the supplier according to the financial loan contract (see the cash flow in Figure 1). Based on the trade flow, the cash flow paid by the retailer, and confirmation information from the supplier, the SCF service provider will pay the corresponding payments $\hat{r} \cdot pq$ to the supplier. Once the supplier receives all the payments pq, they will arrange to ship the order products to the retailer, which is the logistics (see Figure 1). Obviously, to get higher finance loans from the SCF service provider, the supply chain members are prone to collusion, which leads to the false increase in the transaction value of order product between the supplier and retailer.

Although only one kind of collusion exists in the two-echelon supply chain, three different types of collusion among different members exist in the three-echelon supply chain (see Figure 2). We develop various game models to identify the boundary conditions of collusion in the two-echelon supply chain and three-echelon supply chain. We also study the different boundary conditions of collusion among the master-slave relation and equivalent relation in each hierarchical transaction structure. The notation and description of various game models are defined in Table 1.

4. Collusion in the Two-Echelon Supply Chain

In this section, we study collusion in the two-echelon supply chain with one supplier and one retailer. Following Loch and Wu [38], we suppose that the market demand is a simple linear demand function, assuming that $q = d - p_1 - p_2$, where p_1 and p_2 are the marginal revenue (price) of supplier and retailer, respectively. The price game of the vertical two-echelon supply chain is a sequential game process, the supplier (first mover) firstly determines its marginal price p_1 (equivalent to the wholesale price minus the cost $w - c$), and then the retailer (second mover) decides its marginal price p_2 (equivalent to the retail price minus the wholesale price $p - w$). Then, the two marginal prices jointly determine the final market price of the product $p = p_1 + p_2$ (for ease of calculation, the product cost c is ignored as 0). The profit of supplier or retailer is given as follows:

$$\pi_i = p_i q = p_i (d - p_1 - p_2) = p_i \left(d - \sum_{j=1}^{2} p_j \right), \quad i = 1, 2. \tag{1}$$

4.1. Collusion under Sequential Game.

According to collusion theory (CT), we first analyze collusion between supplier and retailer in the two-echelon supply chain under the sequential game. The sequential game is similar to Stackelberg game in which the supplier and retailer quote in turn.

4.1.1. Sequential Stackelberg Model.

When the supplier and retailer play sequential game, the solution of reverse selection is as follows.

First, the maximization profit of the retailer is

$$\begin{aligned} \pi_{s2}^{\text{Seq}} &= \max_{p_2} \pi_2 (p_1, p_2), \\ \text{s.t. } p_i &\geq 0, \quad 5i = 1, 2. \end{aligned} \tag{2}$$

Therefore, the optimal reaction curve of retailer to supplier's price quotation is

$$\begin{aligned} \frac{d\pi_2 (p_1, p_2)}{dp_2} &= d - p_1 - 2p_2 = 0, \\ p_2 (p_1) &= \frac{1}{2} (d - p_1). \end{aligned} \tag{3}$$

Substituting the above reaction curve $p_2(p_1)$ into the supplier decision function to solve the optimal price quotation, we have

$$\begin{aligned} \pi_{s1}^{\text{Seq}} &= \max_{p_1} \pi_1 (p_1, p_2 (p_1)), \\ \text{s.t. } p_i &\geq 0, \quad i = 1, 2, \\ \frac{d\pi_1 (p_1, p_2 (p_1))}{dp_1} &= \frac{1}{2} d - p_1 = 0. \end{aligned} \tag{4}$$

Then, we obtain the optimal marginal price of the supplier $p_{s1}^{\text{Seq}*} = (1/2)d$ and the retailer $p_{s2}^{\text{Seq}*} = (1/4)d$, the optimal demand $q_s^{\text{Seq}*} = (1/4)d$, and the maximum profit of the supplier $\pi_{s1}^{\text{Seq}*} = (1/8)d^2$ and retailer $\pi_{s2}^{\text{Seq}*} = (1/16)d^2$.

4.1.2. Sequential Collusion Model.

According to CT, when the supplier and retailer collude price to maximize profits, their decision objective of collusion becomes

$$\begin{aligned} \pi_{mi}^{\text{Seq}} &= \max_{p_1, p_2} \frac{1}{2} [\![\pi_1 (p_1, p_2) + \pi_2 (p_1, p_2)]\!], \\ \text{s.t. } p_i &\geq 0, \quad i = 1, 2. \end{aligned} \tag{5}$$

This analysis model is similar to microeconomics [2], assuming that supplier and retailer equally allocate all profits come from collusion. This paper also gives a more comprehensive analysis in Section 7, considering the random profit sharing of price collusion.

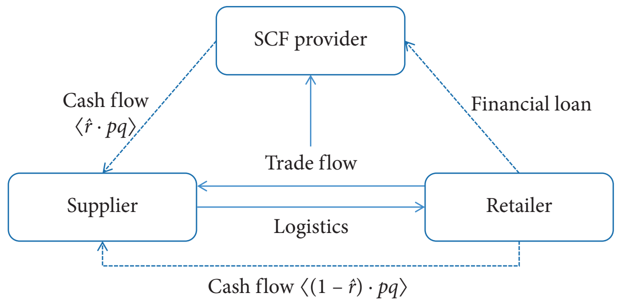

FIGURE 1: SCF transaction structure of the two-echelon supply chain.

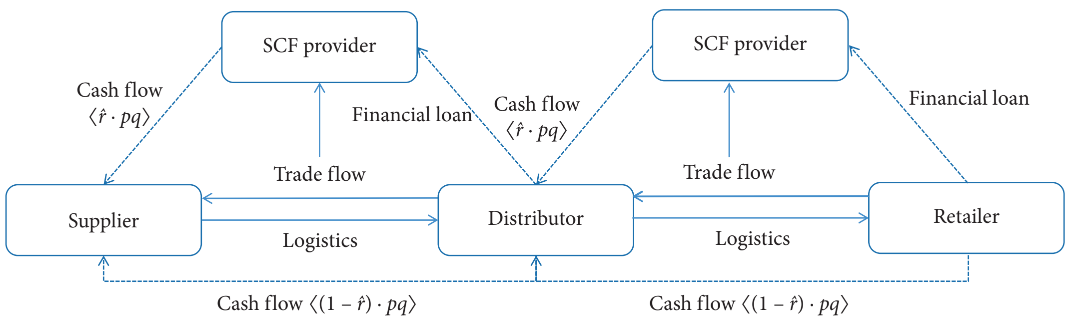

FIGURE 2: SCF transaction structure of the three-echelon supply chain.

$$\frac{\partial (1/2)[\![\pi_1(p_1,p_2)+\pi_2(p_1,p_2)]\!]}{\partial p_i}=\frac{1}{2}d-(p_1+p_2)=0, \quad i=1,2. \tag{6}$$

Through the above solution, we have the optimal marginal price of the supplier $p_{m1}^{\mathrm{Seq}*}=(1/4)d$ and the retailer $p_{m2}^{\mathrm{Seq}*}=(1/4)d$ under the price collusion, the optimal demand $q_m^{\mathrm{Seq}\,*}=(1/2)d$, and the maximum profit of the supplier and retailer $\pi_{m1}^{\mathrm{Seq}*}=(1/8)d^2$ and $\pi_{m2}^{\mathrm{Seq}*}=(1/8)d^2$.

4.1.3. Sequential Cheat Model. In the sequential game, the supplier has the first-mover advantage over the retailer. However, this advantage becomes a disadvantage in collusion. When the supplier and retailer quote price one after another, the retailer is most likely to cheat in price collusion to maximize its profits at a given supplier price, thus damaging the profits of supplier. We analyze the cheat behavior in collusion as follows.

According to the collusion agreement, the supplier first quotes $p_{d1}^{\mathrm{Seq}*}=(1/4)d$ based on the goal of maximizing the profit of collusion. However, owing to the inferiority of the first mover, the retailer may produce cheat behavior to maximize its own profits. Therefore, the decision function of the retailer will become the following form:

$$\begin{aligned}\pi_{d2}^{\mathrm{Seq}}&=\max_{p_2}\pi_2\left(p_{d1}^{\mathrm{Seq}*},p_2\right),\\ \text{s.t. } p_i&\geq 0, \quad i=2.\end{aligned} \tag{7}$$

Then, we solve the following:

$$\frac{d\pi_2\left(p_{d1}^{\mathrm{Seq}*},p_2\right)}{dp_2}=\frac{3}{4}d-2p_2=0. \tag{8}$$

We get the optimal marginal price of retailer when cheat behavior in collusion $p_{d2}^{\mathrm{Seq}*}=(3/8)d$, the demand $q_d^{\mathrm{Seq}\,*}=(3/8)d$, and the maximized profit of supplier $\pi_{d1}^{\mathrm{Seq}*}=(3/32)d^2$ and retailer $\pi_{d2}^{\mathrm{Seq}*}=(9/64)d^2$. That is, for a single-period game, the profit of cheat behavior is higher than the profit of collusion for retailer, and there is economic temptation of cheat behavior. The profit of retailer for cheat behavior is $\pi_{d2}^{\mathrm{Seq}*}=(9/64)d^2$.

4.1.4. Boundary Condition of Sequential Game. Once producing cheat behavior, the retailer and supplier will stop collusion and resume market price cooperation. Therefore, we compare the profits of collusion and the profits of cheat behavior and maker cooperation for the retailer to determine the boundary conditions of price collusion. At this point, according to CT in microeconomics [2], the decision-making process of the regulatory measures for the cheat behavior in collusion is as follows:

$$\begin{aligned}&\pi_{m2}^{Seq*}+\delta\pi_{m2}^{Seq*}+\delta^2\pi_{m2}^{Seq*}+\delta^3\pi_{m2}^{Seq*}+\cdots+\delta^n\pi_{m2}^{Seq*}+\cdots\\ &>\pi_{d2}^{Seq*}+\delta\pi_{s2}^{Seq*}+\delta^2\pi_{s2}^{Seq*}+\delta^3\pi_{s2}^{Seq*}+\cdots+\delta^n\pi_{s2}^{Seq*}+\cdots,\end{aligned} \tag{9}$$

Table 1: Notation and description.

Notation	Description
i	In the two-echelon supply chain, $i = 1, 2$ is supplier and retailer. In the three-echelon supply chain, $i = 1, 2, 3$ is supplier, distributor, and retailer
p_i	The marginal price (revenue) of i
d	Potential demand of the market
q	The actual demand of the market
π_i	The profits of i
In the two-echelon supply chain with supplier and retailer	
p_{si}^{Seq}	The marginal price (revenue) of i under sequential Stackelberg model
q_s^{Seq}	The actual demand of the market under sequential Stackelberg model
π_{si}^{Seq}	The profits of i under sequential Stackelberg model
p_{mi}^{Seq}	The marginal price (revenue) of i under sequential collusion model
q_m^{Seq}	The actual demand of the market under sequential collusion model
π_{mi}^{Seq}	The profits of i under sequential collusion model
p_{di}^{Seq}	The marginal price (revenue) of i under sequential cheat model
q_d^{Seq}	The actual demand of the market under sequential cheat model
π_{di}^{Seq}	The profits of i under sequential cheat model
p_{ci}^{Sim}	The marginal price (revenue) of i under simultaneous Cournot model
q_c^{Sim}	The actual demand of the market under simultaneous Cournot model
π_{ci}^{Sim}	The profits of i under simultaneous Cournot model
p_{mi}^{Sim}	The marginal price (revenue) of i under simultaneous collusion model
q_m^{Sim}	The actual demand of the market under simultaneous collusion model
π_{mi}^{Sim}	The profits of i under simultaneous collusion model
p_{di}^{Sim}	The marginal price (revenue) of i under simultaneous cheat model
q_d^{Sim}	The actual demand of the market under simultaneous cheat model
π_{di}^{Sim}	The profits of i under simultaneous cheat model
In the three-echelon supply chain with supplier, distributor, and retailer	
p_{si}	The marginal price (revenue) of i under Benchmark_Stackelberg model
q_s	The actual demand of the market under Benchmark_Stackelberg model
π_{si}	The profits of i under Benchmark_Stackelberg model
p_{mi}^{SD}	The marginal price (revenue) of i under S_D_Collusion model
q_m^{SD}	The actual demand of the market under S_D_Collusion model
π_{mi}^{SD}	The profits of i under S_D_Collusion model
p_{di}^{SD}	The marginal price (revenue) of i under S_D_Cheat model
q_d^{SD}	The actual demand of the market under S_D_Cheat model
π_{di}^{SD}	The profits of i under S_D_Cheat model
p_{mi}^{DR}	The marginal price (revenue) of i under D_R_Collusion model
q_m^{DR}	The actual demand of the market under D_R_Collusion model
π_{mi}^{DR}	The profits of i under D_R_Collusion model
p_{di}^{DR}	The marginal price (revenue) of i under D_R_Cheat model
q_d^{DR}	The actual demand of the market under D_R_Cheat model
π_{di}^{DR}	The profits of i under D_R_Cheat model
p_{mi}^{SR}	The marginal price (revenue) of i under S_R_Collusion model
q_m^{SR}	The actual demand of the market under S_R_Collusion model
π_{mi}^{SR}	The profits of i under S_R_Collusion model
p_{di}^{SR}	The marginal price (revenue) of i under S_R_Cheat model
q_d^{SR}	The actual demand of the market under S_R_Cheat model
π_{di}^{SR}	The profits of i under S_R_Cheat model
π_{Simi}	The profits of i under the simultaneous game
δ_{Seq}^*	The critical discount factor under the sequential game
δ_{Sim}^*	The critical discount factor under the simultaneous game
$\delta_2^{\text{SD}*}$	The critical discount factor under the S_D_Collusion game
$\delta_3^{\text{DR}*}$	The critical discount factor under the D_R_Collusion game
$\delta_3^{\text{SR}*}$	The critical discount factor under the S_R_Collusion game
(γ_1, γ_2)	Profit sharing factor between the supplier and retailer
$(\varepsilon_1, \varepsilon_2)$	The probability of cheating of the supplier and retailer
γ	Probability of collusion

*In the two-echelon supply chain, sequential Stackelberg model represents the benchmark model under the sequential game, sequential collusion model represents the collusion model under the sequential game, sequential cheat model represents the cheat model under the sequential game, simultaneous Cournot model represents the benchmark model under the simultaneous game, simultaneous collusion model represents the collusion model under the simultaneous game, and simultaneous cheat model represents the cheat model under the simultaneous game. In the three-echelon supply chain, Benchmark_Stackelberg model represents the benchmark model (i.e., Stackelberg game), S_D_Collusion model represents the collusion model between the supplier and distributor, S_D_Cheat model represents the cheat model between the supplier and distributor, D_R_Collusion model represents the collusion model between the distributor and retailer, D_R_Cheat model represents the cheat model between the distributor and retailer, S_R_Collusion model represents the collusion model between the supplier and retailer, and S_R_Cheat model represents the cheat model between the supplier and retailer.

where $\delta \in [0,1]$ refers the discount factor of the profit.

$$\pi_{m2}^{Seq*} \lim_{n\longrightarrow\infty} \frac{(1-\delta^n)}{1-\delta} > \pi_{d2}^{Seq*} + \pi_{s2}^{Seq*} \lim_{n\longrightarrow\infty} \frac{\delta(1-\delta^n)}{1-\delta},$$
$$\frac{\pi_{m2}^{Seq*}}{1-\delta} > \pi_{d2}^{Seq*} + \frac{\delta\pi_{s2}^{Seq*}}{1-\delta}, \tag{10}$$
$$\pi_{m2}^{Seq*} > (1-\delta)\pi_{d2}^{Seq*} + \delta\pi_{s2}^{Seq*}.$$

Seeing that $\pi_{d2}^{Seq*} > \pi_{m2}^{Seq*} > \pi_{s2}^{Seq*}$, then

$$\delta \geq \delta_{\mathrm{Seq}}^{*} = \frac{\pi_{d2}^{Seq*} - \pi_{m2}^{Seq*}}{\pi_{d2}^{Seq*} - \pi_{s2}^{Seq*}} = \frac{(9/64)d^2 - (8/64)d^2}{(9/64)d^2 - (4/64)d^2} = \frac{1}{5} > 0. \tag{11}$$

According to the hypothesis of punishment strategy, when the discount factor satisfies the above conditions, the collusion is stable and cannot be disintegrated.

Proposition 1. *In a two-echelon supply chain under the sequential game, the profits of retailer in collusion, cheating, and sequential game satisfy* $\pi_{d2}^{Seq*} = (9/64)d^2 > \pi_{m2}^{Seq*} = (8/64)d^2 > \pi_{s2}^{Seq*} = (4/64)d^2$.

(1) *When the discount factor satisfies $\delta \geq \delta_{Seq}^{*} = (1/5)$, the supplier and retailer are likely to collude to get higher loans from the SCF service provider in the two-echelon trade-based SCF transaction structure.*

(2) *When the discount factor satisfies $\delta < \delta_{Seq}^{*} = (1/5)$, the two-echelon trade-based SCF transaction structure has the ability to actively restrain price collusion, that is, self-restraint, which can effectively avoid the price collusion behavior.*

Proof. It follows directly from the above analysis and is thus omitted. □

4.2. Collusion under Simultaneous Game. The simultaneous game is similar to Cournot game in which the supplier and retailer quote at the same time.

4.2.1. Simultaneous Cournot Model. When the supplier and retailer play simultaneous game, they first consider the reaction curve of each other to their own pricing decision and then make the optimal pricing decision in the way of reverse selection. After repeated games, the equilibrium strategy of the simultaneous game will be fixed at the intersection of the response curve of supplier and retailer to each other's pricing decision. First, the profit maximization of the supplier and retailer respectively is as follows:

$$\begin{cases} \pi_{c1}^{\mathrm{Sim}} = \max\limits_{p_1} \pi_1(p_1, p_2), \\ \pi_{c2}^{\mathrm{Sim}} = \max\limits_{p_2} \pi_2(p_1, p_2), \end{cases} \tag{12}$$
$$\text{s.t. } p_i \geq 0, \quad i = 1, 2.$$

Therefore, under the simultaneous game, the optimal reaction curves of the supplier to retailer's quoted price and the retailer to supplier's quoted price are as follows:

$$\begin{cases} \dfrac{d\pi_1(p_1,p_2)}{dp_1} = d - 2p_1 - p_2 = 0, \\ \dfrac{d\pi_2(p_1,p_2)}{dp_2} = d - p_1 - 2p_2 = 0, \end{cases}$$
$$\begin{cases} p_{c1}^{\mathrm{Sim}}\left(p_{c2}^{\mathrm{Sim}}\right) = \dfrac{1}{2}\left(d - p_{c2}^{\mathrm{Sim}}\right), \\ p_{c2}^{\mathrm{Sim}}\left(p_{c1}^{\mathrm{Sim}}\right) = \dfrac{1}{2}\left(d - p_{c1}^{\mathrm{Sim}}\right). \end{cases} \tag{13}$$

Based on the homologous structures of the above two reaction functions, the optimal pricing for the simultaneous game equilibrium can be easily found by substituting the first reaction curve into the second one. Then, we get the optimal marginal price of the supplier $p_{c1}^{Sim*} = (1/3)d$ and the retailer $p_{c2}^{Sim*} = (1/3)d$, the optimal demand $q_c^{Sim*} = (1/3)d$, and the maximum profit of the supplier and retailer $\pi_{c1}^{Sim*} = (1/9)d^2$ and $\pi_{c2}^{Sim*} = (1/9)d^2$.

4.2.2. Simultaneous Collusion Model. According to CT, when the supplier and retailer collude price to maximize profits, their price collusion decision objectives are as follows:

$$\pi_{mi}^{\mathrm{Sim}} = \max_{p_1,p_2} \frac{1}{2} [\![\pi_1(p_1,p_2) + \pi_2(p_1,p_2)]\!],$$
$$\text{s.t. } p_i \geq 0, \quad i = 1, 2. \tag{14}$$

This analysis method is similar to microeconomics, assuming that supplier and retailer equally distribute all profits of price collusion.

$$\frac{\partial(1/2)[\![\pi_1(p_1,p_2) + \pi_2(p_1,p_2)]\!]}{\partial p_i} = \frac{1}{2}d - (p_1 + p_2) = 0, \quad i = 1, 2. \tag{15}$$

Through the above solution, we have the optimal marginal price of the supplier $p_{m1}^{Sim*} = (1/4)d$ and the retailer $p_{m2}^{Sim*} = (1/4)d$ under the price collusion, the optimal demand $q_m^{Sim*} = (1/2)d$, and the maximum profit of the supplier and retailer $\pi_{m1}^{Sim*} = (1/8)d^2$ and $\pi_{m2}^{Sim*} = (1/8)d^2$.

4.2.3. Simultaneous Cheat Model. Based on the analysis of the optimal pricing decision under the price collusion and simultaneous games, the possible cheat behaviors of the supplier and retailer are analyzed. As the leader of two-level supply chain, the original advantages of supplier become disadvantages when cheat occurs under the sequential game. Under the premise of the sequential game, it is almost impossible for the supplier to cheat because its cheating behavior can be discovered by the retailer in "one time" game, but the cheat behavior of the retailer can be found at least twice in the game process. Then, supplier thinks the retailer may be cheating. When the hypothesis becomes a simultaneous game, the supplier and retailer may cheat because there is no sequential relationship between their pricing behaviors. Next, we analyze the cheat behaviors of the supplier and retailer.

According to the collusion agreement, the supplier first quotes $p_{d1}^{Sim*} = (1/4)d$ on the basis of the decision of maximizing the profit of price collusion. However, the supplier realizes that the retailer may take cheating to damage his own interests. After the supplier completes his own pricing, the decision making of the retailer's cheat behavior is based on the new profit function to decide its new quotation p_2.

$$\pi_{d2}^{\mathrm{Sim}} = \max_{p_2} \pi_2\left(p_{d1}^{Sim*}, p_2\right), \quad \text{s.t. } p_i \geq 0, \quad i = 2. \tag{16}$$

Then, we solve the following:

$$\frac{d\pi_2\left(p_{d1}^{Sim*}, p_2\right)}{dp_2} = \frac{3}{4}d - 2p_2 = 0. \tag{17}$$

We have the optimal marginal price of retailer when cheating in price collusion $p_{d2}^{Sim*} = (3/8)d$, the demand $q_d^{Sim*} = (3/8)d$, and the maximum profit $\pi_{d1}^{Sim*} = (3/32)d^2$ and $\pi_{d2}^{Sim*} = (9/64)d^2$. The profit of cheating for retailer is higher than the profit of price collusion for the single-period game, and there is the economic temptation of cheat. The cheat profit of retailer is $\pi_{d2}^{Sim*} = (9/64)d^2$.

4.2.4. Boundary Condition of Simultaneous Game. According to CT, the idea of preventing price collusion parties from cheat is to make the present value of price collusion profits higher than the present value of cheat and simultaneous game profits. Both the supplier and retailer are likely to cheat under the simultaneous game, so taking the larger critical discount factor as the constraint condition is necessary to regulate the occurrence of cheat in price collusion.

The "threat" of punishment at this time is that if the supplier or the retailer cheats in the price collusion, they will enter the simultaneous game forever, so$\delta_{\mathrm{Sim_2}}^* = (\pi_{d2}^{Sim*} - \pi_{m2}^{Sim*}/\pi_{d2}^{Sim*} - \pi_{c2}^{Sim*})$, which shows that

$$\delta_{\mathrm{Sim\_2}}^* = \frac{\pi_{d2}^{Sim*} - \pi_{m2}^{Sim*}}{\pi_{d2}^{Sim*} - \pi_{c2}^{Sim*}} = \frac{(9/64)d^2 - (8/64)d^2}{(9/64)d^2 - (1/9)d^2} = \frac{9}{17}. \tag{18}$$

Because the supplier and retailer are homogeneous in the simultaneous game, the following is easy to know:

$$\delta_{\mathrm{Sim\_1}}^* = \delta_{\mathrm{Sim\_2}}^*. \tag{19}$$

Therefore, $\delta \geq \delta_{\mathrm{Sim}}^* = \max\{\delta_{\mathrm{Sim\_1}}^*, \delta_{\mathrm{Sim\_2}}^*\} = (9/17)$, and the critical discount factor in the simultaneous game is $\delta_{\mathrm{Sim}}^* = (9/17)$.

Proposition 2. *In a two-echelon supply chain under the simultaneous game, the profits of retailer in price collusion, cheating, and simultaneous game satisfy* $\pi_{d2}^{Sim*} = (9/64)d^2 > \pi_{m2}^{Sim*} = (8/64)d^2 > \pi_{c2}^{Sim*} = (1/9)d^2$.

(1) *When the discount factor satisfies* $\delta \geq \delta_{Sim}^* = (9/17)$, *the supplier and retailer are likely to collude price to get higher loans from the SCF service provider in the two-echelon trade-based SCF transaction structure.*

(2) *When the discount factor satisfies* $\delta < \delta_{Sim}^* = (9/17)$, *the two-echelon trade-based SCF transaction structure has the ability to actively restrain price collusion, that is, self-restraint, which can effectively avoid the price collusion behavior.*

Proof. It follows directly from the above analysis and is thus omitted. □

5. Price Collusion in the Three-Echelon Supply Chain

Considering that the three-echelon supply chain is composed of one supplier, one distributor, and one retailer, the increase of supply chain levels leads to different forms of price collusion. This section focuses on the following different forms of price collusion under complete information:

(1) Price collusion between the supplier and distributor (see Figure 3(a))

(2) Price collusion between the distributor and retailer (see Figure 3(b))

(3) Price collusion between the supplier and retailer (see Figure 3(c))

The market demand assumption in this section also refers to Loch and Wu [38]. Therefore, the general linear demand can be expressed as

$$q(p_1, p_2, p_3) = d - p_1 - p_2 - p_3 = d - \sum_{i=1}^{3} p_i. \tag{20}$$

The profit function of each member in the three-echelon supply chain can be expressed as follows:

$$\pi_i(p_1, p_2, p_3) = p_i q(p_1, p_2, p_3) = p_i\left(d - \sum_{i=1}^{3} p_i\right), \quad i = 1, 2, 3. \tag{21}$$

5.1. Price Collusion under Sequential Game. According to CT, we first analyze price collusion with or without cheat behavior of the supplier, distributor, and retailer in the three-echelon supply chain under the sequential game. The sequential game is similar to Stackelberg game in which the supplier, distributor, and retailer quote in turn.

5.1.1. Benchmark Model: Stackelberg Game. Stackelberg game is a benchmark model for the supplier, distributor, and retailer to quote in turn. According to CT, we first analyze the Stackelberg game in the three-echelon supply chain and

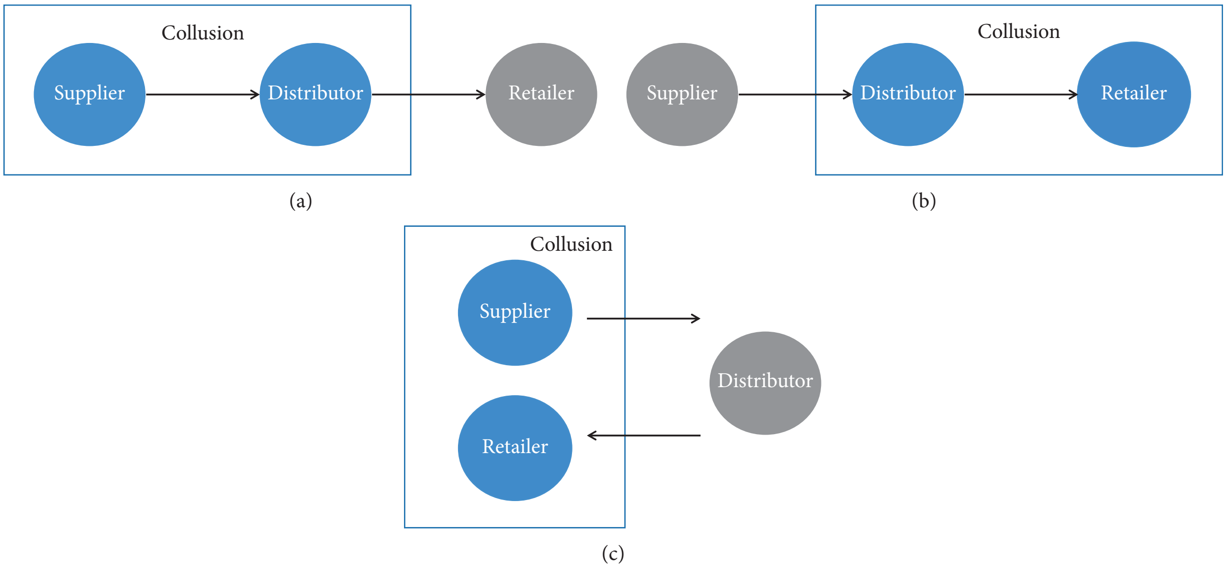

Figure 3: (a) Collusion between the supplier and distributor. (b) Collusion between the distributor and retailer. (c) Collusion between the supplier and retailer.

then the price collusion and cheating in three different forms of price collusion. When the supplier, distributor, and retailer play Stackelberg game, the solution of reverse selection is as follows. First, the profit maximization of the retailer is

$$\pi_{\mathrm{Seq3}} = \max_{p_3} \pi_3 (p_1, p_2, p_3),$$
$$\text{s.t. } p_i \geq 0, \quad i = 1, 2, 3. \tag{22}$$

Therefore, the optimal reaction curve of retailer to the supplier's and distributor's quotations is as follows:

$$\frac{d\pi_3 (p_1, p_2, p_3)}{dp_3} = d - p_1 - p_2 - 2p_3 = 0,$$
$$p_3 (p_1, p_2) = \frac{1}{2} (d - p_1 - p_2). \tag{23}$$

Substituting the above reaction curve $p_3(p_1, p_2)$ into the decision function of the distributor to solve the optimal quoted price, we have

$$\pi_{\mathrm{Seq2}} = \max_{p_2} \pi_2 (p_1, p_2, p_3 (p_1, p_2)),$$
$$\text{s.t. } p_i \geq 0, \quad i = 1, 2. \tag{24}$$

Then, the optimal reaction curve of the distributor to the supplier's quotation is

$$\frac{d\pi_2 (p_1, p_2, p_3 (p_1, p_2))}{dp_2} = \frac{1}{2} (d - p_1) - p_2 = 0,$$
$$p_2 (p_1) = \frac{1}{2} (d - p_1). \tag{25}$$

Substituting the above reaction curve $p_2(p_1)$ into the decision function of the supplier to solve the optimal quoted price, we get

$$\pi_{\mathrm{Seq1}} = \max_{p_1} \pi_1 (p_1, p_2 (p_1)),$$
$$\text{s.t. } p_i \geq 0, \quad i = 1, \tag{26}$$
$$\frac{d\pi_1 (p_1, p_2 (p_1))}{dp_1} = \frac{1}{4} d - \frac{1}{2} p_1 = 0.$$

At last, we obtain the optimal marginal price of the supplier $p_{s1}^* = (1/2)d$, the distributor $p_{s2}^* = (1/4)d$, and the retailer $p_{s3}^* = (1/8)d$, the optimal demand $q_s^* = (1/8)d$, and the maximum profit of the supplier, the distributor, and the retailer
$\pi_{\mathrm{Seq1}}^* = (1/16)d^2$, $\pi_{\mathrm{Seq2}}^* = (1/32)d^2$, and $\pi_{\mathrm{Seq3}}^* = (1/64)d^2$.

5.1.2. Price Collusion between the Supplier and Distributor. (1) S_D_Collusion Model. According to CT, when the supplier and distributor collude price in order to maximize profits, the decision objectives of collusion will be

$$\pi_{mi}^{\mathrm{SD}} = \max_{p_1, p_2} \frac{1}{2} [\![\pi_1 (p_1, p_2, p_3 (p_1, p_2)) + \pi_2 (p_1, p_2, p_3 (p_1, p_2))]\!],$$
$$\text{s.t. } p_i \geq 0, \quad i = 1, 2. \tag{27}$$

However, to solve the problem of profit maximization, the first step is to determine the optimal price reaction curve of the retailer to the price quotation of the supplier and the distributor based on the reverse selection strategy. We can know that the profit maximization of the retailer is

$$\pi_{m3}^{\mathrm{SD}} = \max_{p_3} \pi_3 (p_1, p_2, p_3),$$
$$\text{s.t. } p_i \geq 0, \quad i = 1, 2, 3. \tag{28}$$

We easily get this optimal reaction curve as follows:

$$\frac{d\pi_3(p_1,p_2,p_3)}{dp_3} = d - p_1 - p_2 - 2p_3 = 0, \qquad p_3(p_1,p_2) = \frac{1}{2}(d - p_1 - p_2). \tag{29}$$

Substituting the above reaction curve $p_3(p_1,p_2)$ into the decision function of price collusion, we can solve the optimal quoted price as follows:

$$\frac{\partial (1/2)[\![\pi_1(p_1,p_2,p_3(p_1,p_2)) + \pi_2(p_1,p_2,p_3(p_1,p_2))]\!]}{\partial p_i} = \frac{1}{4}d - \frac{2}{4}(p_1+p_2) = 0. \tag{30}$$

At last, we obtain the optimal marginal price of the supplier $p_{m1}^{\mathrm{SD}*} = (1/4)d$, the distributor $p_{m2}^{\mathrm{SD}*} = (1/4)d$, and the retailer $p_{m3}^{\mathrm{SD}*} = (1/4)d$, the optimal demand $q_m^{SD*} = (1/4)d$, and the maximum profit of the supplier, the distributor, and the retailer $\pi_{m1}^{SD*} = (1/16)d^2$, $\pi_{m2}^{SD*} = (1/16)d^2$, and $\pi_{m3}^{SD*} = (1/16)d^2$.

(2) S_D_Cheat Model. This model is similar to the previous analysis of the cheating model because the first-mover advantage of the supplier becomes a disadvantage. The distributor is most likely to cheat in the price collusion, thus damaging the profit of supplier. The profit maximization and reaction curve of retailer are as follows:

$$\pi_{d3}^{\mathrm{SD}} = \max_{p_3} \pi_3(p_1,p_2,p_3), \quad \text{s.t. } p_i \geq 0, \quad i = 1,2,3, \quad p_3(p_1,p_2) = \frac{1}{2}(d - p_1 - p_2). \tag{31}$$

According to the price collusion agreement, the supplier shall first quote $p_{d1}^{SD*} = (1/4)d$ on the basis of the decision of maximizing the profit of price collusion. After the supplier completes his own pricing, the decision making of distributor's cheating behavior is to decide his new quotation p_2 based on the new profit function.

$$\pi_{d2}^{\mathrm{SD}} = \max_{p_2} \pi_2\left(p_{d1}^{SD*}, p_2, p_3\left(p_{d1}^{SD*}, p_2\right)\right), \quad \text{s.t. } p_i \geq 0, \quad i = 2. \tag{32}$$

Through the above objective function, we can have the entire optimal marginal price $p_{d1}^{SD*} = (1/4)d$, $p_{d2}^{SD*} = (3/8)d$, and $p_{d3}^{SD*} = (3/16)d$, the optimal demand $q_d^{SD*} = (3/16)d$, and all the optimal profits $\pi_{d1}^{SD*} = (3/64)d^2$, $\pi_{d2}^{SD*} = (9/128)d^2$, and $\pi_{d3}^{SD*} = (9/256)d^2$.

According to the punishment mechanism of CT in microeconomics, the critical discount factor can be solved as follows:

$$\delta_2^{\mathrm{SD}} \geq \delta_2^{SD*} = \frac{\pi_{d2}^{SD*} - \pi_{m2}^{SD*}}{\pi_{d2}^{SD*} - \pi_{s2}^{*}} = \frac{(9/128)d^2 - (1/16)d^2}{(9/128)d^2 - (1/32)d^2} = \frac{1}{5}. \tag{33}$$

Proposition 3. *In a three-echelon supply chain, the distributor's profits of distributor in price collusion, cheating, and Stackelberg game satisfy* $\pi_{d2}^{SD*} = (9/128)d^2 > \pi_{m2}^{SD*} = (1/16)d^2 > \pi_{s2}^{*} = (1/32)d^2$.

(1) *When the discount factor satisfies* $\delta_2^{SD} \geq \delta_2^{SD*} = (1/5)$, *the supplier and distributor are likely to collude price to get higher loans from the SCF service provider in the three-echelon trade-based SCF transaction structure.*
(2) *When the discount factor satisfies* $\delta_2^{SD} \geq \delta_2^{SD*} = (1/5)$, *the three-echelon trade-based SCF transaction structure has the ability to actively restrain price collusion between the supplier and distributor, that is, self-restraint, which can effectively avoid the price collusion behavior.*

Proof. It follows directly from the above analysis and is thus omitted. □

5.1.3. Price Collusion between the Distributor and Retailer. *(1) D_R_Collusion Model.* According to CT, when the distributor and retailer collude price to maximize profits, their collusion decision objectives are

$$\pi_{mi}^{\mathrm{DR}} = \max_{p_2,p_3} \frac{1}{2}[\![\pi_2(p_1,p_2,p_3) + \pi_3(p_1,p_2,p_3)]\!], \quad \text{s.t. } p_i \geq 0, \quad i = 2,3. \tag{34}$$

By solving the following partial derivatives, we can get the optimal reaction curve of the distributor and retailer to the supplier' price quotation.

$$\frac{\partial (1/2)[\![\pi_2(p_1,p_2,p_3) + \pi_3(p_1,p_2,p_3)]\!]}{\partial p_i} = \frac{1}{2}(d - p_1) - (p_2 + p_3) = 0. \tag{35}$$

The reaction curve is

$$p_{m2}^{\mathrm{DR}} = \frac{1}{4}(d - p_1),$$
$$p_{m3}^{\mathrm{DR}} = \frac{1}{4}(d - p_1), \quad (36)$$
$$p_{m2}^{\mathrm{DR}} + p_{m3}^{\mathrm{DR}} = \frac{1}{2}(d - p_1).$$

Through the reverse selection strategy, we substitute the above reaction curve into the supplier's profit maximization, and the solution is as follows:

$$\pi_{m1}^{\mathrm{DR}} = \max_{p_1} \pi_1\left(p_1, p_{m2}^{\mathrm{DR}}(p_1), p_{m3}^{\mathrm{DR}}(p_1)\right),$$
$$\text{s.t. } p_i \geq 0, \quad i = 1,$$
$$\frac{d\pi_1\left(p_1, p_{m2}^{\mathrm{DR}}(p_1), p_{m3}^{\mathrm{DR}}(p_1)\right)}{dp_1} = \frac{1}{2}d - p_1 = 0. \quad (37)$$

At last, we obtain the optimal marginal price of the supplier $p_{m1}^{DR*} = (1/2)d$, the distributor $p_{m2}^{DR*} = (1/8)d$, and the retailer $p_{m3}^{DR*} = (1/8)d$, the optimal demand $q_m^{DR*} = (1/4)d$, and the maximum profit $\pi_{m1}^{DR*} = (1/8)d^2$, $\pi_{m2}^{DR*} = (1/32)d^2$, and $\pi_{m3}^{DR*} = (1/32)d^2$.

(2) D_R_Cheat Model. Similar to the analysis of the cheating behavior of the distributor under the price collusion between supplier and distributor, when they collude, the retailer obtains the motivation of cheating in the price collusion. At this time, the optimal marginal price of the supplier and distributor will be similar to that in the D_R_Collusion model, which is $p_{d1}^{DR*} = (1/2)d$ and $p_{d2}^{DR*} = (1/8)d$. Then, the decision making of retailer cheating behavior is based on the new profit function to determine its new quotation p_3:

$$\pi_{d3}^{\mathrm{DR}} = \max_{p_3} \pi_3\left(p_{d1}^{DR*}, p_{d2}^{DR*}, p_3\right),$$
$$\text{s.t. } p_i \geq 0, \quad i = 3. \quad (38)$$

Through the above objective function, we get the retailer's optimal marginal price $p_{d3}^{DR*} = (3/16)d$, the optimal demand $q_d^{DR*} = (3/16)d$, and all the optimal profits $\pi_{d1}^{DR*} = (3/32)d^2$, $\pi_{d2}^{DR*} = (3/128)d^2$, and $\pi_{d3}^{DR*} = (9/256)d^2$.

According to the punishment mechanism of CT in microeconomics, the critical discount factor can be solved as follows:

$$\delta_3^{\mathrm{DR}} \geq \delta_3^{DR*} = \frac{\pi_{d3}^{DR*} - \pi_{m3}^{DR*}}{\pi_{d3}^{DR*} - \pi_{s3}^{*}} = \frac{(9/256)d^2 - (1/32)d^2}{(9/256)d^2 - (1/64)d^2} = \frac{1}{5}. \quad (39)$$

Proposition 4. *In a three-echelon supply chain, the profits of retailer in price collusion, cheating, and Stackelberg game satisfy* $\pi_{d3}^{DR*} = (9/256)d^2 > \pi_{m3}^{DR*} = (1/32)d^2 > \pi_{s3}^{*} = (1/64)d^2$.

(1) *When the discount factor satisfies $\delta_3^{DR} \geq \delta_3^{DR*} = (1/5)$, the distributor and retailer are likely to collude price to get higher loans from the SCF service provider in the three-echelon trade-based SCF transaction structure.*

(2) *When the discount factor satisfies $\delta_3^{DR} < \delta_3^{DR*} = (1/5)$, the three-echelon trade-based SCF transaction structure has the ability to actively restrain price collusion, that is, self-restraint, which can effectively avoid the price collusion behavior.*

Proof. It follows directly from the above analysis and is thus omitted. □

5.1.4. Price Collusion between the Supplier and Retailer. *(1) S_R_Collusion Model.* According to CT, when the supplier and retailer collude to maximize profits, their collusion decision objectives are

$$\pi_{mi}^{\mathrm{SR}} = \max_{p_1, p_3} \frac{1}{2}[\![\pi_1(p_1, p_2, p_3) + \pi_3(p_1, p_2, p_3)]\!], \quad (40)$$
$$\text{s.t. } p_i \geq 0, \quad i = 1, 2, 3.$$

By solving the following partial derivatives, we can get the optimal reaction curve of the supplier and retailer to the distributor's price quotation.

$$\frac{\partial(1/2)[\![\pi_1(p_1, p_2, p_3) + \pi_3(p_1, p_2, p_3)]\!]}{\partial p_i} = \frac{1}{2}(d - p_2) - (p_1 + p_3) = 0. \quad (41)$$

The reaction curve is

$$p_{m1}^{\mathrm{SR}} = \frac{1}{4}(d - p_2),$$
$$p_{m3}^{\mathrm{SR}} = \frac{1}{4}(d - p_2), \tag{42}$$
$$p_{m1}^{\mathrm{SR}} + p_{m3}^{\mathrm{SR}} = \frac{1}{2}(d - p_2).$$

Through the reverse selection strategy, the above reaction curve is put into the profit maximization of distributor, and the solution is as follows:

$$\pi_{m2}^{\mathrm{SR}} = \max_{p_2} \pi_2\left(p_{m1}^{\mathrm{SR}}(p_2), p_2, p_{m3}^{\mathrm{SR}}(p_2)\right),$$
$$\text{s.t. } p_i \geq 0, \quad i = 2,$$
$$\frac{d\pi_2\left(p_{m1}^{\mathrm{SR}}(p_2), p_2, p_{m3}^{\mathrm{SR}}(p_2)\right)}{dp_2} = \frac{1}{2}d - p_2 = 0. \tag{43}$$

At last, we obtain the optimal marginal price of the supplier $p_{m1}^{SR*} = (1/8)d$, the distributor $p_{m2}^{SR*} = (1/2)d$, and the retailer $p_{m3}^{SR*} = (1/8)d$, the optimal demand $q_m^{SR*} = (1/4)d$, and the maximum profit is $\pi_{m1}^{\mathrm{SR}*} = (1/32)d^2, \pi_{m2}^{\mathrm{SR}*} = (1/8)d^2, \pi_{m3}^{\mathrm{SR}*} = (1/32)d^2$.

(2) S_R_Cheat Model. Similar to the analysis of the cheating behavior of the distributor under the price collusion between supplier and distributor, when they collude, the retailer obtains the motivation of cheating in the price collusion. At this time, the optimal marginal price of the supplier and distributor will be similar to that in the S_R_Collusion model, which is $p_{d1}^{\mathrm{SR}*} = (1/8)d$, $p_{d2}^{\mathrm{SR}*} = (1/2)d$. Then, the decision making of the retailer's cheating behavior is to decide its new quotation p_3 based on the new profit function:

$$\pi_{d3}^{\mathrm{SR}} = \max_{p_3} \pi_3\left(p_{d1}^{SR*}, p_{d2}^{SR*}, p_3\right),$$
$$\text{s.t. } p_i \geq 0, \quad i = 3. \tag{44}$$

Through the above objective function, we get the optimal marginal price of retailer $p_{d3}^{SR*} = (3/16)d$, the optimal demand $q_{d3}^{SR*} = (3/16)d$, and all the optimal profit $\pi_{d1}^{SR*} = (3/128)d^2$, $\pi_{d2}^{SR*} = (3/32)d^2, \pi_{d3}^{SR*} = (9/256)d^2$.

According to the punishment mechanism of the CT in the Microeconomics, the critical discount factor can be solved as follows:

$$\delta_3^{\mathrm{SR}} \geq \delta_3^{SR*} = \frac{\pi_{d3}^{SR*} - \pi_{m3}^{SR*}}{\pi_{d3}^{SR*} - \pi_{s3}^{*}} = \frac{(9/256)d^2 - (1/32)d^2}{(9/256)d^2 - (1/64)d^2} = \frac{1}{5}. \tag{45}$$

Proposition 5. *In a three-echelon supply chain, the retailer's profits of price collusion, cheating, and Stackelberg game satisfy* $\pi_{d3}^{SR*} = (9/256)d^2 > \pi_{m3}^{SR*} = (1/32)d^2 > \pi_{s3}^{*} = (1/64)d^2$.

(1) *When the discount factor satisfies* $\delta_3^{SR} \geq \delta_3^{SR*} = (1/5)$, *the supplier and retailer are likely to collude price to get higher loans the SCF service provider in the three-echelon trade-based SCF transaction structure.*

(2) *When the discount factor satisfies* $\delta_3^{SR} < \delta_3^{SR*} = (1/5)$, *the three-echelon trade-based SCF transaction structure has the ability to actively restrain price collusion, that is, self-restraint, which could effectively avoid the price collusion behavior.*

Proof. It follows directly from the above analysis and is thus omitted. □

5.2. Price Collusion under Simultaneous Game. Simultaneous game is similar to Cournot game in which the supplier, distributor, and retailer quote at the same time. According to CT, we analyze the simultaneous game, price collusion, and cheating behaviors of the supplier, distributor, and retailer in the three-echelon supply chain.

5.2.1. Benchmark Model: Simultaneous Game. Simultaneous game (similar to Cournot game) is a benchmark model for the supplier, distributor, and retailer to quote at the same time. According to CT, we first analyze the simultaneous game in the three-echelon supply chain and then the price collusion and cheating in three different forms of price collusion. When the supplier, distributor, and retailer play simultaneous game, the solution of reverse selection is as follows. First, the profit maximization of the supplier is

$$\pi_{\mathrm{Sim1}} = \max_{p_1} \pi_1(p_1, p_2, p_3),$$
$$\text{s.t. } p_i \geq 0, \quad i = 1, 2, 3. \tag{46}$$

Therefore, the optimal reaction curve of supplier to the distributor and retailer's quotations is as follows:

$$\frac{d\pi_1(p_1, p_2, p_3)}{dp_1} = d - 2p_1 - p_2 - p_3 = 0,$$
$$p_1(p_2, p_3) = \frac{1}{2}(d - p_2 - p_3). \tag{47}$$

Following the same principle, we could get $p_2(p_1, p_3)$ and $p_3(p_1, p_2)$. Then, we solve the above three reaction curves simultaneously, that is,

$$\begin{cases} p_1(p_2, p_3) = \frac{1}{2}(d - p_2 - p_3), \\ p_2(p_1, p_3) = \frac{1}{2}(d - p_1 - p_3), \\ p_3(p_1, p_2) = \frac{1}{2}(d - p_1 - p_2). \end{cases} \tag{48}$$

At last, we have $p_1^* = p_2^* = p_3^* = (1/4)d$, $q^* = (1/4)d$, and $\pi_{\mathrm{Sim1}}^* = \pi_{\mathrm{Sim2}}^* = \pi_{\mathrm{Sim3}}^* = (1/16)d^2$.

5.2.2. All the Collusion and Cheating Scenarios under Simultaneous Game. Similar to Sections 5.1.2–5.1.4, we need to analyze all the price collusion and cheating behaviors between any two members in the three-echelon supply chain. To easily compare and analyze all the scenarios, we summarize the calculation results in all cases in Table 2.

Proposition 6. *In a three-echelon supply chain with the supplier, distributor, and retailer, because anyone's profit under price collusion is equal to that under the simultaneous game, colluding price to get high loans is difficult under the simultaneous game.*

According to the calculation results in Table 2, if the distributor and retailer or the supplier and retailer conduct price collusion, we cannot solve any discount factor based on CT because all the supply chain members' profit is equal whether in price collusion or in cheating scenarios. When the supplier and distributor conduct price collusion, the distributor's profit in cheating scenarios is higher than that in price collusion scenarios, but the profit in price collusion scenarios is equal to that in the simultaneous game. Therefore, the supplier and distributor cannot conduct price collusion.

6. Comparative Analysis

In this section, we conduct a comparative analysis of the optimal solutions among different games (i.e., sequential and simultaneous games) in different SCF transaction structures (i.e., two-echelon supply chain and three-echelon supply chain).

6.1. Sequential vs. Simultaneous Game in Two-Echelon Supply Chain. We comparatively analyze and summarize all the optimal marginal prices, demands, and maximum profits of the supplier and retailer with price collusion and cheating behavior in sequential game and simultaneous game. The results are shown in Table 3.

Under the sequential game, when supplier and retailer collude price, the profits of suppliers remain unchanged, but the profits of retailer and the actual market demand increase significantly. The retailer's profit when cheating from the price collusion is higher than that when conducting price collusion, whereas the supplier's is the opposite. From another perspective, considering the advantages of retailer as the buyer's market power, the supplier is likely to be willing to cooperate with retailer in price collusion without damaging their own profits. Of course, if the supplier's product is a best seller and there is no lack of consumer market, the opposite may be true. Under the simultaneous game, both the supplier and retailer's profit when conducting price collusion is higher than that in the simultaneous base game, but only the retailer's profit when cheating from the price collusion is higher than that in price collusion.

Proposition 7. *In a two-echelon supply chain, the discount factor under the simultaneous game is higher than that under the sequential (Stackelberg) game, i.e., $\delta^*_{Sim} = (9/17) > (1/5) = \delta^*_{Seq}$, which means the supplier and retailer are more likely to conduct price collusion to get high loans under the sequential game.*

The above proposition shows that the price collusion stability in the simultaneous game is lower than that in sequential game because both the profits of supplier and retailer in the simultaneous game are higher. Without doubt, the partners involved in the price collusion under the simultaneous game are more likely to cheating. At the same time, the simultaneous game in two-echelon SCF transaction structure can more effectively avoid price collusion and control the risk of SCF than sequential game.

6.2. Two-Echelon vs. Three-Echelon Supply Chain. We comparatively analyze and summarize all the optimal marginal prices, demands, and maximum profits of supplier, distributor, and retailer with price collusion and cheating behavior in the three-echelon supply chain under the sequential game. All the scenarios in the three-echelon supply chain under the simultaneous game are shown in Table 2, and those in the two-echelon supply chain are presented in Table 4. Therefore, we will not repeat them here.

According to the above comparative analysis, we reach the following detailed conclusions.

Observation 1.

(1) In the two-echelon supply chain, there is a greater risk of price collusion to obtain higher loans from the SCF service provider.

 (i) Under the sequential game

  (I) If the discount factor $\delta^*_{\text{Seq}} \geq (1/5)$, it is easy to conduct price collusion; otherwise, if $\delta^*_{\text{Seq}} < (1/5)$, the supply chain can effectively avoid the price collusion behavior.

  (II) As the supplier's profit (or revenue charged from the retailer) does not change $\pi_{s1}^{Seq*} = \pi_{m1}^{Seq*}$, the retailer cannot conduct price collusion to get higher loans.

 (II)Under the simultaneous game

  (I) If the discount factor $\delta^*_{\text{Sim}} \geq (9/17)$, it is easy to conduct price collusion; otherwise, if $\delta^*_{\text{Sim}} < (9/17)$, the supply chain can effectively avoid the price collusion behavior.

  (II) As the supplier's profit (or revenue charged from the retailer) has increased from the price collusion $\pi_{c1}^{Sim*} < \pi_{m1}^{Sim*}$, the retailer can get higher loans from the SCF service provider.

(2) In the three-echelon supply chain, there is a small risk of price collusion to obtain higher loans from the SCF service provider.

 (i) Under the sequential game

  (i) If discount factor $\delta_2^{SD*}, \delta_3^{DR*}, \delta_3^{SR*} \geq (1/5)$, it is easy to conduct price collusion; otherwise if

Table 2: Optimal price, demand, and profit of the supplier, distributor, and retailer in the three-echelon supply chain under the simultaneous game.

	Supplier and distributor	Distributor and retailer	Supplier and retailer
Price collusion	$p_1^* = p_2^* = p_3^* = (1/4)d, q^* = (1/4)d \pi_{m1}^{SD*} = \pi_{m2}^{SD*} = \pi_{m3}^{SD*} = (1/16)d^2$	$p_1^* = p_2^* = p_3^* = (1/4)d,$ $q^* = (1/4)d \pi_{m1}^{DR*} = \pi_{m2}^{DR*} = \pi_{m3}^{DR*} = (1/16)d^2$	$p_1^* = p_2^* = p_3^* = (1/4)d,$ $q^* = (1/4)d \pi_{m1}^{SR*} = \pi_{m2}^{SR*} = \pi_{m3}^{SR*} = (1/16)d^2$
Cheating	$p_1^* = (1/4)d, p_2^* = (3/8)d, p_3^* = (3/16)d,$ $q^* = (3/16)d \pi_{d1}^{SD*} = (3/64)d^2, \pi_{d2}^{SD*} = (9/128)d^2, \pi_{d3}^{SD*} = (9/256)d^2$	$p_1^* = p_2^* = p_3^* = (1/4)d,$ $q^* = (1/4)d \pi_{d1}^{DR*} = \pi_{d2}^{DR*} = \pi_{d3}^{DR*} = (1/16)d^2$	$p_1^* = p_2^* = p_3^* = (1/4)d,$ $q^* = (1/4)d \pi_{d1}^{SR*} = \pi_{d2}^{SR*} = \pi_{d3}^{SR*} = (1/16)d^2$

Table 3: Optimal price, demand, and profit of the supplier and retailer in the two-echelon supply chain.

	Price	Demand	Profit	δ
Seq	$p_{s1}^{Seq*} > p_{m1}^{Seq*} = p_{d1}^{Seq*}\ p_{s2}^{Seq*} = p_{m2}^{Seq*} < p_{d2}^{Seq*}$	$q_s^{Seq*} < q_d^{Seq*} < q_m^{Seq*}$	$\pi_{s1}^{Seq*} = \pi_{m1}^{Seq*} > \pi_{d1}^{Seq*}\ \pi_{s2}^{Seq*} < \pi_{m2}^{Seq*} < \pi_{d2}^{Seq*}$	$\delta_{\text{Seq}}^* = (1/5)$
Sim	$p_{c1}^{Sim*} > p_{m1}^{Sim*} = p_{d1}^{Sim*}\ p_{m2}^{Sim*} < p_{c2}^{Sim*} < p_{d2}^{Sim*}$	$q_c^{Sim*} < q_d^{Sim*} < q_m^{Sim*}$	$\pi_{m1}^{Sim*} > \pi_{c1}^{Sim*} > \pi_{d1}^{Sim*}\ \pi_{c2}^{Sim*} < \pi_{m2}^{Sim*} < \pi_{d2}^{Sim*}$	$\delta_{\text{Sim}}^* = (9/17)$

Seq represents the sequential game, and Sim represents the simultaneous game.

$\delta_2^{SD*}, \delta_3^{DR*}, \delta_3^{SR*} < (1/5)$, the supply chain can effectively avoid the price collusion behavior.

(II) As the supplier's (or distributor's) profit (or revenue charged from the distributor or retailer) does not change $\pi_{s1}^* = \pi_{m1}^{SD*}, \pi_{s2}^* = \pi_{m2}^{DR*}$ in S_D_Collusion and D_R_Collusion, the distributor (or retailer) cannot conduct price collusion to get higher loans.

(II;i) As the distributor's profit (or revenue charged from the retailer) has increased $\pi_{s2}^* < \pi_{m2}^{SR*}$ from the price collusion in S_R_Collusion, the retailer can get higher loans from the SCF service provider. However, at this time, the supplier and the retailer are in price collusion and need the cooperation of the distributor to conduct this kind of price collusion to obtain higher loans from the SCF service provider. In most cases, this is impossible.

(II;)Under the simultaneous game

(I) Seeing that anyone's profit in price collusion is equal to that under the simultaneous game, conducting price collusion to get high loans is difficult under the simultaneous game (see Proposition 6).

7. Extension

In Section 4, the analysis is based on the assumption of complete information and the equal profit allocation between the supplier and retailer in the two-echelon supply chain. In this section, we expand the analysis from two aspects. First, the profits are distributed according to sharing factors. Second, price collusion behavior is analyzed under incomplete information.

7.1. Revenue Sharing. Although the average allocation of the profits may seem fair, such is not always the case because some people value the relative value and others value the absolute value. That is, some firms value the profits of each other. Therefore, we develop the sharing factors to make it lean toward the general sense [39]. We assume that the two individuals involved in the price collusion behavior share the total profits of the price collusion according to a certain sharing factors (γ_1, γ_2) and satisfy $\gamma_1 + \gamma_2 = 1$. We expect to find a suitable proportionality portfolio (γ_1^*, γ_2^*) to allocate the profit of price collusion or concentrate decision-making profit, supplemented by the restrictive constraints of the critical discount factor $\delta \geq \delta^*$. In fact, it is equivalent to finding a coordinated contract combination $(\gamma_1^*, \gamma_2^*, \delta \geq \delta^*)$ to achieve supply chain coordination and obtain the maximum profit of the whole supply chain.

As the whole profit of the price collusion is $\pi^* = (1/4)d^2$, the retailer shares the collusion profit as $\pi_m = (1/4)\gamma_2 d^2, \gamma_2 \in [0, 1]$ and thus

$$\delta \geq \delta^* = \frac{\pi_d - \pi_m}{\pi_d - \pi_s} = \frac{(9/64)d^2 - (8/64)\gamma_2 d^2}{(9/64)d^2 - (4/64)d^2} = \frac{9}{5} - \frac{16}{5}\gamma_2. \tag{49}$$

Because $\delta \in [0, 1]$, $0 \leq (9/5) - (16/5)\gamma_2 \leq 1$, that is, $(4/16) \leq \gamma_2 \leq (9/16)$. Therefore, the above combination contract form $(\gamma_1^*, \gamma_2^*, \delta \geq \delta^*)$ can be expressed as follows:

$$D^* = \begin{cases} \delta \geq \delta^* = \dfrac{9}{5} - \dfrac{16}{5}\gamma_2^*, \\ \gamma_2^* \in \left[\dfrac{4}{16}, \dfrac{9}{16}\right], \quad \delta \in [0, 1], \\ \gamma_1^* + \gamma_2^* = 1. \end{cases} \tag{50}$$

We refer to the above combination as a combined contract, which is based on the following considerations. For the sequential game in the two-echelon supply chain, the leader can be either a supplier or a retailer. If the supplier is a leader, it belongs to the category of price leadership. If the retailer is a leader, it is essentially the category of output leadership, especially when the supplier, as leader, wants to establish strategic partnership with retailer and even performs vertical integration, that is, forward integration. To prevent retailer from collusion in the supply chain, the above combined contracts can be selected as a necessary regulatory measure. As described in the book "Intermediate Microeconomics: A Modern Approach [2]," when the long-term sequential game could be used as a punishment "threat" for price collusion, we can prove that the above regulatory measures are effective.

Proposition 8. *In a two-echelon supply chain under the sequential game with revenue sharing factor* (γ_1, γ_2), *the profits of supply chain in price collusion, cheating, and sequential game, respectively, are* $\pi_m = (8/64)\gamma_2 d^2, \pi_d = (9/64)d^2$, *and* $\pi_s = (4/64)d^2$.

(1) *When the revenue sharing factor and the critical discount factor satisfy* $(\gamma_1^*, \gamma_2^*, \delta^*) \in \mathscr{R}^3 \backslash D^*$, *the two-echelon trade-based SCF transaction structure has the ability to actively restrain price collusion, that is, self-restraint, which can effectively avoid the price collusion behavior* ($\mathscr{R}^3 = [0, 1] \times [0, 1] \times [0, 1]$).

Table 4: Optimal price, demand, and profit of the supplier, distributor, and retailer in the three-echelon supply chain under the sequential game.

	Price	Demand	Profit	δ
S_D	$p_{s1}^* > p_{m1}^{SD*} = p_{d1}^{SD*}$ $p_{s2}^* = p_{m2}^{SD*} < p_{d2}^{SD*}$ $p_{s3}^* < p_{d3}^{SD*} < p_{m3}^{SD*}$	$q_s^* < q_d^{SD*} < q_m^{SD*}$	$\pi_{s1}^* = \pi_{m1}^{SD*} > \pi_{d1}^{SD*}$ $\pi_{s2}^* < \pi_{m2}^{SD*} < \pi_{d2}^{SD*}$ $\pi_{s3}^* < \pi_{d3}^{SD*} < \pi_{m3}^{SD*}$	$\delta_2^{SD*} = (1/5)$
D_R	$p_{s1}^* = p_{m1}^{DR*} = p_{d1}^{DR*}$ $p_{s2}^* > p_{m2}^{DR*} = p_{d2}^{DR*}$ $p_{s3}^* = p_{m3}^{DR*} < p_{d3}^{DR*}$	$q_s^* < q_d^{DR*} < q_m^{DR*}$	$\pi_{m1}^{DR*} > \pi_{d1}^{DR*} > \pi_{s1}^*$ $\pi_{s2}^* = \pi_{m2}^{DR*} > \pi_{d2}^{DR*}$ $\pi_{s3}^* < \pi_{m3}^{DR*} < \pi_{d3}^{DR*}$	$\delta_3^{DR*} = (1/5)$
S_R	$p_{s1}^* > p_{m1}^{SR*} = p_{d1}^{SR*}$ $p_{s2}^* < p_{m2}^{SR*} = p_{d2}^{SR*}$ $p_{s3}^* = p_{m3}^{SR*} < p_{d3}^{SR*}$	$q_s^* < q_d^{SR*} < q_m^{SR*}$	$\pi_{s1}^* > \pi_{m1}^{SR*} > \pi_{d1}^{SR*}$ $\pi_{m2}^{SR*} > \pi_{d2}^{SR*} > \pi_{s2}^*$ $\pi_{s3}^* < \pi_{m3}^{SR*} < \pi_{d3}^{SR*}$	$\delta_3^{SR*} = (1/5)$

(2) *When the revenue sharing factor and the critical discount factor satisfy* $(\gamma_1^*, \gamma_2^*, \delta^*) \in D^*$*, the supplier and the retailer can easily conduct price collusion to get higher loans from the SCF service provider. To control this risk of SCF, we should let the revenue sharing and critical discount factor combination strategy belong to* $\mathscr{R}^3 \backslash D^*$.

Proof. It follows directly from the above analysis and is thus omitted. □

7.2. Incomplete Information. The above analysis ignores that when we assume that one partner cheating, the other partner may cheat at the same time, which is expanded here. When considering cheating in the price collusion, the supplier thinks that the retailer may maintain the quotations of price collusion or may also cheat in the price collusion. Therefore, it is ideal to assume that the retailer will be cheating in the price collusion with a certain probability ε_2. Similarly, the retailer will also make the above considerations, assuming that the probability of cheating of the supplier is ε_1.

According to the previous analysis process, if the supplier and the retailer cheat at the same time, their cheating quotations satisfy $p_1^* = p_2^* = (3/8)d$. At this time, their profits satisfy $\pi_1^* = \pi_2^* = (6/64)d^2$ (see Figure 4.). Obviously, the profits of the supplier and retailer who cheat at the same time are lower than the profits in price collusion, which is not what they want.

When only one of the suppliers and retailers is cheating in the price collusion, the critical discount factor is $\delta_c^* = (9/17)$. When they are cheating at the same time, the critical discount factor at this time satisfies $\delta_c^* = 0$ because the profit of cheating does not meet their respective interests (see Figure 4). Based on the above analysis and the probability distribution of possible cheating behavior, the following propositions can be obtained.

Proposition 9. *In a two-echelon supply chain under the simultaneous game with the probability of cheating of the supplier and retailer* $(\varepsilon_1, \varepsilon_2)$*, the profits of price collusion, only one cheating, both cheating, and simultaneous game, respectively, are* $\pi_m = (8/64)d^2, \pi_i^d = (9/64)d^2, \pi_d = (6/64)d^2$*, and* $\pi_i^c = (1/9)d^2$, $i = 1, 2$.

(1) *The probability of both the supplier and retailer cheating together from the price collusion is* $\varepsilon_1 \times \varepsilon_2$*. At this time, if the critical discount factor satisfies* $\delta \geq \delta_c^* = 0$*, in most cases, the supplier and retailer are likely to conduct price collusion to get higher loans from the SCF service provider in the trade-based SCF transaction structure.*

(2) *The probability of either only the supplier or only the retailer cheating from the price collusion is* $(1-\varepsilon_1)\varepsilon_2 + (1-\varepsilon_2)\varepsilon_1$*. At this time, if the critical discount factor satisfies* $\delta \geq \delta_c^* = (9/17)$*, the supplier and retailer are likely to conduct price collusion to get higher loans from the SCF service provider. However, if the discount factor satisfies* $\delta \geq \delta_c^* = (9/17)$*, the trade-based SCF transaction structure has the ability to actively restrain price collusion, that is, self-restraint, which can effectively avoid the price collusion behavior.*

(3) *The probability of neither the supplier nor the retailer cheating from the price collusion is* $(1-\varepsilon_1)(1-\varepsilon_2)$*. At this point, no matter what the critical discount factor is, the supplier and retailer are likely to conduct price collusion to get higher loans from the SCF service provider.*

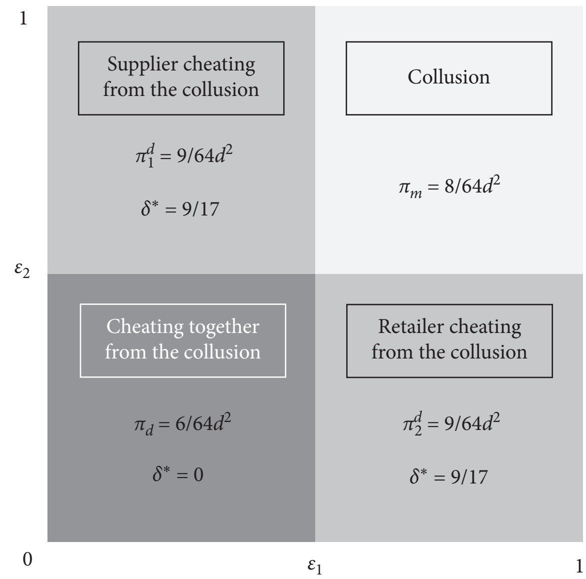

Figure 4: Cheating in the price collusion.

Proof. It follows directly from the above analysis and is thus omitted.

Under the background of the simultaneous game, both the supplier and retailer may cheat in the price collusion at the same time because of the simultaneous quotation, so the critical discount factor depends on the probability of cheating.

Next, we analyze the size of the critical discount factor in both simultaneous and sequential games.

We construct $\delta(\varepsilon_1, \varepsilon_2) = \delta_c^* - \delta_s^* = (9/17)[(1-\varepsilon_1)\varepsilon_2 + (1-\varepsilon_2)\varepsilon_1] - (1/5)$, where $\delta_c^* = (9/17)[(1-\varepsilon_1)\varepsilon_2 + (1-\varepsilon_2)\varepsilon_1]$.

The positive and negative conditions of $\delta(\varepsilon_1, \varepsilon_2)$ are analyzed by numerical simulation with MATLAB. If it is positive, then the price collusion stability in the simultaneous game is lower than the stability in the sequential game, and vice versa. A negative sign of $\delta(\varepsilon_1, \varepsilon_2)$ indicates that the collusion stability in the simultaneous game is higher than that in sequential game.

Looking at the different directions of the following figure, $\delta(\varepsilon_1, \varepsilon_2)$ can be positive or negative (see Figure 5). In two different game situations, the probability assumptions that the supplier and retailer may be cheating change the absolute superiority and inferiority of critical discount factors. The more realistic relationships between the critical discount factors should be relative to the combination

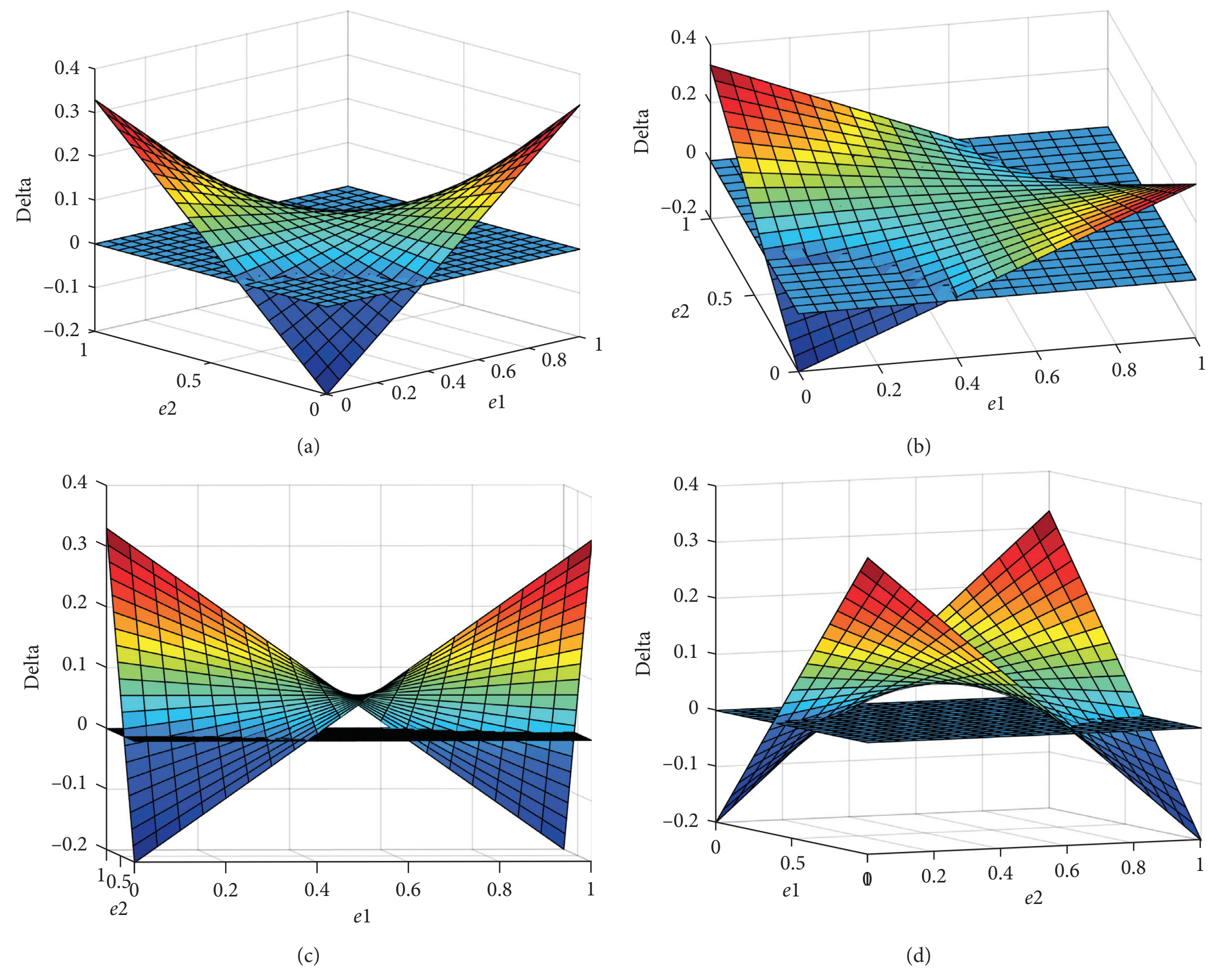

FIGURE 5: Size relationship (the x label $e1$ represents ε_1; y label $e2$ represents ε_2; and z label delta represents δ).

probability $\delta(\varepsilon_1, \varepsilon_2)$ of cheating. In absolute sense, there are no absolute advantages or disadvantages relationship because it is almost impossible to achieve complete information symmetry in reality.

By observing the above figure, we can summarize the relationship between the size relation between the two critical discount factors and the combined probability $(\varepsilon_1, \varepsilon_2)$ as shown in Figure 6, where $\varepsilon_1(\varepsilon_2) = (17/45) - ((11/45)/(1/\varepsilon_2) - 2)$. □

Observation 2.

(1) In the probability of both the supplier and retailer cheating in the price collusion $P_r \in \mathrm{I} \cup \mathrm{III}$, the critical discount factor satisfies $\delta_c^* < \delta_s^*$, and the two-echelon supply chain under the simultaneous game is much more likely to conduct price collusion to get higher loans from the SCF service provider than that in sequential game.

(2) In the probability of both the supplier and retailer cheating in the price collusion $P_r \in \mathrm{II}$, the critical discount factor satisfies $\delta_c^* \geq \delta_s^*$, and the two-echelon supply chain with one supplier and one retailer under the sequential game is much more likely to conduct price collusion to get higher loans from the SCF service provider than that in the simultaneous game.

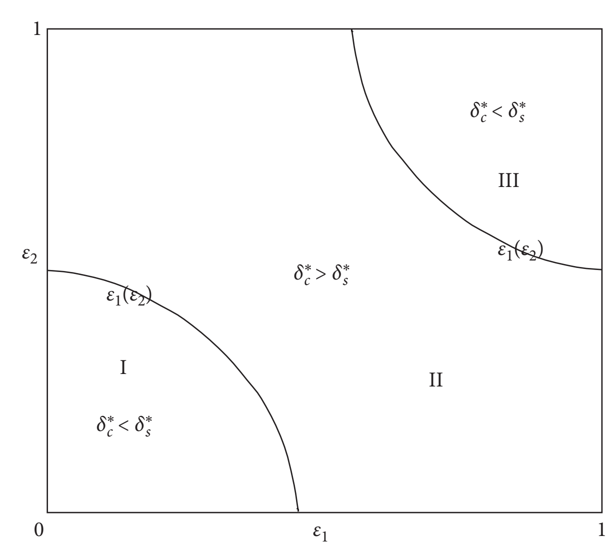

FIGURE 6: Size relationship.

8. Theoretical and Managerial Implications

8.1. Theoretical Implications. Theoretically, this study can provide a new research direction for integrating SCF and price collusion behavior in microeconomics. Although SCF can help supply chain solve the capital limitation problem, price collusion is a very big risk for the customers, whole supply chain, and financial systems. Studies on the price collusion behavior in SCF are very limited. We look forward to providing reference values for the design of SCF transaction structure to effectively avoid the price collusion behavior. A large amount of related research can be conducted in the future along such a research direction. As shown in Figure 7, it constitutes an implementation manual for effective prevention of the price collusion risks in the SCF transaction structure.

This paper provides a solution to avoid the price collusion behavior in SCF. We develop various game models to identify the boundary conditions of price collusion in the different trade-based SCF transaction structures. Then, the results of these models are compared and analyzed to confirm the advantages and disadvantages of different SCF transaction structures on preventing price collusion behavior.

From game model results, we identify influence factors to avoid price collusion. First, SCF transaction structure has an important influence on price collusion behavior. The three-echelon supply chain experiences more difficulties to form price collusion behavior to get higher loans than the two-echelon supply chain. Second, critical discount factor can be adopted to prevent price collusion behavior. Therefore, financial institutions should take corresponding measures to improve the discount factor. Third, the profit sharing and incomplete information also affect the price collusion behavior. This paper develops two types of mechanism, profit sharing and incomplete information, to restrain price collusion.

8.2. Managerial Implications. This section illustrates the managerial implications of this study through two cases, from two-echelon supply chain to three-echelon SCF transaction structure, to effectively control the financial risk of supply chain.

8.2.1. Case Study 1: Xiangyu Co., Ltd vs. JG Group. Xiangyu Co., Ltd. (stock code: 600057) is a supply chain company focusing on bulk commodity procurement, distribution, terminals, logistics, and park development. The company's business philosophy is "create value of the circulation and service for the company's growth." It services an industrial chain, relying on the scientific and advanced management information system, experienced professional operation team, and efficient and rigorous risk control system, with a sound market network, perfect logistics facilities, and good corporate reputation. It provides customers with the full value chain distribution services from the purchasing and supplying of the raw and auxiliary materials and semifinished products to the distribution of finished products. Xiangyu Co., Ltd. assists customers to systematically and comprehensively plan, organize, coordinate, and control the business flow, logistics, capital flow, and information flow throughout the entire process. It also helps the companies of manufacturing and distribution to build the core competitiveness of the supply chain in all directions. In 2018, the company achieved an operating revenue of 234 billion yuan, which is expected to reach 300 billion yuan in 2019.

Jinguang Group is the only large-scale enterprise group with complete stainless steel industrial chain in southwest China and the first private enterprise to complete the entire stainless steel production chain. Jinguang Group has a production capacity of 1.5 million tons of stainless steel smelting and hot rolling and 0.3 million tons of cold-rolled sheet, with an annual sales revenue of more than 20 billion yuan (see Figure 8).

Since 2015, due to the state's macroeconomic policy of regulating steel production capacity, although stainless steel does not belong to the category of traditional steel, stainless steel products are still in short in supply and spot cash transactions, but Jinguang Group is still unable to escape from the bank's loan withdrawal behavior. With its comprehensive service capabilities in logistics and supply chain management, Xiangyu Co., Ltd., has been deeply rooted in the stainless steel industry for many years, providing many customers with SCF services, such as raw material procurement, finished product distribution and receivables, and payable accounts financing. In this context, Xiangyu Co., Ltd., chose to cooperate with Jinguang Group to provide raw material agency procurement, finished product distribution, and financing services. At the same time, through the reengineering of business processes, Xiangyu Co., Ltd., helped Jinguang Group achieve a substantial reduction of its inventory-occupying funds from 2 billion yuan to 600 million yuan and provided SCF services with a total credit line of 600 million yuan. At this time, the two sides' trading agency relationship is a typical two-echelon SCF transaction structure. According to our study on this type of transaction structure design, there is an invisible loophole in which fraud collusion occurs. Shortly after the cooperation between the two parties, the project operators of the two sides colluded, resulting in the fund repayment risks of tens of millions (similar to the case of Luckin Coffee Inc. (NASDAQ: LK)). Therefore, the two sides decided to reform the transaction structure after several rounds of consultations. Local governments took the lead in establishing the state-owned platform company. From the perspective of SCF transaction structure, the platform company is located in the middle of Xiangyu and Jinguang Group. The platform company provides agency procurement and distribution services for the Jinguang Group. Xiangyu shares the platform company's procurement and distribution services, which constitutes a typical three-echelon SCF transaction structure (see Figure 9). According to our research conclusions, we can see spontaneous constraints on the collusion behavior in the three-echelon SCF transaction structure, which can effectively avoid the occurrence of collusion. At the same time, as the main sponsor of the

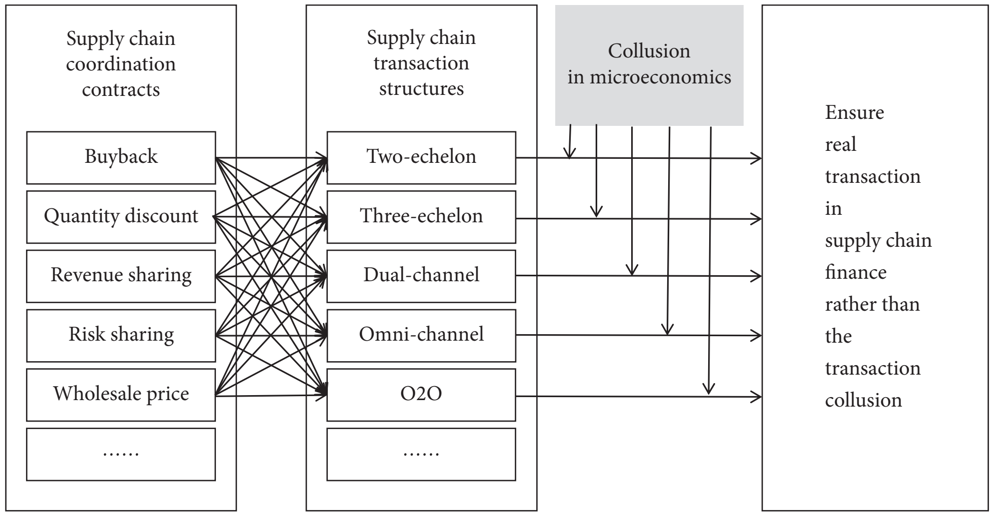

Figure 7: Research directions.

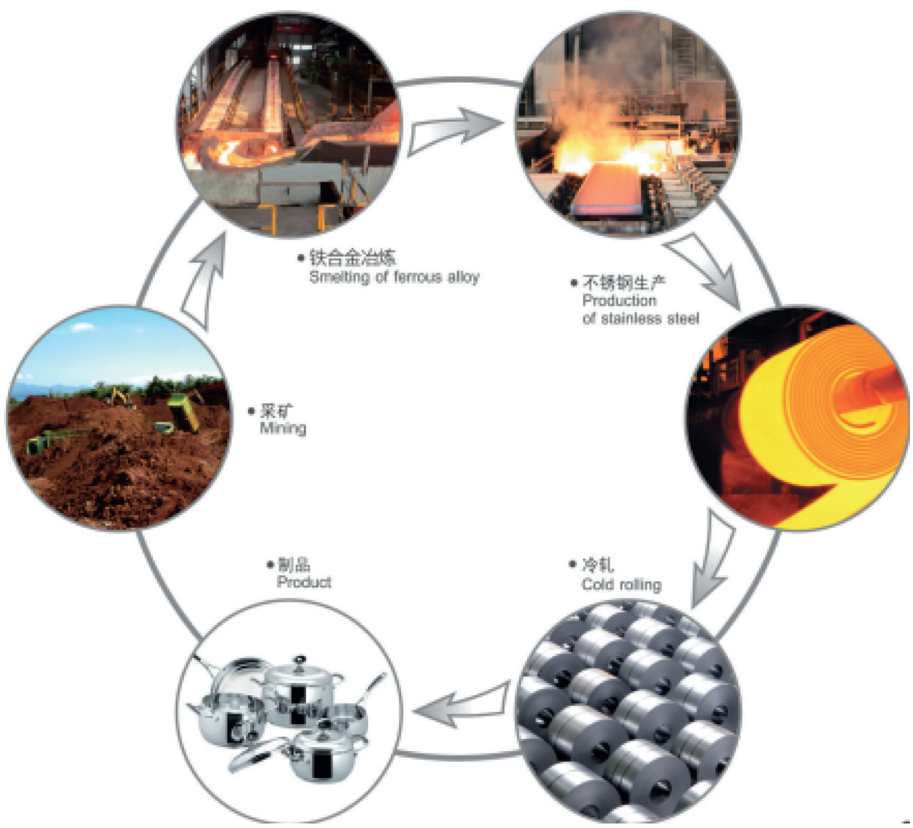

Figure 8: Whole supply chain of Jinguang Group.

platform company, the government has played the role of supervision and deterrence, further enhancing the security and stability of the SCF services.

8.2.2. Case Study 2: Sichuan Logistics and Sichuan Railway Logistics Co., Ltd. Both the Sichuan Logistics and Sichuan Railway Logistics Co., Ltd., are typical kind of "supply chain pallet company," which provide the trade-based supply chain finance service. To control the risk of SCF service, they must change the supply chain transaction structure. For example, if there is a supplier purchasing coal and supplying it to the power company, and it is capital constraint. The supplier wants to get supply chain finance loans from this kind of "supply chain pallet company," such as the Sichuan Logistics Co., LTD, and the supply chain transaction structure must be changed to as follows. The supplier purchases the coal, supplies it to the Sichuan Logistics Co.,

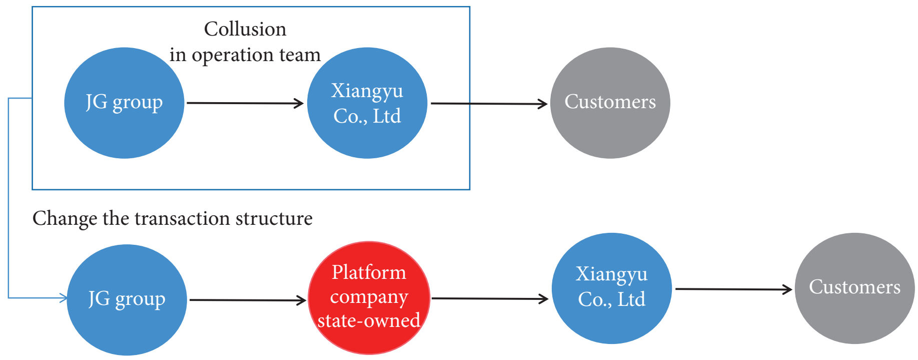

Figure 9: Changing of the transaction structure.

Table 5: Other case companies.

No.	Company (stock code)	Main business	Income (100 million yuan)	Market value (100 million yuan)
1	Wuchan Zhongda Group Co., Ltd. (600704)	Metal materials, chemicals, coal, vehicles, mineral products, *finance, logistics*, etc.	3589.22 (2020,1–12)	239.4
2	Xiamen International Trade Group Co., Ltd. (600755)	*Supply chain management business, financial services*, real estate operations, etc.	2262 (2020,1–9)	127.90
3	Eternal Asia (002183)	380 distribution platform, global procurement platform, *logistics platform, Yushang Financial Control platform*, etc.	436.6 (2020,1–9)	95.52
4	CCS Supply Chain Management Co., Ltd. (600180)	Bulk commodities supply chain, bulk commodities e-commerce platform and *supply chain finance*, etc.	264.23 (2020,1–9)	55.80
5	CMST Development Co., Ltd. (600787)	Commodity circulation, *transportation, finance*, etc.	332.7 (2020,1–9)	111.53

Ltd., and then the Sichuan Logistics Co., Ltd., and supplies it to the power company. Through this kind of supply chain transaction structure change, the supply chain finance service provider, such as the Sichuan Logistics and Sichuan Railway Logistics Co., LTD, can restrain the collusion between the supplier and the downstream company. Other similar listed companies are shown in Table 5.

9. Conclusions, Limitations, and Future Research

Price collusion, which is different from supply chain integration, does great harm to SCF to obtain higher financial loans. We investigate the impact of SCF transaction structures on price collusion behavior under different game models in the two-echelon and three-echelon supply chain. Finally, we develop two types of mechanism, profit sharing and incomplete information, to restraint the price collusion. Through this research, we arrive at a series of interesting conclusions for price collusion in SCF.

In the two-echelon supply chain, the supplier's original leader's preemptive pricing advantage becomes a disadvantage when cheating may occur in the price collusion under the sequential game. In this kind of game, it is almost impossible for the supplier to cheating because the cheating behavior of the supplier can be found by the retailer in one game. The cheating behavior of retailers may be discovered by supplier at least twice in the game process. When our hypothesis changes to simultaneous game, suppliers and retailers may also cheat, and the price collusion stability in the simultaneous game is lower than that in the sequential game. When suppliers and retailers perform the simultaneous game, the profits of both sides are higher than the sequential game, so they are more likely to cheat.

In the three-echelon supply chain, there is no interest basis for any price collusion between any parties, and the SCF transaction structure has spontaneous endogenous constraints on price collusion. In the practice of SCF business, we should give priority to the three-level SCF transaction structure with self-restraint ability as the service object. In this transaction structure, we can use relatively loose revenue sharing and key discount factors. However, for the supply chain that may have price collusion, the financing threshold should be raised, such as using constraint mechanism (a key discount factor) to effectively control the financing risk of the supply chain.

This paper mainly studies the existence and stability of price collusion in a two-echelon or three-echelon supply chain without any supply chain coordination strategy under the assumption of completely rational economic person. The research shows a possible domain space for price collusion in the two-echelon supply chain, and external measures should be taken to avoid price collusion. There is no feasible price collusion in the three-echelon supply chain, and the transaction structure is binding on the price collusion spontaneously, that is, self-restraint. In the future, in the context of more extensive supply chain coordination strategies, such as buyback, quantity discount, revenue sharing, and risk sharing, the price collusion behavior in different types of SCF transaction structures should be analyzed and distinguished to provide decision support and in-depth insights into the actual business environment for SCF practice. At the same time, we need to compare and analyze the price collusion behavior under different market demand structures to eliminate the dependence of research results on specific models as much as possible.

Data Availability

All data in the article are available from the authors upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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Research Article

Research on Regional High-Tech Innovation Efficiency and Influence Factors: Evidence from Yangtze River Economic Belt in China

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China's high-tech innovation and marketization efficiency still need to be optimized, which restricts the promotion of regional innovation and economic development. On such practical problem, this paper mainly focuses on improvement of high-tech efficiency of China, with the hope that the research can help to find ways to improve efficiency in both regions and industry development. Moreover, the impact on the high-tech innovation stage and the marketization stage are analyzed, in order to make clear the main problems in the complex process of high-tech innovation. This paper proposed the super-SBM model and the panel regression model. The conclusions are as follows. (1) The efficiency of high-tech innovation in China is improving, but there are great differences within regions. Therefore, the heterogeneous regional innovation context should be taken into consideration in the institutional management policies. (2) There is a significant positive correlation between government subsidies and R&D intensity in improving the high-tech innovation efficiency. Government needs to carry out appropriate policy guidance, increase financial support, and encourage high-tech enterprises to increase R&D investment. (3) Openness and better innovation environment play a positive role in the technology marketization stage; thus, the establishment of inter-regional cooperation or transnational relations is an effect way. Forming a better innovation environment can also help to enhance international high-technology cooperation and improve marketization efficiency.

1. Introduction

China's economy is not only developing rapidly but also facing multiple challenges, such as lack of core technology innovation, low efficiency of technology transformation, declining rate of economic growth, energy shortages, and environmental pollution [1]. Existing research studies have also proved that technological innovation can affect national or regional economic development and environmental improvement [2]. Therefore, it is very important to promote the regional technology innovation efficiency, especially to improve the efficiency of high-tech industries. The knowledge and technology of high-tech industry are highly concentrated, and high-tech industry has the characteristics of high investment, high risk, and high income. By using advanced technology to produce high-tech products, high-tech industry can have a significant impact on the development of other industries, regional economic structure, and economic growth. The efficient development of the high-tech industry is the key for a country to realize industrial transformation and better participate in global economic competition.

The development level of the high-tech industry can reflect the national and regional technological innovation capabilities and economic development level to a certain extent, and its innovation efficiency directly affects the regional high-quality development. The added value of China's high-tech industry was 11.8% [3]; however, the low efficiency of technological innovation also restricts the improvement of its development level. Although China's high-tech industry creates a high industrial added value every year, can the output value be efficiently transformed into the market value? Has the industry run efficiently? Relevant research studies have pointed out that there is quite difference in the industry performance among different types of enterprises, regions, and different industrial environments. To a certain extent, this shows that the high output of the high-tech industry in some regions of China is due to the high R&D funds and personnel investment, which is not an effective way to improve the innovation efficiency. The economic development and technological innovation of the high-tech industry need to effectively transform the new technology or products into the market value in order to gain advantages in the competition. Therefore, how to evaluate and improve the innovation efficiency of the regional high-tech industry is the key to improve China's regional innovation and economic development. Therefore, it is necessary to analyze the problems and influencing factors that restrict the improvement of innovation efficiency in heterogeneous regions.

The high-tech industry is a technology intensive industry, which can best reflect the regional scientific and technological innovation and economic development. Its innovation efficiency will directly affect the high-quality development of the region. China's high-tech industry is developing rapidly, but there are still some problems. The escalation of international trade frictions also reflects that China's high-tech industry is still facing the key problems of scarcity of core technology and difficult marketization. The difficulty restricted the development of China's high technology development. China's high-tech industry has obvious characteristics of spatial heterogeneity. Regional advantages, resource differences, market environment, regional technical barriers, and other factors make the innovation efficiency of enterprises have obvious spatial imbalance [4]. With the continuous increase of regional high-tech industry innovation investment, how to objectively evaluate and improve the innovation efficiency has become an urgent problem. If we ignore the heterogeneity and assume that they have the same production frontier, we cannot accurately judge the innovation efficiency and technology marketization.

According to the existing research, geographic location can be an exogenous location factor, and enterprises will build on the advantage of geographic location to realize advantages [4]. The Yangtze River Economic Belt covers the Yangtze River Delta Region, central and western regions of China, which are most vibrant and representative Chinese regions with significant development potential [4]. By 2018, the region's overall population and GDP have reached almost 50% of the whole China, and it is an important region in China's economic development strategy. In recent years, the scale of high-tech industries in the Yangtze River economic belt has been expanding. The number of high-tech enterprises increased from 13,044 to 16,546 during 2009 to 2018, accounting for 49.2% of China's high-tech enterprises. High-tech enterprises' revenue in Yangtze River economic belt accounted for 45.8% of whole China, and government financial support for high-tech enterprises accounted for 49.4%. However, regions within the Yangtze River economic belt are in different stages of industrial economic development, while the research on this region lacks accurate consideration of the heterogeneous context. Therefore, on the one hand, the Yangtze River economic belt is an important region for high-tech industry development in China. On the other hand, the obvious regional heterogeneity also makes great differences in its innovation level and efficiency [5]. The Yangtze River economic belt has become a typical region of economic and geographical research, which has strong representativeness and importance. The Yangtze River Economic Belt has achieved remarkable development in recent years, and internal heterogeneity is obvious. How to realize sustainable development of innovation resources is a strategic problem that needs to be solved urgently in China.

The innovation and transformation of the high-tech industry is a complicated process; it is a process in which participants in technology creation and marketization activities turn resources into new technology and then into productivity and realize marketization. This paper focuses on technological innovation and marketization of the high-tech industry, taking the Yangtze River economic belt as a case region, and this paper attempt to discuss the following. (1) How is the overall efficiency of high-tech industry innovation in the Yangtze River economic belt? What is the different within the heterogeneity region? (2) What is the feature of different innovation stages? How does the efficiency of each stage evolve over time? (3) What are the main factors affecting high-tech industry innovation in the Yangtze River economic belt? What is the mechanism of improving high-tech innovation efficiency?

In this paper, we mainly contribute to the existing research on high-tech efficiency in the following points. On the one hand, we focus on improvement of high-tech efficiency in representative region of China and hope the research can help to improve overall efficiency of high-tech innovation in both regions and industry development. On the other hand, we analyze not only the impact factors of the overall efficiency but also the impact of both the high-tech innovation stage and the marketization stage, in order to accurately reflect the main problems in different process of high-tech innovation. Moreover, the super-SBM model has proven to be an effective analytical tool in efficiency research; based on the model, we made more objective and distinctive values of innovation efficiency. This paper analyses high-tech innovation efficiency in Yangtze River Economic Belt, which has practical significance for empirical analysis on high-tech innovation and marketization in China's heterogeneous regions.

This paper is organized as follows. Section 2 is the review of technology innovation and innovation performance. Section 3 is is the description of data and methodology of our research. Section 4 describes heterogeneity feature and overall efficiency of the high-tech industry in Yangtze River Economic Belt. The stage efficiency of technology creation, the marketization of the high-tech industry, and the influence factor are presented in Section 5. In Section 6, we offer some concluding remarks.

2. Literature Review and Research Strategy

2.1. Classification and Innovation Feature of the High-Tech Industry. In the 1960s, the word "high technology" appeared in the United States. It is used to express advanced technology that can achieve significant economic benefits. The high-tech industry is based on advanced science and technology, through high-intensity research and development to produce knowledge intensive new products. China's high-tech industry mainly includes aerospace and equipment manufacturing, medical equipment and instrument manufacturing industry, manufacturing of electronic communication equipment, medical manufacturing, and computer and office equipment manufacturing (Figure 1).

The high-tech industry is characterized by high investment, high risk, and high income [6]. The high-tech firms focus on creation of new technology and new products [7]. No matter the research and development of new technology or the introduction of new equipment, high-tech industries are highly dependent on capital and talent investment. On the one hand, the high risk is due to the strong uncertainty of high-tech innovation and technology development activities; on the other hand, whether the long-term marketization of new technology or new products can be successfully realized is another risk. High yields are an important feature of technological innovation in high-tech industry. Once the new technology or new product is successfully developed and recognized by the market, it can produce a high market value.

Most of the innovation comes from "reference" rather than "originality" [8]; the "silence" and "environmental sensitivity" of science and technology make technological innovation and transformation more complex than the simple process of technology introduction [9]; innovation participants need to have a certain understanding ability to absorb and apply these technologies efficiently [10, 11]. In the process of industrialization, developing countries catch up with developed countries through technology introduction and FDI (foreign direct investment) etc., so as to improve the technological innovation ability and achieve rapid economic growth [12, 13]. Schumpeter once pointed out that promoting innovation by technology introduction can improve innovation efficiency. High-tech industry is based on new science and technology [14], and it requires advanced science and technology to be put into the whole process of technology production, processing, outputting, and recycling of high-tech products, and technology and talents play an important role in the development of the high-tech industry.

2.2. Analytical Framework of Innovation Efficiency of the High-Tech Industry. The existing research on the efficiency evaluation of technological innovation is mainly divided into regional [15], industrial [16], and enterprise [17, 18] levels. The research on the innovation efficiency of the high-tech industry in heterogeneous regions confirms that the technological innovation efficiency varies greatly in different regions and different innovation stages, regardless of Europe or China's coastal and inland regions [19–21]. The less developed countries or regions in the late catch-up stage are not necessarily low in innovation efficiency. Through the analysis of 192 European regions' technological innovation efficiency, it is concluded that the underdeveloped regions have high efficiency [20]. From the perspective of industry, the innovation efficiency of China's high-tech industry in 2012–2018 varies greatly among different categories [21, 22]. High-tech enterprises are mainly faced with the problem of insufficient transformation ability, which leads to the low efficiency of high-tech innovation [3].

Most of the existing research studies regard the input-output of the high-tech industry as a whole process [23]. The characteristics of the high-tech industry determine that its technological innovation process is a complex process, and different regions, industries, and enterprises have diverse innovation characteristics. It is necessary to carry out accurate evaluation and mechanism research on the innovation efficiency of the high-tech industry.

DEA (data envelopment analysis) [24, 25] and SFA (stochastic frontier analysis) [26–28] have been used to measure the innovation efficiency in western developed countries and find out the factors restricting the transformation process. DEA is a scientific method of efficiency evaluation, which avoids the inaccuracy of subjective weight setting. However, in the empirical research, the input and output of DEA mainly focus on the initial input resources and final output [29]. The "black box" research method does not include the intermediate stage of transformation into the innovation chain model. With the optimization of the efficiency measurement model, based on the innovation process analysis framework, the efficiency research is divided into different stages for evaluation [30]. Focus on the substages of the innovation process and establish the relationship among different stages [31]. In this paper, the SBM method is used. According to the innovation chain of the high-tech industry, the input-output division is divided into two stages which can not only systematically grasp the total efficiency of the innovation chain but also accurately analyze the efficiency problems in different stages.

Only by scientifically evaluating the innovation efficiency of the high-tech industry can we make clear the problems existing in the innovation activities and put forward targeted suggestions to solve the problems. Existing research has provided an important basis; however, there are still controversies and problems in the existing research studies. The high-technology creation and transformation process actually a complex multistage activity, which is a multistage chain process of multiple inputs and outputs [32]. Most of the existing efficiency evaluation research studies regard the transformation process as a single input-output stage or only focus on a certain part of the overall activity. The analysis of a single stage of the transformation process ignores the systematisms and cannot evaluate efficiency pertinently.

Rothwell pointed out that technology promotion and market pull are the basis for the formation of technological innovation chain [33]. Hage and Hollingsworth proposed "idea innovation chain" and divided it into basic research

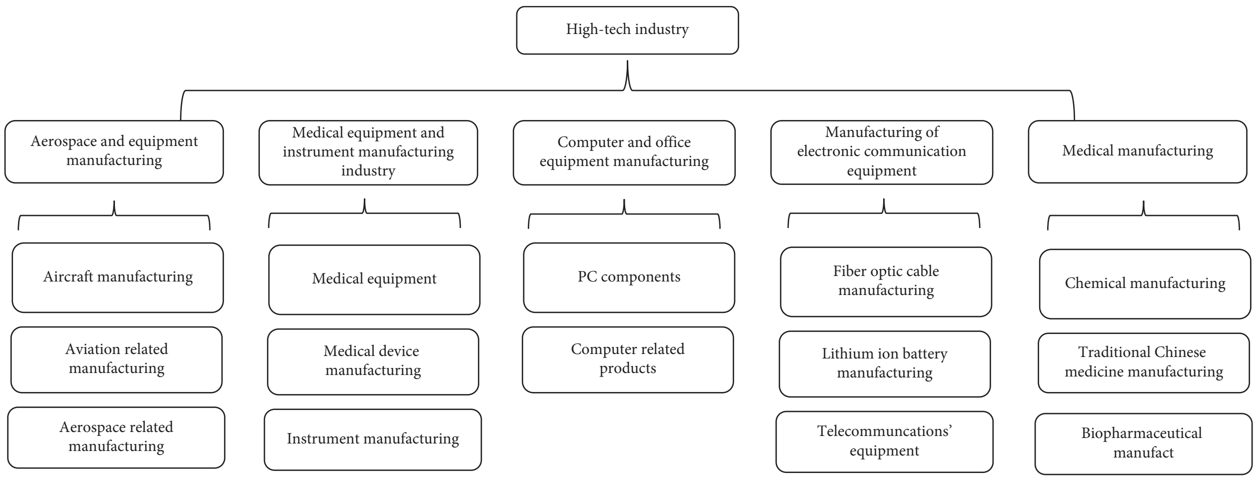


FIGURE 1: Classification of the high-tech industry in China. Source: statistical yearbook of China's high-tech industry.

[34], applied research, and development research. The existing research attempts to divide the technological innovation process of the high-tech industry into technology development and innovation transformation stages and empirically study the innovation efficiency and influencing factors of American photovoltaic industry and Chinese high-tech industry [30]. This paper focuses on the innovation efficiency of the high-tech industry and regards it as an innovation chain composed of new technology creation and transformation paths. Each stage in the whole process is an innovation aspect, and different innovation aspects are interrelated to form a complete chain of technology creation and technology marketization. This paper constructs the conceptual model of high-tech innovation process as follows (Figure 2).

From the perspective of technological innovation efficiency of the high-tech industry, what we are thinking about is not only whether higher economic or higher resources input will have better efficiency but also how the innovation efficiency improves over time and what is the difference between each innovation stage and which will then move us one step further to make clear what really matters for technological innovation efficiency improvement of the high-tech industry in China. We attempt to make a preliminary regulation summary of technological innovation efficiency improvement in different transformation stages.

3. Methodology

3.1. Research Method. Existing research studies analyze the innovation efficiency from perspectives of comparison of research methods, evaluation of transformation ability, and DEA efficiency evaluation [35, 36]. The traditional DEA model normally ignores the different stages of the whole transform process and cannot measure overall efficiency of the chain process. The efficiency evaluation of multi-department decision-making units is carried out separately, which does not consider the relationship among stages. This paper uses the SBM model [37] to deal with efficiency of subunits of interrelationship in DMU (decision-making unit), which can effectively solve the problem of intermediate investment. Tone and Tsutsui proposed the nonradial and nonangle SBM mode [38], and the advantage is that the efficiency value decreases monotonously with the change of input and output relaxation [39]. The synthetic efficiency of the SBM model can be expressed by the following equation:

$$\min \rho_0^* = \frac{\sum_{k=1}^{K} w^k \left[1 - (1/m_k)\left(\sum_{i=1}^{m_k} s_{io}^{k-}/x_{io}^k\right)\right]}{\sum_{k=1}^{K} w^k \left[1 + (1/r_k)\left(\sum_{i=1}^{r_k} s_{ro}^{k+}/y_{ro}^k\right)\right]}$$

$$\text{s.t.} \begin{cases} \sum_{k=1}^{K} w^k = 1, \quad w^k \geq 0\,(\forall k) \\ x_0^k = X^k\lambda^k + s_0^{k-}, \quad (k = 1,\ldots,K) \\ y_0^k = Y^k\lambda^k - s_0^{k+}, \quad (k = 1,\ldots,K) \\ e\lambda^k = 1, \quad (k = 1,\ldots,K) \\ S_0^{k+}, S_0^{k-}, \lambda^k \geq, \quad 0\,(\forall k) \\ z_0^{(k,h)} = Z^{(k,h)}\lambda^h, \quad (\forall (k,h)) \\ z_0^{(k,h)} = Z^{(k,h)}\lambda^k, \quad (\forall (k,h)), \end{cases} \tag{1}$$

where ρ_0^* is the overall efficiency of DMU_0, $X_{i0}^k \in R_+^{m_k}$ is the input vector of DMU_0 department K, m_k is the input type of sector K, $Y_{r0}^k \in R_+^{r_k}$ is the output vector of sector K, r_k is the output type of sector k, s_{i0}^{k-} and S_{r0}^{k+} are, respectively, relaxation variables of input and output, w^k is the weight of department k, $\lambda^k \in R_n^+$ is a nonnegative vector, e is a constant, which means non-Archimedean infinitesimal, and $Z_0^{(k,h)}$ is the intermediate variable, which is the output of k sector and the input of h sector, while the model cannot distinguish difference between effective DMU. In super-SBM [37] differences between valid DMU can be distinguished. The performance of DMU in superefficiency network SBM can be expressed by equation (2). Among which S_{i0}^{k-*} and S_{r0}^{k+*} are optimal input relaxation variables and optimal output

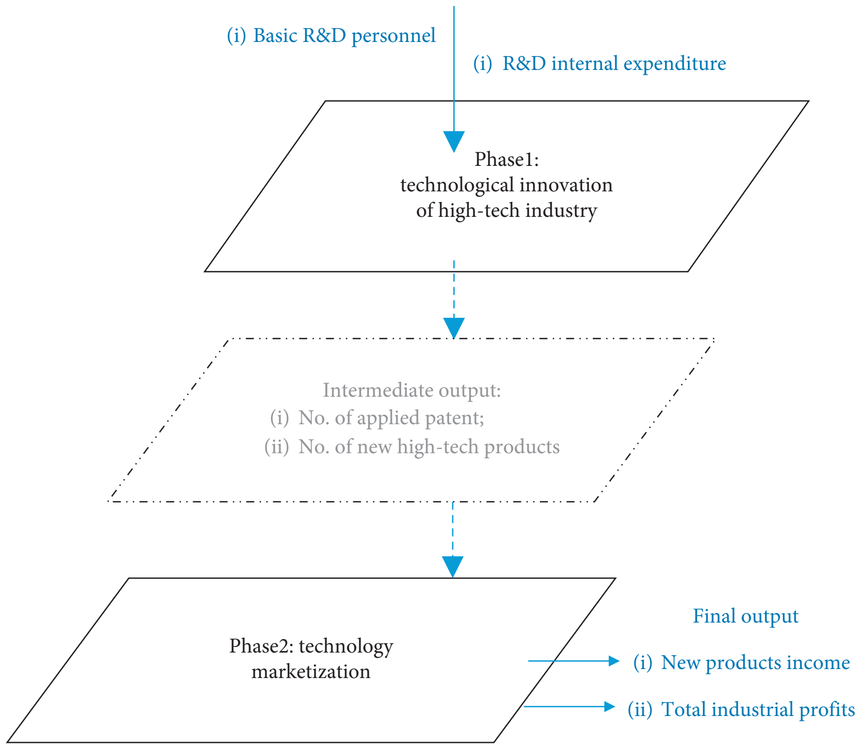


Figure 2: Conceptual model of technological innovation of the high-tech industry.

relaxation variables, respectively. If $\rho_0^* = 1$, DMU_0 is effective, and the performance of transformation reaches the highest level. If $\rho_k = 1$, it shows that the K department in the DMU is efficient. The superefficiency network SBM model in this paper evaluates the three stages efficiency of high-tech industry transformation in Chinese. This can help to find out the problems in different high-tech transformation stages and are more accurate to find ways to improve the efficiency problem:

$$\rho_k = \frac{1 + (1/m_k)\left(\sum_{i=1}^{m_k} \left(s_{io}^{k-*}/x_{io}^k\right)\right)}{1 - (1/r_k)\left(\sum_{r=1}^{r_k} s_{ro}^{k+*}/y_{ro}^k\right)}, \quad (k = 1, \ldots, K). \tag{2}$$

From efficiency index aspect, the input-output index of existing research usually takes R&D personnel, R&D internal expenditure, applied patent [40], new products, etc. as input indicators of different efficiency calculation stages. Number of applied patents and number of new products are taken as output indicators [28, 32, 41]. In this paper, the two-stage efficiency indicators are selected based on the existing research. According to the characteristics of different transformation stages and considering the relationship between stages, different input-output indicators are considered (Table 1). This paper selects 2009–2018 as the research period, and the selected indicators cover all regions in Yangtze River economic belt in China. Considering the lag feature of patent and products related data, this paper selects one-year lag patents and new products' data. Moreover, input-output data of the innovation efficiency of the high-tech industry are from "Statistical yearbook of China's high technology industry (2009–2019);" data of influencing factors are from "China City Statistical Yearbook (2009–2019)" and "Statistical Yearbook of China Science and Technology (2009–2019)."

Table 1: Indicator of high-tech innovation efficiency.

Phase	Input	Output
Phase 1	Basic R&D personnel R&D internal expenditure	No. of applied patent No. of new products
Phase 2	No. of applied patent No. of new products	New products income Total industrial profits

(1) In high-tech innovation stage, high-tech firms or related research institute apply R&D personnel and R&D expenditure in process of new technology creation. After creating new inventions or technologies, enterprises will apply for patents to protect their technologies. The new technology can also be used in new high-tech products. Therefore, patents and new products are main outputs in this stage. (2) In the technology marketization stage, the aim of high-tech firms is to serve the demand of the market, and the products and technology transform into the market value. High-tech firms gain profit; therefore, new products' income and total industrial profits represent the main output in this stage.

3.2. Panel Regression. The influencing factors of regional technological innovation efficiency of the high-tech industry involve complex aspects. Based on existing research and the reality of Chinese high-tech industry, considering data availability, the innovation efficiency of two stages are selected as dependent variables, taking the government subsidies, R&D intensity, enterprise scale, market structure, innovation environment, and regional openness as the influencing factors. Constructing the panel regression model of influencing factors on the efficiency of the high-tech industry innovation progress:

$$TE_{it} = \alpha + \beta_1 GS_{it} + \beta_2 R\ DI_{it} + \beta_3 OPEN_{it} + \beta_4 ENVIR_{it} + \beta_5 MS_{it}, \tag{3}$$

where "TE_{it}" is the technology innovation efficiency of the ith city in Yangtze River Economic Belt in the T year, "α" is a constant term, $\beta_1 \ldots \beta_5$ is the regression coefficient of each explanatory variable, "GS_{it}, RDI_{it}, $OPEN_{it}$, $ENVIR_{it}$, and MS_{it}," represent government subsidies, R&D intensity, openness, innovation environment, market structure of the ith city in the T year, and ε_{it} is random disturbance.

(1) Government subsidies (GS_{it}): it is a form of financial support to the enterprise from the government, generally with the aim of promoting technological innovation. Some research studies prove positive relationship between government subsidies and innovation efficiency [42, 43]. In the R&D expenditure of the regional high-tech industry, the proportion of government investment is used to represent government subsidies [44].

(2) R&D intensity (RDI_{it}): R&D intensity represents the technological R&D and innovation intensity of regional innovation participants. Innovation participants promote technological innovation through resource sharing and cooperation, which is an important indicator affecting the efficiency of technological innovation. Existing research proved that R&D intensity can reflect the impact of R&D resource on innovation effect, which is expressed by the ratio of R&D expenditure and regional GDP.

(3) Innovation environment ($ENVIR_{it}$): regions with better innovation environment can usually gather more technical talents. Regions with better innovation environment and higher level of economic development, where people's consumption desire is stronger, can promote faster the commercialization process of new technology. Better innovation environment can also effectively promote the openness of the region. A sufficient number of R&D institutions is very important to create a better innovation environment, which is normally expressed by the number of regional R&D institutions.

(4) Regional openness ($OPEN_{it}$): regional openness usually helps enterprises to achieve better knowledge and technology. Especially for the high-tech industry, its knowledge intensive features need global key technology. Existing research studies normally measure regional openness by the ratio of FDI to GDP or the ratio of industrial export delivery value to main business income. Considering the innovation characteristics and data integrity of the high-tech industry, this paper selects the former as the regional openness index.

(5) Market structure (MS_{it}): market structure is usually used to measure the number and distribution of trading participants, the degree of product differentiation, industry competition, and monopoly. Existing research on China's industrial development has proved that market structure is related to industrial technical efficiency, high-tech industrial competition, and innovation [45]. Based on the existing research, this paper selects the ratio of the main business income of large and medium-sized high-tech enterprises to the total income of the main business as the analysis index

4. Overall Innovation Efficiency of the High-Tech Industry in Yangtze River Economic Belt

This paper uses superefficiency network SBM model to calculate the innovation efficiency of high-tech industry in Yangtze Economic Belt from 2009 to 2018. Based on the characteristics of regional heterogeneity, this paper divides Yangtze River economic belt into three regions: the Yangtze River Delta region (Yangtze River Delta region: according to "Yangtze river delta regional planning (2010)" there are one direct-controlled municipality and two provinces: Shanghai, Jiangsu, and Zhejiang, 16 core cities within this region.), the middle region (middle region contains four provinces: Anhui, Jiangxi, Hubei, and Hunan.), and the western region (western region area contains three provinces and one direct-controlled municipality: Chongqing, Sichuan, Yunnan, and Guizhou.). Due to huge regional economic heterogeneity, differences in innovation volume among regions are inevitable. Therefore, when analyzing areas with large spans and significant internal differences, we should not only focus on the absolute amount of innovation volume but also ignore question of whether knowledge or R&D resources are reasonably configured. Therefore, when analyzing the innovation efficiency of the high-tech industry and the influence factors, this paper takes regional heterogeneity into consideration and analyzes overall efficiency and evolution characteristics of the heterogeneous region.

During 2009–2018, average high-tech efficiency of Yangtze River Delta (0.519) is higher than that of middle (0.406) and western (0.477) region (Table 2). The overall efficiency of the three regions shows a slow upward trend, which indicates that the high-tech industries in the Yangtze River economic belt have gradually realized the path of efficient innovation in recent years. The technological innovation of enterprises and the marketization efficiency of new technologies and new products have also been improved. However, the whole efficiency in the Yangtze River economic belt is not high. Therefore, it is necessary to analyze the efficiency and its influencing factors in different transform stages in order to improve high-tech innovation efficiency.

From 2009 to 2018, Jiangsu has become the region with the highest high-tech innovation efficiency in Yangtze River Delta, and the average efficiency in recent ten years is 0.7, which is much higher than the regional average level (0.519). The overall efficiency in Jiangsu has been ahead of other

Table 2: Innovation efficiency of the high-tech industry in Yangtze Economic Belt from 2009 to 2018.

Region	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Average
Shanghai	0.543	1.054	0.466	0.277	0.248	0.349	0.354	0.348	0.381	0.569	0.459
Jiangsu	0.417	0.739	0.651	0.550	1.302	0.643	0.712	0.659	0.570	0.762	0.700
Zhejiang	0.241	0.538	0.365	0.261	0.472	0.351	0.374	0.354	0.347	0.548	0.385
Anhui	0.395	0.364	0.391	0.414	0.434	0.518	0.574	0.462	0.422	0.773	0.475
Delta average	0.383	0.696	0.535	0.418	0.499	0.501	0.546	0.505	0.456	0.650	0.519
Jiangxi	0.545	0.495	0.359	1.000	0.575	0.631	0.816	1.028	0.852	0.680	0.698
Hubei	0.271	0.575	0.243	0.187	0.150	0.244	0.316	0.351	0.376	0.578	0.329
Hunan	0.343	1.000	1.345	1.000	1.000	0.558	0.500	0.580	0.334	0.525	0.719
Middle average	0.284	0.570	0.357	0.270	0.280	0.374	0.435	0.480	0.431	0.574	0.406
Chongqing	0.518	1.000	1.141	0.401	0.338	1.000	0.910	0.699	0.745	0.909	0.766
Sichuan	1.000	0.432	0.815	0.463	0.353	0.685	0.378	0.578	0.446	0.424	0.557
Guizhou	0.274	0.235	0.251	0.134	0.076	0.208	0.302	0.403	0.394	0.483	0.276
Yunnan	1.213	0.774	0.475	0.260	0.552	0.488	0.412	0.705	1.571	1.000	0.745
West average	0.378	0.387	0.656	0.358	0.284	0.577	0.494	0.557	0.505	0.570	0.477
Country	0.355	0.712	0.462	0.349	0.390	0.468	0.505	0.480	1.000	0.658	0.538

Source: calculated by National Bureau of Statistics of China (NBSC), Statistical Yearbook of China's High Technology Industry, Beijing: China Statistics Press, 2009–2019.

regions in the Yangtze River Delta. The industrial development of Jiangsu has entered the postindustrialization stage, and enterprises have stronger innovation ability and better innovation environment. In 2017, there were 25,400 R&D institutions in Jiangsu, 1.8 times more than in 2011. The number of scientific and technological personnel reached 1.22 million, an increase of 49.5% over 2011. Jiangsu's R&D expenditure accounts for 2.7% of GDP, and the R&D willingness of technology enterprises is higher than that of enterprises in other regions. Shanghai is China's economic and financial center with outstanding advantages in scientific research and innovation, while the efficiency of Shanghai changes from 0.543 to 0.569. Therefore, it is urgent for Shanghai to solve the problem of insufficient high-tech innovation in order to realize the high-level development of regional innovation.

In middle regions, the overall level of GDP in Hubei is higher than that in other two regions, and the internal R&D expenditure also has advantage, but the efficiency of high-tech innovation is the lowest in the past decade. It shows that the large number of R&D personnel and findings in Hubei have not been used efficiently. Optimizing the resource efficiency of Hubei is important to improve the overall regional high-tech innovation. The innovation efficiency of Hunan's high-tech industry is the highest (0.719), but it shows a decrease trend.

The overall high-tech efficiency of the western region is higher than that of the middle region; the innovation efficiency of the high-tech industry in Yunnan and Chongqing is higher than that in other regions. This is consistent with the conclusion that the main goal of interregional network innovation cooperation innovation of western region is to realize the new technology application and marketization [5].

Regions with relatively insufficient economic base and innovation input are not absolutely deficient in the high-tech innovation efficiency, and regions with rapid economic development and higher technology investment cannot necessarily achieved high efficiency. In the process of technological innovation of the high-tech industry, which stages really affect the improvement of regional overall efficiency? We need to think about which stages in the process really affect the efficiency improvement of the region. As the process of high-tech innovation can be divided into two main stages, technology innovation and technology marketization, this paper further attempts to analyze the stage efficiency and its main influence factors. This paper tries to find out the stage problems in high-tech innovation process in Yangtze River economic belt and puts forward some possible suggestions to improve the efficiency.

5. Stage Analysis of Innovation Efficiency of the High-Tech Industry

5.1. Computation of Two-Stage Innovation Efficiency. From the perspective of computation of two-stage innovation efficiency of the high-tech industry, the average efficiency level of technology innovation in Yangtze River economic belt gradually increased. The average efficiency in Yangtze River Delta, middle, and western region distinctly rise from 0.383, 0.283, and 0.377 in 2009 to 0.649, 0.573, and 0.569 in 2018 (Figure 3). From evolution perspective, Shanghai in the Yangtze River Delta has obvious advantages from 2008 to 2010. After 2012, Anhui and Jiangsu got caught up advantages; the technological innovation efficiency of the high-tech industry is constantly improving. It proves that the regional R&D funding and personnel have been used efficiently. However, average efficiency (0.405) of the middle region is the lowest, among which Hubei (0.329) is lower than the regional average level. The average efficiency of technological innovation in the western region (0.476) is higher than that in the middle region; the average efficiency of Guizhou (0.276) is much lower than that of Chongqing (0.766), Yunnan (0.745), and Sichuan (0.557). Guizhou has become a region that needs to focus on improving the technological innovation efficiency. Therefore, how to improve the efficiency of technological innovation in the

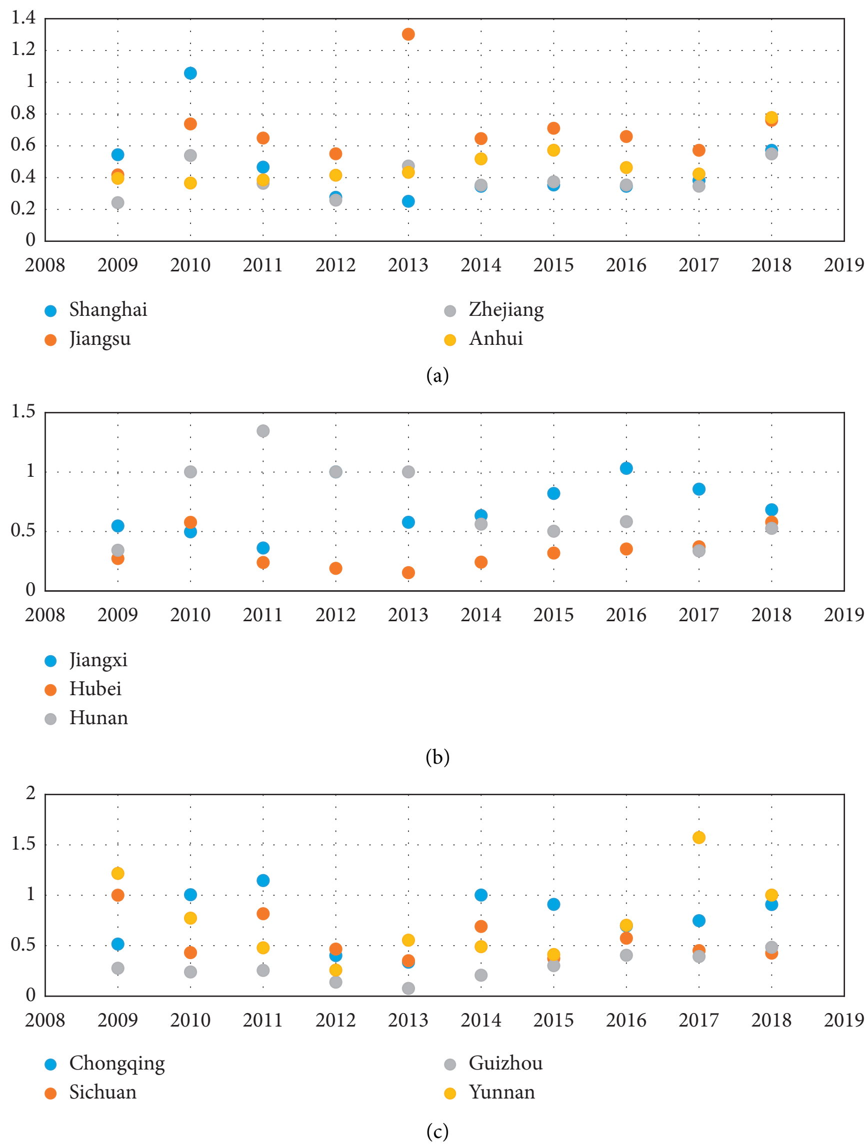
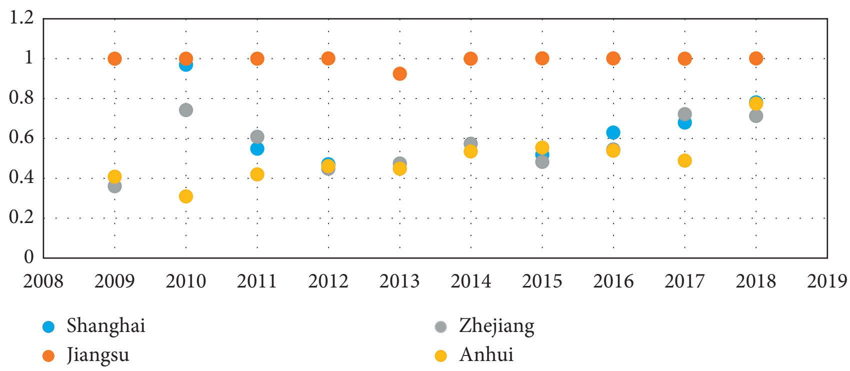


Figure 3: Efficiency of the high-tech industry in the technological innovation stage (2009–2018). (a) Stage1 of Yangtze River Delta. (b) Stage1 of the Middle Region. (c) Stage1 of the Western Region. Source: calculated by National Bureau of Statistics of China (NBSC), Statistical Yearbook of China's High Technology Industry, Beijing: China Statistics Press, 2009–2019.

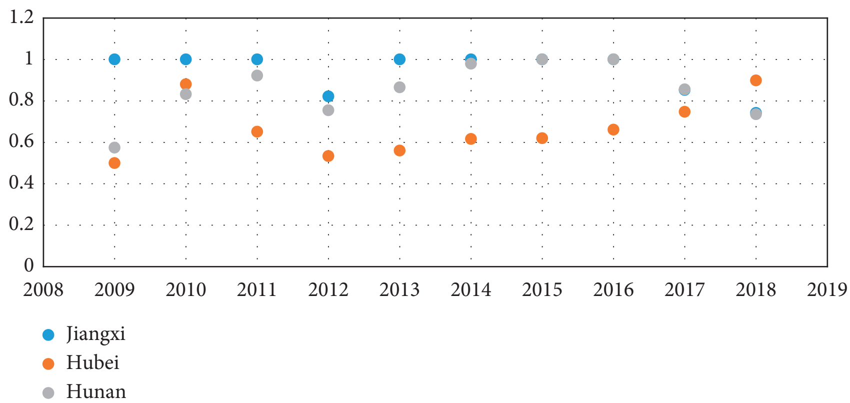
middle and western regions is the key to the high-tech innovation in the Yangtze River economic belt.

The marketization stage of technological achievements is the second stage of innovation efficiency evaluation of the high-tech industry. Whether the new technological or products can be successfully marketed and produce value for regions and enterprise is an important manifestation of the success technology transformation. The marketization efficiency of technological achievements in most regions of the Yangtze River economic belt shows an upward trend. From 2009 to 2018, the average efficiency of marketization stage in the Yangtze River Delta increased from 0.73 to 0.84, the middle region increased from 0.55 to 0.78, and the western region increased from 067 to 0.71 (Figure 4).

Within the Yangtze River Delta, Jiangsu has the highest marketization efficiency (0.99); the average marketization efficiency of Shanghai is higher than that of Anhui and Zhejiang, but the efficiency showed a decrease trend. It shows that the new technological cannot effectively match the market demand and realize technological transformation. Therefore, in order to ensure the high-quality development of regional high-tech industry, regions need to pay more attention to the reasons for the reduction of efficiency in recent years. Although Hubei and Hunan in the middle of the Yangtze River started with low market efficiency, they showed an increase trend, the efficiency values were 0.89 and 0.73 by 2018. With the improvement of the marketization efficiency of high-tech achievements, Hunan achieved the sales revenue of 2747.835 billion yuan of high-tech products by 2018, with an increase of 12.9%. The added value of the high-tech industry in Hubei increased by 14.4%. The overall efficiency trend of the western region is basically the same,



(a)



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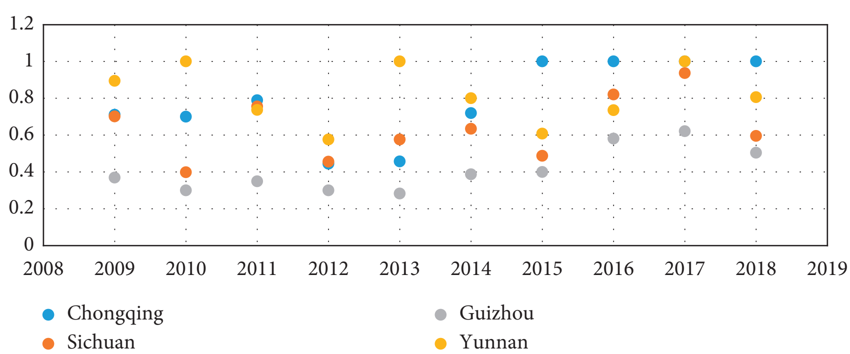

(c)

FIGURE 4: Efficiency of the high-tech industry in the technological marketization stage (2009–2018). (a) Stage2 of Yangtze River Delta. (b) Stage2 of the Middle Region. (c) Stage2 of the Western Region. Source: calculated by National Bureau of Statistics of China (NBSC), Statistical Yearbook of China's High Technology Industry, Beijing: China Statistics Press, 2009–2019.

and the average level of marketization efficiency in Yunnan is higher than that in other regions (0.81). Chongqing (0.78) and Sichuan (0.63) were lower than Yunnan, and Guizhou had the lowest (0.40) marketization efficiency. Therefore, the key to improve technological innovation is to find out the reasons for the low efficiency of heterogeneous regions.

5.2. Analysis of Influencing Factors of Stage Efficiency. This part applied the panel regression model to find out the main influencing factors of high-tech innovation in the Yangtze River economic belt. The variables passed the multicollinearity and autocorrelation test, which met the requirements of panel regression. According to panel regression analysis, government subsidies show strong positive significance in both stage one and stage two, better foundation of government support is conducive to enterprise innovation investment, and higher efficiency of technological innovation is achieved (Table 3). This indicates that the national industrial support and capital investment have a positive role in promoting the technological innovation and transformation of the high-tech industry [42, 43]. On the one hand, government subsidies provide support for technology research and development; on the other hand, it reduces the risk of technology marketization. Therefore, improving the positive guidance and support of the

Table 3: Influence factor of innovation efficiency of the high-tech industry in Yangtze River economic belt.

	Phase 1		Phase 2	
	Coef.	$P > \|t\|$	Coef.	$P > \|t\|$
Government subsidies	0.110*** (0.320)	0.001	0.074*** (0.225)	0.001
R&D intensity	0.118*** (0.290)	≤0.001	0.070 (0.124)	0.573
Innovation environment	0.029 (0.320)	0.355	0.229* (0.118)	0.052
Regional openness	0.024 (0.193)	0.212	0.044*** (0.014)	0.003
Market structure	0.064 (0.869)	0.461	0.060 (0.059)	0.303
Cons	−1.049 (0.367)	0.004	−0.228 (0.445)	0.608
R-squared	0.282		0.331	
Hausman P	0.0607		0.393	
Model	Random efficiency		Random efficiency	

*denotes $P < 0.1$, ** denotes $P < 0.05$, and *** denotes $P < 0.01$. Number of observations: 110. Source: calculated by (1) National Bureau of Statistics of China (NBSC), Statistical Yearbook of China's High Technology Industry, Beijing: China Statistics Press, 2009–2019, (2) National Bureau of Statistics of China (NBSC), China City Statistical Yearbook, Beijing: China Statistics Press, 2009–2019, and (3) National Bureau of Statistics of China (NBSC), Statistical Yearbook of China Science and Technology, Beijing: China Statistics Press, 2009–2019.

government plays a positive role in improving the innovation efficiency of the regional high-tech industry.

The effect of R&D intensity on regional high-tech industry innovation is in the stage of industrial technology innovation, and the effect is significant. The investment characteristics of the high-tech industry require large amount of capital investment in its technological innovation activities. The higher the investment intensity of high-tech R&D, the more likely it is to improve its innovation level, so as to improve the efficiency of technological innovation. The significance of R&D intensity shows that the increase of R&D investment in the Yangtze River economic belt is not only conducive to regional technology innovation but also has a positive impact on the management of high-tech enterprises and the overall innovation system, promoting the efficiency of technological innovation. This plays an important role in improving innovation efficiency.

Regional openness has a strong positive impact on the transformation and marketization stage of innovation. The high-tech industry is a technology intensive industry, and technology transformation activities cannot be completed by a single organization or a single region. High-tech transformation and marketization are interregional and global technological activities, which can be realized through interregional cooperation of technological innovation organizations. With the improvement of regional openness, high-tech firms can have more opportunities to participate in international industry cooperation and realize international technology innovation. The improvement of international relations also requires firms to continuously improve the technology transformation efficiency, so as to better meet the requirements of participating in international knowledge competition and global markets.

Innovation environment has a positive impact on the transformation and marketization stage of innovation. The increase and agglomeration of R&D institutions significantly improve the allocation and transformation efficiency of innovation resources. This also shows that the increase in the number of regional R&D institutions can provide a better innovation environment for high-tech enterprises [46]. At the same time, it can provide technology resources and innovation platform and form better technology transformation system. Regional high-tech enterprises implement technological innovation through cooperative innovation or technology trading, so as to improve the efficiency of technology marketization.

There is positive relationship between market structure and technological innovation of regional high-tech industry, but the impact is still not significant. It indicates that the market structure can reflect the competition of high-tech enterprises to a certain extent. Optimizing the market structure can promote the efficiency of high-tech innovation, and the results also show the competitive advantage of foreign-funded enterprises in the high-tech market. Although the proportion of large and medium-sized state-owned high-tech enterprises in China is high, they still need to further improve their technology market competition and influence. Only in this way can Chinese high-tech enterprises play a stronger role in adjusting the structure of technology market and improving the efficiency of technological innovation.

6. Conclusion and Discussion

This paper proposed the two-stage efficiency analytical framework for regional technology innovation of the high-tech industry in Yangtze River Economic Belt, which regards the innovation activity as a complex process with mutual relations. The whole process is divided into two main stages: technology innovation and technology marketization. The super-SBM model is used to estimate efficiency of technology innovation activities of the high-tech industry in

Yangtze River economic belt. It is helpful to accurately measure both the stage efficiency and the whole process in heterogeneous region in China.

(1) The whole efficiency of high-tech innovation in the Yangtze River economic belt has been improved, but there are great differences within regions. Therefore, the heterogeneous regional innovation context should be taken into consideration in the institutional management of regional and industrial policies. The high-tech innovation efficiency in Yangtze River economic belt is not high, but in recent years, the efficiency has been gradually improved. It must be admitted that the R&D resources invested in regional high-tech enterprises in Yangtze River economic belt are getting more efficiently utilized. There are regional efficiency differences within the Yangtze River economic belt, the efficiency of Yangtze River Delta is slightly higher than that of the central and western regions, and the innovation efficiency of in the central region is the lowest. Shanghai is the financial center of China, with outstanding economic and technology research advantages. How to realize high innovation efficiently and avoid waste or redundancy of resources is the main problem.

   There is a certain correlation between the economic foundation and overall innovation efficiency, which has been proved by existing research. However, the efficiency with insufficient economic foundation is not necessarily low. The innovation and transformation of high technology should not only focus on whether there is large amount of funds or personnel input. In order to effectively promote technology innovation and avoid waste of R&D resources, targeted adjustment should be made according to the regional heterogeneity and transformation stage.

(2) From perspective of the high-tech innovation stage, there is a significant positive correlation between government subsidies and R&D intensity to improve the efficiency of regional high-tech innovation, and the government subsidy continues to play a positive role in the technology marketization stage. Generally, government support is still crucial to the innovation and marketization of China's high-tech industry. Therefore, in order to realize the reginal and enterprise innovation and transformation, the government needs to carry out appropriate policy guidance, increase financial support for high-tech enterprises, and encourage high-tech enterprises to realize technological innovation by increasing R&D investment.

   Combined with the regional heterogeneity of the high-tech innovation stage in the Yangtze River economic belt, the technological innovation efficiency of the Yangtze River Delta is higher than that of the middle and western regions. This is mainly because the government support and R&D investment in the Yangtze River Delta are much higher than those in the central and western regions. Although the economic foundation and R&D resources of the middle and western regions do not have comparative advantages, however, the government can actively guide by building the policy management system and encourage enterprises to increase the proportion of R&D investment, so as to improve the efficiency of technological innovation by enhancing the R&D intensity of enterprises.

(3) From perspective of the high-tech marketization stage, technology transformation and successful marketization is the key to reflect the value of new technology and products in high-tech enterprise. In the new technology marketization stage, in addition to government support and the regional and enterprises openness, better innovation environment also plays positive role. Innovative high technology usually not only serves the local market but also realizes its value through interregional cooperation and transaction. Therefore, openness is very important for the establishment of interregional cooperation or transnational relationships. On the one hand, the existing interregional relationship has realized the marketization of new technology, On the other hand, it also helps to build more market relations, which forms a virtuous circle of technology marketization. The innovation environment can help form innovative talents pool and help enterprises to form cooperative relationship with technology R&D or transformation institutions. This relationship will also help to bridge interregional connection, which will strengthen the external linkages and further contribute to the long-distance technology marketization process.

   Combined with the characteristics of technology marketization in the heterogeneous regions of the Yangtze River economic belt, the efficiency of marketization of technology achievements of high-tech enterprise in the Yangtze River economic belt has risen slowly, which shows that high-tech firms in China gradually have the ability of combining technology creation with practice and creating market value. The average efficiency of marketization in Yangtze River Delta is the highest, which is related to the well-developed headquarters economy, agglomeration of high-tech enterprises, R&D institutions, R&D talents, and significant advantages of FDI. In terms of policy-making, and it is necessary to learn from technology marketization advantage regions. The government needs to guide high-tech enterprises to pay more attention to the integration of interregional resources. Marketization efficiency can be improved by constructing the interregional transformation platform and cooperation system. At the same time, enterprises are encouraged to create better innovation ecological, overcome their own disadvantages and improve innovation efficiency through the increase of R&D intensity.

(4) China's high-tech innovation and marketization efficiency still need to be optimized. On the one hand, national and local governments need to provide support for high-tech innovation by policy guidance and financial support. On the other hand, the technology marketization efficiency can be improved by the construction of interregional technology cooperation and technology transformation system. The R&D resource of China's high-tech enterprises has not yet reached the optimal level and needs further optimized. High tech enterprises should not only pay attention to the quantity of innovation output but also pay attention to the optimal of interregional resources. Regions with relatively insufficient development advantages can promote innovation efficiency by enhancing R&D intensity.

Sometimes, high-tech enterprise has rich innovation output, but these outputs have not been successfully transformed into market value due to their quality or tech level. This requires enterprise to pay more attentions on interregional or international cooperation to access key technology to meet the market demand and to avoid the dilemma that the quantity of technology achievements is large, but it is difficult to transform to market value. Moreover, it is necessary to enhance the technology innovation ability of high-tech enterprise, produce high-level technology achievements, and strengthen the transformation and marketization of new technology and products. Creating real market value for regional economy is the key to Chinese high-tech enterprise in the future.

Innovation and technology creation are the key to triggering fundamental economic and social changes [47]. Enterprises are key members of innovation system in high-tech industry, and regions are considered as important space carriers for technology innovation activities. Regional innovation system is composed of enterprises, universities, and research institutions, which can continuously produce innovation [48]. Technology and new products creation and marketization of enterprises and other organizations in regional innovation system are conducive to the improvement of innovation efficiency in the region. Therefore, the analysis and mechanism exploration of high-tech enterprise technology creation and marketization will help to understand and improve regional innovation.

Realization of technology innovation activity is a complex process. Due to data availability, there are still some limitations in selection of indicators in influence mechanism analysis. Moreover, analysis of spatial heterogeneity only compares differences in two transformation stages, but does not take internal spatial interaction and the network relationship into consideration. These will be the discussion points of our further research.

Data Availability

The data used to support the findings of the study can be obtained from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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Review Article

Government Low-Carbon Regulations Based on Supply Chain Members' Behavior and Consumers' Channel Preference in a Dual-Channel Supply Chain

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As carbon emissions are increasing due to the development of economy, low-carbon supply chain plays an important role in carbon emissions reduction and the dual-channel supply chain has become a hit because online shopping is developing rapidly. Therefore, this paper builds a Stackelberg game model led by the manufacturer in a dual-channel supply chain to examine the reaction of the government under centralized or decentralized decisions-making structures with different low-carbon strategies. The result shows that the government can achieve higher profits by taking incentive or punitive measures for centralized decision-making supply chain no matter they invest in emissions reduction or not. Moreover, for decentralized decision-making mode, increasing low-carbon subsidies for retailers can achieve a win-win result between the supply chain and the government; and, finally, channel competition is good for improving the supply chain and social benefits. Therefore, the government is responsible for taking reasonable subsidy policies, formulate industry's low-carbon standards, and properly guide competition between supply chain members to achieve higher profits.

1. Introduction

Recently, climate change has become a major challenge for countries across the world [1, 2]. Some developed countries pay more attention to low-carbon economy by formulating administrative intervention policies and promulgating laws and regulations. For example, some western countries, like Sweden, Norway, Finland, Denmark, and so on, levy carbon taxes to control carbon emissions of companies [3]. As the largest CO_2 emitter, China has pledged to control its CO_2 emissions as a binding development and economic target at the Paris Climate Conference in 2015 [4], setting a target to peak emissions before 2030 and become carbon-neutral before 2060. To achieve the emission reduction goals, the government has initiated regulations to promote low-carbon supply chain and control the carbon emissions consequently.

With the development of mobile Internet, online shopping is becoming more popular in China than before. In 2020, the number of online shopping consumers reached 782 million, accounting for 79.1% of the total netizens. At the same time, the amount of online retail sales has also maintained rapid growth, with 11.76 trillion yuan, an increase of 10.9% over 2019. Therefore, manufactures can provide products to customers directly with online channel and can react to their preference quickly. Thus, many manufacturers, such as Interface and GREE, decide to sell products in both traditional retail channels (offline channels) and direct sales channels (online channels) to improve their competitiveness, which is defined as the dual-channel supply chain. In this supply chain, manufacturers are not only retailer's suppliers but also their competitors. However, when they cooperate, they are partners to bear carbon reduction costs together. Thus, while enhancing distribution channels, companies should also consider the impact of decision-making methods among supply chain members on emission reduction costs. Facing with different decision-making modes among supply chain members and emission reduction strategies of them, governments will take different measures to motivate or punish these supply chain node companies, which is bound to affect the optimal profit of supply chain members and social profits. Therefore, studying the effect of government regulations with different decision-making modes and low-carbon strategies is meaningful to reduce carbon emissions and maximize the profit of all parties. Moreover, dual channels have changed consumers' channel preference obviously, because online direct sales channels have convenience and low-cost advantages. Therefore, consumers' channel preference is also significant for the profit of supply chain members and the government.

In this paper, we construct a Stackelberg game model between a manufacturer as the leader and a retailer as the follower in a dual-channel supply chain, where one manufacturer has both traditional retailer channel and direct sales channel. Meanwhile, the manufacturer decides whether to invest in emissions reduction under centralized and decentralized decision-making model, respectively. If they make centralized decisions, they are regarded as a whole to share benefits and risks from the government; otherwise, they will bear each part of the benefits and risks from the government. The government has two regulation strategies, providing subsidies when companies have emission reduction investment and charging fines when they do not have emission reduction costs.

Then the optimal price decisions and the profits of supply chain members and the government's utility are given among these four models, which is the basic of governmental low-carbon regulations for the supply chain. This paper aims to explore the following questions: (1) What are the impacts of government subsidies and consumer preferences on each supply chain member's profit and social benefits? (2) How does the government formulate appropriate low-carbon regulatory strategies based on the low-carbon decisions of enterprises?

The rest of this paper is organized as follows. Section 2 summarizes the literature review. Section 3 presents the description and assumptions of the model. Section 4 and Section 5 are main parts of this paper: the former shows four models based on two decision-making modes under different carbon reduction strategies and theoretical analysis, and the latter gives further numerical analysis to clarify theoretical results. Then Section 6 concludes this study.

2. Literature Review

Carbon emissions have become a commonly important issue around the world, and many scholars are interested in low-carbon supply chains. As for low-carbon supply chain researches, they can be divided into two kinds of supply chain, single-channel supply chain and dual-channel supply chain. In single-channel supply chain researches, Ghosh and Shah [5] studied coordination problems among members in a single-channel supply chain and explored the impact of cost-sharing contract on the key decisions of supply chain players undertaking green initiatives. Du et al. [6] focused on the supply chain consisting of one single emission-dependent manufacturer and one single emission permit supplier in the "cap-and-trade" system and found that the system-wide and manufacturer's profits increase with the emission cap, while the supplier's permit decreases. Besides, Xu et al. [7] also explored the impact of carbon allowances and transaction supervision on production and emission reduction strategies in a single-channel supply chain. However, with the rapid development of e-commerce, the scale of online sales has shown a sharp growth in recent years. Since then, the dual-channel supply chain in which online direct sales channels coexist with traditional retail channels has become the main distribution model for manufacturers.

At present, a number of studies about dual-channel supply chain mainly focus on pricing strategy [8, 9], channel coordination [10, 11], and carbon reduction strategy [12, 13]. The most extensive research has been done in the stream of pricing strategy. Some examples are listed as follows. Barman et al. [14] constructed a dual-channel supply chain, containing a manufacturer and a retailer, in which the manufacturer has sold the product through the online channel along with the traditional retail channel to optimize the pricing decisions and maximize the profit. Zhang et al. [15] investigated a dynamic pricing strategy and greening issues for a two-stage dual-channel supply chain and found that reviewing price periodically is able to enlarge supply chain profits and market demands. Zhou et al. [16] and Li et al. [17] also studied the pricing decisions using the Stackelberg game model.

With regard to channel coordination, it is formed on the basis of centralized decision-making and decentralized decision-making patterns. Contracts can equal the optimal decision of the decentralized supply chain and that of the centralized supply chain, which also means that supply chain coordination and pareto improvement in profits can be obtained by contracts. Popular supply chain contracts that have been designed in the literature include price discount contract [18, 19], quantity discount contract [20, 21], revenue-sharing contract [22, 23], cost-sharing contract [24, 25], wholesale price contract [26, 27], and option contract [28, 29]. Cai et al. [19] introduced price discount contracts into the dual-channel supply chain and proved that the cases with price discount contracts can outperform the noncontract cases from supplier Stackelberg, retailer Stackelberg, and Nash game theoretic perspectives. Xie and Huang [20] established a quantity discount model and pointed out that both members in the mixed-channel supply chain can achieve a win-win situation by adjusting the quantity discount rate. Xu et al. [22] proposed a two-way revenue-sharing contract not only to coordinate the dual-channel supply chain but also to create a win-win situation among supply chain members. Moreover, cost-sharing contracts have been widely used as an effective mechanism to encourage supply chain coordination, which is also highly related to our study [30]. Wang et al. [31] established single and joint emission reduction models with one-way or two-way cost-sharing contracts. They found that the implementation of contracts is beneficial to the increase of carbon emission abatement level and product quantity as well as supply chain profit. Particularly, the two-way cost-sharing contract is positive for supply chain when the sharing rate is in a small range. This model also offers better performance in extended multiple retailers' mode.

Besides, the carbon reduction strategy has also been quite popular recently. Some papers discussed the emission reduction decisions of corporates. For example, Sarkar et al. [32] established a three-echelon supply chain model to reduce supply chain costs, considering variable and fixed carbon emissions when transporting products; Li et al. [33] studied the optimal decision-making of the supply chain, including a manufacturer and two competing retailers, for vertical and horizontal cooperation in emission reduction; Aljazzar et al. [34] considered delayed payment, transportation costs, and carbon emission costs to study various situations in which buyers delay payment after receiving items. However, emission reduction is closely related to the government and enterprises, so it is necessary for the government to formulate reasonable and effective regulations to promote carbon reduction in enterprises [35]. There are many ways of government regulations, including subsidies and fines [36], carbon taxes [37], quotas [38], and carbon transactions [6]. Wu [39] examined the effect of different types of government intervention, including a fixed tax or subsidy on the firm side, a unit tax or subsidy on the firm side, and a unit tax or subsidy on the consumer side. Except for the policy with the fixed subsidy to the independent remanufacturer, the proposed policies can reduce the environmental burden and mitigate the intensity of price competition effectively. Zhang et al. [40] examined progressive carbon tax mechanism and its impacts on the production/pricing and abatement level decisions of the manufacturers as well as the influences of the online channel introduction on supply chain network equilibrium decisions, carbon emissions, and profits. Meanwhile, consumers' channel preferences also affect pricing decisions in the case of dual-channel sales coexistence. Zhang and Hezarkhani [41] studied the effect of consumers' channel preferences on channel strategies. Tian et al. [42] found that a great adjustment of supply order quantity in direct channels, retailer's order quantity, consumers' channel preference, and sales effort will cause the system to lose stability and trap into complexity. Meng et al. [43] proposed a green dual-channel supply chain considering consumer green preference and channel preference and compared the optimal solutions with or without government subsidies. Their results show that government subsidies are beneficial to the manufacturer, and the impact on retailer's profit depends on the amount of government subsidies.

In general, previous literature has made great contributions to the knowledge of supply chains, but there are still some gaps shown as follows: First, online shopping has changed the competitive relationship between manufacturers and retailers, so fierce competition exists between traditional retail channel and direct sales channel. Simultaneously, online channel has propelled carbon emissions during the process of transportation. However, to the best of our knowledge, there are relatively few studies exploring low-carbon strategies in dual-channel supply chain, so it will be scientific to study low-carbon strategies in different channels. Second, previous studies generally studied how supply chain members are affected by different government regulations. Actually, governments also need to adjust their own low-carbon regulations according to supply chain members' low-carbon decisions, so it is meaningful to explore how the governments react when companies make different low-carbon decisions. Furthermore, most of existing articles simply analyzed the effect of single parameter, such as the cross-price elasticity coefficient of the alternative channel and the level of emission reduction, but only a few articles focus on government regulations and consumers' channel preference. Actually, government and consumers are two main bodies to affect the profits of the supply chain, so the change of them has an uncertain impact on the profit of all members and social benefits.

Compared with existing research, the main contributions of this paper are given as follows. First, this paper studied low-carbon strategies in a dual-channel supply chain, where there exist a traditional retail channel and an online direct sale channel, which is more realistic as online direct sale channel is significant to reduce carbon emissions during the processes of production, transportation, and distribution; and the change of prices in different sales channel is able to influence the overall profits of manufacturers and retailers. Second, different from previous research, this paper is from the perspective of the government rather than supply chain members to study what the government should do to achieve optimal social benefits and supply chain profits facing different companies' low-carbon emissions strategies, which could provide more practicality and specific details for the government to regulate carbon emissions. Third, this paper studied the effect of the supply chain members' low-carbon behavior and consumers' retail channel preference on the profits of the supply chain and social profits, which is more comprehensive to show how the government guides the competition between different channels.

3. Description of the Problem

3.1. Model Description. This paper builds a two-echelon dual-channel supply chain system consisting of a manufacturer and a retailer. The manufacturer sells products not only through traditional retail channels but also through online direct sale channels, so they need to determine both the wholesale price w and the direct sale price pe to the retailer and consumers, respectively, while the retailer only needs to decide the retail price pr based on market demand. In addition, because the asymmetry of information often exists between competitors and the manufacturer has strong economic strength, the manufacturer is generally assumed to dominate the model, and the retailer is a subsidiary in the decision-making process. Therefore, this paper builds a Stackelberg game to show the symmetry in decision-making, which is more realistic. Besides, the government provides low-carbon subsidies as incentive measures when companies invest in carbon emissions reduction and charges fines as punitive measures when they do not do so. The structure of the dual-channel sales supply chain is shown in Figure 1.

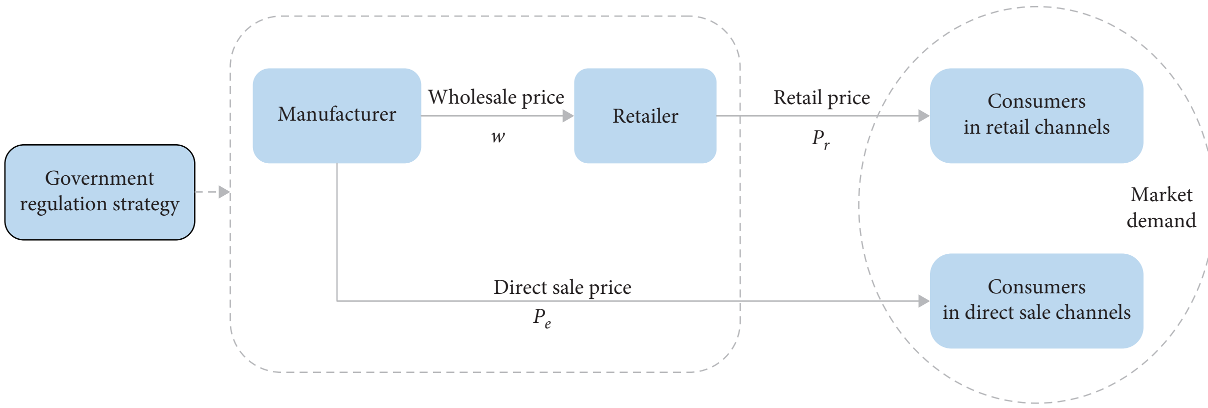

FIGURE 1: Dual-channel supply chain structure.

3.2. Notation and Assumption. The notations and the symbolic descriptions of the model are summarized in Table 1.

To simplify the research, the following are the necessary assumptions for the model:

(1) Assume that the manufacturer is the leader and the retailer is the follower; both are risk-neutral and seek to maximize their own profits.

(2) In order to simplify the calculation, the production cost is neglected, and there is no inventory cost as this paper assumes that the retailer's order quantity is the same as the demand function.

(3) Considering the fact that the higher the carbon emission reduction level is, the higher the corresponding cost is, the cost of emission reduction function can be assumed as a convex function about the emission reduction level θ, which is shown as follows:

$$I(\theta) = \frac{1}{2}\mu\theta^2, \tag{1}$$

where $\mu > 0$, representing the manufacturer's cost elasticity coefficient of emission reduction; and, according to cost-sharing contract [31], assume that the manufacturer invests in reducing emissions, and the retailer bears a certain percentage of emission reduction costs.

(4) The demand function of the channel in the dual-channel supply chain is affected by the price of its own channel and that of the alternative channel. From [22], we consider the demand function to be the linear function with respect to the sales prices, which is constructed as

$$\begin{aligned} q_r &= \rho a - \beta p_r + r p_e, \\ q_e &= (1-\rho)a - \beta p_e + r p_r. \end{aligned} \tag{2}$$

In the above equation, a is a constant indicating the total of market demand; $\rho\,(0 < \rho < 1)$ indicates the degree of consumer preference for the retail channel; r indicates the cross-price elasticity coefficient of the alternative channel. Since the price of the own channel has a greater influence on the demand than that of the alternative channel, the range of r is between 0 and 1. In order to simplify the calculation, suppose that the price elasticity coefficient of the own channel β is 1.

TABLE 1: The description of the symbols.

Notation	Description
p_r	The per unit retail price
p_e	The per unit direct sales price
w	The per unit wholesale price
Π_M	The profit of the manufacturer
Π_R	The profit of the retailer
Π_{SC}	The profit of the total supply chain
Π_G	The utility of the government
a	The potential market demand
ρ	The degree of consumer preference for the retail channel
r	The cross-price elasticity coefficient of the alternative channel
β	The price elasticity coefficient
θ	The level of emission reduction
μ	The cost elasticity coefficient of emission reduction.
λ	The proportion of emission reduction costs
s	The government's subsidy coefficient
m	The share proportion of the retailer

4. Model Solution and Analysis

In this section, we consider two decision-making modes among supply chain members. One is centralized decision-making of the entire supply chain, and the other is decentralized decision-making of the manufacturer and the retailer independently. In each mode, the game model between supply chain members and the utility of government model is established under two different low-carbon decisions by the manufacturer and expected to find the equilibrium solution to promote better emission reduction decision-making by all parties.

4.1. Manufacturers' Emission Reduction Investment Model

4.1.1. Centralized Decision.

When the manufacturer and the retailer make centralized decisions, they consider the overall profit of the supply chain. At this time, the unit subsidy given by the government is s, and the total profit function of the supply chain is

$$\pi_{SC}^{YC} = (p_r + s\theta)(\rho a - p_r + r p_e) + (p_e + s\theta)((1-\rho)a - p_e + r p_r) - \frac{1}{2}\mu\theta^2. \tag{3}$$

From (3), the Hessian matrix of π_{SC}^{YC} with p_r and p_e is $H^{YC} = \begin{bmatrix} -2 & 2r \\ 2r & -2 \end{bmatrix}$. According to assumption (4), the range of r is between 0 and 1; then $|H_1^{YC}| = -2 < 0$ and $|H_2^{YC}| = 4(1-r^2) > 0$, so H^{YC} is a negative definite matrix. It means that the total profit function of the supply chain is concave with respect to p_r and p_e and there exists a maximum.

From (3), the first-order derivatives of p_r and p_e are

$$\begin{cases} \dfrac{\partial \pi_{SC}^{YC}}{\partial p_r} = \rho a - 2p_r + 2r p_e - (1-r)s\theta = 0, \\ \dfrac{\partial \pi_{SC}^{YC}}{\partial p_e} = (1-\rho)a - 2p_e + 2r p_r - (1-r)s\theta = 0. \end{cases} \tag{4}$$

The optimal retail price and direct sales price are shown as follows:

$$p_r^{YC} = \frac{(\rho + r - \rho r)a - (1-r^2)s\theta}{2(1-r^2)}, \tag{5}$$

$$p_e^{YC} = \frac{(1 - \rho + \rho r)a - (1-r^2)s\theta}{2(1-r^2)}. \tag{6}$$

Taking (5) and (6) into (3), the total profit of the supply chain is

$$\pi_{SC}^{YC} = \frac{(1 - 2\rho(1-\rho)(1-r))a^2 + 2s\theta(1-r^2)a + 2s^2\theta^2(1-r)(1-r^2)}{4(1-r^2)} - \frac{1}{2}\mu\theta^2, \tag{7}$$

and the utility of the government is

$$\pi_G^{YC} = \pi_{SC}^{YC} - s\theta(q_r + q_e) = \frac{(1 - 2\rho(1-\rho)(1-r))a^2 - 2s^2\theta^2(1-r)(1-r^2)}{4(1-r^2)} - \frac{1}{2}\mu\theta^2. \tag{8}$$

4.1.2. Decentralized Decision.

When the manufacturer and the retailer make decentralized decisions, the per unit products of subsidies given by the government to encourage the manufacturer and the retailer to reduce emissions are s_1 and s_2, respectively. The following are the profit functions of the manufacturer and the retailer:

$$\pi_M^{YD} = (w + s_1\theta)(\rho a - p_r + r p_e) + (p_e + s_1\theta)((1-\rho)a - p_e + r p_r) - \frac{1}{2}(1-\lambda)\mu\theta^2, \tag{9}$$

$$\pi_R^{YD} = (p_r - w + s_2\theta)(\rho a - p_r + r p_e) - \frac{1}{2}\lambda\mu\theta^2. \tag{10}$$

According to Stackelberg game theory, the manufacturer, as the leader in the supply chain, determines the wholesale price w and the direct sales price p_e at first, and then the retailer determines the retail price p_r as the follower. Based on the converse approach, the retailer's objective function is

$$\max_{p_r} \pi_R^{YD} = (p_r - w + s_2\theta)(\rho a - p_r + r p_e) - \frac{1}{2}\lambda\mu\theta^2, \quad (11)$$

and, from (11), the optimal retail price of the retailer is

$$p_r^{YD} = \frac{\rho a + w + r p_e - s_2\theta}{2}. \quad (12)$$

Taking (12) into (9), the manufacturer's objective function is

$$\max_{p_e, w} \pi_M^{YD} = (w + s_1\theta)\left(\frac{\rho a - w + r p_e + s_2\theta}{2}\right) + (p_e + s_1\theta)\left((1-\rho)a - p_e + r\left(\frac{\rho a + w + r p_e - s_2\theta}{2}\right)\right) - \frac{1}{2}(1-\lambda)\mu\theta^2. \quad (13)$$

Obviously, π_M^{YD} is a joint strictly concave function with p_e and w. According to its first-order derivative, the optimal wholesale price and direct sales price are shown as follows:

$$w^{YD} = \frac{(\rho + (1-\rho)r)a - (1-r^2)s_1\theta + (1-r^2)s_2\theta}{2(1-r^2)}, \quad (14)$$

$$p_e^{YD} = \frac{(1-\rho+\rho r)a - (1-r^2)s_1\theta}{2(1-r^2)}. \quad (15)$$

Taking (14) and (15) into (12), the optimal retail price can be calculated as

$$p_r^{YD} = \frac{(3\rho + (2(1-\rho) - \rho r)r)a - (1-r^2)(1+r)s_1\theta - (1-r^2)s_2\theta}{4(1-r^2)}. \quad (16)$$

Then, taking (14)–(16) into (9) and (10), the profits of the manufacturer and the retailer are shown, respectively, as follows:

$$\pi_M^{YD} = \frac{(2 - 4\rho(1-r) + \rho^2(1-r)(3-r))a^2 - 2s_1\theta a(1-r^2)(2-\rho(1-r)) + 2\rho s_2\theta a(1-r^2) + (1-r^2)(1-r)(3+r)s_1^2\theta^2 + 2(1-r^2)(1-r)s_1 s_2\theta^2 + (1-r^2)s_2^2\theta^2}{8(1-r^2)} - \frac{1}{2}(1-\lambda)\mu\theta^2,$$

$$\pi_R^{YD} = \frac{(\rho a + (1-r)s_1\theta + s_2\theta)^2}{16} - \frac{1}{2}\lambda\mu\theta^2. \quad (17)$$

Therefore, the following are the total profit of the supply chain and the utility of the government sequentially:

$$\pi_{SC}^{YD} = \frac{(4 - 8\rho(1-r) + \rho^2(1-r)(7-r))a^2 + s_1\theta a(1-r^2)(6\rho(1-r) - 8) + 6\rho s_2\theta a(1-r^2) + (1-r^2)(1-r)(7+r)s_1^2\theta^2 + 6(1-r^2)(1-r)s_1 s_2\theta^2 + 3(1-r^2)s_2^2\theta^2}{16(1-r^2)} - \frac{1}{2}\mu\theta^2,$$

$$\pi_G^{YD} = \frac{(4 - 8\rho(1-r) + \rho^2(1-r)(7-r))a^2 + 2s_1\theta a(1-r^2)(5\rho(1-r) - 8) + 2\rho s_2\theta a(1-r^2) - (1-r^2)(1-r)(3r+5)s_1^2\theta^2 - 2(1-r^2)(1-r)s_1 s_2\theta^2 - (1-r^2)s_2^2\theta^2}{16(1-r^2)} - \frac{1}{2}\mu\theta^2. \quad (18)$$

4.2. No Manufacturers' Emission Reduction Investment Model

4.2.1. Centralized Decision. When the manufacturer does not invest in emission reduction, the government will charge fines of F_m on the supply chain. In this case, the total profit function of the supply chain is

$$\pi_{SC}^{NC} = p_r(\rho a - p_r + r p_e) + p_e((1-\rho)a - p_e + r p_r) - F_m. \quad (19)$$

Similar to (3), the Hessian matrix of π_{SC}^{NC} with p_r and p_e is $H^{NC} = \begin{bmatrix} -2 & 2r \\ 2r & -2 \end{bmatrix}$. Because $|H_1^{NC}| = -2 < 0$ and $|H_2^{NC}| = 4(1-r^2) > 0$, H^{NC} is also a negative definite matrix and there exists a maximum.

From (9), the first-order derivatives of p_r and p_e are shown as follows:

$$\begin{cases} \dfrac{\partial \pi_{SC}^{NC}}{\partial p_r} = \rho a - 2p_r + 2rp_e = 0, \\ \dfrac{\partial \pi_{SC}^{NC}}{\partial p_e} = (1-\rho)a - 2p_e + 2rp_r = 0, \end{cases} \tag{20}$$

and the optimal retail price and direct sales price can be attained:

$$\begin{aligned} p_r^{NC} &= \frac{(\rho + r - \rho r)a}{2(1-r^2)}, \\ p_e^{NC} &= \frac{(1-\rho+\rho r)a}{2(1-r^2)}. \end{aligned} \tag{21}$$

Therefore, the total profit of the supply chain and the utility of the government without emission reduction investment are as follows:

$$\begin{aligned} \pi_{SC}^{NC} &= \frac{(1-2\rho(1-\rho)(1-r))a^2}{4(1-r^2)} - F_m, \\ \pi_G^{NC} &= \frac{(1-2\rho(1-\rho)(1-r))a^2}{4(1-r^2)}. \end{aligned} \tag{22}$$

4.2.2. Decentralized Decision. If the manufacturer invests nothing in emission reduction, the retailer will bear a certain percentage of fines when they decide separately. When the percentage of fines is m, the profit functions of the manufacturer and the retailer are

$$\pi_M^{ND} = w(\rho a - p_r + rp_e) + p_e((1-\rho)a - p_e + rp_r) - (1-m)F_m, \tag{23}$$

$$\pi_R^{ND} = (p_r - w)(\rho a - p_r + rp_e) - mF_m. \tag{24}$$

Applying the converse approach, at the first stage, the optimal retail price with given wholesale price w can be worked out as follows:

$$p_r^{ND} = \frac{\rho a + w + rp_e}{2}. \tag{25}$$

At the second stage, taking (25) into (28), the optimal wholesale price and direct sales price are

$$\begin{aligned} w^{ND} &= \frac{(\rho + (1-\rho)r)a}{2(1-r^2)}, \\ p_e^{ND} &= \frac{(1-\rho+\rho r)a}{2(1-r^2)}. \end{aligned} \tag{26}$$

Then, the optimal retail price is

$$p_r^{ND} = \frac{(3\rho + (2(1-\rho) - \rho r)r)a}{4(1-r^2)}. \tag{27}$$

At last, the optimal profit of the manufacturer is

$$\pi_M^{ND} = \frac{\left(\left(\rho^2(3-r) - 4\rho\right)(1-r) + 2\right)a^2}{8\left(1-r^2\right)} - (1-m)F_m. \tag{28}$$

The optimal profit of the retailer is

$$\pi_R^{ND} = \frac{\rho^2 a^2}{16} - mF_m. \tag{29}$$

The optimal profit of the total supply chain is

$$\pi_{SC}^{ND} = \frac{\left(\rho^2(1-r)(7-r) - 8\rho(1-r) + 4\right)a^2}{16\left(1-r^2\right)} - F_m. \tag{30}$$

The optimal utility of the government is

$$\pi_G^{ND} = \frac{\left(\rho^2(1-r)(7-r) - 8\rho(1-r) + 4\right)a^2}{16\left(1-r^2\right)}. \tag{31}$$

The profits of the supply chain and government in four models are summarized in Table 2.

4.3. Model Analysis

Proposition 1. *When companies invest in carbon emissions based on centralized decision modes, proper channel competition can increase the profits of the supply chain and social benefits.*

Proof. According to equation (7), $((\partial \pi_{SC}^{YC})/\partial \rho) = ((a^2(2\rho-1))/2(1+r))$, so when $\rho < 0.5$, $(\partial \pi_{SC}^{YC}/\partial \rho) < 0$ and when $\rho > 0.5$, $(\partial \pi_{SC}^{YC}/\partial \rho) > 0$, it means that the total profit of the supply chain witnesses a downward trend as the degree of consumer preference for the retail channel is greater and when ρ equals 0.5 it reaches the lowest point, but it begins to rise after that moment. Based on equation (8), $(\partial \pi_G^{YC}/\partial \rho) = ((a^2(2\rho-1))/(2(1+r)))$, and the same results can be attained in the social benefits. □

Proposition 2. *When companies invest in carbon emissions based on centralized decision modes, increasing government subsidies is beneficial to the overall benefits of the supply chain but is not conducive to social benefits.*

Proof. According to equation (7), $(\partial \pi_{SC}^{YC}/\partial s) = ((\theta a + 2s\theta^2(1-r))/2) > 0$; meanwhile, based on equation (8), $(\partial \pi_G^{YC}/\partial s) = -s\theta^2(1-r) < 0$, so it is obvious that this proposition stands. □

Proposition 3. *The greater the consumer's preference for retail channels, the higher the price of products in retail channels but the lower the price of products in direct sales channels.*

Proof. The supply chain companies formulate their optimal emission reduction levels based on the government's subsidy coefficients s_1 and s_2. From (13), the Hessian matrix of π_M^{YD} with w, p_e, and θ is

Table 2: The profits of the supply chain and government in four models.

	Manufacturers' emission reduction investment	No manufacturers' emission reduction investment
Centralized decision	$\pi_{SC}^{YC} = (((1-2\rho(1-\rho)(1-r))a^2 + 2s\theta(1-r^2)a + 2s^2\theta^2(1-r)(1-r^2))/4(1-r^2)) - (1/2)\mu\theta^2$ $\pi_{G}^{YC} = (((1-2\rho(1-\rho)(1-r))a^2 - 2s^2\theta^2(1-r)(1-r^2))/4(1-r^2)) - (1/2)\mu\theta^2$	$\pi_{SC}^{NC} = (((1-2\rho(1-\rho)(1-r))a^2)/4(1-r^2)) - F_m$ $\pi_{G}^{NC} = (((1-2\rho(1-\rho)(1-r))a^2)/4(1-r^2))$
Decentralized decision	$\pi_{SC}^{YD} = ((a^2[4-8\rho(1-r)+\rho^2(1-r)(7-r)] + s_1\theta a(1-r^2)[6\rho(1-r)-8] + 6\rho s_2\theta a(1-r^2) + (1-r^2)(1-r)(7+r)s_1^2\theta^2 + 6(1-r^2)(1-r)s_1 s_2\theta^2 + 3(1-r^2)s_2^2\theta^2)/16(1-r^2)) - (1/2)\mu\theta^2$ $\pi_{G}^{YD} = ((a^2[4-8\rho(1-r)+\rho^2(1-r)(7-r)] + 2s_1\theta a(1-r^2)[5\rho(1-r)-8] + 2\rho s_2\theta a(1-r^2) - (1-r^2)(1-r)(5+3r)s_1^2\theta^2 - 2(1-r^2)(1-r)s_1 s_2\theta^2 - (1-r^2)s_2^2\theta^2)/16(1-r^2)) - (1/2)\mu\theta^2$	$\pi_{SC}^{ND} = (((\rho^2(1-r)(7-r) - 8\rho(1-r) + 4)a^2)/16(1-r^2)) - F_m$ $\pi_{G}^{ND} = (((\rho^2(1-r)(7-r) - 8\rho(1-r) + 4)a^2)/16(1-r^2))$

$$H = \begin{bmatrix} -1 & r & \frac{s_2}{2} - (1-r)\frac{s_1}{2} \\ r & r^2 - 2 & \frac{rs_2}{2} - \frac{(1-r)(2+r)s_1}{2} \\ \frac{s_2}{2} - (1-r)\frac{s_1}{2} & \frac{rs_2}{2} - \frac{(1-r)(2+r)s_1}{2} & (1-r)s_1s_2 - (1-\lambda)\mu \end{bmatrix}. \quad (32)$$

When $s_1s_2 < ((1-\lambda)\mu/(1-r))$, $(\partial^2\pi_M^{YD}/\partial\theta^2) = (1-r)s_1s_2 - (1-\lambda)\mu < 0$, so π_M^{YD} is a strictly concave function of θ. As $r^2 - 2 < 0$, $-(r^2-2) - r^2 = 2(1-r^2) > 0$, and π_M^{YD} is also a joint concave function with w and p_e. Because it is uncertain whether $(1-\lambda)\mu - (1-r)s_1s_2 - ((s_2/2) - (1-r)(s_1/2))^2$ is positive or not, π_M^{YD} is not a joint concave function with w and θ and is not a joint concave function with w, p_e, and θ, which is the reason why the overall optimal results cannot be calculated by the first-order derivative.

However, as π_M^{YD} is a joint concave function with w and p_e, the manufacturers' optimal price can be attained at first with fixed θ, followed by taking it into formula (9) to work out the optimal carbon emissions level. Therefore, the optimal decision-makings of the manufacturer are shown as follows:

$$\begin{aligned} \theta^* &= \frac{2\left(1-r^2\right)(2-\rho+\rho r)a}{8\mu(1-\lambda)C_2 - \left(4rC_3 + 2C_2\left(3-r^2\right)\right)s_1^2 - 2C_3s_2^2 - 4C_2(1-r)s_1s_2}, \\ p_r^{YD} &= \frac{(3\rho + (2(1-\rho) - \rho r)r)a - \left(1-r^2\right)(1+r)s_1\theta^* - \left(1-r^2\right)s_2\theta^*}{4\left(1-r^2\right)}, \\ w^{YD} &= \frac{(\rho + (1-\rho)r)a - \left(1-r^2\right)(s_1 - s_2)\theta^*}{2\left(1-r^2\right)}, \\ p_e^{YD} &= \frac{(1-\rho+\rho r)a - \left(1-r^2\right)s_1\theta^*}{2\left(1-r^2\right)}. \end{aligned} \quad (33)$$

The level of carbon emissions should be positive, so $\theta^* > 0$. According to $0 < r < 1$ and $0 < \rho < 1$, we can get $8\mu(1-\lambda)C_2 - (4rC_3 + 2C_2(3-r^2))s_1^2 - 2C_3s_2^2 - 4C_2(1-r)s_1s_2 > 0$. Denoting that $C_4 = 8\mu(1-\lambda)C_2 - (4rC_3 + 2C_2(3-r^2))s_1^2 - 2C_3s_2^2 - 4C_2(1-r)s_1s_2 > 0$, the first-order derivatives of p_r^{YD} and p_e^{YD} with ρ are $(\partial p_r^{YD}/\partial\rho) = (((3+r)a)/(4(1+r))) + (((1-r^2)^2 s_1 a)/2C_4) + ((1-r^2)(1-r)s_2 a/2C_4) > 0$ and $(\partial p_e^{YD}/\partial\rho) = -(a/2(1+r)) + (((1-r^2)(1-r)s_1 a)/C_4) < 0$, which means that the relationship between the price of products in retail channels and consumers' preference for retail channels is positively correlated, while that in direct sales channels is opposite. □

Proposition 4. *When the supply chain makes decentralized decision-making, the greater the government's low-carbon subsidies to the manufacturer, the lower the retail price, the wholesale price, and the direct sales price; the greater the government's low-carbon subsidies to the retailer, the lower the retail price but the higher the wholesale price.*

Proof. As for the dual-channel supply chains, the optimal prices are as follows:

$$p_r^{YD} = \frac{(3\rho + (2(1-\rho) - \rho r)r)a - \left(1-r^2\right)(1+r)s_1\theta - \left(1-r^2\right)s_2\theta}{4\left(1-r^2\right)},$$
$$w_D^{YD} = \frac{(\rho + (1-\rho)r)a - \left(1-r^2\right)s_1\theta + \left(1-r^2\right)s_2\theta}{2\left(1-r^2\right)}, \quad (34)$$
$$p_e^{YD} = \frac{(1-\rho+\rho r)a - \left(1-r^2\right)s_1\theta}{2\left(1-r^2\right)}.$$

Therefore, we can get

$$\frac{\partial p_r^{YD}}{\partial s_1} = -\frac{1+r}{4}\theta < 0,$$
$$\frac{\partial p_r^{YD}}{\partial s_2} = -\frac{1}{4}\theta < 0,$$
$$\frac{\partial w_D^{YD}}{\partial s_1} = -\frac{1}{2}\theta < 0, \quad (35)$$
$$\frac{\partial w_D^{YD}}{\partial s_2} = \frac{1}{2}\theta > 0,$$
$$\frac{\partial p_e^{YD}}{\partial s_1} = -\frac{1}{2}\theta < 0.$$

That is, the retail price is negatively correlated with the government's low-carbon subsidy coefficients s_1 and s_2 to manufacturers and retailers; the wholesale price is negatively correlated with the government's low-carbon subsidy coefficient s_1 for the manufacturer but positively correlated with s_2 for the retailer; the direct sales price in the dual-channel supply chain is negatively correlated with s_1 for the manufacturer. □

Proposition 5. *In the case of supply chain companies that invest in emission reductions, for any given θ, ρ, and r, in the case of the government's subsidy coefficient s, s_1 and s_2 for the emission reduction per unit product satisfy the relationship $s = \sqrt{((\rho^2 a^2 - 2s_1\theta a(5\rho C_1 - 8) - 2\rho s_2\theta a + (5+3r)C_1 s_1^2\theta^2 + 2C_1 s_1 s_2\theta^2 + s_2^2\theta^2)/8C_1\theta^2)}$; the government's emission reduction subsidies for centralized and decentralized decision-making supply chains achieve the same social benefits.*

Proof. $\pi_G^{YC} = \pi_G^{YD}$ is shown as

$$\frac{(1-2\rho(1-\rho)(1-r))a^2 - 2s^2\theta^2(1-r)\left(1-r^2\right)}{4\left(1-r^2\right)} - \frac{1}{2}\mu\theta^2$$
$$= \frac{\left\{\begin{array}{l}\left(4 - 8\rho(1-r) + \rho^2(1-r)(7-r)\right)a^2 + 2s_1\theta a\left(1-r^2\right)(5\rho(1-r)-8) + 2\rho s_2\theta a \\ \left(1-r^2\right) - \left(1-r^2\right)(1-r)(3r+5)s_1^2\theta^2 - 2\left(1-r^2\right)(1-r)s_1s_2\theta^2 - \left(1-r^2\right)s_2^2\theta^2\end{array}\right\}}{16\left(1-r^2\right)} - \frac{1}{2}\mu\theta^2. \quad (36)$$

Then

$$s = \sqrt{\frac{\rho^2a^2 - 2s_1\theta a(5\rho C_1 - 8) - 2\rho s_2\theta a + (5+3r)C_1s_1^2\theta^2 + 2C_1s_1s_2\theta^2 + s_2^1\theta^2}{8C_1\theta^2}}, \quad (37)$$

is attained, where $C_1 = 1 - r$. It means that when the government's low-carbon subsidy coefficient of the supply chain under different decision-making situations meets the above formula with the same emission reduction level, the social benefits obtained are the same. □

Proposition 6. *In the case of supply chain companies that do not invest in emission reductions, the government can obtain higher social benefits by imposing fines on the centralized decision-making supply chain compared with the other supply chain model.*

Proof. The utilities of the government in the centralized decision-making and the decentralized decision-making are $\pi_G^{NC} = (((1 - 2\rho \quad (1 - \rho)(1 - r))a^2)/(4(1 - r^2)))$ and $\pi_G^{ND} = (((\rho^2(1 - r)(7 - r) - 8(1 - r) + 4)a^2)/(16(1 - r^2)))$, respectively. The difference between them is $\pi_G^{NC} - \pi_G^{ND} = (((\rho^2 \quad (1 - r^2) + 8(1 - r)(1 - \rho))a^2)/(16(1 - r^2)))$, where $0 < r < 1$ and $0 < \rho < 1$, so $1 - r^2 > 0$ and $1 - \rho > 0$; then $\pi_G^{NC} - \pi_G^{ND} > 0$ always stands up. In other words, when companies do not invest in emission reduction, the government will obtain higher social benefits by imposing fines on centralized supply chains. □

Proposition 7. *The supply chain can achieve coordination through low-carbon subsidies and fines in the whole supply chain with the same level of emission reduction.*

Proof. If $\pi_{SC}^{YC} = \pi_{SC}^{YD}$, then $s = \left(\left(\sqrt{2C_2\theta \left\{ \begin{array}{c} (2C_2\theta - \rho\eta_1 C_1^2)a^2 + C_1\eta_2 s_1^2\theta^2 + C_1\eta_3 s_1 s_2 \theta^2 \\ +3C_1C_2 s_2^2\theta^2 + 2C_1C_2\theta a(4s_1 + \rho C_1 s_1 + 3\rho s_2) \end{array} \right\}} - 2C_2\theta a\right)/(4C_1C_2\theta a)\right)$, where $C_2 = 1 - r^2, C_3 = 1 + r^2, \eta_1 = 1 + 7\rho - \rho r$, $\eta_2 = (1 - r^2)(1 - r)(7 + r)$, and $\eta_3 = 6(1 - r^2) \quad (1 - r)$. It means that when the government's low-carbon subsidy coefficient of the supply chain meets the above formula with any given emission reduction level, the entire supply chain is coordinating with the same profits in different decision-making cases.

If $\pi_{SC}^{NC} = \pi_{SC}^{ND}$ or $(((1 - 2\rho(1 - \rho)(1 - r))a^2)/(4(1 - r^2))) - F_m^C = (((\rho^2(1 - r)(7 - r) - 8\rho(1 - r) + 4)a^2)/16(1 - r^2)) - F_m^D$, the relationship between F_m^C and F_m^D is $F_m^C = F_m^D + ((\rho(8r + \rho r^2 - 7\rho))/(16(1 - r^2)))$, which presents that when the fines meet the above formula with any given emission reduction level, the entire supply chain can achieve coordination in different decision-making cases. □

5. Numerical Experiments

5.1. Centralized Decision. For a centralized supply chain, the optimal emission reduction level is obtained according to formula (7): $\theta^{YC} = (sa/(2\mu - 2(1 - r)s^2))$. In centralized decision-making mode, assuming that $a = 100$, $\mu = 300$, $\lambda = 0.3$, $r = 0.6$, $s = 2$, and $\theta = 0.34$, the impacts of ρ on the prices and profits are shown in Table 3 and Figure 2.

It can be seen that when consumers prefer the retail channel, the retail price increases, while the direct sales price decreases; at the same time, the relationship between the profit of the supply chain or the government and consumers' preference for retail channels shows U-shape trends, which means that the overall profit of the supply chain and the government utility both see a decreasing trend firstly and then an increasing trend. When $\rho = 0.5$, which means that the retail channel and the direct sales channel share the equal market, the retail price is the same as the direct sales price, and the overall profit of the supply chain and the government utility reach the lowest point. Therefore, when the competition among supply chain companies is stronger, the utility of all members will be higher under the same conditions.

Table 4 and Figure 3 show the effect of the government's subsidy coefficient s on prices and profits. As we can see directly in Figure 3, giving subsidies to supply chain members can reduce the prices in different sales channels. The reason is that subsidies can cut down the cost of products paid by companies themselves, so the more subsidies are, the lower prices are, not only for the retail price but also for the direct sales price. Obviously, the total profit of the supply chain increases as prices reduce. However, government subsidies will increase fiscal expenditures, so it is not conducive to the improvement of the overall social benefits.

5.2. Decentralized Decision. For a decentralized supply chain, the optimal emission reduction level is θ^*, assuming that $a = 100$, $\mu = 300$, $\lambda = 0.3$, $r = 0.6$, $\theta = 0.34$, $s_1 = 1.5$, and $s_2 = 1$, and the impacts of ρ on prices (p_r^{YD}, p_e^{YD}, w) and profits $(\pi_M^{YD}, \pi_R^{YD}, \pi_{SC}^{YD}, \pi_G^{YD})$ in the supply chain are shown in Table 5. Figures 4 and 5 show the effects of ρ on prices and profits, respectively. As consumers prefer the retail channel, the retail price and wholesale price increase, while the direct sales price decreases. It can be explained that when the demand of retail channel is rising, the price in this channel is also climbing, but the demand of alternative channel and the price is reducing; and, in Figure 5, the manufacturer and the retailer see totally different trend as ρ is rising. On the contrary, as shown in this figure, the profit of the total supply chain and the utility of the government change consistently, and they will meet the lowest point when $\rho = 0.6$. In order to ensure that the retailer wholesales products from the manufacturer, it must be $p_e^{YD} > w$. Only in this way can the retail channel be effective. It can be seen from Table 5 that when $\rho < 0.4$ with given $s_1 = 1.5$ and $s_2 = 1$, the dual-channel supply chain is effective. Therefore, in decentralized decision modes, the degree of consumer preference for the retail channel is only of benefit to the retailer.

Assuming that $\rho = 0.4$, $a = 100$, $\mu = 300$, $\lambda = 0.3$, $r = 0.6$, and $\theta = 0.34$, the impacts of s_1 and s_2 on the supply chain and the government utility are shown in Table 6 and more specific changes can be seen from Figures 6–9. When the government's low-carbon subsidy coefficient for retailers is fixed, every price is lower when the government gives more subsidies to the manufacturer; and the higher low-carbon

Table 3: The effect of the degree of consumer preference for the retail channel ρ based on centralized decision.

No.	ρ	p_r^{YC}	p_e^{YC}	π_{SC}^{YC}	π_G^{YC}
1	0.1	49.66	74.66	3641.75	3607.57
2	0.2	52.79	71.54	3423.00	3388.82
3	0.3	55.91	68.41	3266.75	3232.57
4	0.4	59.04	65.29	3173.00	3138.82
5	0.5	62.16	62.16	3141.75	3107.57
6	0.6	65.29	59.04	3173.00	3138.82
7	0.7	68.41	55.91	3266.75	3232.57
8	0.8	71.54	52.79	3423.00	3388.82
9	0.9	74.66	49.66	3641.75	3607.57

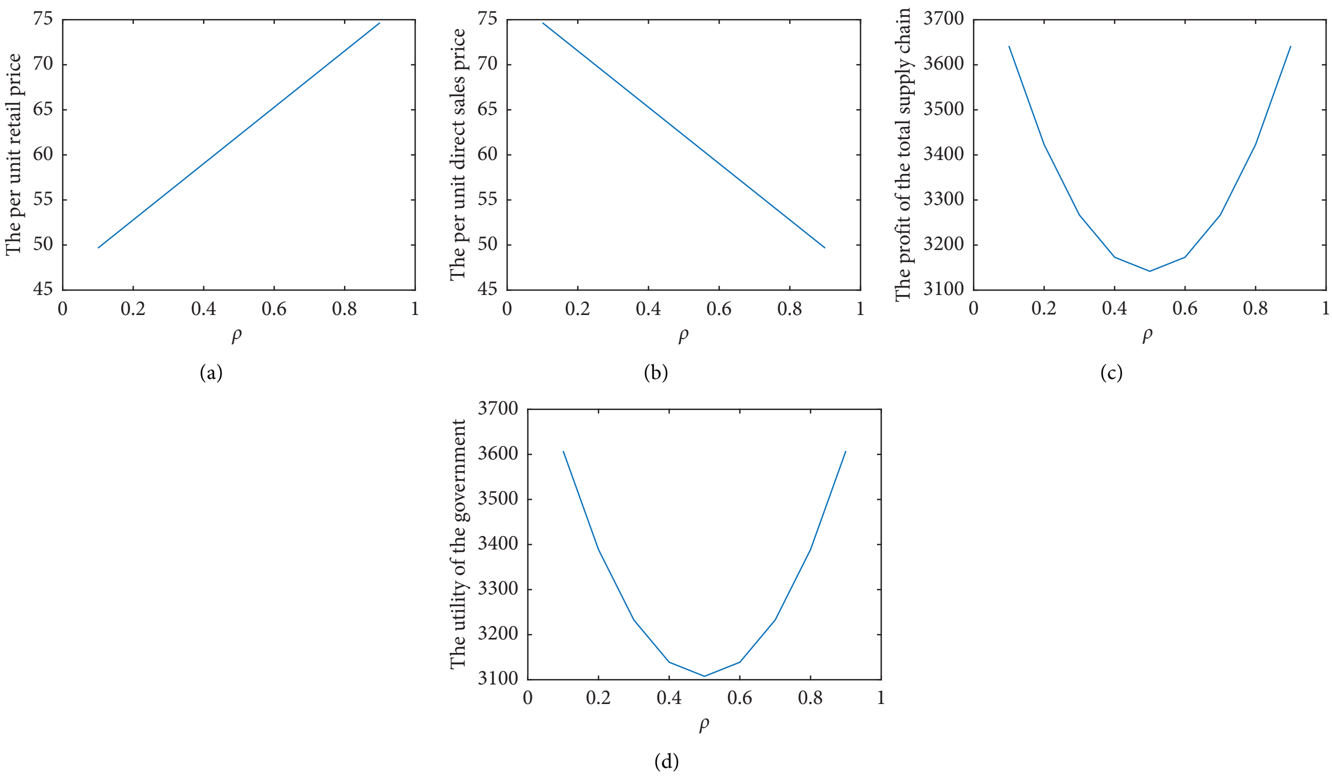

Figure 2: The effect of the degree of consumer preference for the retail channel ρ based on centralized decision.

Table 4: The effect of the government's subsidy coefficient s based on centralized decision.

No.	s	p_r^{YC}	p_e^{YC}	π_{SC}^{YC}	π_G^{YC}
1	0.5	59.29	65.54	3147.42	3138.90
2	1.0	59.21	65.46	3155.93	3138.89
3	1.5	59.12	65.37	3164.46	3138.86
4	2.0	59.04	65.29	3173.00	3138.82
5	2.5	58.95	65.20	3181.55	3138.77

subsidy coefficient for the manufacturer, the higher profits of the retailer but the lower profits of the manufacturer, the whole supply chain, and the government. It means that more subsidies to the manufacturer can weaken supply chain and social benefits. On the other hand, it can be seen that when the government's low-carbon subsidy coefficient to the manufacturer is constant, increasing it to the retailer will increase the wholesale price as well as the profits of all supply chain members and social benefits. Therefore, the government needs to reasonably decide the scope of subsidies for the manufacturer and the retailer to encourage emission reduction investment and increase social benefits as a result.

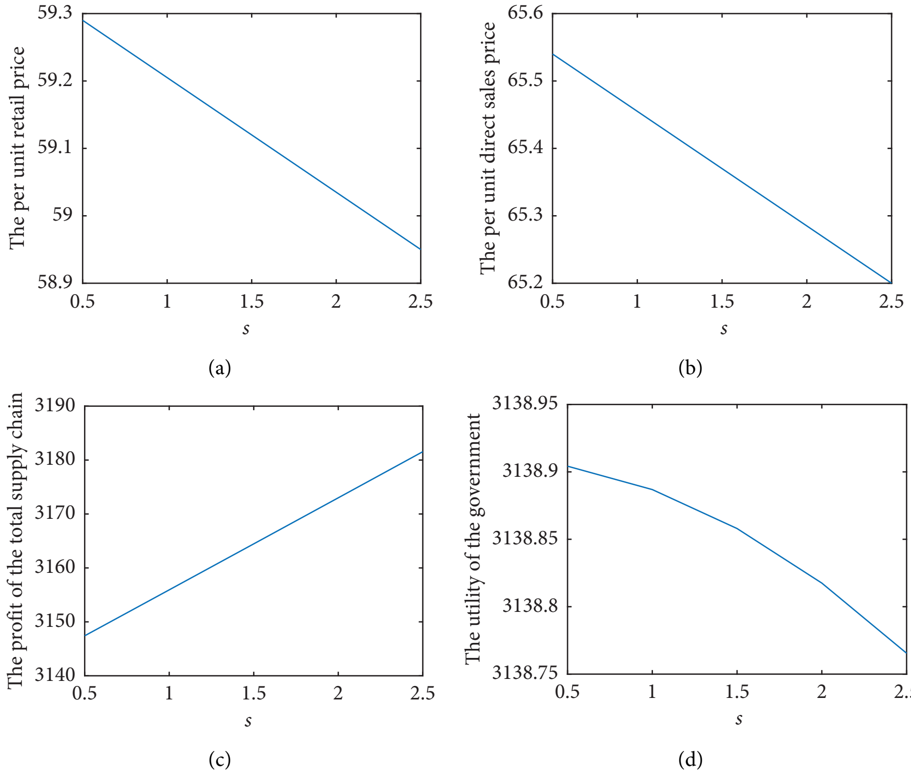

FIGURE 3: The effect of the government's subsidy coefficient s based on centralized decision.

TABLE 5: The effect of the degree of consumer preference for the retail channel ρ based on decentralized decision.

No.	ρ	p_r^{YD}	p_e^{YD}	w	π_M^{YD}	π_R^{YD}	π_{SC}^{YD}	π_G^{YD}
1	0.1	28.77	74.75	49.92	3576.30	1.75	3578.05	3552.05
2	0.2	39.09	71.62	53.04	3321.41	21.18	3342.59	3316.25
3	0.3	49.40	68.50	56.17	3104.02	53.11	3157.13	3130.45
4	0.4	59.71	65.37	59.29	2924.13	97.54	3021.67	2994.65
5	0.5	70.02	62.25	62.42	2781.74	154.47	2936.21	2908.85
6	0.6	80.34	59.12	65.54	2676.85	223.90	2900.75	2873.05
7	0.7	90.65	56.00	68.67	2609.46	305.83	2915.29	2887.25
8	0.8	100.96	52.87	71.79	2579.57	400.26	2979.83	2951.45
9	0.9	111.27	49.75	74.92	2587.18	507.19	3094.37	3065.65

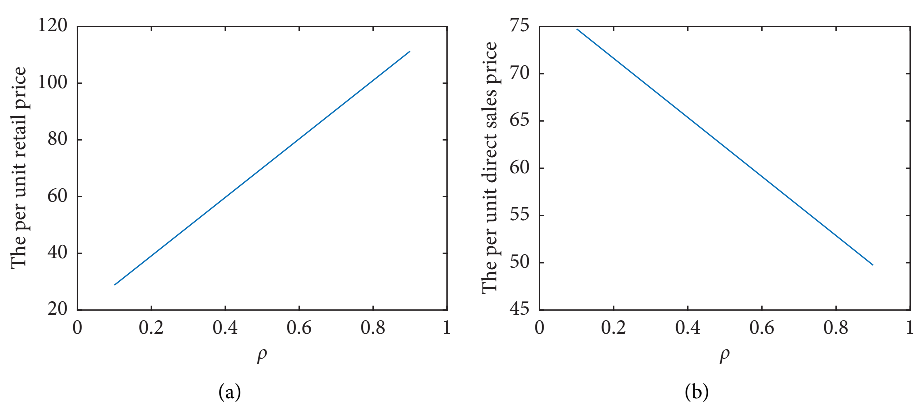

FIGURE 4: Continued.

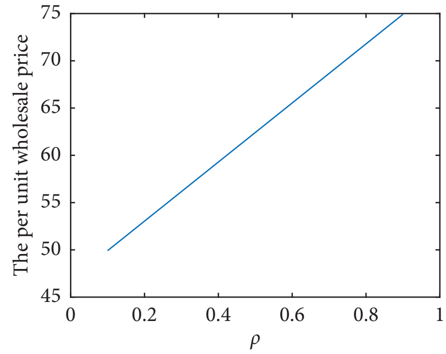

FIGURE 4: The effect of the degree of consumer preference for the retail channel ρ on prices based on decentralized decision.

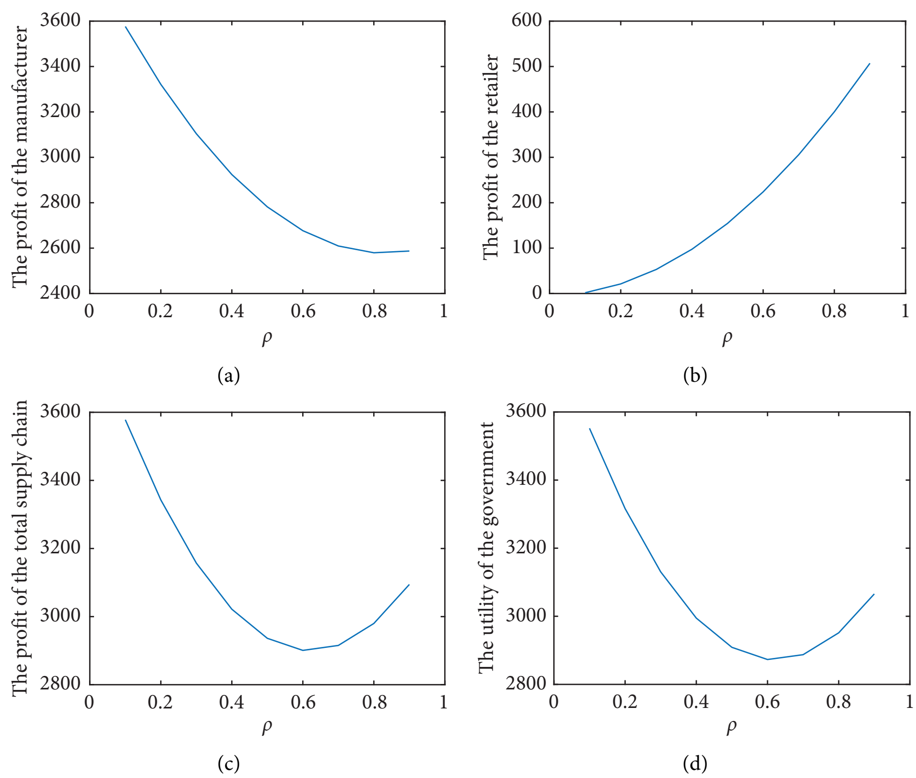

FIGURE 5: The effect of the degree of consumer preference for the retail channel ρ on profits based on decentralized decision.

TABLE 6: The effect of the government's subsidy coefficient s_1 and s_2 based on decentralized decision.

No.	s_1	s_2	p_r^{YD}	p_e^{YD}	w	π_M^{YD}	π_R^{YD}	π_{SC}^{YD}	π_G^{YD}
1	0.5	1	59.85	65.54	59.46	2939.72	96.85	3036.57	3025.29
2	1	1	59.78	65.46	59.38	2931.92	97.19	3029.11	3009.98
3	1.5	1	59.71	65.37	59.29	2924.13	97.54	3021.67	2994.65
4	2	1	59.64	65.29	59.21	2916.35	97.88	3014.23	2979.31
5	2.5	1	59.58	65.20	59.12	2908.59	98.23	3006.81	2963.97
6	1.5	0.5	59.75	65.37	59.21	2922.41	96.68	3019.09	2993.81
7	1.5	1	59.71	65.37	59.29	2924.13	97.54	3021.67	2994.65
8	1.5	1.5	59.67	65.37	59.38	2925.86	98.40	3024.26	2995.49
9	1.5	2	59.63	65.37	59.46	2927.59	99.27	3026.86	2996.32
10	1.5	2.5	59.58	65.37	59.55	2929.33	100.14	3029.47	2997.15

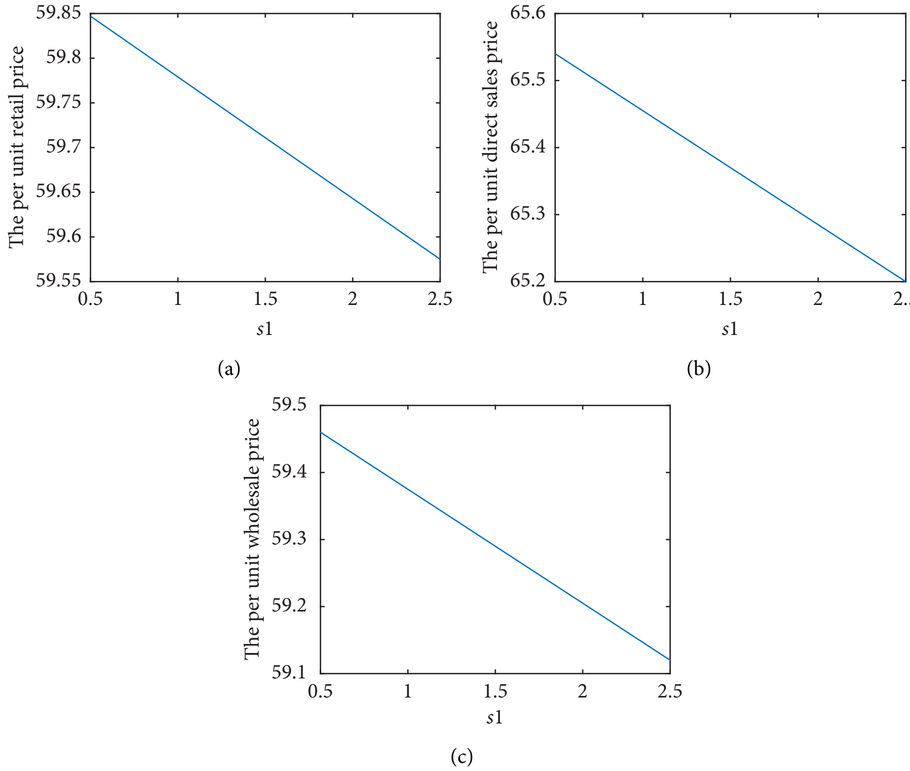

Figure 6: The effect of the government's subsidy coefficient to the manufacturer s_1 on prices and profits based on decentralized decision.

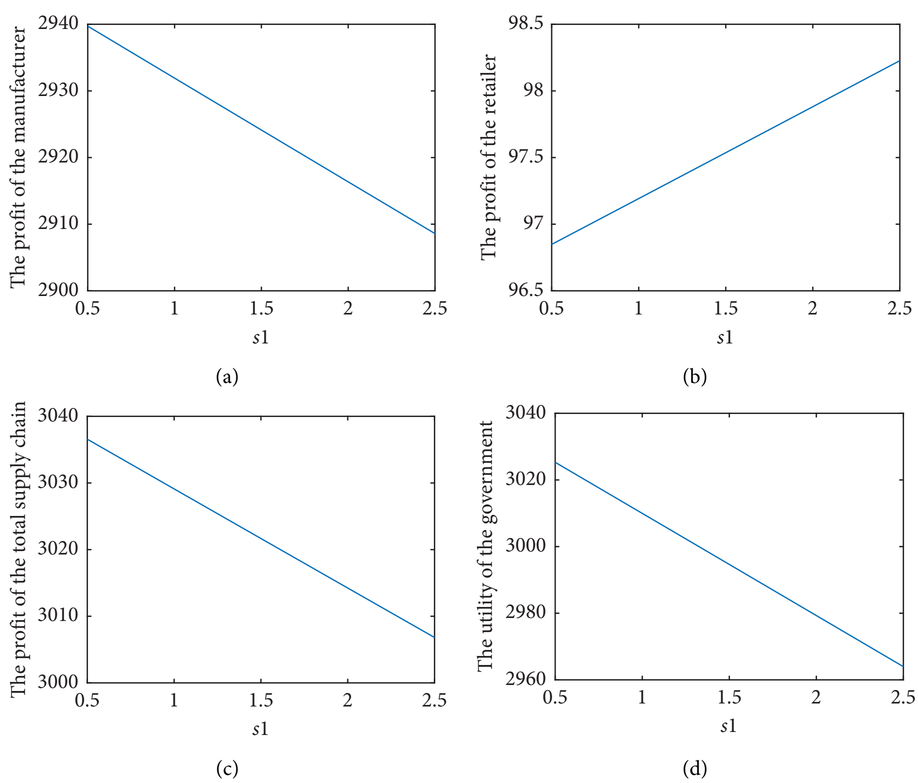

Figure 7: The effect of the government's subsidy coefficient to the manufacturer s_1 on profits based on decentralized decision.

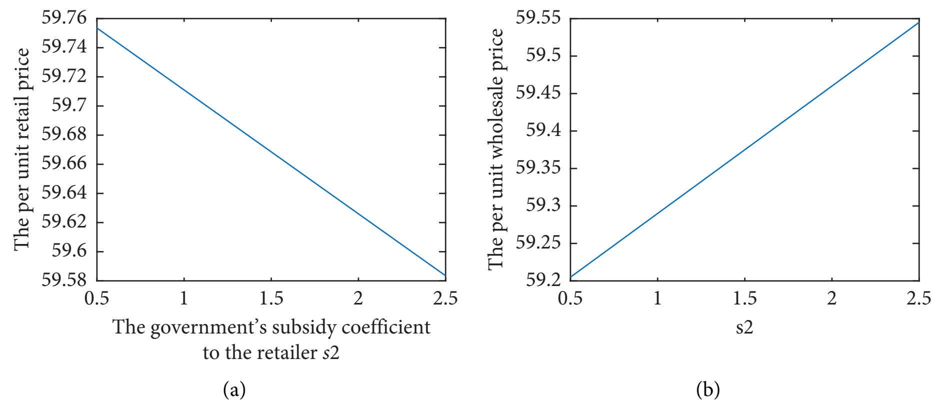

Figure 8: The effect of the government's subsidy coefficient to the retailer s_2 on prices based on decentralized decision.

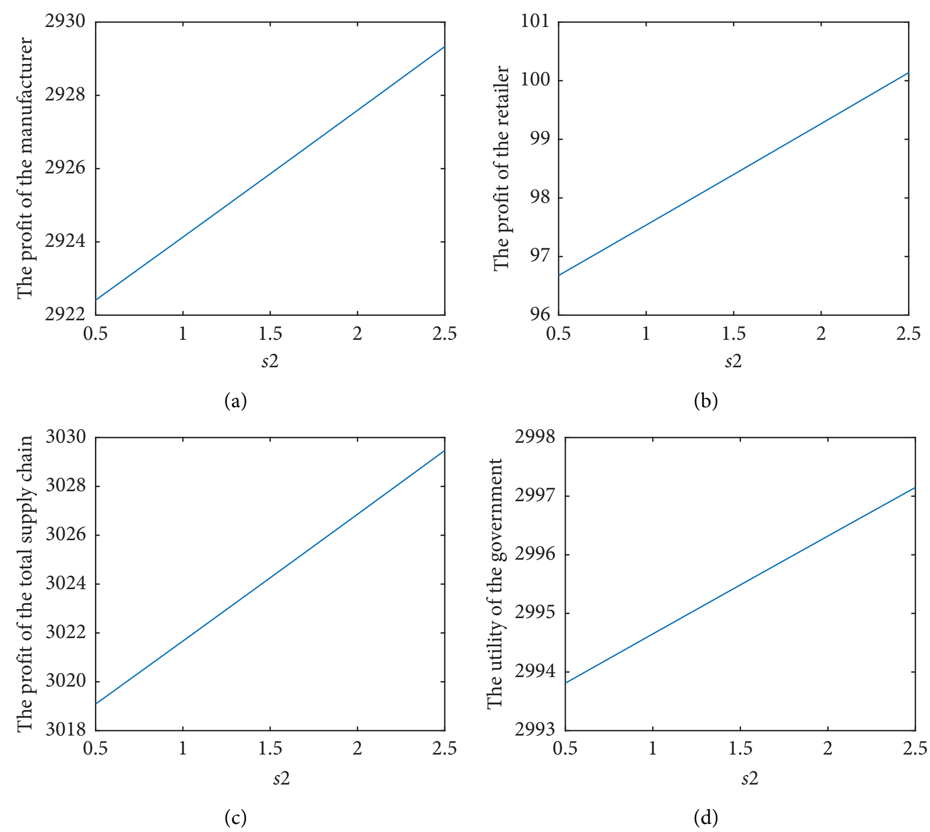

Figure 9: The effect of the government's subsidy coefficient to the retailer s_2 on profits based on decentralized decision.

6. Conclusions

Considering consumers' channel preferences and supply chain members' behavior, this paper constructs a game model led by manufacturer to study what the government should do when manufacturers invest in emission reductions or not in a dual-channel supply chain; and the supply chain members adopt a centralized or decentralized decision-making model. Based on this model, this paper introduces the consumers' channel preference coefficient and the government subsidy coefficient to analyze how they affect the supply chain and government benefits and aims to guide the government to take incentive or penalties measures to encourage supply chain members to reduce carbon emissions. The main results are summarized as follows:

(1) When manufacturers invest in carbon emissions reduction, for centralized decision-making model, this study found that the government is supposed to take incentive measures in order to maximize supply chain profits, but the cost is the decrease of social benefits. As for consumers channel preference, no matter which sales channel they prefer, it is beneficial

to improve the overall supply chain and social benefits at the same time.

(2) In decentralized decision-making model when manufacturers invest in reducing carbon emissions, the government adopts incentive measures with low-carbon subsidies for retailers to be able to increase the profits of all supply chain members and social benefits. However, low-carbon subsidies for manufacturers and the degree of consumer preference for the retail channel only increase the profits of the retailer.

(3) When manufacturers do not take low-carbon investments, compared with centralized and decentralized decision-making supply chain, the government can obtain higher social benefits by imposing fines on the former one.

Based on the results of this paper, some government implications can be attained as follows. First, the government should reasonably plan subsidy policies for supply chain members and appropriately increase the proportion of subsidies to retailers, which will help supply chain members and the government achieve a win-win result. Second, when the supply chain does not invest in reducing carbon emissions, it is better for the government to issue the penalties of entire industrial regarding supply chain members as a whole, so the government should guide the formulation of industry's low-carbon standards. Third, based on fully respecting the laws of the market, the government can regulate market low-carbon behavior of manufacturers and retailers by guiding market expectations, stimulating market vitality, and clarifying investment directions, which is beneficial for them to compete healthily, because good market competition is conducive to the supply chain profits and government utility.

Our research has some limitations and further research can be done at least in the following aspects. First, this article explored incentive measures represented by low-carbon subsidies and punitive measures represented by fines. Other governmental measures such as carbon taxes and carbon trade are also worth studying in further research. Second, this article studied a simple two-echelon supply chain with one manufacturer and one retailer. Actually, a supply chain is likely to include multiple manufacturers and multiple retailers, so multiple supply chain members can be considered in the future.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Research Article

Stability, Multistability, and Complexity Analysis in a Dynamic Duopoly Game with Exponential Demand Function

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In this paper, a discrete-time dynamic duopoly model, with nonlinear demand and cost functions, is established. The properties of existence and local stability of equilibrium points have been verified and analyzed. The stability conditions are also given with the help of the Jury criterion. With changing of the values of parameters, the system shows some new and interesting phenomena in terms to stability and multistability, such as V-shaped stable structures (also called Isoperiodic Stable Structures) and different shape basins of attraction of coexisting attractors. The eye-shaped structures appear where the period-doubling and period-halving bifurcations occur. Finally, by utilizing critical curves, the changes in the topological structure of basin of attraction and the reason of "holes" formation are analyzed. As a result, the generation of global bifurcation, such as contact bifurcation or final bifurcation, is usually accompanied by the contact of critical curves and boundary.

1. Introduction

Nonlinear dynamical system can describe many complicated and curious phenomena, and the theory of nonlinear dynamics is widely applied in many fields of scientific research studies. As an important branch of modern mathematics, nonlinear theory makes up the defect of the linear function and can be well used to characterize the regularities of ecosystem [1], economical model [2, 3], and so on. A function in the exponential form [4] has a good property of nonnegativity, which can make sure that the solutions of the exponential function are all greater than zero. According to this practical economic significance, it is necessary to adopt this nonlinear type of demand function with exponential. In other words, the exponential demand function guarantees that the price of the product is always positive.

For the process of dynamical system evolution, most scholars usually pay attention to or are interested in whether the dynamical system will keep in the steady state for a long time rather than experience a short transient state. Hence, the game evolution plays an important role in describing decision-making process, showing the collision of strategic sparks and the wisdom of strategies. In a dynamical system, nonlinear dynamics theory can clearly explain evolution regularities and complex dynamic behaviors. Especially in the economic field [5, 6], with the deepening of the research level, many scholars have gradually taken many practical factors into account in modeling process and combining nonlinear dynamics with game theory. In the real market, the cost function may not be monotonous or has a linear relationship with the total supply, that is to say, the nonlinear cost form is closer to the reality. Brianzoni et al. [7] changed the form of the cost function from linear to nonlinear, and they analyzed dynamic characteristics of a Bertrand competition system. Pu and Ma [8] investigated a dynamic game model with four oligopolistic players, in which a cubic total-cost demand function was considered. It is worth noticing that a group of scholars, Peng et al. [9] considered a quadratic form of the cost function to establish a remanufacturing duopoly model and to study its complex dynamic characteristics. In addition, an economic duopoly dynamical system with taking the nonlinear cost function into consideration has been built in this paper, and a lot of very peculiar and complex dynamic characteristics will arise, such as bifurcations, chaos, and coexisting attractors, which we will discuss in later sections.

In real market competitions, the more market information the firm has, the more rational it is. However, in order to completely master whole market information, the firms must need to pay an extremely high amount of information cost. It is rational that no one wants to pay such high information cost. As a result, most firms in real market do grasp some market information but not all, which leads the firms to form "myopic" in some respects, so the firms will constantly adjust their decision in order to maximize their own interests. Such a decision-making process is also known as "trial and error." The classical adjustment rule, i.e., "rule of thumb" (which can be also called as the gradient adjustment mechanism), does not require the firms to have a high degree of rationalities and has been widely used in many investigations; for instance, Zhou et al. [10], Guo and Ma [11], Elsadany [12], and Cao et al. [13]. Furthermore, the boundedly rational firms adjust and update their competitive strategies in the next period by utilizing local estimation of their marginal profits in the previous period. Therefore, the firms, who implement such local adjustment rule, do not need to have whole knowledge on demand and cost of the market.

At the end of the last century, Bischi et al. [14] built a dynamic Cournot duopoly model and found that an interesting phenomenon of synchronization may occur, where the global dynamics had been analyzed by critical curves. At the beginning of this century, Bischi et al. [15, 16], Agliari et al. [17], Agiza and Elsadany [18], and other scholars had done much work on studying global bifurcation of a dynamical system. Their remarkable achievements laid the foundation for the analysis of complex dynamic phenomena by using noninvertible mapping and critical curves. Global bifurcations usually happen when the contacts occur between critical curves and boundaries of basins of attraction or between borders of attractors and boundaries of basins of attraction. After global bifurcation, many interesting and complex phenomena will appear. Generally speaking, complex dynamic phenomena usually include multistability, such as coexistence of attractors between periodic points or between chaotic attractors and periodic points, the occurrence of "holes" [15, 16], and so on. Due to these complex phenomena, the structure and stability of basin of attraction may dramatically change. Zhou and Wang [19] analyzed the properties in terms of bifurcation and multistability in a two-stage duopoly game with differentiated product and R&D spillovers. Cavalli and Naimzada [20] also had described complex dynamic behaviors and the phenomenon of multistability. The critical curve is one of the noticeable features for the noninvertible map, and we can use critical curves to analyze and investigate complex dynamic behaviors appearing in the dynamical system.

In addition, the method of critical curves (see in Ref. [21] and references therein) is an efficient approach to further investigate global dynamics. Bischi and Lamantia [22] studied complex structures of basins of attraction and the phenomenon of coexisting attractors in a discrete dynamic economy game. Gao [23] also had carried out some works on complex properties about a noninvertible iteration map. Besides this, the paper also used center manifold and bifurcation to give the conditions when classical bifurcations arise, that is, pitch-fork bifurcation, flip bifurcation, and Neimark–Sacker bifurcation. Most recently, the scholars Bischi and Baiardi [24, 25], Cao et al. [13], and Zhang et al. [26] all utilized critical curves to study the complex dynamics of the built models.

The primary purpose of this paper is to establish a discrete-time dynamic duopoly game model with bounded rationality, where both demand and cost functions are considered in nonlinear forms. Furthermore, the dynamic properties of the built system can be understood more clearly by numerical simulation, so we mainly use the single-parameter (1D) bifurcation diagram, the double-parameter (2D) bifurcation diagram, the largest Lyapunov exponent diagram, and the basin of attraction. By changing the values of the parameters, there are much complex phenomena that may arise, and we can further study their influences on the stability of the system or the structure of the basin of attraction through utilizing the theory of critical curves in subsequent sections.

The rest parts of this paper are organized as follows. In Section 2, a dynamic duopoly Cournot game under the exponential demand function and quadratic cost function is established, where these two firms are both considered as having bounded rationality. The existence of equilibrium points has been verified. The locally stable conditions of equilibrium points have been discussed in Section 3. In Section 4, we have analyzed the distinct routes of the system to chaotic states and found that there are some interesting and curious phenomena of stability and multistability, including the basin of attraction, coexisting attractors, and so on, by numerical simulation. Furthermore, we also use critical curves to study the steady state of the system and the change process of the structure of basin of attraction. Finally, some conclusions have been drawn in Section 5.

2. Modeling and the Existence of Equilibria

It is supposed that there are two firms i (labeled by $i = 1$ and 2) in the economic market, producing homogeneous products, and both these two kinds of homogeneous products are supplied to a same market. The prices of products may have some relations with the total quantity or the production costs or some other elements. In this paper, it is assumed that the price of firm $i\,(i = 1$ and $2)$ is an exponential inverse demand function defined by the outputs $q_i \geq 0$ of two firms, that is, $P(Q) = ae^{-(q_1+q_2)}$, in which $a > 0$ is the maximum selling price of the products in the market and $Q = q_1 + q_2$ is the number of total quantity of these two kinds of homogeneous products. The exponential inverse demand function has good nonnegativity, so we can be sure that the solutions of the exponential function are all greater than zero, even tending to infinity, or even tending quite near to zero. In addition, in order to be closer to reality, we consider that the cost function of the firm i has a quadratic form, that is, $C_i(q_i) = c_i q_i^2$, where $c_i > 0$ is the marginal cost, and the relation between a and c_i satisfies $a > c_i$. Hence, the profits of these two firms can be, respectively, written as follows:

$$\left\{ \prod_1 = a e^{-(q_1+q_2)} q_1 - c_1 q_1^2, \prod_2 = a e^{-(q_1+q_2)} q_2 - c_2 q_2^2. \right. \quad (1)$$

Let $\prod_i$, respectively, deduce the derivative with regard to the output q_i, $i = 1$ and 2. Then, we can get the corresponding marginal profit functions as follows:

$$\left\{ \frac{\partial \prod_1}{\partial q_1} = a(1-q_1)e^{-(q_1+q_2)} - 2c_1 q_1, \frac{\partial \prod_2}{\partial q_2} = a(1-q_2)e^{-(q_1+q_2)} - 2c_2 q_2. \right. \quad (2)$$

In the fierce market competition, for the sake of becoming completely rational and having whole information of the market, the firms must need to pay great number of information costs, whereas most firms are not willing to do this activity. In fact, in addition to that, it is really difficult to master some aspects of market information, let alone all market information. Hence, in this situation, the two firms we considered before can be seen as having incomplete market information. In other words, the firm $i (i = 1 \text{ and } 2)$ is boundedly rational. The firms adjust their production strategies in next period $t+1$ in terms of their marginal profit in the previous period t. It means that if the marginal profit in t period is greater than zero (or less than zero), then the firm i will increase (or decrease) its outputs q_i. If the marginal profit in t period is equal to zero, then the firm i will keep its volume of production unchanged. The "gradient adjustment mechanism" is a useful method to simulate how the firms adjust their decisions so as to make sure to get maximum interests. Thus, we introduce this classical adjustment rule into our model, and then, the dynamic adjustment mechanism of the firm i with respect to its outputs can be described in the following form:

$$q_i(t+1) = q_i(t) + v_i q_i(t) \frac{\partial \prod_i(t)}{\partial q_i(t)}, \quad t \in Z, \quad (3)$$

in which $v_i > 0$ represents the adjustment speed of the firm i. Through substituting equation (2) into equation (3), the discrete-time dynamic adjustment mechanism of the two firms can be specifically expressed as follows:

$$\begin{cases} q_1(t+1) = q_1(t) + v_1 q_1(t)\left[\dfrac{a(1-q_1(t))}{e^{q_1(t)+q_2(t)}} - 2c_1 q_1(t)\right], \\ q_2(t+1) = q_2(t) + v_2 q_2(t)\left[\dfrac{a(1-q_2(t))}{e^{q_1(t)+q_2(t)}} - 2c_2 q_2(t)\right]. \end{cases} \quad (4)$$

For simplicity, the auxiliary variables have been introduced in system (4), that is, $\alpha_i = c_i v_i$ and $\beta_i = a v_i (i = 1 \text{ and } 2)$, and we have that α_i and $\beta_i \in (0, +\infty)$. We introduce an evolutionary operator T and auxiliary variables as $\alpha_i = c_i v_i$ and $\beta_i = a v_i$, $i = 1$ and 2, where α_i and $\beta_i \in (0, +\infty)$. Hence, a discrete-time dynamic duopoly Cournot game can be further simplified as the following:

$$T: \begin{cases} q_1(t+1) = q_1(t) + \beta_1 q_1(t)(1-q_1(t))e^{-(q_1(t)+q_2(t))} - 2\alpha_1 q_1^2(t), \\ q_2(t+1) = q_2(t) + \beta_2 q_2(t)(1-q_2(t))e^{-(q_1(t)+q_2(t))} - 2\alpha_2 q_2^2(t), \end{cases} \quad (5)$$

in which T is an evolutionary operator.

According to the knowledge of nonlinear dynamics, let $q_i(t+1) = q_i(t)$, $i = 1$ and 2, so we can know that the equilibrium point in system (5) must satisfy the conditions listed as follows:

(i) $q_1 = 0$ or

(ii) $\beta_1(1-q_1)e^{-(q_1+q_2)} = 2\alpha_1 q_1$

(iii) $q_2 = 0$ or

(iv) $\beta_2(1-q_2)e^{-(q_1+q_2)} = 2\alpha_2 q_2$

On the basis of the above conditions, we can deduce that there are four equilibrium points existing in system (5). For instance, when condition (i) and condition (iii) simultaneously hold, the equilibrium point $E_1 = (0, 0)$ of system (5) can be obtained. For the rest of the boundary equilibrium points, we can draw the following conclusions:

(1) The boundary equilibrium point $E_2 = (x^*, 0)$ can be obtained by condition (ii) and condition (iii), where x^* satisfies the equation $\beta_1(1-x^*)e^{-x^*} = 2\alpha_1 x^*$. If we rewrite this relationship as a function with regard

to a variable z, that is, $g(z) = 2\alpha_1 z - (\beta_1(1-z)/e^z)$, then we have $g(0) = -\beta_1 < 0$ and $g(1) = 2\alpha_1 > 0$. So we can know that there is at least one point $x^* \in (0,1)$ that satisfies $\beta_1(1-x^*)e^{-x^*} = 2\alpha_1 x^*$. Finally, the existence of $E_2 = (x^*, 0)$ is verified.

(2) Analogously, the boundary equilibrium point $E_3 = (0, y^*)$ can be obtained by condition (i) and condition (iv), where y^* satisfies the equation $\beta_2(1-y^*)e^{-y^*} = 2\alpha_2 y^*$. If we rewrite this equation as a function with respect to a variable z, that is, $w(z) = 2\alpha_2 z - (\beta_2(1-z)/e^z)$, then we will get two inequalities that $w(0) = -\beta_2 < 0$ and $w(1) = 2\alpha_2 > 0$. So we can know that there is at least one point $y^* \in (0,1)$ that satisfies $\beta_2(1-y^*)e^{-y^*} = 2\alpha_2 y^*$. Finally, the existence of $E_3 = (0, y^*)$ is also verified.

Hence, we do verify the existence of these three boundary equilibrium points. Then, the analysis of the Nash equilibrium point and its existence in system (5) is given by the proposition as the following.

Proposition 1. *The unique Nash equilibrium point $E_4 = (m^*, n^*)$ can be obtained through combining of condition (ii) with condition (iv), and m^* satisfies the equation $2\alpha_1 m^* = \beta_1(1-m^*)e^{-((\sigma m^* - \sigma m^{*2} + m^{*2} + m^*)/(\sigma - \sigma m^* + m^*))}$, and n^* satisfies the equation $2\alpha_2 n^* = \beta_2(1-n^*)e^{-((\sigma n^* + \sigma n^{*2} - n^{*2} + n^*)/(1 + \sigma n^* - n^*))}$, where $\sigma = (\alpha_2\beta_1/\alpha_1\beta_2)$.*

Proof. First, the equation $e^{m^*+n^*} = (\beta_1(1-m^*)/2\alpha_1 m^*) = (\beta_2(1-n^*)/2\alpha_2 n^*)$ can be obtained from condition (ii) and condition (iv), where $n^* = (m^*/(\sigma - \sigma m^* + m^*))$ and $m^* = (\sigma n^*/(1 + \sigma n^* - n^*))$. Then, let $h_1(u) = 2\alpha_1 u - \beta_1(1-u)e^{-((\sigma u - \sigma u^2 + u^2 + u)/(\sigma - \sigma u + u))}$, we can easily get two inequalities that $h_1(0) = -\beta_1 < 0$ and $h_1(1) = 2\alpha_1 > 0$. Hence, we can know that there is at least one point m^* in $(0,1)$ that satisfies the equation $2\alpha_1 m^* = \beta_1(1-m^*)e^{-((\sigma m^* - \sigma m^{*2} + m^{*2} + m^*)/(\sigma - \sigma m^* + m^*))}$. Analogously, let $h_2(u) = 2\alpha_2 u - \beta_2(1-u)e^{-((\sigma u + \sigma u^2 - u^2 + u)/(1 + \sigma u - u))}$, we have two inequalities that $h_2(0) = -\beta_2 < 0$ and $h_2(1) = 2\alpha_2 > 0$. So there is at least one point $n^* \in (0,1)$ that satisfies the equation $2\alpha_2 n^* = \beta_2(1-n^*)e^{-((\sigma n^* + \sigma n^{*2} - n^{*2} + n^*)/(1 + \sigma n^* - n^*))}$, where $\sigma = (\alpha_2\beta_1/\alpha_1\beta_2)$. Finally, the existence of the Nash equilibrium point $E_4 = (m^*, n^*)$ is verified.

In a real economic system, the equilibrium point $E_1 = (0,0)$ represents the situation that these two firms both go bankrupt or get out of the market. The boundary equilibrium points $E_2 = (x^*, 0)$ and $E_3 = (0, y^*)$ can be regarded as the situation that one of these two firms gets out of the market, while another one becomes a monopoly. □

3. Local Stability Analyses of Equilibria

From the knowledge of nonlinear dynamics, for the sake of judging the local stability of equilibrium points, we only need to judge the relationship between 1 and the eigenvalue $|\lambda_i|$ ($i = 1$ and 2) of the Jacobian matrix. That is to say, if $|\lambda_i| > 1$ ($i = 1$ and 2), then the equilibrium point is an unstable node. If $|\lambda_i| < 1$ ($i = 1$ and 2), then the equilibrium point is a stable node. While if one of $|\lambda_i|$ ($i = 1, 2$) is great than 1 and the other is smaller than 1, then the equilibrium point is a saddle point. The Jacobian matrix corresponding to system (5) can be expressed as follows:

$$J = \begin{bmatrix} 1 - 4\alpha_1 q_1 + \beta_1\left(1 - 3q_1 + q_1^2\right)e^{-(q_1+q_2)} & \beta_1 q_1(q_1 - 1)e^{-(q_1+q_2)} \\ \beta_2 q_2(q_2 - 1)e^{-(q_1+q_2)} & 1 - 4\alpha_2 q_2 + \beta_2\left(1 - 3q_2 + q_2^2\right)e^{-(q_1+q_2)} \end{bmatrix}. \tag{6}$$

The local stability of boundary equilibrium points of system (5) has been discussed, and the following propositions can be drawn.

Proposition 2. *The boundary equilibrium point $E_1 = (0,0)$ is an unstable node.*

Proof. In system (5), the Jacobian matrix corresponding to the point $E_1 = (0,0)$ can be written as

$$J(E_1) = \begin{bmatrix} 1+\beta_1 & 0 \\ 0 & 1+\beta_2 \end{bmatrix}. \tag{7}$$

It is clear that Jacobian matrix (7) is a diagonal matrix, and the corresponding eigenvalues are $\lambda_1 = 1 + \beta_1$ and $\lambda_2 = 1 + \beta_2$, respectively. Since the nonnegativity of β_1 and β_2, we have that $|\lambda_1| > 1$ and $|\lambda_2| > 1$. Therefore, the equilibrium point $E_1 = (0,0)$ is an unstable node. □

Proposition 3. *The boundary equilibrium point $E_2 = (x^*, 0)$ is unstable.*

(1) When $\beta_1 > -2e^{x^*}/(x^{*2} - x^* - 1)$, then the boundary equilibrium point $E_2 = (x^*, 0)$ is a saddle point

(2) When $\beta_1 < -2e^{x^*}/(x^{*2} - x^* - 1)$, then the boundary equilibrium point $E_2 = (x^*, 0)$ is an unstable focus

Proof. Apparently, the Jacobian matrix at equilibrium point $E_2 = (x^*, 0)$ is an upper triangular matrix, that is,

$$J(E_2) = \begin{bmatrix} 1 + \beta_1 e^{-x^*}\left(x^{*2} - x^* - 1\right) & \beta_1 x^*(x^* - 1)e^{-x^*} \\ 0 & 1 + \beta_2 e^{-x^*} \end{bmatrix}. \tag{8}$$

The eigenvalues corresponding to this Jacobian matrix are $\lambda_1 = 1 + \beta_1 e^{-x^*}(x^{*2} - x^* - 1)$ and $\lambda_2 = 1 + \beta_2 e^{-x^*}$, respectively. Since $x^* \in (0,1)$, we have that $x^{*2} - x^* - 1 < 0$ and $\beta_1 > 0$. Hence, $\lambda_1 < 1$ and $|\lambda_2| > 1$. However, the relationship between $|\lambda_1|$ and 1 needs to be discussed by using classification as follows.

(1) When $\beta_1 > -2e^{x^*}/(x^{*2} - x^* - 1)$, then we can deduce that $\lambda_1 > -1$. Since $\lambda_1 < 1$, then we can know that the moduli of λ_1 and λ_2 satisfy $|\lambda_1| < 1$ and $|\lambda_2| > 1$. As a result, $E_2 = (x^*, 0)$ is a saddle point.

(2) Conversely, when $\beta_1 < -2e^{x^*}/(x^{*2} - x^* - 1)$, then we have a conclusion that $\lambda_1 < -1$. Furthermore, combining the conclusions $|\lambda_1| > 1$ with $|\lambda_2| > 1$, we can conclude that $E_2 = (x^*, 0)$ is an unstable focus. □

Proposition 4. *The boundary equilibrium point $E_3 = (0, y^*)$ is unstable.*

(1) When $\beta_2 > -2e^{y^*}/(y^{*2} - y^* - 1)$, the boundary equilibrium point $E_3 = (0, y^*)$ is a saddle point

(2) When $\beta_2 < -2e^{y^*}/(y^{*2} - y^* - 1)$, the boundary equilibrium point $E_3 = (0, y^*)$ is an unstable focus

Proof. Obviously, the Jacobian matrix at $E_3 = (0, y^*)$ is a lower triangular matrix as the following:

$$J(E_3) = \begin{bmatrix} 1 + \beta_1 e^{-y^*} & 0 \\ \beta_2 y^*(y^* - 1)e^{-y^*} & 1 + \beta_2 e^{-y^*}\left(y^{*2} - y^* - 1\right) \end{bmatrix}. \tag{9}$$

The eigenvalues corresponding to this Jacobian matrix are $\lambda_1 = 1 + \beta_1 e^{-y^*}$ and $\lambda_2 = 1 + \beta_2 e^{-y^*}(y^{*2} - y^* - 1)$, respectively. This is a similar situation like in Proposition 3, so we do same steps as in Proposition 3. Since y^* belongs to interval $(0, 1)$, then we can get two inequalities $y^{*2} - y^* - 1 < 0$ and $\beta_2 > 0$, and then, we already know that $\lambda_1 > 1$ and $\lambda_2 < 1$. However, the relation between $|\lambda_2|$ and 1 needs to be discussed by using classification as follows.

(1) When $\beta_2 > -2e^{y^*}/(y^{*2} - y^* - 1)$, then we can deduce that $\lambda_2 > -1$. Then, we get the moduli of λ_1 and λ_2 satisfy $|\lambda_1| > 1$ and $|\lambda_2| < 1$. As a result, $E_3 = (0, y^*)$ is a saddle point.

(2) When $\beta_2 < -2e^{y^*}/(y^{*2} - y^* - 1)$, then we can deduce that $\lambda_2 < -1$. Then, we get the moduli of λ_1 and λ_2 satisfy $|\lambda_1| > 1$ and $|\lambda_2| > 1$. As a result, $E_3 = (0, y^*)$ is an unstable focus.

As for the unique Nash equilibrium of system (5), the corresponding Jacobian matrix at $E_4 = (m^*, n^*)$ can be expressed as

$$J(E_4) = \begin{bmatrix} 1 + \beta_1 e^{-(m^*+n^*)}\left(m^{*2} - m^* - 1\right) & \beta_1 e^{-(m^*+n^*)} m^*(m^* - 1) \\ \beta_2 e^{-(m^*+n^*)} n^*(n^* - 1) & 1 + \beta_2 e^{-(m^*+n^*)}\left(n^{*2} - n^* - 1\right) \end{bmatrix}, \tag{10}$$

in which m^* satisfies the equation $2\alpha_1 m^* = \beta_1(1 - m^*)e^{-(m^*+n^*)}$ and n^* satisfies the equation $2\alpha_2 n^* = \beta_2(1 - n^*)e^{-(m^*+n^*)}$. Therefore, the trace and the determinant of the Jacobian matrix $J(E_4)$ are denoted as Tr and Det, respectively. The specific expressions corresponding to Tr and Det can be, respectively, written as follows:

$$\begin{aligned} \mathrm{Tr} &= 2 + \beta_1 e^{-(m^*+n^*)}\left(m^{*2} - m^* - 1\right) + \beta_2 e^{-(m^*+n^*)}\left(n^{*2} - n^* - 1\right), \\ \mathrm{Det} &= 1 + e^{-(m^*+n^*)}\left(\beta_1\left(m^{*2} - m^* - 1\right) + \beta_2\left(n^{*2} - n^* - 1\right)\right) + \beta_1\beta_2 e^{-2(m^*+n^*)}\left(1 - m^{*2} - n^{*2} + m^* + n^*\right). \end{aligned} \tag{11}$$

As we all know, the Nash equilibrium point E_4 is stable when the moduli of its eigenvalues corresponding to the Jacobian matrix $J(E_4)$ are all less than 1, while the forms of eigenvalues under the context of the exponential term are quite sophisticated. Therefore, we need to study the local stability around the Nash equilibrium E_4 with the help of the Jury criterion. □

Proposition 5. *The Nash equilibrium point $E_4 = (m^*, n^*)$ is asymptotically stable if and only if one of the following six conditions holds:*

(1) When $(2e^A/-C) < (e^A(-B)/D)$, the values of the parameters β_1 and β_2 satisfy $0 < \beta_2 < (2e^A/-C)$ and $\beta_1 < ((4e^{2A} + 2\beta_2 e^A C)/(2e^A(-B) + \beta_2(-D)))$

(2) When $(2e^A/-C) < ((e^A(-B))/D)$, the values of the parameters β_1 and β_2 satisfy $(2e^A/-C) < \beta_2 < ((e^A(-B))/D)$ and $\beta_1 > 0$

(3) When $(2e^A/-C) < ((e^A(-B))/D)$, the values of the parameters β_1 and β_2 satisfy $((e^A(-B))/D) < \beta_2 < ((2e^A(-B))/D)$ and $0 < \beta_1 < ((\beta_2 e^A(-C))/(e^A B + \beta_2 D))$

(4) When $(2e^A/-C) < ((e^A(-B))/D)$, the values of the parameters β_1 and β_2 satisfy $\beta_2 > ((2e^A(-B))/D)$ and $\beta_1 > ((4e^{2A} + 2\beta_2 e^A C)/(2e^A(-B) + \beta_2 D))$

(5) When $(2e^A/-C) > ((e^A(-B))/D)$, the values of the parameters β_1 and β_2 satisfy $0 < \beta_2 < ((e^A(-B))/D)$ and $\beta_1 > 0$ or $(2e^A/-C) < \beta_2 < ((2e^A(-B))/D)$ and $\beta_1 > 0$

(6) When $(2e^A/-C) > ((e^A(-B))/D)$, the values of the parameters β_1 and β_2 satisfy $((e^A(-B))/D) < \beta_2 < (2e^A/-C)$ and $\beta_1 > ((\beta_2 e^A(-C))/(e^A B + \beta_2 D))$, or $\beta_2 > ((2e^A(-B))/D)$ and $\beta_1 > ((\beta_2 e^A(-C))/(e^A B + \beta_2 D))$

where $A = m^* + n^*$, $B = m^{*2} - m^* - 1$, $C = n^{*2} - n^* - 1$, *and* $D = 1 - m^{*2} - n^{*2} + m^* + n^*$.

Proof. According to the Jury criterion, we can verify the local stability of E_4. In other words, if all of conditions of the Jury criterion hold, then we can know that the Nash equilibrium E_4 is asymptotically stable. The specific expression of the Jury criterion is given as follows:

$$\begin{cases} (i) 1 - \mathrm{Tr} + \mathrm{Det} > 0, \\ (ii) 1 + \mathrm{Tr} + \mathrm{Det} > 0, \\ (iii) 1 - \mathrm{Det} > 0. \end{cases} \quad (12)$$

Substituting the specific formulations of Tr and Det into equation (12), then we will get equivalent expressions as follows:

$$\begin{cases} (i) \beta_1\beta_2 e^{-2(m^*+n^*)}\left(1 - m^{*2} - n^{*2} + m^* + n^*\right) > 0, \\ (ii) 4 + 2\beta_1 e^{-(m^*+n^*)}\left(m^{*2} - m^* - 1\right) + 2\beta_2 e^{-(m^*+n^*)}\left(n^{*2} - n^* - 1\right) + \beta_1\beta_2 e^{-2(m^*+n^*)}\left(1 - m^{*2} - n^{*2} + m^* + n^*\right) > 0, \\ (iii) - \beta_1 e^{-(m^*+n^*)}\left(m^{*2} - m^* - 1\right) - \beta_2 e^{-(m^*+n^*)}\left(n^{*2} - n^* - 1\right) - \beta_1\beta_2 e^{-2(m^*+n^*)}\left(1 - m^{*2} - n^{*2} + m^* + n^*\right) > 0. \end{cases} \quad (13)$$

For simplicity, let $A = m^* + n^*$, $B = m^{*2} - m^* - 1$, $C = n^{*2} - n^* - 1$, and $D = 1 - m^{*2} - n^{*2} + m^* + n^*$. Since the conditions $m^* \in (0,1)$ and $n^* \in (0,1)$, then we can know that $A > 0$, $B < 0$, $C < 0$, and $D > 0$. Then, the three conditions in equation (13) are equivalent to

$$\begin{cases} (i)' & \beta_1\beta_2 D > 0, \\ (ii)' & 4e^{2A} + 2e^A\beta_1 B + 2e^A\beta_2 C + \beta_1\beta_2 D > 0, \\ (iii)' & -\beta_1 e^A B - \beta_2 e^A C - \beta_1\beta_2 D > 0. \end{cases} \quad (14)$$

According to $\beta_i > 0$ and $D > 0$, it can be judged that the condition $(i)'$ in equation (14) (that is, the first condition in the Jury criterion) always holds. Therefore, system (5) will not cross the eigenvalue 1 of the characteristic equation, namely, system (5) will not experience a transcritical bifurcation. Next, we just need to judge whether the last two conditions in the Jury criterion hold, and then, we can define local stability conditions of the Nash equilibrium point E_4. Obviously, the condition $(ii)'$ is equivalent to the form of $\beta_1(2e^A B + \beta_2 D) + 4e^{2A} + 2e^A\beta_2 C > 0$. In addition, in order to further analyze the local stability of E_4 and get the value ranges of the parameters β_1 and β_2, the inequality $\beta_1(2e^A B + \beta_2 D) + 4e^{2A} + 2e^A\beta_2 C > 0$ can be divided into two parts for discussion. One part is equivalent to $\beta_1(2e^A B + \beta_2 D) = 0$, that is, $\beta_2 = ((2e^A(-B))/D)$. Another part is equivalent to $4e^{2A} + 2e^A\beta_2 C = 0$, that is, $\beta_2 = (2e^A/-C)$. Additionally, since $(2e^A/-C) - ((2e^A(-B))/D) < 0$, that is, $(2e^A/-C) < ((2e^A(-B))/D)$, the auxiliary parameter β_i involves the adjustment speed of the firm i, and its value range can be divided into three cases as the following.

(i′) When $0 < \beta_2 < (2e^A/-C)$, $\beta_1 < ((4e^{2A} + 2\beta_2 e^A C)/(2e^A(-B) + \beta_2(-D)))$.

(ii′) When $\beta_2 > ((2e^A(-B))/D)$, $\beta_1 > ((4e^{2A} + 2\beta_2 e^A C)/(2e^A(-B) + \beta_2 D))$.

(iii′) When $(2e^A/-C) < \beta_2 < ((2e^A(-B))/D)$, $\beta_1 > ((4e^{2A} + 2\beta_2 e^A C)/(2e^A(-B) + \beta_2 D))$, while $((4e^{2A} + 2\beta_2 e^A C)/(2e^A(-B) + \beta_2 D)) < 0$, since the nonnegativity of the parameter β_1, $\beta_1 > 0$ in this case.

The above are the value ranges of the auxiliary parameter β_i that need to be satisfied, when the equivalent condition $(ii)'$ in the Jury criterion holds.

The situation is discussed as following, when the equivalent condition $(iii)'$ in the Jury criterion holds. Analogously, we will get an inequality $\beta_2 e^A C + \beta_1(e^A B + \beta_2 D) > 0$, and then, it will be discussed by divided into two cases, that is, $\beta_2 e^A C = 0$ and $\beta_1(e^A B + \beta_2 D) = 0$. In other words,

$$\begin{aligned} \beta_2 e^A C = 0 &\Leftrightarrow \beta_2 = 0, \\ \beta_1\left(e^A B + \beta_2 D\right) = 0 &\Leftrightarrow \beta_2 = \frac{e^A(-B)}{D}. \end{aligned} \quad (15)$$

The discussion in terms of β_1 has two situations.

(iv′) when $\beta_2 > ((e^A(-B))/D)$, $\beta_1 < ((\beta_2 e^A(-C))/(e^A B + \beta_2 D))$.

(v′) when $0 < \beta_2 < ((2e^A(-B))/D)$, $\beta_1 < ((\beta_2 e^A(-C))/(e^A B + \beta_2 D))$; we already know that $((\beta_2 e^A(-C))/(e^A B + \beta_2 D)) < 0$, and since the nonnegativity of the parameter β_1, so we consider that $\beta_1 > 0$ in this situation.

In order to make the Jury criterion hold, we only need to take the intersection of two of the abovementioned five conditions, that is, (i'), (ii'), (iii'), (iv'), and (v'). That is to say, if one of the above six conditions in Proposition 4 holds, then $E_4 = (m^*, n^*)$ is locally asymptotical stable. □

4. Numerical Simulation

In the nonlinear dynamical system, the phase diagram or bifurcation diagram may include a lot of information in terms of evolution process of the dynamical system. Furthermore, due to the exponential term that appears in the equation, it is very difficult for us to get an analytical solution. Therefore, it is of great necessity to exploit the method of numerical simulation to intuitively and deeply explore and display complex dynamics of a discrete-time dynamic duopoly Cournot game proposed above. The main investigation tools that we have used are 1D bifurcation diagram, 2D bifurcation diagram, the largest Lyapunov exponent diagram, the basin of attraction, etc. Hence, in this section, the dynamic behaviors of system (5) are investigated through those numerical methods mentioned above.

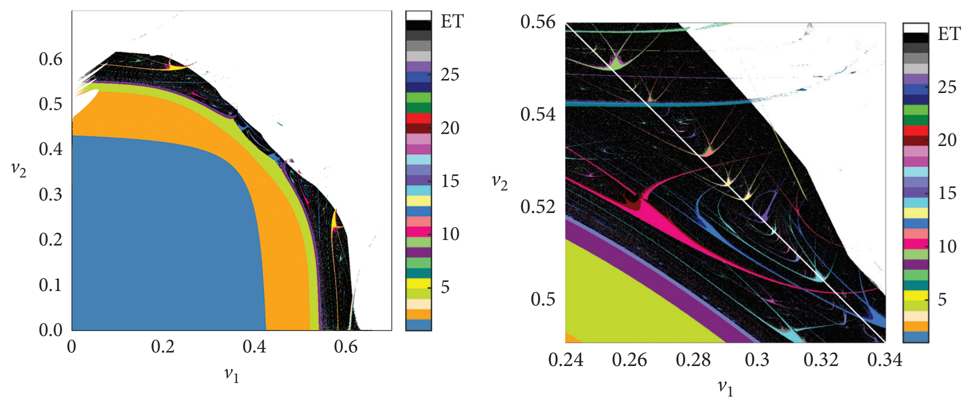
4.1. Complex Dynamic Behaviors. First, a set of parameters is fixed as $a = 11.1542$, $c_1 = 1.8044$, and $c_2 = 1.3949$, and we choose adjustment speeds v_1 and v_2 as the bifurcation parameters. As shown in Figure 1, the color bar is on the right side of figures, in which different colors denote different numbers of the period. The steel blue represents the stable area of the Nash equilibrium point, and the orange represents that the points in this area are at a period-2 state, and analogously, the grass green represents the period-4. The divergent area is denoted as the color white, which is also marked as "ET" in the color bar. However, the meaning of the dark black area is more complex, where the dynamic states included in this area, such as the quasi-period state and chaotic state. From Figure 1(a), abundant dynamic phenomena can be observed. As the values of v_1 and v_2 gradually increase, the bifurcation route of system (5) will start from the period-1 steel blue stable area, then pass through the period-2 orange area and period-4 grass green region, and finally enter into the dark black region, which means that system (5) will change from a stable state to an unstable state. Corresponding to the real economic market, this phenomenon means that if two firms blindly improve their adjustment speeds without strategy, the market will become unstable and eventually may enter into chaos. Furthermore, Figure 1(b) is a local enlargement of Figure 1(a). The structures of shrimp-like are called Isoperiodic Stable Structures (the abbreviation is ISSs), seen in Ref. [27], which can be clearly shown in Figure 1(b). The location where the shrimp-like structures are at is denoted by a white straight line, and the expression of this line is $v_2 = -5.6v_1 + 1.904$.

In Figure 2, the red curve denotes the outputs q_1 of firm 1, and the black curve denotes the outputs q_2 of firm 2. First, choose the adjustment speed v_1 as the bifurcating parameter, and the other parameters are fixed as $a = 11.1542$, $c_1 = 1.8044$, $c_2 = 1.3949$, and $v_2 = 0.1$. Under this group of parameters, system (5) will go through a flip bifurcation at first and finally drop into a chaotic state, as shown in Figure 2(a). The bifurcation diagram of q_2 with respect to v_1, marked by a black box, is displayed in the enlargement. From Figure 2(a), when the adjustment speed of firm 1 satisfies $v_1 < 0.4197$, system (5) is at a period-1 stable state. In addition, $v_1 = 0.4197$ is a bifurcation point, which means that the stability of system (5) at this point will completely change, and then, a period-doubling bifurcation subsequently occurs. Once the value of v_1 is greater than 0.5371, system (5) will uncontrollably reach a disordered chaotic state.

Under same parameter conditions, it can be seen from Figure 2(b) that the dynamic behaviors of system (5) are very complicated when shrimp-like structures appear. At this time, the blue curve represents the largest Lyapunov exponent curve corresponding to the red bifurcation curve. It is well known that we can easily determine the state of a dynamical system through calculating its Lyapunov exponents, and we usually need to calculate the largest one. Therefore, the dynamical system corresponds to a stable state, if the largest Lyapunov exponent is less than zero. Instead, if the largest Lyapunov exponent is greater than zero, it means that the dynamical system is at a chaotic state. In addition, it is worth noting that the largest Lyapunov exponents fluctuate up and down around zero, and then, the dynamical system is at a quasi-period state. There are many phenomena of "periodic window" that exist, and system (5) constantly transforms between the chaotic state and the periodic stable state. With the parameter v_1 further increasing, system (5) will enter a stable state from a chaotic state for a short time and finally return to the chaotic state.

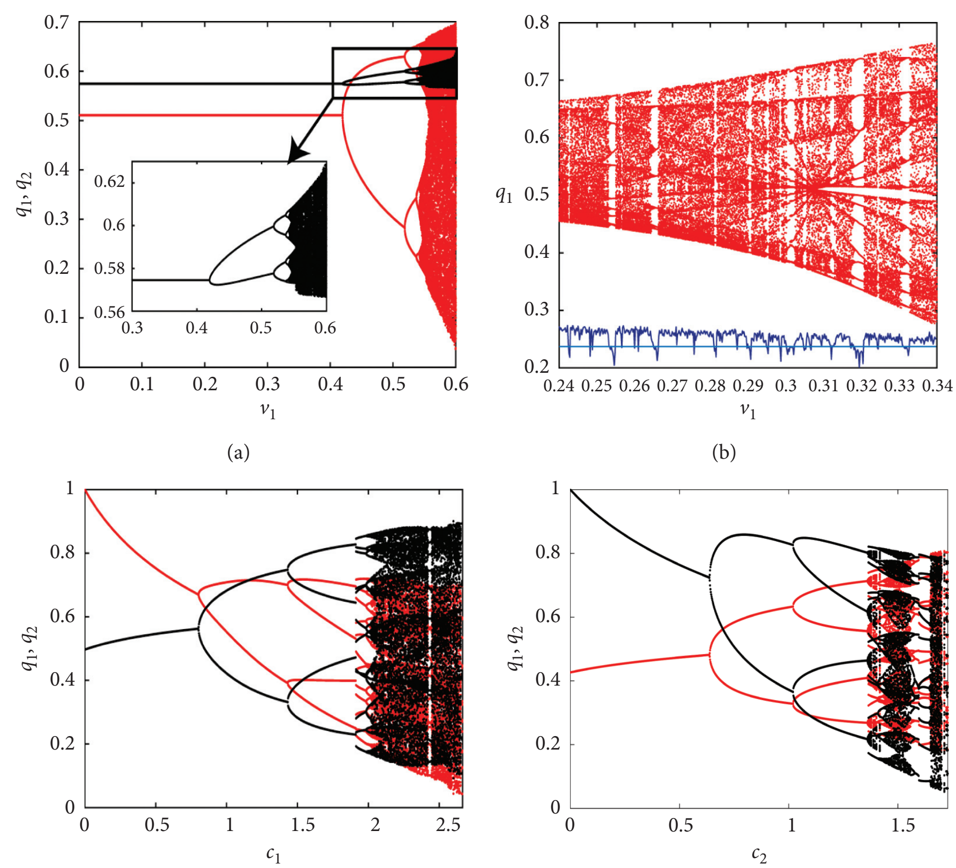
When the parameters are changed to $a = 11.1542$, $v_1 = 0.3625$, and $v_2 = 0.4517$, then we can get two bifurcation diagrams with respect to costs of two firms, respectively. As shown in Figure 2(c), where $c_2 = 1.8$, when $c_1 < 0.7755$, system (5) is at the period-1 stable state. At $c_1 = 0.7755$, a typical flip bifurcation (also called period-doubling bifurcation) occurs. In addition, it is worth to notice that an obvious phenomenon called "jump" appears near $c_1 = 1.8723$, which means that there may be a phenomenon of coexistence. Similarly, we choose $c_1 = 1.8$ in Figure 2(d),then we can know that $c_2 = 0.6330$ is a bifurcation point, and once system (5) crosses this point, then a flip bifurcation will occur. The dynamic phenomena between $1.3500 < c_2 < 1.4180$ are very complicated. There is also a "jump" phenomenon that exists near $c_2 = 1.6083$. With constant increase of costs of two firms, dynamical system (5) will eventually enter into chaos. However, through comparing Figures 2(c) and 2(d), we can draw a result that, under the premise of same costs, the speed of the system entering into chaos with c_2 is higher than that with c_1.

Another group of parameters are fixed as $a = 11.6054$, $c_1 = 2.9154$, and $c_2 = 2.9639$, and we choose adjustment speeds v_1 and v_2 as the bifurcating parameters. A totally different 2D bifurcation diagram is shown in Figure 3(a), in which many colorful and symmetrical structures exist. Similarly, the dark black area includes complex phenomena such as chaos and quasiperiodic states, and the white area denotes the divergent area. It is worth noticing that the dynamic behaviors, marked in a red box, have significances to investigate. Hence, we enlarge it in Figure 3(b) and increase the number of periods to 200. As shown in Figure 3(b), abundant and complex dynamic phenomena are displayed. There are many fractal structures that can be seen, and the eye-shaped structure is symmetrically arranged on both sides of the ribbon. The dynamical behaviors, located in a white box of Figure 3(b), are enlarged in Figure 3(c).



(a) (b)

FIGURE 1: Fixed the parameters as $a = 11.1542$, $c_1 = 1.8044$, and $c_2 = 1.3949$. (a) The double-parameters' bifurcation diagram of system (5). (b) The local enlargement of Figure 1(a).



(a) (b)

(c) (d)

FIGURE 2: Fixed the parameters as $a = 11.1542$, $c_1 = 1.8044$, and $c_2 = 1.3949$. The red curve denotes q_1 of firm 1, and the black curve denotes q_2 of firm 2. (a) The 1D bifurcation diagram when $v_2 = 0.1$. (b) Corresponding to Figure 1(b), the 1D bifurcation diagram on the white straight line is displayed with its largest Lyapunov exponent diagram. Fixed the parameters as $a = 11.1542$, $v_1 = 0.3625$, and $v_2 = 0.4517$. (c) The 1D bifurcation diagram when $c_2 = 1.8$. (d) The 1D bifurcation diagram when $c_1 = 1.8$.

Obviously, there are apparent V-shaped islands called ISSs structures, which are marked as ***a***, ***b***, and ***c*** in the yellow box. It is known that this kind of structures are Lyapunov stable structures or Lyapunov stable islands, that is, if parameters are chosen in these structures, the state of the dynamical system is regular and stable, seen in Ref. [27]. Since the 2D

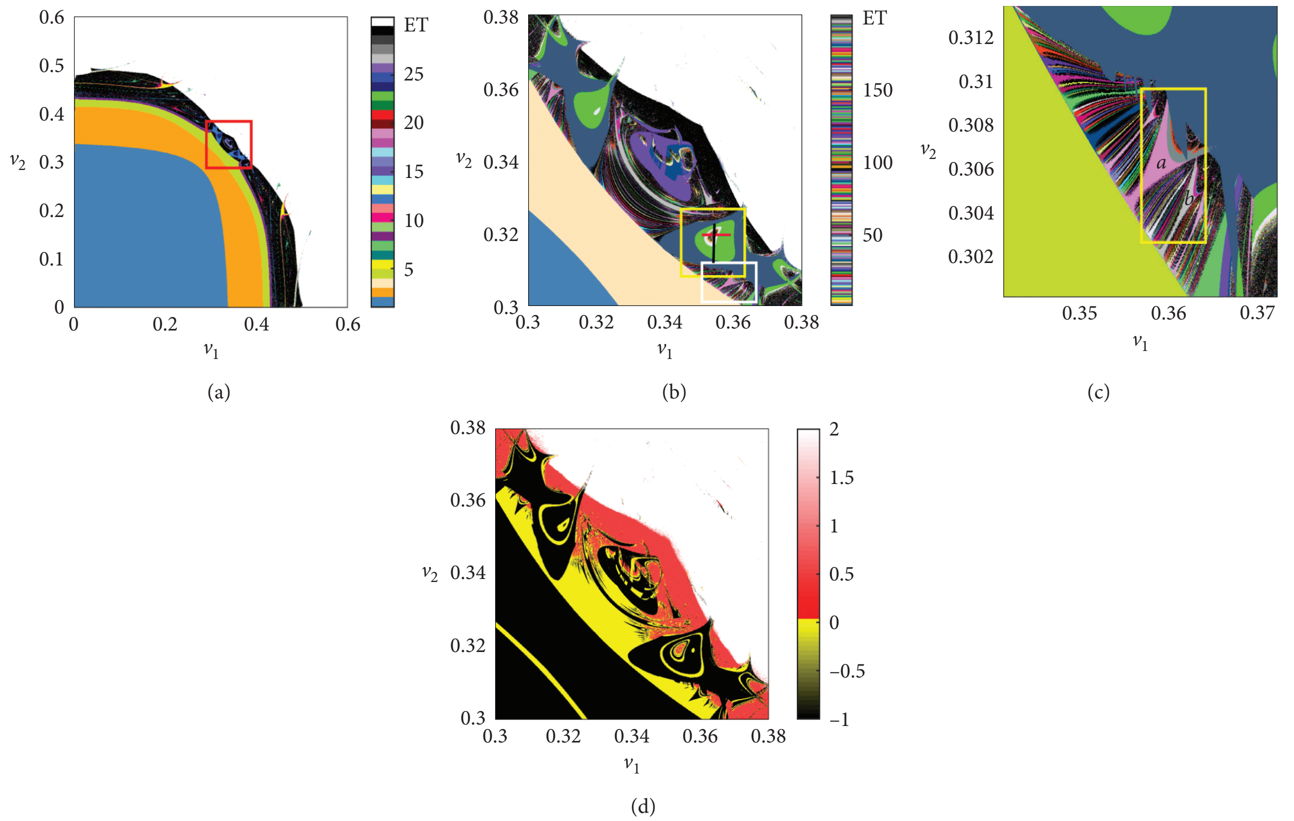


FIGURE 3: Fixed the parameters as $a = 11.6054$, $c_1 = 2.9154$, and $c_2 = 2.9639$. (a) The double-parameter bifurcation diagram with two bifurcating parameters. (b) The enlargement corresponds to the red box in Figure 3(a), while we increase the number of periods to 200 and abundant dynamic phenomena appear. (c) The enlargement corresponding to the white box in Figure 3(b), where we can clearly see that ISSs (shrimp-like) structures exist, which are labeled by **a**, **b**, and **c** (d). The 2D Lyapunov exponent diagram corresponding to Figure 3(b).

Lyapunov exponent diagram is a useful tool to clearly distinguish stable state, quasi-periodic state, chaotic state, and divergent state, we can clearly see the states of the dynamical system. That is to say, if the largest Lyapunov exponent is less than 1 corresponding to the black area in Figure 3(d), the dynamical system corresponds to the periodic state or stable state. When the largest Lyapunov exponent is equal to zero corresponding to the yellow area in Figure 3(d), then the dynamical system is at the quasi-period state. If the largest Lyapunov exponent is greater than zero and less than 2 corresponding to the red area, then the dynamical system corresponds to the chaotic state. Finally, when the largest Lyapunov exponent is equal to 2 corresponding to the white area, the dynamical system is at the divergent state. Therefore, by exploiting the 2D Lyapunov exponent diagram, we can easily distinguish the states of system (5) under this group of parameters and verify that ISSs' structures are indeed Lyapunov stable structures.

The single-parameter diagrams of the eye-shaped structure with respect to adjustment speeds are displayed in Figure 4, where the red curve represents q_1 of firm 1 and the blue curve represents q_2 of firm 2. As shown in Figure 4(a), this bifurcation diagram corresponds to the red line of the yellow box in Figure 3(b), when we fix the adjustment speed of firm 2 as 0.3193. The dynamic behaviors of this eye-shaped structure are quite complex. We can clearly observe that there is a period-doubling bifurcation at first, and then, system (5) will transiently enter into chaos; finally, a period-halving bifurcation occurs, when $v_1 \in (0.345, 0.364)$. This way of bifurcation is also called "hub of periodicity." Similarly, we can also see this kind of bifurcation in Figure 4(b) when we fix the adjustment speed of firm 2 as 0.3193, which corresponds to the black line of the yellow box in Figure 3(b). When $v_2 \in (0.31, 0.322)$, system (5) has a same bifurcation way as that in Figure 4(a). That is to say, the system will experience a period-doubling bifurcation at first and then enter into chaos, and another period-halving bifurcation arises.

In a nutshell, we can also know that both firms, considered in this paper, enter into chaos through a flip bifurcation, and the flip bifurcation is a typical route for a firm to enter into chaos from a steady state after the institutional or technological reform under an ever-changing era. Furthermore, both the two firms are in the Nash equilibrium state when the adjustment speeds are relatively small. At this time, we can adjust strategy within the stable threshold to maximize their respective interests. However, once the adjustment speed exceeds the stable threshold, the stability

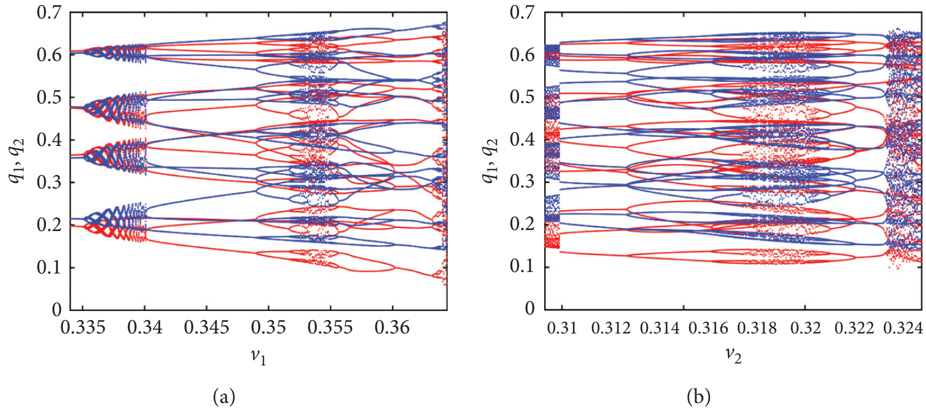


FIGURE 4: Fixed the parameters as $a = 11.6054$, $c_1 = 2.9154$, and $c_2 = 2.9639$. The red curve represents q_1 of firm 1, and the blue curve represents q_2 of firm 2. (a) The single-parameter bifurcation diagram corresponds to the red line of the yellow box in Figure 3(b), when $v_2 = 0.3193$. (b) The single-parameter bifurcation diagram corresponds to the black line of the yellow box in Figure 3(b), when $v_1 = 0.3539$.

of the Nash equilibrium point will be destroyed, and the economic market will enter into chaos after the firms ceaselessly do choice games.

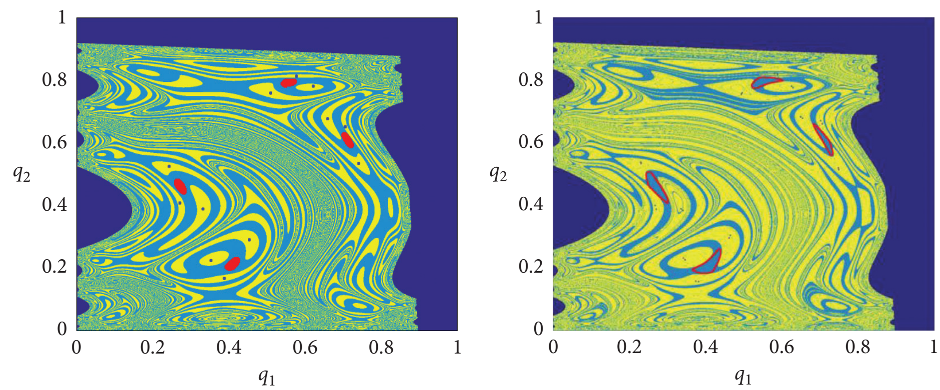
4.2. Multistability. The basin of attraction is used to further investigate complex dynamic behaviors of system (5) in long run. It can be seen from the area near $v_1 \approx 0.45$ and $v_2 \approx 0.35$ in Figure 1(a) that the stable period-4 grass green area is doped with a small part of period-12 lake blue area and period-24 dark blue area, which means that there may be the phenomenon of coexisting attractors.

We keep fixing the parameters as $a = 11.1542$, $c_1 = 1.8044$, and $c_2 = 1.3949$ and choose the adjustment speeds v_1 and v_2 as bifurcation parameters; then, we can get a group of basins of attraction, as shown in Figure 5. The blue points represent attractors, and their stable region is the yellow area. The invariant cycles are denoted as red, and their stable region is marked as the dark sky blue area. The divergent area and chaotic area are denoted by dark blue. In Figure 5(a), the adjustment speeds of two firms are chosen as $v_1 = 0.3605$ and $v_2 = 0.4517$, respectively. There is a coexistence of period-12 attractors and period-4 invariant cycles, and there are many "holes" on boundaries of the basin of attraction. Furthermore, both the values of v_1 and v_2 increase in Figure 5(b), where $v_1 = 0.3625$ and $v_2 = 0.4527$. Apparently, the "holes" at the boundaries of the basin of attraction have not changed significantly. At this time, the complex dynamic behavior of system (5) is depicted as the coexistence of period-24 attractors and period-4 invariant cycles. However, we can clearly see that the dark sky blue stable area is constantly occupied by the yellow attracting area. We can find that the period-4 invariant cycles will keep on becoming bigger until their borders contact the boundary of the yellow-attracting area of periodic attractors; then, a "contact bifurcation" [15] will occur, and the invariant cycles will break and disappear.

Furthermore, we assume from the 2D bifurcation diagram in Figure 1(a) that there is a phenomenon of coexistence of attractors after choosing appropriate parameters in the parameter space. With the adjustment speeds of these two firms gradually increasing, the number of coexisting attractors increases from 12 to 24, and it means that system (5) may get unstable as v_1 and v_2 increase. Again, it shows that, in the economic market, system (5) will remain relatively stable when both firms have small adjustment speeds.

As shown in Figure 6, the values of parameters are chosen as $a = 10.9788$, $c_1 = 0.0806$, and $c_2 = 0.2799$, and we similarly choose v_1 and v_2 as bifurcation parameters. The shapes of these basins of attraction are very peculiar. The green area represents the divergent region, and the points in this region will tend to infinity and finally trap into the chaotic state. The yellow area is the flexible area corresponding to black periodic points or black invariant cycles. In other words, the stable region of these black attractors is the yellow region. The flexible area of other pink attractors is the gray region. In addition, the phenomenon of multistability occurs when $v_1 = 1.1940$ and $v_2 = 0.6810$, and there are period-4 pink attractors coexisting with period-12 black attractors, which can be clearly seen in Figure 6(a). The boundary shape of basin of attraction is irregular, and there are many large "holes" in the upper and lower boundaries of basin of attraction. Then, we keep parameter v_1 unchanged and increase the value of v_2 to 0.6840, and there still is a phenomenon of coexistence between distinct numbers of periodic attractors in Figure 6(b). That is, the period-12 attractors bifurcate to the period-24 attractors via a period-doubling bifurcation. Moreover, viewing this situation from a whole, yellow region occupies a large number of spaces of the gray region, and the whole shape of basin does not significantly change. There is a pretty fractal structure on the head of basin of attraction in Figure 6(b), which is enlarged in Figure 6(c).

However, when the bifurcation parameters are varied as $v_1 = 1.1671$ and $v_2 = 0.7110$, another different coexisting situation will arise. Four-piece black invariant cycles coexist with period-16 pink points, and there is the phenomenon of "holes" appearing at all boundaries of basin of attraction, as shown in Figure 6(d). The boundaries of invariant cycles almost contact with the borders of their flexible area, and a



(a) (b)

FIGURE 5: Fixed the parameters as $a = 11.1542$, $c_1 = 1.8044$, and $c_2 = 1.3949$. A group of basins of attraction corresponding to system (5) when varying the adjustment speeds v_1 and v_2. The yellow area is the stable region of blue attractors, and the dark sky blue area is the stable region of red invariant cycles. In addition, the divergent area and chaotic area are denoted by dark blue. (a) $v_1 = 0.3605$ and $v_2 = 0.4517$. (b) $v_1 = 0.3625$ and $v_2 = 0.4527$.

"contact bifurcation" may happen. In the following steps, we just change the value of adjustment speed v_2. It can be clearly seen in Figure 6(e) that the black invariant cycles have completely disappeared due to a contact bifurcation. Instead, only two pieces of chaotic attractors exist inside the basin of attraction, and the "holes" on the boundaries of basin of attraction slightly become much bigger and bigger. Interestingly, these two pieces chaotic attractors gradually become larger and finally connect each other to form one piece chaotic attractor, where there may be a homoclinic bifurcation that happens in Figure 6(f). Consequently, the firms should not substantially increase their adjustment speeds in order to improve their own interests because this will not only not generate considerable profits but also will lead to a disordered competition among firms, then enter into a chaotic state, and never able to return to a stable state. Even if we make small adjustments to the adjustment speed, it will have an irreversible effect on the whole economic system in the market. Therefore, the system will be more stable if the firm maintains a relatively small adjustment speed.

4.3. Global Dynamics and Critical Curves. Through the above simple investigations of basin of attraction, we will exploit the method of critical curves to further study some global properties of system (5) and the reason of "holes" formation and its evolution process. It is well known that the term LC (which is a brief expression of the term critical curve) originates from notion of critical points in one-dimensional map. The global bifurcation is the main reason, which causes qualitative change of the basin of attraction. Firstly, the rank-1 preimage LC_{-1} of critical curves LC is formed by a trajectory of points where the determinant of the Jacobian matrix disappears. In other words, LC and LC_{-1} satisfy a relation that $LC = T(LC_{-1})$, that is, the points on LC_{-1} will be mapped to LC through mapping T. In this situation, the points on the LC_{-1} need to satisfy a condition, that is, the determinant of Jacobian matrix (6) is equal to zero. Those points satisfy the equation as follows:

$$\begin{aligned}&\left(-4\left(\alpha_2 q_2-\frac{1}{4}\right)\left(q_1^2-3q_1+1\right)\beta_1-4\left(\alpha_1 q_1-\frac{1}{4}\right)\left(q_2^2-3q_2+1\right)\right)\beta_2\Big)e^{-q_1-q_2}\\&-2\beta_1\beta_2\left(\left(q_2-\frac{1}{2}\right)q_2^2+\left(q_2-4q_2+\frac{3}{2}\right)q_1-\frac{q_2^2}{2}+\frac{3q_2}{2}-\frac{1}{2}\right)e^{-2q_1-2q_2}\\&+16\left(\alpha_1 q_1-\frac{1}{4}\right)\left(\alpha_2 q_2-\frac{1}{4}\right)=0.\end{aligned} \tag{16}$$

Obviously, the expression of equation $\mathrm{Det}(J) = 0$ is very complex so that we cannot directly obtain analytic solutions with respect to q_1 and q_2. However, we can graphically display the shape of LC_{-1} by numerical simulation. Two magenta branches of a hyperbola consist the LC_{-1}, which is denoted as $LC_{-1}^{(a)}$ and $LC_{-1}^{(b)}$, respectively. The critical curve LC is formed by two curves, marked by $LC^{(a)}$ and $LC^{(b)}$, where $LC^{(a)} = T(LC_{-1}^{(a)})$ and $LC^{(b)} = T(LC_{-1}^{(b)})$. It is apparent that these two critical curves separate the plane (q_1, q_2) into three zones Z_0, Z_2, and Z_4. That is to say, $LC^{(b)}$ separates zone Z_0 from zone Z_2 and $LC^{(a)}$ separates zone Z_2 from Z_4. The points in zone Z_0 have no preimages, while the

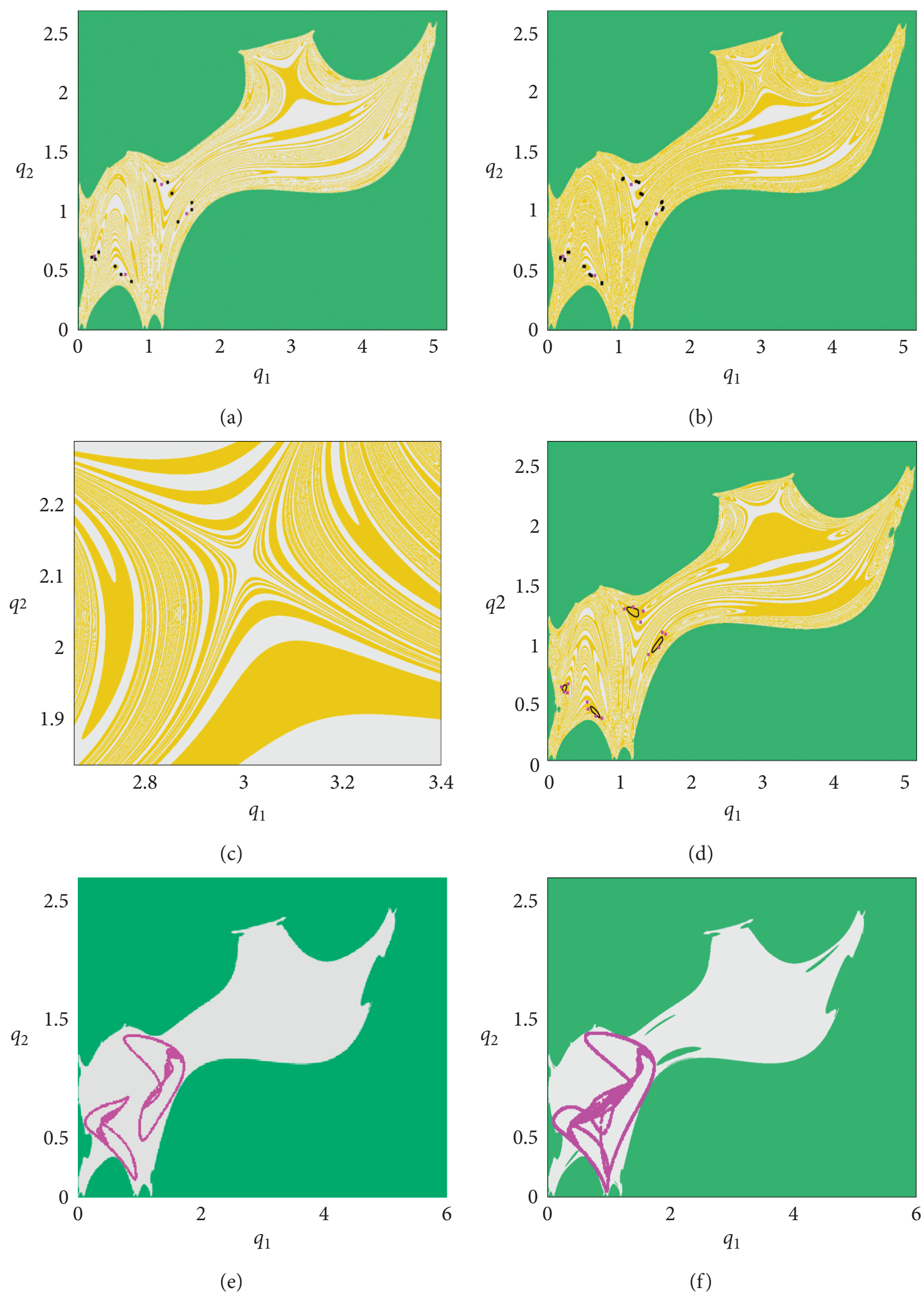


FIGURE 6: Fixed the parameters as $a = 10.9788$, $c_1 = 0.0806$, and $c_2 = 0.2799$. A group of basins of attraction corresponding to system (5) when varying the adjustment speeds v_1 and v_2. (a) $v_1 = 1.1940$ and $v_2 = 0.6810$. (b)$v_1 = 1.1940$ and $v_2 = 0.6840$. (c) The local enlargement corresponding to Figure 6(b) shows a manifest fractal structure. (d) $v_1 = 1.1671$ and $v_2 = 0.7110$. (e) $v_1 = 1.1671$ and $v_2 = 0.7264$. (f) $v_1 = 1.1671$ and $v_2 = 0.7307$.

points in zone Z_2 have two different rank-1 preimages, and the points in zone Z_4 have four distinct rank-1 preimages. It is usual that the origin point $O = (0,0)$ always locates in the zone Z_4, which means that the origin point $O = (0,0)$ has four different rank-1 preimages. One of them is itself, $O = (0,0)$. Two of them are located on coordinate axes, $O_{-1}^{(1)} = (q_1^*, 0)$ and $O_{-1}^{(2)} = (0, q_2^*)$, where q_1^* satisfies the equation $\beta_1(1-q_1)e^{-q_1} = 2\alpha_1 q_1$ and q_2^* satisfies the equation $\beta_2(1-q_2)e^{-q_2} = 2\alpha_2 q_2$. The last one is $O_{-1}^{(3)} = (q_1^{**}, q_2^{**})$, which is the intersection of preimages of two lines $OO_{-1}^{(1)}$ and $OO_{-1}^{(2)}$. That is to say, line $O_{-1}^{(2)}O_{-1}^{(3)}$ is the preimage of line $OO_{-1}^{(1)}$, and line $O_{-1}^{(1)}O_{-1}^{(3)}$ is the preimage of line $OO_{-1}^{(2)}$. q_1^{**} and q_2^{**} simultaneously satisfy the formula as follows:

$$\begin{cases} 0 = \beta_2 (1 - q_2) e^{-(q_1+q_2)} - 2\alpha_2 q_2, \\ 0 = \beta_1 (1 - q_1) e^{-(q_1+q_2)} - 2\alpha_1 q_1. \end{cases} \quad (17)$$

These four preimages of origin point $O = (0,0)$ form the size and vertexes of the basin of attraction.

As shown in Figure 7, the parameters are fixed as $a = 11.1542$, $c_1 = 1.8044$, and $c_2 = 1.3949$. According to above-proposed Propositions 2–4, we can easily judge out that origin point $O = (0,0)$ is always an unstable node and both $O_{-1}^{(1)}$ and $O_{-1}^{(2)}$ are saddle points. Moreover, $O_{-1}^{(1)}$ has a stable manifold along line $OO_{-1}^{(1)}$ on q_1-axis, and $O_{-1}^{(2)}$ also has a stable manifold along line $OO_{-1}^{(2)}$ on q_2-axis. In Figure 7(a), when bifurcation parameters are chosen as $v_1 = 0.3625$ and $v_2 = 0.4517$, we can obviously see that only period-2 blue points exist inside the basin of attraction and its stable area is marked as yellow. There are no "holes" on the boundary of basin of attraction because the critical curves, $LC^{(a)}$ and $LC^{(b)}$, are totally inside the basin of attraction. The stable manifolds on the boundaries of basin, $OO_{-1}^{(1)}$ and $OO_{-1}^{(2)}$, have not been destroyed. However, one of critical curves, $LC^{(b)}$, almost contacts with the boundary line $O_{-1}^{(2)}O_{-1}^{(3)}$ and already contacts with one of two period-2 points. With the adjustment speed v_2 increasing to 0.4257, the period-2 points bifurcate to the period-4 points via a flip bifurcation. Since the critical curve $LC^{(b)}$ once has crossed rank-1 preimage point $O_{-1}^{(2)}$, then the stability of stable manifold of $O_{-1}^{(2)}$ will not exist anymore. It can be clearly seen from Figure 7(b) that the phenomenon "holes" occurs on the line $OO_{-1}^{(2)}$ and its preimage $O_{-1}^{(1)}O_{-1}^{(3)}$. This kind of bifurcation which has been mentioned in the previous section can be called a "contact bifurcation." As v_2 constantly increases, a new phenomenon of coexisting attractors arises, that is, period-12 points coexist with period-4 invariant cycles, as shown in Figure 7(c). The size of "holes" apparently becomes bigger than before. Moreover, it is worth noticing that period-4 red invariant cycles gradually get bigger till they contact with a branch of critical curves, $LC^{(b)}$. Then, there will be another "contact bifurcation" occurrence. As shown in Figure 7(d), four invariant cycles simultaneously break, and period-12 newly forms into four pieces of chaotic attractors. There are some phenomena of "lakes" that appear inside the basin of attraction. These four pieces of chaotic attractors get bigger as the parameters v_1 and v_2 increase till they contact with critical curves $LC^{(a)}$ and $LC^{(b)}$. Then, there will be a "final bifurcation" [15], which causes the destruction of four pieces of chaotic attractors and leads the adjustment mechanism to lose its predictability. Although these four pieces of chaotic attractors disappear after a "final bifurcation," its skeleton still exists inside the original basin of attraction, which is formed by uncountable dense points. Finally, the structure of basin of attraction has been completely destroyed with dense repelling points nested inside. As mentioned above, this phenomenon can be called as "ghost." Hence, a contact between the boundary of basin of attraction and critical curves or a contact between the boundary of chaotic attractors and critical curves both do have the negative influence on the stability of the structure of the basin of attraction. They may destroy the stability property of system (5) and may cause nonpredictability of tendency of game process.

A group of basins of attraction with interesting shapes of "holes" located on the boundary can be observed, when we fix the parameters as $a = 11.1542$, $v_1 = 0.3625$, and $v_2 = 0.4517$ and choose parameters c_1 and c_2 as bifurcation parameters. The meanings of magenta curves, green curves, and two black lines are same as in Figure 7. As shown in Figure 8, we change the values of production cost of two firms to investigate their influence on the shape and stability property of the basins of attraction. The origin point $O = (0,0)$ is still an unstable node, and its manifolds along both q_1-axis and q_2-axis which are unstable, while both $O_{-1}^{(1)}$ and $O_{-1}^{(2)}$ are saddle points so that $O_{-1}^{(1)}$ has a stable manifolds along line $OO_{-1}^{(1)}$ on q_1-axis and $O_{-1}^{(2)}$ also has a stable manifold along line $OO_{-1}^{(2)}$ on q_2-axis. As shown in Figure 8(a), when we fix the bifurcation parameters as $c_1 = 2.8860$ and $c_2 = 0.9090$, there are period-12 blue periodic points coexisting with period-4 black periodic points, where the stable areas corresponding to period-4 blue points and period-4 black points are marked as pink and orange, respectively. The blue area represents the divergent area. Another significant phenomenon is that a branch of critical curves, $LC^{(b)}$, have already crossed both $O_{-1}^{(1)}$ and $O_{-1}^{(2)}$, which means that two stable manifolds along line $OO_{-1}^{(1)}$ on q_1-axis and line $OO_{-1}^{(2)}$ on q_2-axis both have been completely destroyed. As a consequence, the phenomena of "holes" in the shape of aliens, but of different sizes, appear on all boundaries of the basin of attraction.Because the critical curve $LC^{(b)}$ has contacted with period-12 blue points, and then, it is highly possible that a "contact bifurcation" may happen. Then, we fix the value of c_1 unchanged and increase the value of c_2 little by little to 0.9590, so we can clearly see in Figure 8(b) that a "contact bifurcation" do occurs, and there are phenomena of "lakes" that also appear besides the phenomena of "holes" on boundaries of basin. In addition, period-4 black points coexist with period-12 chaotic attractors, where the stable attracting area of period-4 black points is still the orange area and the stable attracting area of chaotic attractors is the pink area. In this situation, the critical curve $LC^{(b)}$ contacts with chaotic attractors. Moreover, after this kind of contact, the chaotic attractors will first become bigger for a very short time and then break but still exist in original basin of attraction, as shown in Figure 8(c). However, this phenomenon is not so called "ghost," because the period-4 black points still exist inside the basin of attraction and have their own domain of attraction in plane (q_1, q_2). We also can clearly see that the "lakes" notably grow bigger.

As the value of c_2 constantly increases to 1.0750, period-4 points bifurcate to two pieces of chaotic attractors, and its stable area is still the orange area, while the pink area disappears, which can be clearly displayed in Figure 8(d). The "lakes" inside the basin of attraction have been connected with the "holes" on the boundary of basin of attraction and newly form interesting shapes of "holes" located on all sides of basin of attraction. It is apparent that the boundary of two pieces of black chaotic attractors almost contacts again with both two branches of critical curves.

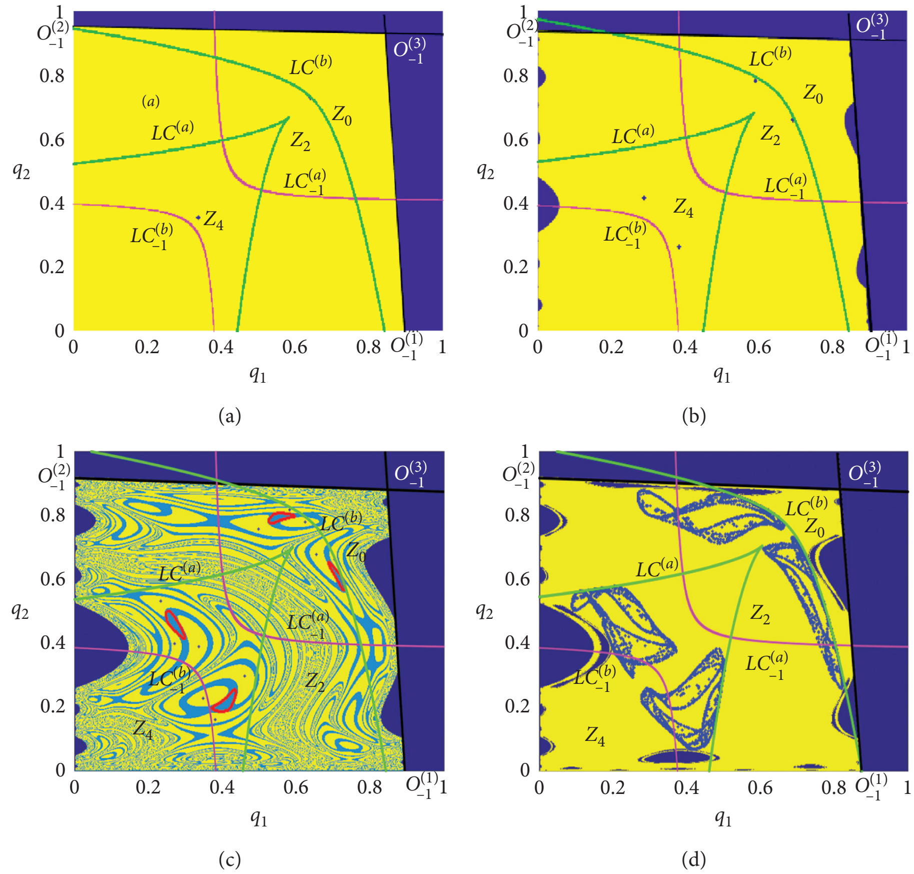


FIGURE 7: Fixed the parameters as $a = 11.1542$, $c_1 = 1.8044$, and $c_2 = 1.3949$. The boundaries of basin of attraction are denoted as the black lines. The magenta curves represent preimages of critical curves. The critical curves of system (5) are denoted as green curves, and these two critical curves separate the plane into three zones, labeled by Z_0, Z_2, and Z_4. (a) $v_1 = 0.3625$ and $v_2 = 0.4057$. (b) $v_1 = 0.3625$ and $v_2 = 0.4257$. (c) $v_1 = 0.3625$ and $v_2 = 0.4517$. (d) $v_1 = 0.3875$ and $v_2 = 0.4517$.

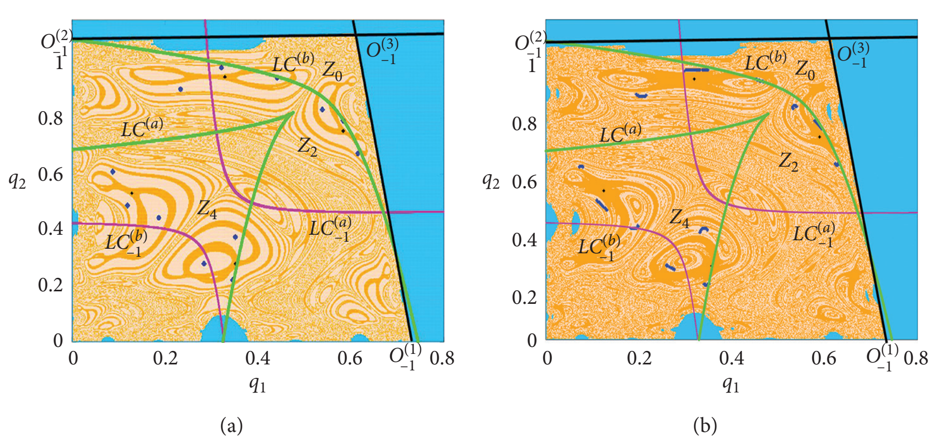


FIGURE 8: Continued.

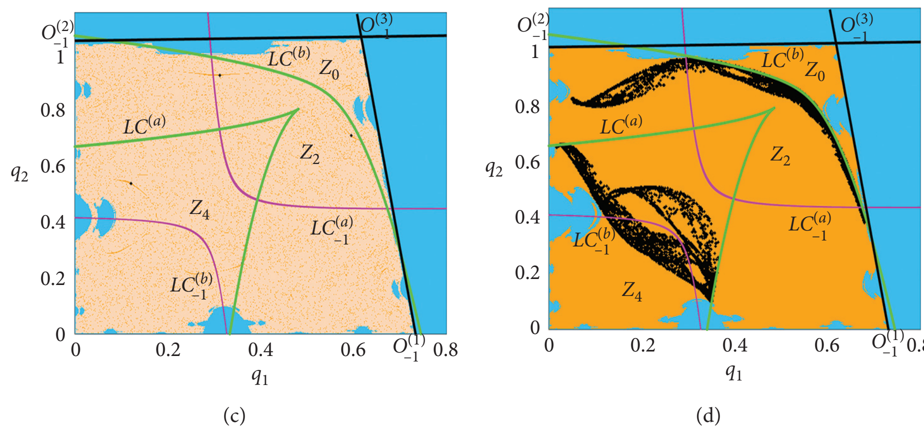


FIGURE 8: Fixed the parameters as $a = 11.1542$, $v_1 = 0.3625$, and $v_2 = 0.4517$. The boundaries of basin of attraction are denoted as the black lines. The magenta curves represent preimages of critical curves. The critical curves of system (5) are denoted as green curves, and these two critical curves separate the plane into three zones, labeled by Z_0, Z_2, and Z_4. (a) $c_1 = 2.8860$ and $c_2 = 0.9090$. (b) $c_1 = 2.8860$ and $c_2 = 0.9590$. (c) $c_1 = 2.8860$ and $c_2 = 1.0000$. (d) $c_1 = 2.8860$ and $c_2 = 1.0750$.

Finally, there will be a "final bifurcation" occurrence. Consequently, these two pieces of chaotic attractors simultaneously break out but their skeletons of the basin of attraction still exist, which are formed by infinitely many unstable points. Hence, increasing the value of a pair of parameters c_1 and c_2 similarly has significant influence on the stable property and structure of the basin of system (5). The firms in the market better consider to take some actions to decrease its production cost, as one of them has high cost that may irreversibly lead the game to a chaotic state so that the future destiny of firms cannot be forecasted.

5. Conclusions

In this paper, on the basis of considering the exponential demand function, the cost function is improved to quadratic cost. The firms considered in the market both have incomplete market information. Therefore, they are boundedly rational. Then, a discrete-time evolution model of the duopoly game with bounded rationality is built. The gradient adjustment mechanism is introduced to adjust the production strategy. Although we have analyzed the local stability property of both boundary equilibrium points and Nash equilibrium point, we cannot obtain a clear analytic solution. Hence, we utilize numerical simulation to further study more properties and the influence of parameters on the stability of the established model. With the parameters continually changing, there are complex dynamic phenomena that arise, such as V-shaped structures (ISSs), eye-shaped structures, and the coexistence between different periods periodic points, or between periodic points and invariant cycles, or between periodic points and chaotic attractors. Through the method of critical curves, we describe the change process of the structure of basin of attraction and then the causes of "holes" formation. As a result, once the parameters exceed the stable threshold, the global bifurcations such as "contact bifurcation" and "final bifurcation" may appear, and then, the market will irreversibly enter into a chaotic state after the firms ceaselessly do choice games.

Data Availability

No data were used to support the findings of this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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Research Article

Selecting the Strategic Port of "the Belt and Road" Based on the Global Network

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Under "the Belt and Road" initiative, China promoted cooperation between domestic enterprises and international ports vigorously, which brought back fruitful results, while the rational selection of strategic pivots ports and the optimization of the layout of the port network are important guarantees to a further promotion to the economic development of "the Belt and Road" ports and give full play to the driving and radiation role of strategic pivots ports. On the basis of constructing a network of 155 ports in the world, according to the number of ports crossed by the shortest path and betweenness centrality in the network, this paper uses K-Medoids clustering algorithm to train the strategic importance of ports and verifies the reliability of the analysis results. On this basis, the joint coverage analysis of strategically important ports is carried out, 17 ports are identified as strategic pivots ports of the global port network, and, finally, based on the two attributes of "the Belt and Road" and "Chinese enterprise participation" of strategic pivots ports, the leading role of strategic pivots ports in geographical location, path coverage, development potential, cooperation stability, and control is analyzed, and instructive suggestions are put forward.

1. Introduction

Since China launched "the Belt and Road" initiative in 2013, China's nonfinancial investment in "the Belt and Road" Agreement countries has exceeded US$100 billion by the end of 2019 (over the past seven years, China's total imports and exports of goods with countries along "the Belt and Road" have increased to $1.34 trillion[N]. Economic Daily, 2020-09-07), including 103 port cooperation projects involving 94 ports (the original reference is 101 projects involving 90 ports, and this article completes the data until August 2020) [1]. Not only are international ports the foundation and artery of international trade, but also the resulting network is an important platform to promote international industrial integration and optimize the allocation of international resources, and the world in the operation of more than 480 international ports, each port in geographical location, throughput capacity, cargo adaptability, and hinterland countries industrial economic conditions and bilateral trade relations with China and other countries have certain differences. Therefore, in the network of international ports, how to determine the strategic pivots of ports, effectively lay out the global port network, open up a new engine of port economic development, play the leading role of "the Belt and Road" initiative, and further promote the integration of China and "the Belt and Road" countries along the political and economic relations are of great significance.

From a global perspective, international politics and economics, as well as global governance and international rules, place new historical demands on "the Belt and Road" initiative's international cooperation in the areas of global debt and financing, green development, inclusive development, transparency and anticorruption, and third-party market cooperation [2]. "The Belt and Road" initiative is a major strategy for China to implement all-round opening up to the outside world and has built a new platform for mutually beneficial and win-win cooperation for deepening and expanding new sino-foreign cooperative relations, forming a multilevel and multiform pattern of cultural and economic exchanges, accelerating the economic transformation, and upgrading and developing the countries along the path in the new era [3]; based on economic exchanges, political mutual trust, people-to-people exchanges, and civilizational mutual learning, the common development of countries and regions along the path on the basis of "common business, coconstruction, and sharing" has been promoted, and the construction of a community of human destiny in the new era has been accelerated [4]. With the continuous promotion of "the Belt and Road," the current domestic affairs and contemporary international affairs have been integrated; in order to promote the reform of global economic governance, we must use the development-oriented and practical rationality to strengthen each other's theoretical thinking, combined with the practice of "development win-win" inclusive globalization operation logic, and put forward the "China Program" of global economic governance with inclusive development mechanism as the core concept [5].

From the perspective of national strategy, the essence of the "the Belt and Road" network economy is the logistics and communication network between countries, and its development focuses on the cognition and practice among countries, so the perspective of "the Belt and Road" is the spatial paradigm of network form, not geopolitical strategy [6]. On the one hand, "the Belt and Road" initiative not only is closely in line with China's national strategic objectives such as national rejuvenation but also achieves the diplomatic goals of "world peace and development" by deepening China's relations with its neighbors [7]; on the other hand, "the Belt and Road" initiative has promoted changes in economic structure [8, 9], trade patterns [10, 11], and green development [12] along the path, not only easing the tension caused by regional economic development differences but also promoting the development of global economic integration, and to a certain extent curbed terrorism in poor areas [13]. In addition, the industrial transfer of countries along the Belt and Road is mutually beneficial to the upgrading of bilateral or multilateral value chains, and symbiosis is an important transmission path to promote industrial transfer in countries along "the Belt and Road," including China [14].

The strategic pivots are the apes of a particular network that has greater influence and control over the entire network. In the network of countries along "the Belt and Road," strategic pivots countries not only have the basis and influence to promote strategic position, the radiation capability, common interests, level of bilateral relations, and so on [15] but also have special geographical status, economic demonstration role and key strategic values, and other basic functions [16], while in the strategic pivots city of space structure network [17, 18], the strategic pivots industry in complex structural networks [19] needs to be strategic enough to play a strong leading role. The pivots of maritime strategy have always been the hot direction of academic research, which is beneficial to realizing the layout of overseas port construction from a global perspective and to the investment construction of overseas port [20]; as a fixed supply point, rest point, and ship aircraft berth repair point overseas, the maritime strategic pivots are crucial to maintaining maritime transport security, promoting practical cooperation at sea, and realizing the strategy of maritime power [21], but the maritime strategic pivots are not only a strategic hub at sea but also a strategic channel, and strategic maritime areas are structurally and spatially different [22], which requires an overall optimization of the layout of the marine strategic network to lay the foundations of the marine security and economic strategy [23, 24].

From the abstract network point of view, the betweenness centrality of vertexes [25] and adaptive merest centrality [26] are the important basis for selecting the strategic pivots of the network, the port industry network covers a wide range, the situation is more complex, and the problems are endless [27], but the port industry is an important index to realize the development of the port; from the perspective of the global port system, the shipping network, and hub port space pattern, strategic pivots port is bound to be the main hub and important channel of the maritime shipping network system [28]; it has a great influence on the analysis, as collectivity, accessibility, and interconnectedness of coastal port networks in various countries [29]; from the spatial contact and regional difference panel data of the shipping network in the past 10 years, the global ocean shipping adversity coefficient has been gradually improved, the average path length of shipping has been gradually shortened, and the functional difference of transit connection is getting smaller and smaller [30], but the existing maritime distribution network has been shown to meet the rapid growth of cargo throughput [31], with higher requirements for line network and connectivity measurements, as well as for the efficiency of shipping and port operations [32]. The selection of strategic pivots such as other transportation networks [33], aviation logistics networks [34], and passenger flow networks also requires measuring the importance and influence of nodes [35].

The above research results have laid a good foundation, but the "the Belt and Road" initiative has not been put forward for a long time; the relevant experience data are relatively scarce, so its academic research is still in its infancy, the systematic research results are less, especially for the global port network strategic pivots selection, and optimization results are much rare. Under the "the Belt and Road" initiative, based on the fruitful results of domestic enterprises participating in international port investment, construction, and operation, how to find strategic pivots ports, optimize the layout of the port network, and promote the port economic development of countries along "the Belt and Road" is particularly important.

2. The Setting and Processing of the Basic Data of the Port Network

Set the port network vertexes, edges, rights, and other basic data, and carry out the following steps to process them.

2.1. Port Sample Selection

2.1.1. Alternative Conditions Setting for Port Samples. In order to ensure that port sample data are covert, targeted, and important, alternative port sample selection ensures several principles: ensuring that countries along the main sea paths have port access to alternative samples, ensuring that alternative samples are accessed by the world's major maritime ports, basically ensuring that the Belt and Road Agreement countries have alternative samples for port access, and basically ensuring that ports have access to alternative samples for each maritime area.

To this end, the following alternative port samples are proposed: (1) ports in which Chinese enterprises are involved in investment, construction, and operation are all included in the alternative port sample; (2) the largest ports of the countries along "the Belt and Road" path are included in the sample of alternative ports; (3) when "the Belt and Road" countries span multiple maritime areas, ensure that each of the countries has at least one sample of alternative ports in each marine area; (4) the ports in the top 40 in world throughput in 2019 are used as samples of alternative ports.

2.1.2. Noise Reduction of Alternative Port Samples. In order to ensure the validity of the data and the time-ability of simulation verification, the alternative port samples were optimized for the noise reduction, excluding port samples that clearly did not meet the strategic pivots requirements, and the noise reduction conditions were as follows: (1) ports of island countries that did not enter the top 100 in 2019 were not considered as alternative samples; (2) there are no more than two alternative samples of a country's ports in the same sea area from the same continent.

2.1.3. Port Sample Results. After the selection and optimization of the port samples in the above two steps, 155 alternative port samples are obtained, as in Table 1.

The above alternative ports, including 79 countries that have signed "the Belt and Road" Agreement, as well as 64 ports in which China is involved in investment, construction, and operation, fully cover the major existing international sea paths and have a broad industry coverage base.

2.2. Set the Path between Ports. To set the path between ports is to set the rules for direct connections (direct connection: a straight line between ports) between ports. In order to simplify the calculation and ensure that the port connection is set in accordance with the rules of realistic sea paths, the rules for direct port connections are as follows: (1) All continents are nonnavigational. (2) All waters are navy accessible. (3) There is no transcontinental connection between ports, which is a valid path. (4) A direct connection within a neighboring port on the same continent crosses the continent in which it is located, and the direct connection is a valid path. (5) A direct connection within a port that does not conform to (3) and (4) transverses the continent and is invalid. (6) Ports cannot be connected to themselves.

Keep the valid path, cancel the invalid path, and get a connection between the vertexes that are not authorized to be identified by the port network diagram, that is, the path between the alternate ports.

2.3. Determine the Distance between Ports. The distance between ports is given to the corresponding effective path, that is, to the edge of the port network. Rules of empowerment are as follows: (1) The right to an effective path is the distance between ports (sea) (available directly at port.sol.com.cn, SeaRates.com, and McDistance shipping calculation tools. If there is a large difference in data between the three queries, the average method is used for optimization). (2) The right of the invalid path is recorded as $+\infty$.

The distance of the adjacent port is obtained through the official website and the shipping distance calculation tool (adjacent port distances are available through port.sol.com.cn, SeaRates.com, and McDistance shipping calculation tools), and the average of the three types of data serves as the final distance of the adjacent port. Since the network map of the adjacent port does not cover all ports, there is a certain difference between the shortest path value and the actual value of the nondirect port, but the error is small and the substantive influence on the choice of hub strategic pivots is limited.

The direct connection and distance between the alternative ports are determined, and, according to the characteristics of the two-way passage of sea paths, the port network is a nondirectional right network containing 155 vertices, which is recorded as $G(V, E, C)$, where V represents the vertexes of G, $V = \{v_1, v_2, \ldots, v_{155}\}$, E is the edge of G, and C is the right of direct connection. The distance between the alternative ports is represented by a matrix $G(C)$, which is the direct distance from port v_i to port v_j, "null" if the port-to-port is an invalid path, or 0 if the distance is 0, and the distance matrix $G(C)$ between the alternative ports is represented as

$$G(C) = \begin{bmatrix} c_{1-1} & c_{1-2} & \cdots & c_{1-155} \\ c_{2-1} & c_{2-2} & \cdots & c_{2-155} \\ \vdots & \vdots & \ddots & \vdots \\ c_{155-1} & c_{155-2} & \cdots & c_{155-155} \end{bmatrix} = \begin{bmatrix} 0 & 944.6 & \cdots & \text{null} \\ 944.6 & 0 & \cdots & \text{null} \\ \vdots & \vdots & \ddots & \vdots \\ \text{null} & \text{null} & \cdots & 0 \end{bmatrix}. \tag{1}$$

Table 1: List of alternative port samples.

Area	Alternative Ports
Asia (45)	Shanghai Port, Guangzhou Port, Hong Kong, Kaohsiung Port, Hanoi Port, Da Nang, Sihanoukville, Bangkok Port, Laem chabang, Kuantan Port, Melaka Gateway, Kuala Selangor, Penang Port, Singapore Port, Manila Port, Abu Dhabi Port, Gwadar Port, Yokohama Port, Chongjin Port, Busan, Dhaka Port, Chattogram Port, Kyaukpyu Port, Colombo Port, Hambantota Port, Mumbai Port, Chennai Port, Istanbul Port, Qishm, the Port of Chahbahar, Dammam Port, Jeddah, Doha Port, Salalah Port, Aden Port, Haifa Port, Jakarta-Kariburu, Jambi International Port, Tanjung Priok, Jerusalem Port, Batumi Port, Kuwait Port, Nicosia Port, Basrah Port, Lattakia Port
Africa (37)	Tunisia Port, Cherchell Port, Suez Port, Damietta Port, Por Said Port, Luanda Port, Bata Port, Lome Port, Masawa Port, Pointe Noire Port, Matadi Port, Djibouti Port, Boke Terminal, Conakry Port, Tema Port, Kribi Port, Abidjan Port, Mombasa Port, Tamataf Port, Dakar Port, Monrovia Port, Gentil Port, Cotonou Port, Tangier Port, Dakhla Port, Nouakchott Port, Beira Port, Maputo Port, Walvis Port, Lagos Tingcan Port, Sao Tome and Principe Port, Sudan Port, Dar es Saalam Port, Tripoli Port, Berbera Port, Cape Town Port, Durban Port
Europe (33)	Hamburg Hafen, London Port, Liverpool Port, Le Havre Port, Marseille Port, Lisbon Port, Hammerforst Port, Oslo Port, the Kingdom of Denmark, Stockholm Port, Helsinki Port, Gdańsk Port, Archangelsk Port, Vladivostok Port, Murmansk Port, Nakhodka Port, Sochi Port, Port of Rotterdam, Port of Amsterdam, Antwerp Port, Zebrukh Port, Valencia Port, the Port of Gibraltar, Bilbao Port, Piraeus Port Terminal, Wado Port, San Marino Port, Reykjavík Port, Rijeka Port, Durres Port, Constanta Port, Odessa Port, Varna Port
Oceania (7)	Darwin Port, Melbourne Port, Fremantle Port, Newcastle Port, Lae Port, Wellington Port, Suva Port
North America (22)	Manzanillo Port, Veracruz Port, New York Port, Port of Long Beach, Los Angeles, New Orleans Port, Vancouver Port, Churchill Port, Montreal Port, Havana port, Pilon port, Kingston harbor, Santo Domingo Port, Port-au-Prince, Guatemala Port, Puerto Barrios Port, Honduras Port, Managua Port, Cabesas Port, San Jose Port, Puerto Limon, Colon Port, Panama City Port
South America (11)	Cali port, Barranquilla Port, Guayaquil Port, Kayao Port, San Diego Port, Punta Arenas Port, La Guaira Port, Buenos Aires Port, Paranagua Port, Santos Port, St Louis Port

See the Table Port Distance and the Table Port Shortest Path Value (the Distance data between ports can be searched or downloaded from the Table Port Distance and the Table Port Shortest Path Value in the following link: https://doi.org/10.4121/14298851) for specific data.

3. The Choice of Strategic Pivots of the Port Network Based on the Number of Ports Crossed by the Shortest Path

The port and path are abstracted into the port network model, the shortest path between the two ports is solved, the shortest path is calculated through the port, the strategic importance of the port is judged as superior or not, and the strategic pivots of the port network are finally selected.

3.1. Building a Model about the Number of Ports Crossed by the Shortest Path. Using the Floyd algorithm, the shortest path between two ports in the port network diagram is solved (there may be several shortest paths between the two ports, but this is not the case here, and the results simulated by Python are used as the only final result. The results of the shortest path solution can be searched or downloaded from the Table Port Shortest Path in the following link: https://doi.org/10.4121/14298851). Ports are connected only to each other, not directly to each other, and the shortest path between ports may include, in addition to the port from port to port, the passage through intermediate ports, which together with the port from the beginning constitute the shortest path from port to port. To solve the number of ports crossed by the shortest path, it needs to be solved in three steps.

3.1.1. Determine Whether a Port Is Crossed by a Shortest Path. Determine whether the shortest path from port v_i to port v_j crossed port v_k or not, and remember z_{kij}. If $z_{kij} = 1$, it indicates that the shortest path from port v_i to port v_j crossed port v_k. If $z_{kij} = 0$, it indicates that the shortest path crossed port v_k. The judgment vector for the shortest path between port v_i and port v_j can then be expressed as $[z_{kij}]$, where $i \neq j, k = 1, 2, \cdots, 155$.

3.1.2. Solving a Collection of the Shortest Path between Ports. Based on port v_i to port v_j judgment vector, a collection A_{ij} of ports crossed by the shortest path between the two ports are expressed as follows:

$$A_{ij} = \left\{ v_k | z_{kij} = 1 \right\}, \quad \forall k, i \neq j. \tag{2}$$

The collection of the shortest paths between all ports can be represented by a matrix as follows:

$$A = \begin{bmatrix} A_{1-1} & A_{1-2} & \cdots & A_{1-155} \\ A_{2-1} & A_{2-2} & \cdots & A_{2-155} \\ \vdots & \vdots & \ddots & \vdots \\ A_{155-1} & A_{155-2} & \cdots & A_{155-155} \end{bmatrix} = \begin{bmatrix} \varnothing & A_{1-2} & \cdots & A_{1-155} \\ A_{2-1} & \varnothing & \cdots & A_{2-155} \\ \vdots & \vdots & \ddots & \vdots \\ A_{155-1} & A_{155-2} & \cdots & \varnothing \end{bmatrix}. \quad (3)$$

3.1.3. Solving the Number of Ports Crossed by the Shortest Path. Order X_k is the total number of the shortest paths between two ports in the port network through the k port; then there is

$$X_k = \sum_{i=1}^{155}\sum_{j=1}^{155} z_{kij}, \quad j \neq i, k = 1, 2, 3, \cdots, 155. \quad (4)$$

3.2. Presentation and Analysis of Simulation Results

3.2.1. Simulation Data Analysis of the Number of Ports Crossed by the Shortest Path. Based on the model in the above section, the number of crosses between ports is solved and the results are sorted from more to less, as in Table 2.

In Table 2, the total number of all ports crossed by the shortest path is 176,897, of which the top 17 ports, with a total of 88,949 times, accounted for 10.97% of the total number of all ports crossed by the shortest path of 50.32%; the top 23 ports, with a total of 107,177 times, accounted for 14.84% of the total number of all ports crossed by the shortest path of 60.63%; the top 31 ports, with a total of 124,614 times, accounted for 20% of the total number of all ports crossed by the shortest path of 70.49%; the top 41 ports, with a total of 141,902 times, accounted for 26.45% of the total number of all ports crossed by the shortest path of 80.26%.

The simulation results show that the quantity concentration of the shortest path crossing each port is high, which meets the requirements of port network strategic pivots selection, and also show that the algorithm is effective for port network strategic pivots selection.

3.2.2. Analysis of the Distribution of the Number of Ports Crossed by the Shortest Path. In order to present the simulation results more intuitively, the number of the shortest path crosses of each port is presented on the map in the form of heat attempt, and the degree of heat of the port being crossed by the shortest path is represented by thick red to light blue, and the thermal distribution results of the port are shown in Figure 1.

To better demonstrate the effect of the port thermal distribution, take only the first 41 ports, the sum of the number of ports crossed by the shortest path is more than 80% of the total number of ports crossed by the shortest path as shown in the thermodynamic diagram in Figure 2.

As can be seen from the above two thermodynamic diagrams, most of the ports that are through are located in the channel between the major oceans, such as the Strait of Malacca between the Pacific Ocean and the Indian Ocean, the African coastline between the Indian Ocean and the Atlantic Ocean, the Red Sea Strait between the Indian Ocean and the Mediterranean Sea, the Strait of Gibraltar between the Mediterranean Sea and the Atlantic Ocean, the English Channel between the Atlantic Ocean and the North Sea, and the Panama Canal connecting the Atlantic Ocean and the Pacific Ocean.

The actual situation of the port thermodynamic diagram distribution and the main international shipping paths is consistent, which shows that the basic data such as port samples, direct edge processing, and port distance data are reasonable and effective and also shows that the algorithm is feasible and effective to select the strategic pivots of the port network.

3.3. Analysis of the Strategic Importance of the Port.

The strategic pivots of the port network are to select some ports as strategic pivots in the port network, so as to pry the development of the whole port network and promote the common economic development of the port hinterland countries and neighboring countries.

According to the model solution principle of the shortest path of the network, the more times a network has been crossed by the shortest path, the closer the connection between the network and the other network outlets, the greater the role of the network, and the greater its strategic importance. Therefore, according to the number of ports crossed by the shortest path of each port in the port network, it is the standard to judge the strategic importance of the port, that is, whether the port is selected as the strategic pivot.

3.3.1. Building an Analysis Model of the Strategic Importance of the Port. According to the grouping rules with similar number of ports crossed by shortest path, the K central point cluster analysis model is constructed, and the port training is divided into three groups with specific ideas:

(1) The array $(X = \{x_i | x_1, x_2, \cdots, x_{155}\})$ of the shortest path crossing each port is used as the object of machine learning and training, and x_i corresponds to the number of the shortest paths crossing ports v_i.

(2) Three values are found in the array with the number of centers (y_j); according to the principle of the minimum difference between the values in the array and the number of centers, all the values in the number of values in the array are divided into three groups; each value is assigned to the group with the smallest difference from the number of centers; that is, all the values in the group have the closest number of crosses by the shortest path, the values x_i are assigned to group j then marked x_{ij}, and $x_{ij} = x_i$ are not assigned to group j; then $x_{ij} = 0$.

Table 2: The number of ports crossed by the shortest path (ports with values equal to 0 are not listed in the table; they can be searched or downloaded from the following link: https://doi.org/10.4121/14298851).

Rank	The port code	Name of Port	The number of ports crossed by the shortest path
1	v70	Piraeus Port Terminal	8032
2	v35	Aden Port	7738
3	v83	Por Said Port	7440
4	v80	Cherchell Port	7186
5	v81	Suez Port	6992
6	v79	Tunisia Port	6636
7	v32	Jeddah	6602
8	v26	Mumbai Port	4842
9	v24	Colombo Port	4768
10	v68	The Port of Gibraltar	4064
11	v14	Singapore Port	4038
12	v102	Tangier Port	3872
13	v98	Dakar Port	3498
14	v144	Panama City Port	3338
15	v13	Penang Port	3322
15	v91	Boke Terminal	3322
17	v143	Colon Port	3242
18	v92	Conakry Port	3150
19	v11	Melaka Gateway	3148
20	v12	Kuala Selangor	3108
21	v99	Monrovia Port	3062
22	v130	Montreal Port	3038
23	v95	Abidjan Port	2716
24	v3	Hong Kong	2608
25	v134	Santo Domingo Port	2556
26	v49	Le Havre Port	2127
27	v125	New York Port	2112
28	v17	Gwadar Port	2058
29	v109	Sao Tome and Principe Port	2050
30	v103	Dakhla Port	1968
31	v104	Nouakchott Port	1950
32	v100	Gentil Port	1890
33	v88	Pointe Noire Port	1848
34	v89	Matadi Port	1792
35	v107	Walvis Port	1790
36	v113	Berbera Port	1754
37	v84	Luanda Port	1736
38	v34	Salalah Port	1712
39	v114	Cape Town Port	1634
40	v118	Fremantle Port	1568
41	v96	Mombasa Port	1554
42	v141	San Jose Port	1514
43	v28	Istanbul Port	1490
44	v66	Zebrukh Port	1485
45	v30	The Port of Chahbahar	1480
46	v111	Dar es Saalam Port	1374
47	v29	Qishm	1198
48	v135	Port-au-Prince	1184
49	v133	Kingston Harbor	1082
50	v115	Durban Port	1046
51	v105	Beira Port	1008
52	v63	Port of Rotterdam	940
53	v106	Maputo Port	912
54	v54	The Kingdom of Denmark	906
55	v20	Busan	890
56	v145	Cali Port	804
57	v4	Kaohsiung Port	760
58	v71	Wado Port	740
59	v117	Melbourne Port	688

Table 2: Continued.

Rank	The port code	Name of Port	The number of ports crossed by the shortest path
60	v64	Port of Amsterdam	672
61	v131	Havana Port	646
62	v139	Managua Port	640
63	v18	Yokohama Port	632
64	v93	Tema Port	624
65	v53	Oslo Port	588
66	v46	Hamburg Hafen	560
67	v147	Guayaquil Port	552
68	v6	Da Nang	452
69	v86	Lome Port	422
70	v136	Guatemala Port	416
71	v37	Jakarta-Kariburu	372
72	v39	Tanjung Priok	364
73	v15	Manila Port	350
74	v132	Pilon Port	328
75	v60	Murmansk Port	324
75	v138	Honduras Port	324
77	v59	Vladivostok Port	312
78	v52	Hammerforst Port	308
79	v148	Kayao Port	306
80	v5	Hanoi Port	302
80	v33	Doha Port	302
80	v75	Durres Port	302
83	v78	Varna Port	300
84	v47	London Port	296
85	v73	Reykjavík Port	294
86	v9	Laem Chabang	280
87	v142	Puerto Limon	268
88	v119	Newcastle Port	240
89	v140	Cabesas Port	234
90	v10	Kuantan Port	230
91	v48	Liverpool Port	224
92	v23	Kyaukpyu Port	216
92	v101	Cotonou Port	216
94	v150	Punta Arenas Port	208
95	v2	Guangzhou Port	202
96	v123	Manzanillo Port	194
97	v43	Nicosia Port	172
98	v110	Sudan Port	170
98	v149	San Diego Port	170
100	v50	Marseille Port	154
101	v72	San Marino Port	152
102	v22	Chattogram Port	148
103	v67	Valencia Port	146
103	v112	Tripoli Port	146
105	v82	Damietta Port	132
105	v87	Massawa Port	132
107	v85	Bata Port	124
108	v116	Darwin Port	82
109	v8	Bangkok Port	66
110	v120	Lae Port	50
111	v7	Sihanoukville	8
111	v108	Lagos Tingcan Port	8
113	v62	Sochi Port	4
113	v94	Kribi Port	4
115	v31	Dammam Port	2
115	v40	Jerusalem Port	2
115	v42	Kuwait Port	2
115	v45	Lattakia Port	2
115	v76	Constanta Port	2
115	v137	Puerto Barrios Port	2

Figure 1: The thermodynamic diagram about the number of ports crossed by the shortest path.

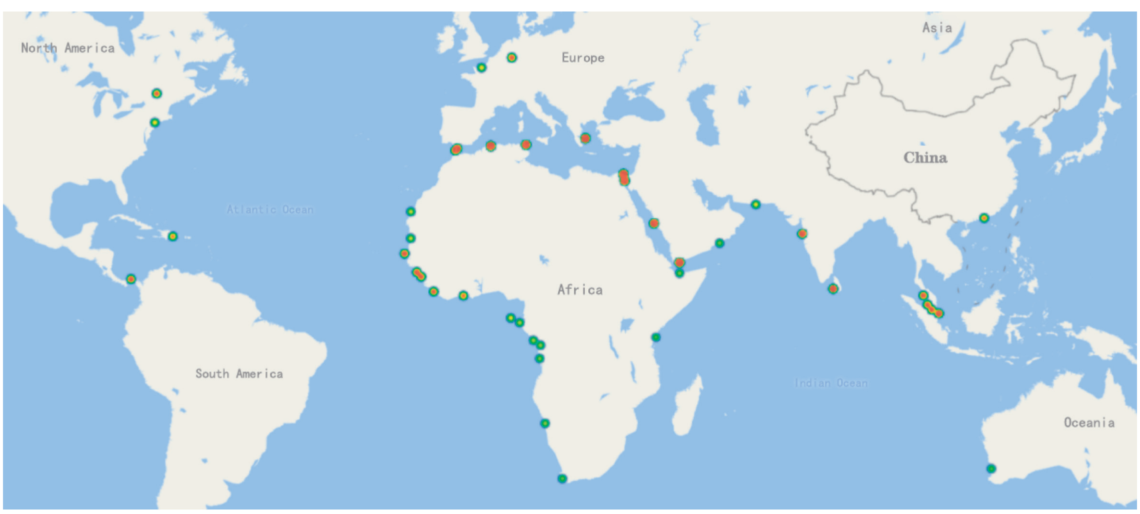

Figure 2: The thermodynamic diagram about rank in the top 41 of the number of ports crossed by the shortest path.

(3) Group to solve the distance between all the values of this group and the number of centers of this group, and group cumulatively adding up to Y_1, Y_2, and Y_3:

$$Y_j = \sum_{i=1}^{155} x_{ij}, \quad j = 1, 2, 3. \tag{5}$$

(4) Add the differences between the groups and add them up; get $Z = \sum_{j=1}^{3} Y_j$.

(5) At the end of the training, when the sum Z value is the minimum value ($Z_{\min}$), the resulting grouping is the final grouping of strategic importance of the port; on this basis, according to the average size of the number of each group of ports crossed by the shortest path, the three types of ports are divided into the strategic importance "superior" group, "general" group, and "inferior" group.

3.3.2. Superior Analysis and Verification of the Port Strategic Importance. According to the above grouping ideas, build an unsealed learning model; the solution results show that when $Z_{\min} = 58186$, the three centers are 6992, 2050, and 296; the strategic importance of the "superior" group has 9 ports, "general" group has 39 ports, and "inferior" group has 107 ports; the specific data can be seen in Table 3.

Table 3: The results of the training grouping of the number of ports crossed by the shortest path (ports in the "inferior" group are not listed; specific and available data can be searched or downloaded from the Table Port Betweenness Centrality in the following link: https://doi.org/10.4121/14298851).

Strategic importance	The list of ports
"Superior" group (9)	Piraeus Port Terminal, Aden Port, Por Said Port, Cherchell Port, Suez Port, Tunisia Port, Jeddah, Mumbai Port, Colombo Port
"General" group (39)	The Port of Gibraltar, Singapore Port, Tangier Port, Dakar Port, Panama City Port, Yokohama port, Boke Terminal, Colon Port, Conakry Port, Melaka Gateway, Kuala Selangor, Monrovia Port, Montreal Port, Abidjan Port, Hong Kong, Santo Domingo Port, Le Havre Port, New York Port, Gwadar Port, Sao Tome and Principe Port, Dakhla Port, Nouakchott Port, Gentil Port, Pointe Noire Port, Matadi Port, Walvis Port, Berbera Port, Luanda Port, Salalah Port, Cape Town Port, Fremantle Port, Mombasa Port, San Jose Port, Istanbul Port, Zebrukh Port, the Port of Chahbahar, Dar es Saalam Port, Qishm, Port-au-Prince

Table 4: Kruskal–Wallis test grouping results.

Variable	Constituencies	Average	Standard deviation	The number of samples	Kruskal–Wallis inspection	
					The card square value	P value
The number of ports crossed by the shortest path	The first group (superior)	6692.89	1168.27	9	21.49^{***}	$P \leq 0.01$
	The second group (general)	2342.31	847.77	39		
	The second group (general)	2342.31	847.77	39	85.16^{***}	$P \leq 0.01$
	The third group (inferior)	235.10	289.84	107		

For the above training results, the grouping results were analyzed by Kruskal–Wallis test, as in Table 4.

The test results show that the variance test value is less than 0.01%, which is significant and shows that the results of strategic importance are reliable and effective.

4. Strategic Pivots Selection Based on Betweenness Centrality of the Port Network

Betweenness centrality is one of the measures of network vertexes to network graph centrality. For the whole port network, the greater the value of the betweenness centrality of the port is, the greater the influence and control of the port on the entire port network are, the stronger its strategic importance is, and the more the port should be preferred as the strategic pivots port of the entire network.

4.1. Building a Strategically Important Model of Port Network. According to the principle of betweenness centrality model, the number $Q_{ij(k)}$ of port v_k through the shortest path between port v_i and port v_j in the whole network, and the ratio of the total number Q_{ij} of shortest paths between port v_i and port v_j, the sum of the ratios throughout the network is as follows:

$$BC_k = \sum_{i \neq j \neq k \in N} \frac{Q_{ij(k)}}{Q_{ij}}. \quad (6)$$

That is the betweenness centrality of the port.

4.2. Presentation and Analysis of Simulation Results. To be comparable, the underlying data and settings in this section are the same as in the previous section.

4.2.1. Analysis of Betweenness Centrality Values. According to the betweenness centrality model, the betweenness centrality of each port is solved and the results are sorted, as in Table 5.

In the table above, the sum of the betweenness centralities of all ports is 118306, of which, for the top 14 ports, the sum of their betweenness centralities is 60091.60, and 9.03% of the port number accounts for 50.79% of the betweenness centrality sum; for the top 19 ports, the sum of their betweenness centralities is 71457.63, and 12.26% of the port number accounts for 60.4% of the betweenness centrality sum; for the top 26 ports, the sum of their betweenness centralities is 84108.40, and 16.77% of the port number accounts for 71.09% of the betweenness centrality sum; for the top 34 ports, the sum of their betweenness centralities is 95163.40, and 21.94% of the port number accounts for 80.44% of the betweenness centrality sum. The simulation results show that the centralization of the port is high, and, from the point of view of the concentration of the betweenness centrality, the simulation results meet the requirements of the port strategy pivots selection, and they also show that it is effective in judging the strategic importance of the port in the whole network based on the betweenness centrality.

Table 5: The betweenness centrality for each port.

The port code	Port	Betweenness centrality
v118	Fremantle Port	6431.97
v35	Aden Port	5826.28
v14	Singapore Port	5088.82
v144	Panama City Port	4863.39
v125	New York Port	4716.63
v114	Cape Town Port	4706.16
v143	Colon Port	4501.09
v3	Hong Kong	4325.15
v104	Nouakchott Port	3762.52
v154	Santos Port	3721.93
v70	Piraeus Port Terminal	3403.56
v80	Cherchell Port	3346.09
v83	Por Said Port	2850.96
v32	Jeddah	2547.05
v81	Suez Port	2532.32
v134	Santo Domingo Port	2371.64
v68	The Port of Gibraltar	2170.51
v107	Walvis Port	2156.25
v26	Mumbai Port	2135.30
v17	Gwadar Port	2059
v109	Sao Tome and Principe Port	1956.94
v24	Colombo Port	1862.11
v102	Tangier Port	1858.771
v130	Montreal Port	1839.79
v71	Wado Port	1558.43
v37	Jakarta-Kariburu	1515.73
v28	Istanbul Port	1492
v79	Tunisia Port	1479.56
v150	Punta Arenas Port	1458.78
v140	Cabesas Port	1427.31
v132	Pilon port	1356.69
v47	London Port	1351.42
v18	Yokohama Port	1254.07
v39	Tanjung Priok	1235.17
v16	Abu Dhabi Port	1085.33
v54	The Kingdom of Denmark	1083.86
v99	Monrovia Port	1076.67
v1	Shanghai Port	1074.54
v34	Salalah Port	1073.07
v115	Durban Port	1047.97
v135	Port-au-Prince	836.05
v131	Havana Port	782.24
v155	St Louis Port	757.51
v152	Buenos Aires Port	674.36
v49	Le Havre Port	570.08
v48	Liverpool Port	554.59
v66	Zebrukh Port	530.32
v153	Paranagua Port	515.64
v29	Qishm	506
v113	Berbera Port	432.03
v116	Darwin Port	414.89
v98	Dakar Port	405.60
v33	Doha Port	400.67
v30	The Port of Chahbahar	394.67
v59	Vladivostok Port	381.27
v117	Melbourne Port	375.67
v141	San Jose Port	370.95
v60	Murmansk Port	369.73
v145	Cali Port	359.73
v12	Kuala Selangor	347.00

Table 5: Continued.

The port code	Port	Betweenness centrality
v2	Guangzhou Port	320.10
v149	San Diego Port	318.28
v75	Durres Port	299.52
v97	Tamataf Port	295.74
v88	Pointe Noire Port	272.74
v96	Mombasa Port	255.33
v111	Dar es Saalam Port	253.41
v106	Maputo Port	216.67
v20	Busan	212.17
v119	Newcastle Port	210.52
v84	Luanda Port	201.06
v13	Penang Port	193.72
v147	Guayaquil Port	173.53
v8	Bangkok Port	172.66
v53	Oslo Port	170.08
v103	Dakhla Port	161.42
v133	Kingston Harbor	151.63
v148	Kayao Port	151.39
v4	Kaohsiung Port	147.902
v95	Abidjan Port	137.31
v112	Tripoli Port	136.92
v151	La Guaira Port	134.38
v91	Boke Terminal	133.99
v11	Melaka Gateway	129.34
v92	Conakry Port	117.8
v90	Djibouti Port	111.56
v82	Damietta Port	102.8
v15	Manila Port	100.04
v87	Masawa Port	91.45
v5	Hanoi Port	89.57
v6	Da Nang	87.97
v62	Sochi Port	77
v64	Port of Amsterdam	75.59
v41	Batumi Port	75
v77	Odessa Port	75
v78	Varna Port	75
v128	Vancouver Port	72.38
v43	Nicosia Port	64.60
v72	San Marino Port	61.73
v138	Honduras Port	58.97
v121	Wellington Port	55.77
v7	Sihanoukville	49.75
v10	Kuantan Port	49.75
v67	Valencia Port	46.27
v50	Marseille Port	44.04
v46	Hamburg Hafen	38.64
v129	Churchill Port	34.24
v110	Sudan Port	33.85
v146	Barranquilla Port	29.047
v142	Puerto limon	28.57
v73	Reykjavík Port	23.04
v127	New Orleans Port	22.08
v100	Gentil Port	11.41
v124	Veracruz Port	7.36
v137	Puerto Barrios Port	7.36
v63	Port of Rotterdam	5.33
v120	Lae Port	3.83
v122	Suva Port	3.83
v105	Beira Port	3.67
v9	Laem Chabang	3

Table 5: Continued.

The port code	Port	Betweenness centrality
v42	Kuwait Port	3
v89	Matadi Port	2.75
v93	Tema Port	2.67
v52	Hammerforst Port	2.57
v38	Jambi International Port	2.33
v22	Chattogram Port	2
v27	Chennai Port	2
v76	Constanta Port	2
v85	Bata Port	1.83
v123	Manzanillo Port	1.79
v139	Managua Port	1.79
v126	Port of Long Beach, Los Angeles	1.186
v23	Kyaukpyu Port	1
v40	Jerusalem Port	1
v45	Lattakia Port	1
v86	Lome Port	1
v94	Kribi Port	1
v101	Cotonou Port	1
v108	Lagos Tingcan Port	1
v136	Guatemala Port	0.79
v31	Dammam Port	0.67
v44	Basrah Port	0.67
v19	Chongjin Port	0

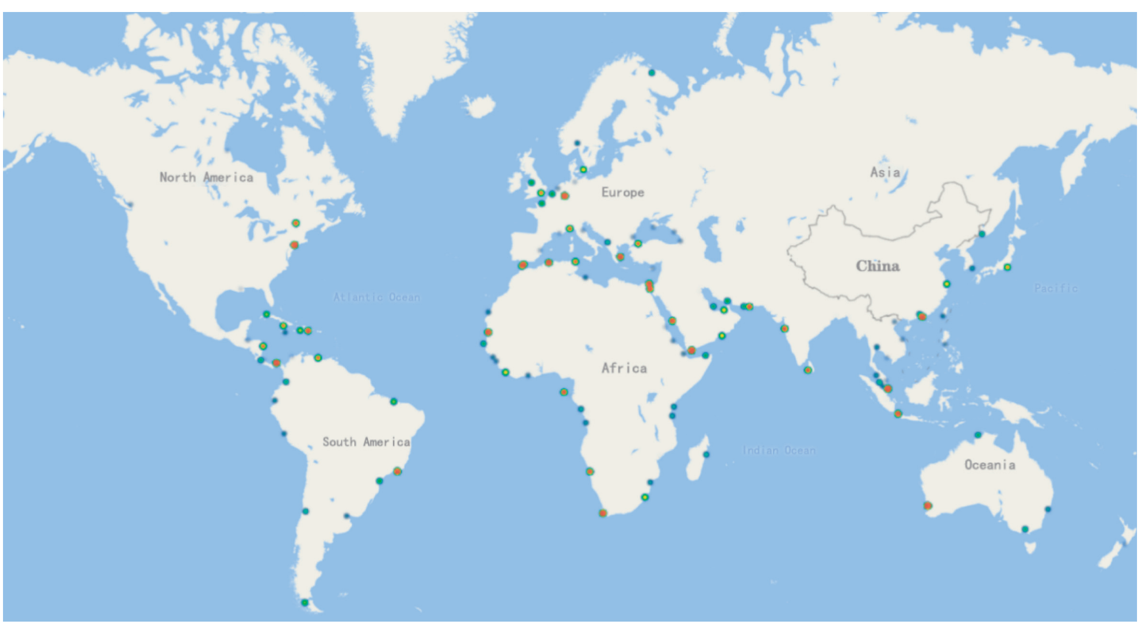

Figure 3: The thermodynamic diagram about the betweenness centrality of each port.

4.2.2. Analysis of Betweenness Centrality Distribution Map. In order to present the simulation results more intuitively, the betweenness centrality of each port is presented on the map in the form of heat-trying, and the degree of the betweenness centrality of the port is represented by thick red to light blue, and the distribution results of the port thermal force are shown in Figure 3.

In order to better demonstrate the distribution effect of port betweenness centrality heat, only the top 34 are shown, and the sum of betweenness centralities exceeds 80% of the port heating, as shown in Figure 4.

From the above two thermal distribution charts, it can be seen that most of the ports with large betweenness centrality values are distributed in the channels between the major oceans; it can be seen that the distribution of port betweenness centrality heat is consistent with the actual situation of the major international shipping paths, indicating that the basic data such as port samples, direct edge

Figure 4: The thermodynamic diagram about rank in the top 34 ports in the betweenness centrality.

Table 6: Group results by interstitial central numerical training (ports in the “inferior” group are not listed; specific and available data can be searched or downloaded from the Table Port Betweenness Centrality in the following link: https://doi.org/10.4121/14298851).

Strategic importance	The list of ports
“Superior” group (12)	Fremantle Port, Aden Port, Singapore Port, Panama City Port, New York Port, Cape Town Port, Colon Port, Hong Kong, Nouakchott Port, Santos Port, Piraeus Port Terminal, Cherchell Port
“General” group (30)	Por Said Port, Jeddah, Suez Port, Santo Domingo Port, the Port of Gibraltar, Walvis Port, Mumbai Port, Gwadar Port, Sao Tome and Principe Port, Colombo Port, Tangier Port, Montreal Port, Wado Port, Jakarta-Kariburu, Istanbul Port, Tunisia Port, Punta Arenas Port, Cabesas Port, Pilon Port, London Port, Yokohama Port, Tanjung Priok, Abu Dhabi Port, the Kingdom of Denmark, Monrovia Port, Shanghai Port, Salalah Port, Durban Port, Port-au-Prince, Havana Port

Table 7: Kruskal–Wallis test grouping results.

Variable	Constituencies	Average	Standard deviation	The number of samples	Kruskal–Wallis inspection	
					The card square value	P value
The number of ports crossed by the shortest path	The first group (superior)	4557.80	940.66	12	25.12^{***}	$P \leq 0.01$
	The second group (general)	1617.65	54.12	30		
	The second group (general)	1617.65	54.12	30	70.63^{***}	$P \leq 0.01$
	The third group (inferior)	133.48	171.87	113		

processing, and port distance data are reasonable and effective and that the algorithm is feasible and effective to carry out strategic pivots analysis of the port network.

4.3. Superior Analysis and Verification of the Port Strategic Importance. According to the model solution principle of betweenness centrality, the greater the betweenness centrality value of a dot in the network, which indicates closer connection between the dot and other networks in the network, the greater the influence, the greater the role played on the network, and the greater the strategic importance.

According to the third part of the clustering algorithm, the training results show that when the three sets of data difference $Z_{\min} = 35688.46$, the three centers are 4706.16, 1479.56, and 61.73; the strategic importance of the

Table 8: A joint coverage matrix of strategically important "superior" ports.

		The number of ports crossed by the shortest path		
		Superior	General	Inferior
Betweenness centrality	Superior	Piraeus Port Terminal, Aden Port, Cherchell Port	Hong Kong, Singapore Port, Nouakchott Port, Cape Town Port, Fremantle Port, New York Port, Colon Port, Panama City Port	Santos Port
	General	Por Said Port, Suez Port, Tunisia Port, Jeddah, Mumbai Port, Colombo Port		
	Inferior			

Table 9: A double attribute category table for strategic pivot ports.

		Whether Chinese companies participate in attributes	
		Yes	No
"The Belt and Road" country properties	Yes	Hong Kong, Colombo Port, Piraeus Port Terminal, Cherchell Port, Suez Port, Por Said Port, Nouakchott Port, Colon Port	Aden Port, Singapore Port, Tunisia Port, Jeddah, Cape Town Port, Panama City Port
	No	Zero	Fremantle Port, New York Port, Mumbai Port

"superior" group has 12 ports, "general" group has 30 ports, and "inferior" group has 113 ports, as in Table 6.

For the above training results, the grouping results were analyzed by Kruskal–Wallis test, as in Table 7.

According to the above test results, the average variance of the three sets of data is less than 0.01%.

5. Conclusions

The number of ports is crossed by the shortest path and betweenness centrality of the two simulations of the port in the network as "superior," "general," and "inferior" groups; the grouping results test is valid, but the results of the grouping are the same, so it is necessary to further the above two simulation results of joint coverage analysis and finally determine the strategic pivots port.

Both sets of simulation results are "general" or "inferior" ports of strategic importance; we think that should not be selected as the strategic pivots of the port network; therefore, the two sets of simulation results, only for at least one set of simulation results, show the strategic importance of "superior" ports, a joint coverage analysis. Among them, for the strategic importance of the "superior" group, the number of ports crossed by the shortest path in the "superior" group is 9 ports, the betweenness centrality dimension "superior" group of 12 ports; the specific results can be seen in Table 8.

Based on the data in the table above, only the ports in the upper left triangle matrix are strategically important "superior" ports, so the four sets of ports are analyzed.

(1) The strategic importance of both simulation results is that there are three "superior" ports. Geographically, the three ports are located in the channel from the Indian Ocean, through the Red Sea, the Mediterranean Sea and into the Atlantic Ocean, with the Aden Port and the Cherchell Port as the ports at the mouth of the channel, while the Piraeus Port is at the Centre of the Mediterranean Sea and is the main transit point between the ports of European and North African countries. The three ports are located in the busiest shipping lanes in the world, so it is realistic and reasonable that the three ports should be chosen as strategic pivots ports.

(2) The number of ports crossed by the shortest path simulation is grouped as "superior" and the betweenness centrality simulation is grouped into "general" with six ports. Four of these ports are located in the Channel from the Indian Ocean, through the Red Sea, the Mediterranean Sea and into the Atlantic Ocean, while the Mumbai Port and the Colombo Port are located at the Pacific to Indian Ocean exits and are the main shipping lanes connecting the Pacific and the Indian Oceans; from this point of view, the six ports selected as strategic pivot ports are realistic and reasonable.

(3) The number of ports crossed by the shortest path simulation is grouped into "general," and the betweenness centrality simulation is grouped into "superior" with eight ports. Among them, the Hong Kong and the Singapore Port are located at the entrance of the Pacific to Indian Ocean path, the ports of Nouakchott and Cape Town are located on the southern path between the Indian Ocean and the Atlantic Ocean, and the Colombo Port and the Panama City Port are the two ports connecting the Pacific Ocean and the Atlantic Ocean, while the ports of New York Port and the Fremantle Port are the main points of entry for the North American continent and the Australian mainland. These ports are located on major international paths, so it is realistic and reasonable that they should be chosen as strategic pivot ports.

(4) The number of ports crossed by the shortest path simulation is grouped as "inferior," and the port

with the betweenness centrality simulation grouped as "superior" is only the Santos Port. The Santos Port is an important port in Brazil; from the simulation process, it can be seen that Santos, in the grouping results of the large error, because the route Santos has strong substitutability, and there are more ports on the east coast of the Atlantic than the west coast of the Atlantic; therefore, the Santos Port is divided into the number of ports crossed by the shortest path dimension "down" group. For this reason, the Santos Port should not be chosen as a strategic pivots port.

In summary, 17 of the 18 ports with "superior" strategic importance above, with the exception of the Santos Port, have been identified as strategic pivot points of the global port network.

6. Suggestions and Discussions

6.1. "The Belt and Road" Strategic Pivots Port Analysis and Instructive Suggestions. "The Belt and Road" initiative is a new engine for promoting international capacity cooperation and a strong guarantee for win-win cooperation among the agreed countries. "Belt and Road," the economic industry across Asia, Europe, and Africa, covers 60% of the world's population, including 30% of the global economy; there is a huge potential for development. If the "Belt and Road" Agreement is signed in the hinterland of the port, it will certainly get a great deal of assistance in infrastructure and will play a more important role in the economic and trade exchanges between the countries of the agreement.

Chinese enterprises are involved in investment, construction, and operation of ports; whether from the commercial logic or from a technical point of view, the future cooperation will greatly improve control and stability. Although there are sovereign barriers between countries, the commercial rules of the world economy run through the beginning and the end of economic development.

In view of the 17 ports where the above strategic pivot points are "superior," if China wants to develop the strategic layout of its port network in the world, it needs to consider the economic development potential of the port network from China's perspective, as well as the controllability and stability of future cooperation. Therefore, the two attributes of "One Belt and One Road" and "whether Chinese enterprises participate" of these strategic pivot ports are analyzed by analogy analysis. Based on these two attributes, strategic pivot ports are grouped into four categories, as in Table 9.

According to the properties of strategic pivots ports, they are analyzed separately and enlightening suggestions are made:

(1) There are eight strategic pivot ports with the participation of Chinese enterprises and hinterland countries that have signed "the Belt and Road" Agreement. From the geographical location of the international shipping paths, two ports are the main ports of the Indo-Pacific sea path (the Indo-Pacific sea path is a sea path connecting India and the Pacific Ocean), four ports are the main ports connecting the Indian Ocean and the Atlantic Ocean north path, a port connects the Atlantic Ocean and the Pacific Ocean, and one of these ports is an important port from Africa radiation to North America, South America, and Europe; from this point of view, these eight ports are located on the main international shipping paths, and comprehensive coverage of several major maritime paths connects several major sea areas. The hinterland countries in which the port is located have signed "the Belt and Road" Agreement, with low political risks and great potential for economic development, and the role of the port in the future economic development process will become more and more important. The port has Chinese enterprises involved in investment, construction, and operation; in the future cooperation of the port, Chinese enterprises will have a strong voice. Therefore, it will play a vital role to give priority to the development of these eight strategic pivot ports and take these eight ports as the core hubs of "the Belt and Road" port network to radiate and lead the economic development of the countries along "the Belt and Roa."

(2) The port hinterland countries have signed "the Belt and Road" Agreement but there are six strategic pivot ports in which Chinese enterprises are not involved in investment and construction operations. Geographically, it is the Indo-Pacific sea path, the Indo-Atlantic North Sea path, the Indo-Atlantic South Sea path (the Indo-Atlantic North Sea path is a sea path connecting India and the Atlantic Ocean, via the Red Sea and the Mediterranean Sea, and the Indo- Atlantic South sea path is a sea path connecting India and the Atlantic Ocean, through the Mozambique Strait and through South Africa), the Indian-South Sea path refers to the sea path connecting India and the Atlantic Ocean, through the Red Sea, the Mediterranean Sea, the main port of the Atlantic and Pacific Panama paths. The hinterland countries in which these ports are located have signed "the Belt and Road" Agreement, which has a good basis for political and economic cooperation, and need to vigorously promote cooperation between Chinese enterprises and these ports at the commercial or technical level, which is not only conducive to enhancing the stability of "the Belt and Road" port network but also conducive to promoting the participation of these countries in "the Belt and Road" other industrial energy and other aspects of cooperation.

(3) There are three ports where neither attribute is available. Geographically, these ports are not the main sea paths of the port but are important medium-transformation ports. New York Port is the main transshipment port on the west coast of the Atlantic Ocean, Fremantle Port is an important transshipment port to the Australian mainland in

other waters, and Mumbai Port is an important transshipment port on the east coast of the Indian Ocean. Therefore, it is necessary to strengthen cooperation with the commercial level of these ports, reduce the transit costs of maritime transport, and enhance the competitiveness of “the Belt and Road” port network.

6.2. Discussion of Other Association Studies. This paper abstracts the global port and path into a nondirected power network and considers the shortest path between ports, the shortest path through the port, the betweenness centrality of the port network and other factors, from whether the strategic importance of the port is superior to judge and choose whether it should be identified as the strategic pivot of the global port network; the strategic layout of the global port network to promote “the Belt and Road” along the port economic development has a strong reference significance. However, the influence factors do not take into account the cost of actual shipping, port throughput capacity, and trade volume between countries and other factors; therefore, in practice, the impact factors for further in-depth study can also be increased.

Data Availability

The data used to support the findings of this study have been deposited in the 4TU.Research Data (SCIENCE· ENGINEERING· DSIGN) repository (https://doi.org/10.4121/14298851).

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Supplementary Materials

The materials in the text files are raw data which are used to derive the data in the tables in the manuscript. (*Supplementary Materials*)

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Research Article

Economic Dependence Relationship and Spatial Stratified Heterogeneity in the Eastern Coastal Economic Belt of China

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In this paper, the method of mutual information is used to study the economic dependence among the provinces in China's Eastern Coastal Economic Belt from 2015 to 2020, and the core structure of the dependence is depicted. The results show that, first of all, there is a wide range of economic dependence among the provinces in the Eastern Coastal Economic Belt, and the dependence changes with the different states of economic development. Secondly, the phenomenon of geographical clustering is not obvious. Most provinces maintain a strong economic dependence relationship with the economically developed provinces, and this dependence relationship is relatively stable, while the economically underdeveloped provinces are often on the edge of the dependence structure. Finally, the economically developed provinces maintain strong economic dependence with each other, such as Jiangsu (No. 7), Shandong (No. 9), and Zhejiang (No. 12), and Beijing (No. 1), Guangdong (No. 3), and Shanghai (No. 10). However, the former three provinces are more in the core position of this structure, that is, the other provinces maintain the stronger dependence relationship with these three provinces.

1. Introduction

At present, the development of China has entered a new era of comprehensively deepening reform and opening-up and is in a critical period of transforming from a stage of high-speed growth to a stage of high-quality development. After more than 40 years of reform and opening-up, China's economic and social development has made remarkable achievements. Among them, the urbanization rate has exceeded the 50% dividing line and has entered the middle and late stage of rapid development. Strengthening the cooperation of regional space, promoting the integrated development, and then obtaining a higher level of division of labor and transforming potential demand into actual demand are not only an important way to continue or maintain the current high-speed growth but also the direction of the evolution of the spatial structure of a mature economy.

In the past decades, on the basis of summing up the practical experience of China's regional coordinated development, the 11th Five Year Plan for national economic and social development has put forward a comprehensive and systematic strategy for regional development, that is, to implement the strategy of the development of the western region, the revitalization of the northeast area, the rise of central China, and the leading development of the eastern region. Since then, the four regional development strategies have become the pillar of China's overall regional development strategy. In recent years, at the national level, more attention has been paid to the construction of the top-level design, and more attention has been paid to the overall planning and integrity of regional planning. Whether it is the overall consideration of the four regional development strategies, or the demonstration role of the coordinated development of Beijing-Tianjin-Hebei on the coordinated development of the national region, all of them put forward strong direction and guidance for local economic and social development, and the coordinated development of the region adapts to China's future regional development strategy, conforms to the development concept of regional opening, cooperation, and coordination, and is conducive to strengthening regional economic integration, continuously improving the efficiency of factor spatial allocation, and improving the quality and efficiency of regional development.

Nowadays, China has formed a targeted overall regional development strategy based on the four regions of the east, the middle, the west, and the northeast of China, while the policies and resource concentration in the eastern coastal areas have gradually formed since the 1990s. As one of the Three Golden Support Belts in the development of China's regional integration, the Eastern Coastal Economic Belt plays an important leading and exemplary role in deepening China's reform and opening-up, accelerating the formation of a new regional coordinated development mechanism with strong overall planning, orderly competition, green coordination, and win-win sharing, and promoting regional coordinated development. The Eastern Coastal Economic Belt is not only an important engine of China's economic development, but also an important base of scientific and technological innovation. Its total GDP accounts for nearly 70% of mainland China, and the number of listed companies accounts for nearly 3/4 of mainland China. Among the 12 provinces in China's Eastern Coastal Economic Belt, there are not only China's political center, Beijing; China's economic and financial center, Shanghai; but also the forefront of China's reform and opening-up, Guangdong; and the important eastern central provinces of the Yangtze River Economic Belt and the Yellow River Economic Belt, Jiangsu, Zhejiang, and Shandong. Therefore, exploring the economic dependence relationship and the core dependence structure among the provinces in the Eastern Coastal Economic Belt plays an important role in the sustainable economic development of this region in China.

Regional economic integration refers to the process of achieving a certain commitment, contract or forming a certain form of regional economic cooperation organization among cities in a specific region, to seek the liberalization of regional commodity circulation or factor flow and the optimization of production division, and on this basis to form a unified product and factor market, and a unified economic and social policies or systems. At present, scholars have carried out a series of studies on the coordinated development of regional economy, regional connection, and interaction, and the dynamic mechanism of regional economic development. Among them, in the research method of regional spatial connection, gravity model is usually used to measure the interaction strength between cities, which has become one of the main forms to study the evolution pattern and spatial network of cities [1, 2]. In the research content, the related research studies focus on the economic effect, institutional structure, and influencing factors of regional integration from the aspects of regional industrial transfer and innovation agglomeration, so as to further analyze the dynamic mechanism of coordinated development of regional economy [3–6].

In addition, some studies focus on the interaction and dependence among various units in regional integration from the aspects of regional linkage development and complementary relationship, industrial cluster [7], institutional performance [8], industrial competitiveness [9], industry city interaction [10], and spatial evolution of regional ties [11, 12]. At the same time, academia and policy-making departments are increasingly aware of the regional coordinated development, which plays a more and more important role in the sustainable development of each unit in the region, and even in a wider range of cities and industries. More and more scholars carry out the research and analysis from the respect of institutional arrangement, functional positioning, competitiveness, and linkage development to analyze the coordinated and sustainable regional development, and the relevant research studies mainly focus on the coordination of system and main interests, industrial ecology, linkage, and sustainable development [13, 14]. The literature on the spatial pattern of regional coordinated development mainly focuses on the spatial-temporal evolution of regional development gap [15], the spatial pattern of regional ecological difference [16], the influencing factors of regional development imbalance [17], the influencing factors of regional income gap [18], the influencing factors of regional green development [19], and the spatial pattern of urban-rural coordinated development [20]. Among them, Ma uses the theory of system dissipative structure to conduct quantitative research on the coordinated development of regional economy and establishes a system coordination evaluation model based on the grey relational theory with annual GDP as the order parameter, and evaluated and measured the degree of regional coordinated development [21]. Qi et al. construct a systematic analysis framework of low-carbon collaborative development in Beijing-Tianjin-Hebei and propose to build a regional low-carbon collaborative development path from three levels of government, industry, and consumers [22]. Fan et al., from the perspective of coordinated development of regional economy and ecological environment, combine regional expansion with ecological compensation, construct a regional economy and ecological coordinated development model, and take Fuzhou coastal area as an empirical study case to conduct in-depth discussion on regional expansion prediction, ecological compensation, and regional spatial simulation [23].

Due to the complex nonlinear characteristics of economic time series, it is not only dominated by certain deterministic laws but also shows random characteristics, that is, it has the characteristics of time-varying, randomness, and fuzziness, and the traditional econometric model could not meet the measurement of regional economic dependence. Therefore, in order to further improve the accuracy of calculation, entropy theory is applied to the study in economic time series [24–27]. This paper uses the method of mutual information to construct the economic dependence relationship among the provinces in China's coastal economic belt and shows the dependence results and core structure of the dependence relationship by means of heat map and maximum spanning tree. The rest of this paper is organized as follows. Section 2 mainly introduces mutual information and kernel density estimation methods. Section 3 is the selection of data and basic mathematical statistics. Section 4 is the main results and analysis of the results, and Section 5 is the conclusion.

2. Methods

In this study, mutual information and kernel density estimation are used to calculate the economic dependence relationship among the provinces in the Eastern Coastal Economic Belt of China. Compared with the previous studies, mutual information and kernel density estimation have the following advantages. First of all, some studies have proved that the economic time series often show the characteristics of nonlinear; however, mutual information could not only be used to calculate the dependence relationship between variables under the linear condition, but also be applied in the nonlinear condition. Besides, mutual information is model-free, so it is not necessary to set the model in advance. Finally, the kernel density estimation method does not depend on the specific assumptions of data distribution, which makes the estimation more accurate.

2.1. Mutual Information. The definition of information entropy was given by Shannon in the 1940s, and it has been considered that information entropy could be used to measure the uncertainty of the event. According to the definition given by Shannon, the entropy of a discrete random variable x could be expressed as

$$H(X) = -\sum_{x\in\chi} p(x)\log\, p(x), \tag{1}$$

where χ is the set of all states of the random variable x and $p(x)$ is the probability of x. It measures the extent of uncertainty. The base of the logarithm is commonly chosen as 2, and the unit is bit.

For the two random variables x and y, the joint entropy between these two variables could be defined as

$$H(X,Y) = -\sum_{x\in X}\sum_{y\in Y} p(x,y)\log\, p(x,y), \tag{2}$$

where $p(x,y)$ is the joint probability of x and y.

The definition of MI between X and Y is given as follows [28]:

$$MI(X,Y) = \sum_{x\in X}\sum_{y\in Y} p(x,y)\log\frac{p(x,y)}{p(x)p(y)}. \tag{3}$$

According to formulas (1) and (2), MI could be rewritten as follows [29]:

$$MI(X,Y) = H(X) + H(Y) - H(X,Y). \tag{4}$$

MI measures the information which one variable discloses about another one, and if two variables are interdependent, their MI will be greater than zero. Stronger interdependence produces larger MI [30].

2.2. Kernel Density Estimation. Let $\mathbf{U} = \{\mathbf{u}_1, \mathbf{u}_2, \ldots \mathbf{u}_\mathbf{N}\}$ be a d-dimensional real number variable, and the kernel density of its probability density function could be estimated as follows:

$$\hat{f}(u_j) = \frac{1}{Nh^d}\sum_{i=1}^{n} K\left(\frac{u_j - u_i}{h}\right), \tag{5}$$

where h is the window parameter, also known as bandwidth, and $K(\cdot)$ is the d-dimensional kernel function. Then, under the Gaussian kernel function, formula (5) could be transformed into

$$\hat{p}(\mathbf{u}_j) = \frac{1}{Nh^d}\sum_{i=1}^{n}\frac{1}{\sqrt{(2\pi)^d|S|}}\exp\left(-\frac{(\mathbf{u}_j - \mathbf{u}_i)^T S^{-1}(\mathbf{u}_j - \mathbf{u}_i)}{2h^2}\right), \tag{6}$$

where S is the value of the determinant of its covariance matrix.

The choice of bandwidth has a great influence on the estimation effect. According to reference [20], this paper selects the optimal bandwidth, as follows:

$$h = \left(\frac{4}{d+2}\right)^{(1/(d+4))} N^{(-1/(d+4))}. \tag{7}$$

The probability density of samples could be obtained by kernel density estimation, and then, the entropy formula could be obtained as follows:

$$H(\mathbf{U}) = -\frac{1}{N}\sum_{t=1}^{N}\log\hat{p}(\mathbf{u}_t). \tag{8}$$

Combined with formulas (4) and (8), we can get the final formula to calculate the mutual information value of the two variables, as follows:

$$I(X,Y) = -\frac{1}{N}\sum_{t=1}^{N}\log\hat{p}(x_t) - \frac{1}{N}\sum_{t=1}^{N}\log\hat{p}(y_t) + \frac{1}{N}\sum_{t=1}^{N}\log\hat{p}(x_t, y_t). \tag{9}$$

3. Data

This paper selects China's regional stock price index as the research object, which reflects the overall performance of listed companies in different regions of China's A-share market, depicts the development characteristics of the regional economy and capital market, and becomes an important indicator to measure the development of regions. The data selected in this paper come from the Wind database, and the time range of the data is from 5 January 2015 to 31 December 2020, a total of 6 years of index daily closing price. The numbers and index names are listed in Table 1.

According to the experience of the previous literature, this paper calculates the logarithmic return of each index according to formula (10), where $p\ (t)$ and $p\ (t-1)$ are the daily closing price of the regional index on dates t and $t-1$ respectively, and $R\ (t)$ is the logarithmic return of the regional index on date t.

$$R(t) = \ln\, P(t) - \ln\, P(t-1). \tag{10}$$

Table 1: The details of the 12 regional indexes.

No.	Index name	Code
1	Beijing index	CN6002
2	Fujian index	CN6003
3	Guangdong index	CN6005
4	Guangxi index	CN6006
5	Hainan index	CN6008
6	Hebei index	CN6009
7	Jiangsu index	CN6015
8	Liaoning index	CN6017
9	Shandong index	CN6021
10	Shanghai index	CN6024
11	Tianjin index	CN6026
12	Zhejiang index	CN6030

Since the calculating of mutual information needs the time series to be stationary, in this paper we apply augmented Dickey–Fuller (ADF) test to examine the stationarity of the 12 regional indexes series. Besides, the Jarque–Bera test is also used to examine whether the indexes series obey Gaussian distribution, and the results are shown in Table 2. It could be seen that all of the 12 regional indexes series are stationary and all of them do not obey Gaussian distribution.

4. Results and Discussion

4.1. MI Value among the Provinces. In this section, we first calculate the mutual information among the regional indexes of 12 provinces in the Eastern Coastal Economic Belt of China, which represents the degree of economic dependence among the provinces. In order to clearly observe the dependence and the change of the dependence between the provinces from the year 2015 to 2020, we use the heat map to express the calculation results of mutual information.

Figure 1 shows the economic dependence of the provinces in the Eastern Coastal Economic Belt of China in each year from 2015 to 2020. The numbers in abscissa and ordinate in the figure are the number of indexes of each province in Table 1, and the value of economic dependence is replaced by the colored squares in the figure. If the value of MI between province i and province j is nonzero, there exists an edge with the weight of the value of MI. In order to analyze the change of this dependence in these six years, this paper adjusts the maximum value of the thermal chart to 2.8, because in the above six years, the maximum value of mutual information among provinces is 2.7966, which is the mutual information value between Jiangsu (No. 7) and Zhejiang (No. 12) in 2016.

It can be seen from the results in Figure 1 that the economic dependence among provinces has changed greatly in the six years from 2015 to 2020, among which the economic dependence is stronger in 2015 and 2016, and in 2017, the dependence is the weakest. In terms of the degree of dependence among provinces, Hainan (No. 5) has the weakest economic dependence with other provinces in the above six years, while Jiangsu (No. 7), Shandong (No. 9), and Zhejiang (No. 12) have strong economic dependence with each other. According to the ranking of total GDP of the provinces in mainland China in 2019, Jiangsu (No. 7), Shandong (No. 9), and Zhejiang (No. 12) ranked the second, third, and fourth place, respectively, in the 12 provinces of the Eastern Coastal Economic Belt, while Hainan (No. 5) ranked the last. Therefore, we can get a preliminary conclusion that the provinces with more developed economies maintain strong economic interdependence with each other, while the economic dependence between the provinces with poor economic development level and other provinces is weak.

Table 3 shows the average economic dependence of 12 provinces in China's eastern coastal area from 2015 to 2020. It can be seen that the average economic dependence of each province is the largest in 2016, whose value is 1.7498, while the average economic dependence of each province is the smallest in 2017, whose value is only 0.8556, which is less than a half of 2016. This also confirms the results shown in Figure 1.

From the results in Table 3, we can generally see the changes in the economic dependence among the provinces. Among them, in the years 2015 and 2016, due to the overheated phenomenon of China's economy in these two years, a large number of bubbles appear in the capital market, especially the stock market. This overheated phenomenon of economic development and capital market increase the economic activities and capital flows in the eastern coastal areas, thus enhancing the economic links among the provinces in the region. In order to alleviate the phenomenon of overheated economy and drastic fluctuations in the capital market, the Chinese government subsequently introduced a series of measures. Therefore, in 2017, the economic interdependence among provinces reaches the lowest value of 0.8556 in six years, only 48.90% of that in 2016. In 2018 and 2019, the economic dependence among provinces increases steadily. However in 2020, because of the outbreak of COVID-19, especially the strictly closed management in the first half of 2020, the frequency of the flow of funds, goods, and personnel among the provinces is greatly reduced, which makes the dependence relationship among the provinces in 2020 be the minimum after 2017 and the value is only 1.2268.

Next, we calculate the node strength of economic dependence among provinces in the Eastern Coastal Economic Belt of China from 2015 to 2020. The node strength reflects the sum of mutual information values between each province and the other 11 provinces in each year, as follows:

$$NS_i = \sum w_{ij}. \tag{11}$$

Among them, W_{ij} is the mutual information value (economic dependence) between province i and province j.

Figure 2 shows the node strength of each province in the six years. The abscissa is the number of each province in Table 1, and the ordinate is the value of node strength. In order to compare the changes of node strength of each province in different years, the value range of node strength in the ordinate is set as 0–25.

From the results shown in Figure 2, it can be seen that, in the six years from 2015 to 2020, the node strength of each

Table 2: Statistical characteristics of the 12 regional indexes.

No.	Mean	Std. dev.	Skewness	Kurtosis	ADF statistic	Jarque–Bera statistic
1	$6.38e-05$	0.0149	−1.0635	9.1520	-35.9878^{***}	2579.38^{***}
2	$3.83e-04$	0.0156	−1.0168	8.3178	-35.2657^{***}	1973.27^{***}
3	$4.30e-04$	0.0163	−0.9243	7.3282	-36.3008^{***}	1348.43^{***}
4	$-1.74e-04$	0.0178	−1.0625	7.9552	-33.9727^{***}	1769.66^{***}
5	$-3.40e-04$	0.0181	−0.9089	6.0244	-34.3165^{***}	757.98^{***}
6	$6.50e-05$	0.0186	−0.8247	6.8638	-35.2829^{***}	1074.40^{***}
7	$3.26e-04$	0.0176	−0.9911	7.3350	-35.3176^{***}	1383.16^{***}
8	$-1.47e-04$	0.0182	−1.1442	8.3958	-34.9918^{***}	2091.15^{***}
9	$3.25e-04$	0.0176	−1.0762	7.7907	-35.3807^{***}	1679.15^{***}
10	$4.73e-05$	0.0164	−0.9857	9.1630	-35.6746^{***}	2548.80^{***}
11	$-4.23e-05$	0.0191	−1.0779	7.4558	-35.5162^{***}	1491.51^{***}
12	$3.35e-04$	0.0182	−0.9918	7.1405	-35.2817^{***}	1283.14^{***}

***Statistical significance at the 1% level.

province changes greatly, that is, the total economic dependence between one province and the other 11 provinces has a great difference in different years. The difference is mainly reflected that the node strength is in a higher position in 2015 and 2016, which decreases rapidly in 2017 and rises steadily in 2018 and 2019. Although the node strength of individual provinces decreased in 2020, the overall change is not significant. From the point of view of node strength of each province, Jiangsu (No. 7), Shandong (No. 9), and Zhejiang (No. 12) always maintain a high node strength, which indicates that these three provinces not only maintain a large economic dependence with each other (the conclusion in Figure 1), but also maintain a strong economic dependence with the other provinces, while Hainan (No. 5) has the weakest economic dependence in all six periods. The above conclusions are consistent with the results in Figure 1 and Table 3. In addition, from Figures 2(d)–2(f), the economic dependence among provinces has remained stable throughout the three years from 2017 to 2020 after the economy stabilization policy implemented by the Chinese government in 2017. Though affected by COVID-19 in 2020, the node strength of all provinces decreases to varying degrees, but it does not change by a large margin. Table 4 shows the standard deviation of node strength of the 12 provinces from 2018 to 2020, from which we can see the change of node strength of each province in these three years.

It can be seen from the results in Table 4 that Guangdong (No. 3), Jiangsu (No. 7), and Shanghai (No. 10) have the smallest standard deviation of node strength, while Guangxi (No. 4), Hainan (No. 5), and Hebei (No. 6) have the largest standard deviation of node strength. Combined with the economic development level of each province, it can be seen that the node strength of economically developed provinces fluctuates less, that is, the economic dependence between these provinces and the other 11 provinces is relatively stable, while for those provinces with poor economic development level, whose node strength fluctuates greatly, that is to say, the overall economic dependence between these provinces and the other 11 provinces is not stable and is greatly affected by the external environment. In particular, the standard deviation of node strength of Hainan (No. 5) reaches 2.0089; combined with Figures 2(d)–2(f), we can see that after the adjustment of the economy in 2017, the node strength of the province increases significantly from 2018 to 2019, but in 2020, it drops to the level in 2018 because of the COVID-19.

Based on the analysis of the above results, we can draw the following conclusions. First of all, the economic dependence among the provinces in China's eastern coastal economic belt changes with the change of economic development status. In the overheated stage of economy, such as 2015 and 2016, the dependence is relatively strong, while in the stage of contraction of economic development or in the stage of total demand reduction, such as 2017 and 2020, the dependence is relatively weak. Secondly, the economic dependence between each province and the other provinces is also different. The economically developed provinces, such as Jiangsu (No. 7), Shandong (No. 9), and Zhejiang (No. 12), not only always maintain a strong dependence with each other, but also maintain a strong dependence with the other provinces in terms of node strength, while Hainan (No. 5) has the weakest economic dependence with the other provinces. Therefore, it could be concluded that the economically developed provinces maintain strong economic dependence not only among themselves, but also with other provinces, while the economically less-developed provinces have weak economic dependence with other provinces. Finally, the node strength of the developed provinces fluctuates less, and the economic dependence with other provinces is more stable, while the node strength of the provinces with relatively poor economic development level fluctuates more, and the economic dependence with other provinces is less stable, which is greatly affected by the external environment.

4.2. Maximum Spanning Tree. The maximum spanning tree is an effective method to clearly depict the core structure of the dependence relationship of each node. By selecting the maximum edge weight between two nodes, the dependence relationship between the two nodes is constructed [31]. Figure 3 shows the results of depicting the core structure of economic dependence among 12 provinces in China's

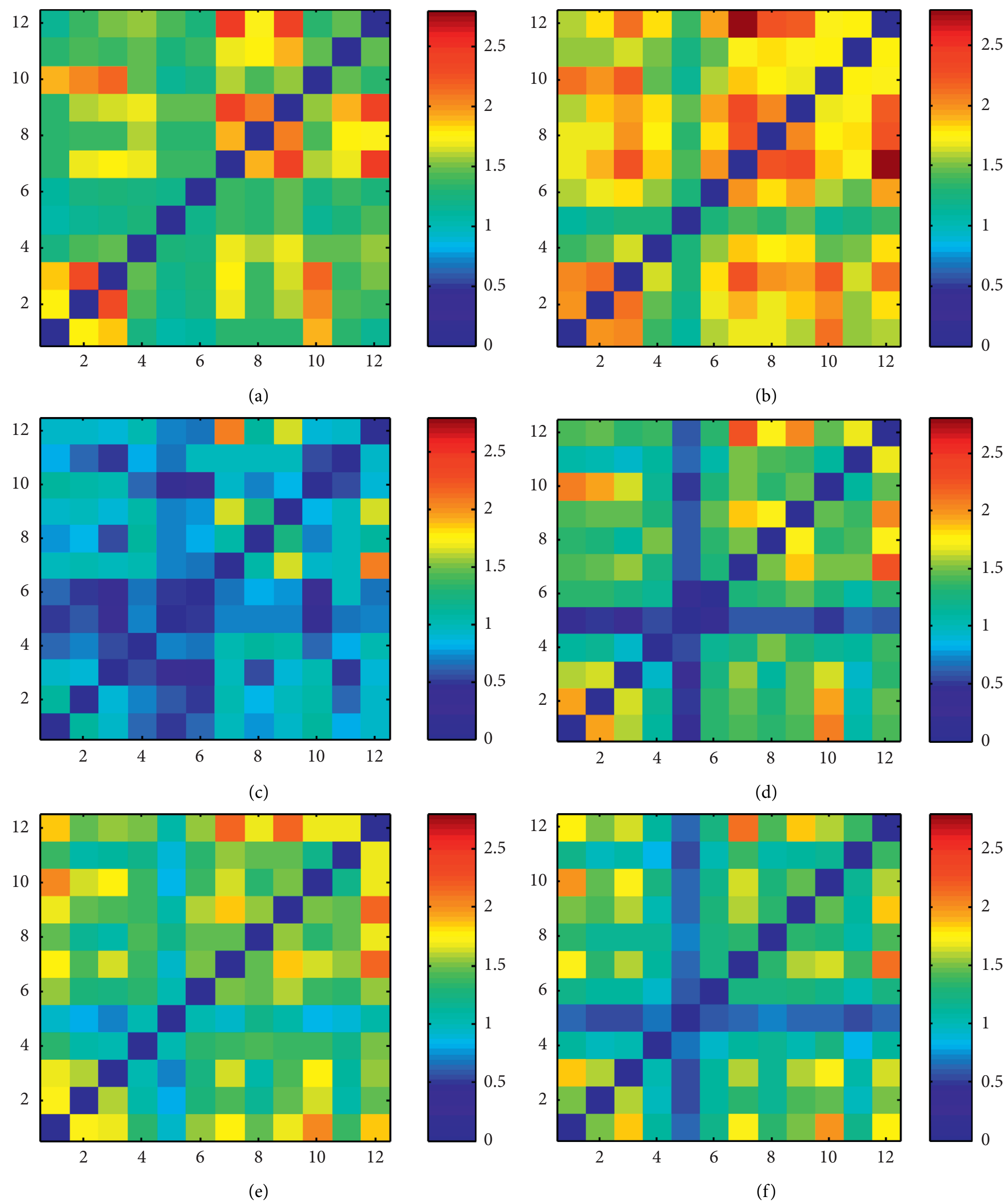

Figure 1: Colormaps of the MI among the 12 provinces during the six years. (a) 2015. (b) 2016. (c) 2017. (d) 2018. (e) 2019. (f) 2020.

Table 3: Average MI between regional indexes in the six years, respectively.

	2015	2016	2017	2018	2019	2020
Average MI	1.5362	1.7498	0.8556	1.2797	1.4088	1.2268

Eastern Coastal Economic Belt from 2015 to 2020 by using the maximum spanning tree method.

As is shown from the results in Figure 3, first of all, Jiangsu (No. 7), Shandong (No. 9), and Zhejiang (No. 12) have the largest number of sides, respectively, in the six years from 2015 to 2020, that is, the number of provinces maintaining the strongest economic dependence with the above three provinces is the largest. Among them, Jiangsu (No. 7) has five sides in 2016 and three sides in 2017; Shandong (No. 9) has five sides in 2015 and three sides in

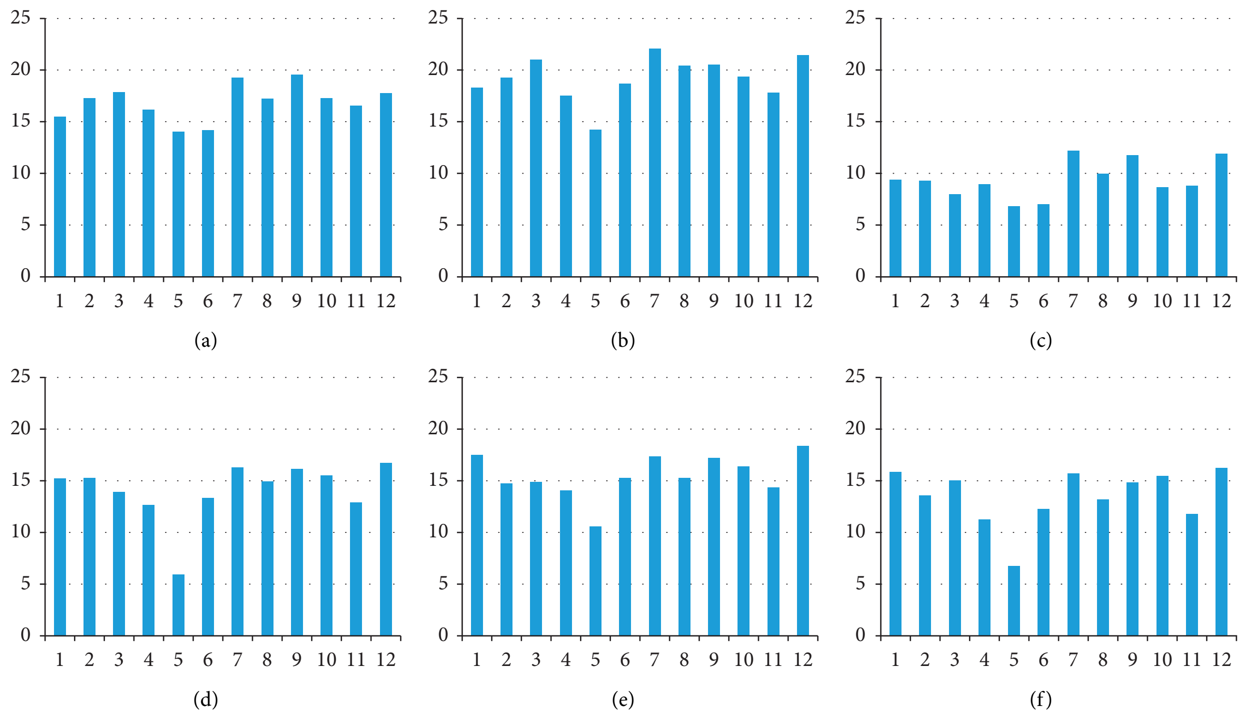

Figure 2: The NS value of the 12 provinces' indexes in the six years. (a) 2015. (b) 2016. (c) 2017. (d) 2018. (e) 2019. (f) 2020.

Table 4: The standard deviation of NS of the provinces, respectively, during 2018 to 2020.

	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
Standard deviation	0.9439	0.7207	0.4932	1.1538	2.0089	1.2575
	No. 7	No. 8	No. 9	No. 10	No. 11	No. 12
Standard deviation	0.6778	0.9111	0.9747	0.4364	1.0424	0.9161

2018; Zhejiang (No. 12) has three sides in 2017 and 2018, six sides in 2019 and four sides in 2020; the more sides there are, the more provinces have the strongest economic dependence with them. In addition, Jiangsu (No. 7), Shandong (No. 9), and Zhejiang (No. 12) have always maintained a close dependence relationship. In 2015 and 2016, the three provinces maintain a structure of No. 9-No. 7-No. 12; from 2017 to 2020, the three maintain a structure of No. 7-No. 12-No. 9; this conclusion also echoes and enriches some of the conclusions in Section 4.1.

Secondly, Beijing (No. 1), Guangdong (No. 3), and Shanghai (No. 10), which are also the developed provinces in the eastern coastal area of China, have always maintained the strongest economic dependence except in 2018, and most of the time, the number of edges between the above three provinces and the other provinces is very few, almost at the edge of the maximum spanning tree every year, which is different from the performance of Jiangsu (No. 7), Shandong (No. 9), and Zhejiang (No. 12). Guangdong (No. 3) is the first economically developed province in mainland China, and Beijing (No. 1) and Shanghai (No. 10) are, respectively, the political and economic centers of China, whose infrastructure and economic development strength and potential are at the best level. However, these three provinces are like Jiangsu (No. 7), Shandong (No. 9), and Zhejiang (No. 12) and do not maintain the largest dependence with other provinces.

Finally, for the less economically developed provinces, Guangxi (No. 4), Hainan (No. 5), and Hebei (No. 6) are in the marginal position in the past six years, which shows that these three provinces have only one largest edge connected with other provinces, and the dependence with other provinces is weak.

4.3. Spatial Stratified Heterogeneity. Spatial stratified heterogeneity (SSH), as a basic phenomenon in geography study, is a quantitative index used to show that the variance in the layer is less than that among layers. As a practical statistical method, the method has been widely used in the measurement of spatial differentiation or spatial stratification in climate characteristics, air quality, land resource management, and regional economic development level [32–36]. In this study, the economic development dependence of the 12 provinces in the Eastern Coastal Economic Belt of China has been measured by using the methods of mutual information and maximum spanning tree, and the core structure of the dependence has also been described. The results show that there is an obvious spatial stratified phenomenon in the economic dependence relationship among the above provinces, that is, the close economic dependence relationship is always maintained among some individual provinces, but the economic dependence among other provinces is weak.

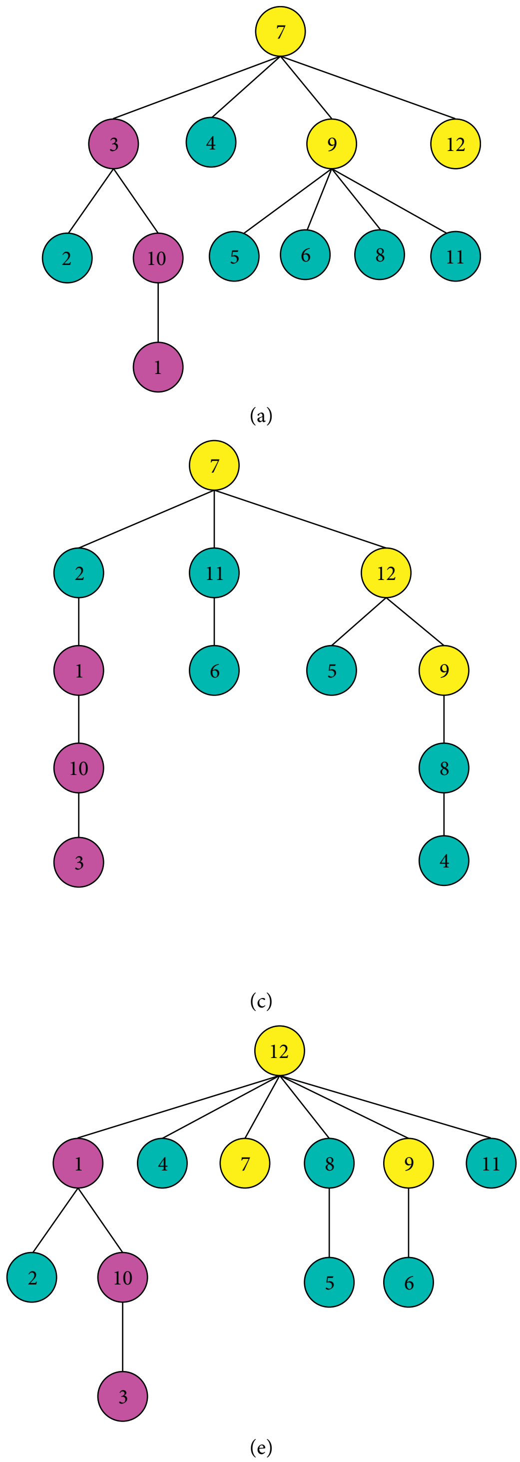

FIGURE 3: Maximum spanning trees (MSTs) of the 12 provinces. (a) 2015. (b) 2016. (c) 2017. (d) 2018. (e) 2019. (f) 2020.

In this study, MI and SSH are used to measure the spatial stratified heterogeneity. Firstly, the core structure of the economic dependence relationship among the provinces in the Eastern Coastal Economic Belt of China is constructed by MI and maximum spanning tree. By observing the core structure of economic dependence from 2015 to 2020, several major spatial stratification categories of the 12 provinces are summarized, for example, some provinces always maintain strong economic dependence with each other, while some provinces are always on the edge of the core structure of the economic dependence relationship. Based on the above identified spatial stratification categories, SSH is used to determine which kind of spatial stratification categories is the most suitable from the quantitative perspective. Therefore, SSH could be considered as the accuracy and supplement to the results of MI and maximum spanning tree.

According to the characteristics of economic dependence among provinces, the 12 provinces in the Eastern Coastal Economic Belt of China could be divided into several levels. However, the core structure and level division of economic dependence among the provinces in Figure 3 are summarized according to the results of the maximum spanning tree in the six years from 2015 to 2020. In order to describe the economic dependence structure and level division more scientifically, in this study, the method of geographic detector is used to compare the results of several level divisions, so as to select the most accurate one.

Geographic detector is a statistical method to detect spatial stratification, the q value is used to measure the degree of spatial differentiation in the range of [0, 1], and the expression is shown as follows:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2}, \tag{12}$$

where $h = 1, \ldots, L$ is the stratification of variables, N_h and N are the unit numbers of layer h and the whole area, respectively, and σ_h^2 and σ^2 are the variance of layer h and the whole region, respectively.

From the results of the colormaps and the maximum spanning tree, it could be seen that the 12 provinces in the Eastern Coastal Economic Belt of China could be divided into the following four categories, namely, (A) (1), (3), (7), (10), (12) and (2), (4), (5), (6), (8), (11); (B) (1), (3), (10), (2), (4), (5), (6), (8), (11), and (7), (9), (12); (C) (1), (3), (10), (2), (8), (11), (4), (5), (6), and (7), (9), (12); (D) (1), (3), (7), (9), (10), (12), (2), (8), (11), and (4), (5), (6). Among them, the spatial stratification structure A means the 12 provinces of the whole Coastal Economic Belt are divided into two levels, the provinces with the number of (1), (3), (7), (9), (10), (12) as one level and the provinces with the number of (2), (4), (5), (6), (8), (11) as another level. The meanings of stratification structure B, C, and D are the same as that of A.

q_A, q_B, q_C, and q_D are used to represent the q value of the above four kinds of spatial differentiation structures, and it is found that the relationship among the above four kinds of structures q values is $q_B > q_C > q_A > q_D$; this shows that structure B could better reflect the spatial stratification relationship among the provinces in the Eastern Coastal Economic Belt of China, that is to say, the 12 provinces in China's Eastern Coastal Economic Belt should be divided into three levels, namely, (1) Beijing (3) Guangdong (10) Shanghai at the same level, (7) Jiangsu (9) Shandong (12) Zhejiang at the same level, and (2) Fujian (4) Guagnxi (5) Hainan (6) Hebei (8) Liaoning (11) Tianjin at the same level.

Based on the above results, we can find the phenomenon of geographical clustering, that is, the two adjacent geographical units often show strong dependence, is not obvious in the eastern coastal provinces of China. For example, Beijing (No. 1), Guangdong (No. 3), and Shanghai (No. 10) maintain the strongest dependence with each other in almost all periods, but in terms of geographical location, these three provinces are separated by at least the other two provinces. On the other hand, the phenomenon of geographical clustering is also reflected to some extent. For example, Jiangsu (No. 7), Shandong (No. 9), and Zhejiang (No. 12) have always maintained the strongest dependence, and in the geographical position, these three provinces are adjacent. Besides, Jiangsu (No. 7) and Zhejiang (No. 12) are the two important provinces in the lower reaches of the Yangtze River Economic Belt, and with the deepening of the construction of the Yangtze River Delta urban agglomeration, the degree of integration between the two provinces is deeply enhanced. In addition, Hainan (No. 5) is the only island province among the 12 eastern coastal provinces in this study. Compared with the close links between other eastern coastal areas brought by dense road and railway traffic, the economic main body of Hainan (No. 5) has no strong links with other provinces, so it shows that the economic dependence between Hainan and other 11 provinces is the weakest in the past six years.

4.4. Dynamic Evolution of the Dependence Relationship. The above two sections have analyzed the economic dependence and the core structure of the 12 provinces in China's Eastern Coastal Economic Belt in the past six years from 2015 to 2020. In this part, the sliding window method will be used to measure the dependence from a dynamic perspective. In this study, the width of the sliding window is set to 150, and the sliding distance of each window is set to 20. The reason is that, for the data of 150 trading days in each window, it can guarantee the amount of data needed for mutual information calculation, and the data of 20 trading days in each sliding are just corresponding to one month, which is more convenient in analysis. According to the above settings of window width and sliding distance, this study can be divided into 66 windows.

Figure 4 shows the provinces with the maximum and minimum node strength in all 66 sliding windows, that is, the provinces with the strongest and weakest overall economic dependence with the other 11 provinces. The number of abscissae in Figure 4 represents the position of the window, and the number of ordinates represents the index of 12 provinces in Table 1. It can be seen from the figure that, in almost all the windows, Jiangsu (No. 7), Shandong (No. 9), and Zhejiang (No. 12) are the provinces with the strongest node strength. While the provinces with the least node strength are all concentrated in Guangxi (No. 4), Hainan (No. 5), and Hebei (No. 6), this conclusion is consistent with the above static analysis.

It is displayed in Table 5 that, in the 66 sliding windows, with which one, a certain province maintains the strongest dependence relationship, in other words, which province is most closely related to the certain one. For example, if the maximum weight of province A connects province B, then we add 1 to the position of matrix (A, B), and the initial value

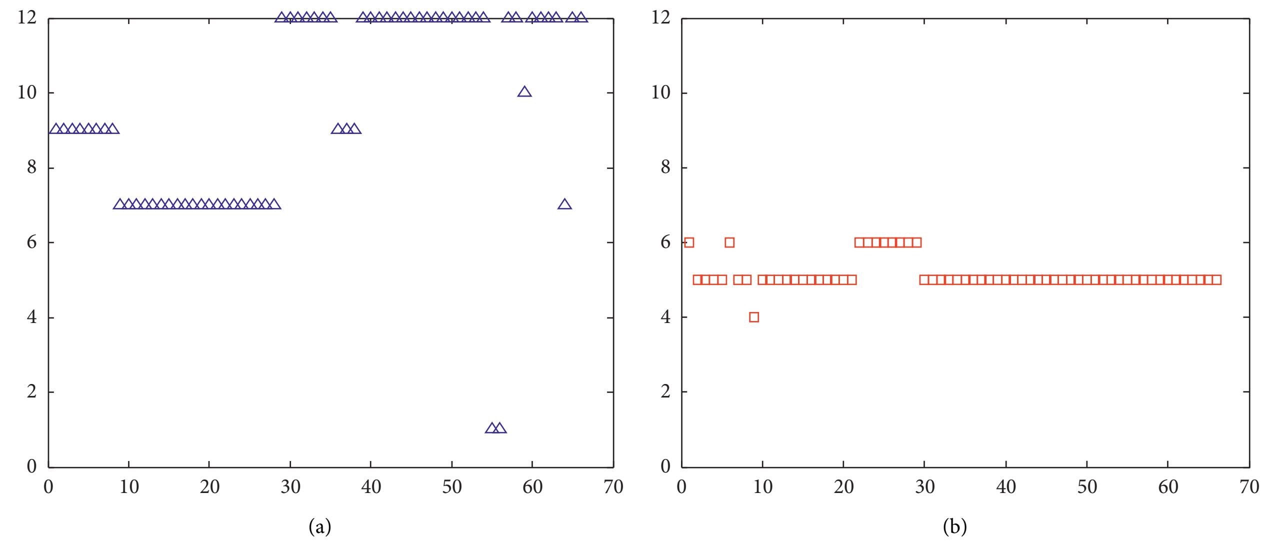

FIGURE 4: The province indexes with the largest or smallest node strength. (a) The largest node strength. (b) The smallest node strength.

TABLE 5: Total number of the strongest edge between the indexes in rolling windows.

No.	1	2	3	4	5	6	7	8	9	10	11	12	Sum
1	0	11	7	0	0	0	1	0	0	46	0	1	66
2	24	0	30	0	0	0	4	0	0	7	0	1	66
3	7	18	0	0	0	0	12	0	0	28	0	1	66
4	0	0	0	0	0	0	17	24	5	11	0	9	66
5	0	0	0	6	0	0	2	21	23	0	10	4	66
6	4	0	2	0	0	0	11	9	28	1	9	2	66
7	0	0	0	0	0	0	0	0	1	0	0	65	66
8	1	0	0	1	0	0	8	0	26	0	0	30	66
9	0	0	0	0	0	0	25	0	0	0	0	41	66
10	45	5	16	0	0	0	0	0	0	0	0	0	66
11	0	0	0	0	0	7	8	5	9	6	0	31	66
12	3	0	0	0	0	0	56	0	7	0	0	0	66
Sum	84	34	55	7	0	7	144	59	99	99	19	185	—

of position (A, B) is 0. It can be found from Table 5 that the table is not symmetric because the maximum weight edge of province A may connect province B, while the maximum weight edge of province B may connect another province C, which leads to asymmetry.

It can be seen from the results in Table 5 that, first of all, Jiangsu (No. 7) and Zhejiang (No. 12) have the most number of times obtaining the strongest dependence with the other provinces, 144 times and 185 times, respectively. This shows that, for the other 11 provinces, of the whole 726 times (66×11) strongest economic dependence, keep the strongest economic dependence with Jiangsu (No. 7) 144 times and keep the strongest economic dependence with Zhejiang (No. 12) 185 times. The other provinces with the most number of times obtaining the strongest dependence with the other provinces are Shandong (No. 9), Shanghai (No. 10), and Beijing (No. 1), and the times are 99, 99, and 84, respectively, and all of the above provinces are economically developed provinces in the Eastern Coastal Economic Belt of China. On the other hand, Guangxi (No. 4), Hainan (No. 5), and Hebei (No. 6) have the least number of times obtaining the strongest dependence with the other provinces. Especially, in Hainan (No. 5), the times are 0, and this shows that, for the other 11 provinces, none of their 726 times strongest economic dependence connected with it. This also echoes the above research conclusion, that is, each province is more willing to maintain a strong economic dependence with the developed provinces and rarely maintain a strong economic connection with the less developed provinces.

Secondly, Jiangsu (No. 7), Shandong (No. 9), and Zhejiang (No. 12) maintain the strongest dependence with each other. Among the 66 windows, respectively, Jiangsu (No. 7) maintains the largest edge with Zhejiang (No. 12) 65 times and with Shandong (No. 9) once. Shandong (No. 9) maintains the largest edge with Jiangsu (No. 7) 25 times and with Zhejiang (No. 12) 41 times. Zhejiang (No. 12) maintains the largest edge with Jiangsu (No. 7) 56 times and with Shandong (No. 9) 7 times. In particular, for Jiangsu (No. 7) and Zhejiang (No. 12), with the construction of the Yangtze River Economic Belt and the deepening of the construction of the Yangtze River Delta urban agglomeration, Jiangsu and Zhejiang are closely related.

Finally, for Beijing (No. 1) and Shanghai (No. 10), Beijing (No. 1) maintains the strongest economic dependence with Shanghai (No. 10) in 46 windows, while Shanghai (No. 10) maintains the strongest economic dependence with Beijing (No. 1) in 45 windows. As China's political and economic centers, respectively, the economic dependence between Beijing and Shanghai could be explained from the perspective of the implementation of national policies and their special status in the international community. As the two most representative provinces in mainland China and they are the municipalities directly under the central government of China, in the implementation of the relevant policies of national high-tech enterprises and start-up enterprises, they always keep the same pace and give more preferential treatment and support to enterprises from talent, tax, capital, and other aspects. A large number of high-tech enterprises and start-up enterprises are headquartered in Beijing or

Shanghai, and branches will also be set up in these two municipalities. Therefore, the association of innovative enterprises will naturally bring closer economic dependence between the two provinces. At the same time, as the international metropolises, Beijing and Shanghai, the two municipalities directly under the central government, often receive equal attention from the international community, and a large number of foreign-funded enterprises, personnel, and capital enter these two provinces, which also increases the economic ties between them.

5. Conclusions

By using mutual information and maximum spanning tree, this study explores the core structure and changes of the economic dependence among provinces in the Eastern Coastal Economic Belt, which is the most dynamic area in the economic development of China. Based on the above results, the following conclusions can be drawn. First, there is a wide range of economic dependence between provinces in the Eastern Coastal Economic Belt of China. The dependence relationship changes with the degree of economic development. When the economic development is overheated and the capital market fluctuates abnormally, the dependence is stronger, while the economic development is in a contraction state or the total demand is relatively low, the relationship is weakened.

Secondly, the geographical clustering phenomenon of economic dependence among provinces in the Eastern Coastal Economic Belt is not obvious. Most provinces have strong economic dependence with economically developed provinces, such as Jiangsu (No. 7), Shandong (No. 9), and Zhejiang (No. 12), and this dependence is relatively stable, while less economically developed provinces are often on the edge of the dependence structure. In addition, the economically developed provinces also maintain strong economic ties with each other.

Finally, Beijing (No. 1), Guangdong (No. 3), and Shanghai (No. 10) maintain strong economic dependence mutually, especially Beijing and Shanghai, as the political and economic centers of China, respectively, and as the two most representative international metropolises, maintain strong economic ties. However, the above three provinces are not in the core position in the core structure of dependence, not like Jiangsu (No. 7), Shandong (No. 9), and Zhejiang (No. 12), which indicates that the other provinces in Eastern Coastal Economic Belt are more willing to keep the strong dependence with Jiangsu (No. 7), Shandong (No. 9), and Zhejiang (No. 12), rather than Beijing (No. 1), Guangdong (No. 3), and Shanghai (No. 10). Based on the above conclusions, in the process of China's future regional development, more attention should be paid to the development and stability of the economically developed provinces, so as to ensure the healthy and stable operation of the economy of the other provinces which keep the strong economic dependence with them. At the same time, as for the less-developed provinces, to strengthen the economic dependence with other provinces, especially with the economically developed provinces is crucial, so as to promote the economic construction of less-developed provinces and realize the balanced and sustainable development of the whole regional economy.

Data Availability

All data used are downloaded from the WIND database, and the details are shown in Table 1 of this study.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

Xianbo Wu and Xiaofeng Hui proposed the research framework together. Xianbo Wu collected the data, finished the computation, and wrote the paper. Xiaofeng Hui provided some important guidance and advices during the process of this research.

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Research Article

Semi-Analytical Solutions for the Diffusive Kaldor–Kalecki Business Cycle Model with a Time Delay for Gross Product and Capital Stock

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This paper discusses the stability and Hopf bifurcation analysis of the diffusive Kaldor–Kalecki model with a delay included in both gross product and capital stock functions. The reaction-diffusion domain is considered, and the Galerkin analytical method is used to derive the system of ordinary differential equations. The methodology used to determine the Hopf bifurcation points is discussed in detail. Furthermore, full diagrams of the Hopf bifurcation regions considered in the stability analysis are shown, and some numerical simulations of the limit cycle are used to confirm the theoretical outcomes. The delay investment parameter and diffusion coefficient can have great impacts on the Hopf bifurcations and stability of the business cycle model. The investment parameters for the gross product and capital stock as well as the adjustment coefficient of the production market are also studied. These parameters can cause instability in, and the stabilization of, the business cycle model. In addition, we point out that, as the delay investment parameter increases, the Hopf bifurcation points for the diffusion coefficient values decrease considerably. When the delay investment parameter has a very small value, the solution of the business cycle model tends to become steady.

1. Introduction

For a long period of time, many significant nonlinear phenomena have been modelled and described via ordinary or partial differential equations (ODEs or PDEs). For example, these equations have been used to model population ecology [1–4], animals [5, 6], health [7, 8], chemicals [9, 10], and business economics [11–14]. A business cycle model is utilized to explain the working of economic laws and can also be utilized to predict investment status, yield, costs, and other important factors in the business economic model. Also, it can help practitioners avoid fluctuations [15].

One of the important economic models was created by Kaldor [13] in 1940. It uses a nonlinear model constructed with a couple of ODEs, where the nonlinearity of the investment and saving functions lead to periodic limit cycle results. Furthermore, Kalecki [14] considered a time delay between an investment decision and its impact on capital accumulation in the business cycle model. It was shown that earnings are invested, and capital grows due to past investment decisions.

In 1999, Kaddar and Szydlowski [16] developed the Kaldor–Kalecki business cycle system by incorporating the Kalecki concept [13] into the system created by Kaldor [14]. A time delay was included in the investment function for the gross product in the capital equation. Afterwards, Kaddar and Alaoui [17] added a time delay for both gross product and capital stock due to a past decision. Therefore, the Kaldor–Kalecki system became as in [17]:

$$\begin{aligned}\frac{\partial Y}{\mathrm{d}t} &= \alpha[I(Y(t), K(t)) - S(Y(t), K(t))],\\ \frac{\partial K}{\mathrm{d}t} &= I(Y(t-\tau), K(t-\tau)) - \delta K(t),\end{aligned} \tag{1}$$

where $Y(t)$ refers to the gross product; $K(t)$ indicates the capital stock; δ and α are the depreciation value of the capital stock and the adjustment rate of the production market, respectively; $I(Y,K)$ denotes the investment function; $S(Y,K)$ describes the savings function; and $\tau > 0$ is the time delay in investment due to the past investment decision.

The dynamic ODE system in (1) has been studied and discussed by many researchers. Recently, Jianzhi and Hongyan [18] determined that the local stability of the positive equilibrium produces the corresponding characteristic equations. The existence of the Hopf bifurcation, the direction of this bifurcation, and the stability of the limit-cycle outcomes have been studied using numerical simulations. Wu [19, 20] explored the simple-zero and double-zero singularities for the ODE equations presented in (1). They constructed bifurcation diagrams and examined the double-periodic oscillation. Kaddar andTalibi Alaoui [17] proved that Hopf bifurcation points occur when the delay parameter τ is increased. Wu and Wang [21] considered the distribution of the roots of the characteristic equation of the system in (1) at the equilibrium point. They also discussed the Hopf bifurcation and the stability of the limit cycle. Kaddar and Talibi Alaoui [12] illustrated the existence of a local Hopf bifurcation and also used an explicit algorithm to show the direction of the Hopf bifurcation and conduct a stability analysis of the system in (1).

The presence of the diffusion coefficient in both equations in system (1) is extremely important as it can strongly affect the stability. It can also change the Hopf bifurcation points and therefore change the regions used for the stability analysis [1, 22, 23]. Blanke et al. [24] investigated a diffusive Kaldor–Kalecki business cycle system with a time delay under Neumann boundary conditions. They conducted a stability analysis of the model and found that the time delay can give rise to the Hopf bifurcation when the delay stretches beyond a critical point. Furthermore, they showed that the diffusion coefficient played a key role in this model. Szydłowski and Krawiec [25] investigated the Kaldor–Kalecki system as a two-dimensional dynamic model. A time delay was considered for the capital accumulation equation. A qualitative analysis for the differential equations was considered for this model. Finally, they showed that there is a Hopf bifurcation leading to a limit-cycle result.

Based on the previous studies on system (1), it appears that there is a need for additional research on the effects of the diffusion value and the investment delay on the business cycle model. Therefore, it is of importance to study the impacts of the diffusion and delay parameters on the stability and Hopf bifurcation. Thus, this paper will focus on the Kaldor–Kalecki business model with delays in the one-dimensional (1D) domain and has several significant aims. The first aim is to show what theoretical results can be obtained by utilizing the Galerkin technique. This helpful and reliable technique can help solve, and provide an excellent prediction for, the PDE system. Moreover, in order to discuss the effects of the diffusion coefficient d and the investment delay τ on the adjustment coefficient of the production market in detail, the investment parameters for the gross product and capital stock need to be examined. In addition, we also construct full-map diagrams of the Hopf bifurcation points and the stability analysis (stable and unstable regions) using examples of periods in limit cycle maps. All of these aims will help us explore the stability of the business cycle and predict whether policy makers' targets will be met. The knowledge gained may also help practitioners avoid large-scale business fluctuations.

This paper is arranged as follows. Section 2 explains the modelling of dynamic behaviour in the Kaldor–Kalecki business cycle model. Section 3 explains the methodology and the theoretical framework used to determine the Hopf bifurcation map. It also discusses how the Galerkin method can be used to create an ODE system from the PDE model. Section 4 constructs the maps of the Hopf bifurcation regions of stability for both the numerical simulations of the PDEs and the analytical outcome, thus showing the effects of the delay and diffusion parameters on the system. Finally, in Section 5, bifurcation diagrams and periodic oscillation limit-cycle maps showing both stable and unstable results are plotted to confirm the analytical outcomes.

2. Mathematical Model

The dynamic behaviour of the Kaldor–Kalecki business cycle model is considered by using the following replacement equations for the investment $I(Y,K)$ and saving $S(Y,K)$ variables:

$$\begin{aligned} I(Y,K) &= IY - \beta K, \\ S(Y,K) &= \gamma Y, \quad \text{where } \beta > 0 \text{ and } \gamma \in (0,1), \end{aligned} \tag{2}$$

in the ODE equations in (1). For more details regarding the simple mathematical formulations used here, see [16, 17, 21, 26] and the references therein. Therefore, the nonlinear reaction-diffusion business cycle model with a time delay in the gross product and capital stock can be described with the following system:

$$\begin{aligned} \frac{\partial Y}{dt} &= dY_{xx} + \alpha[IY(t) - \beta K(t) - \gamma Y(t)], \\ \frac{\partial K}{dt} &= dK_{xx} + IY(t-\tau) - \beta K(t-\tau) - \delta K(t), \\ Y(x,t) = K(x,t) &= 0, \text{ at } x = \pm 1, Y(x,t) = y_s, K(x,t) \\ &= k_s, \quad -\tau < t \le 0. \end{aligned} \tag{3}$$

Here, parameters $\alpha, \beta, \gamma, \delta$, and τ have the same meaning that they do in system (1). In addition, d denotes the diffusion coefficient of the system. This system is open, with a symmetrical pattern in the outcome in the middle of the domain for $x = 0$. In addition, $Y_s > 0$ and $K_s > 0$ represent the positive initial concentrations for times in the interval $(-\tau, 0)$. Note that $Y_s = K_s = 1$ in all the numerical simulations run in this model. The Runge–Kutta method [27, 28] is used to determine the solutions of the ODE system. The Crank–Nicholson scheme [7, 29] is considered according to the numerical simulation outcomes for PDE system (3). In the numerical simulation, spatial and temporal discretization are applied, i.e., $(\Delta x, \Delta t) = (10 \times 10^{-3}, 10 \times 10^{-4})$.

3. Methodology and Theoretical Analytical Framework

In this section, we identify a reliable technique for solving nonlinear PDE models. The Galerkin analytical technique [30] is applied to a system of PDEs to produce ODE equations. This technique considers the orthogonality of the basic functions to convert the PDEs into an ODE system [10, 27]. Several models have employed this technique, including the Gray and Scott cubic autocatalytic system [10], logistic equations with delays [1, 2, 29], and a viral infection model [7]. In general, all of the researchers who have considered this technique have obtained significant results and validated the method.

In order to use the Galerkin technique, we consider the following trial functions:

$$\begin{aligned} Y(x,t) &= Y_1(t)\cos(\eta_1) + Y_2(t)\cos(\eta_2),\\ K(x,t) &= K_1(t)\cos(\eta_1) + K_2(t)\cos(\eta_2), \end{aligned} \tag{4}$$

where $\eta_1 = (\pi x/2)$ and $\eta_2 = (3\pi x/2)$. The trial equation functions are assumed to be $Y = \sum Y_i = Y_1 + Y_2$. Here, $K = \sum K_i = K_1 + K_2$ refers to the centre profile concentrations at $x = 0$. The trial equation expansion (4) meets the boundary conditions in the PDE model in (3). The free parameters in the system are then examined by computing the values for the delay PDEs. Next, the PDEs are weighted using two trial expansions: $\cos(\eta_1)$ and $\cos(\eta_2)$. The resulting system of four ODE equations is as follows:

$$\begin{aligned} \frac{dY_1}{dt} &= -\frac{\pi^2}{4}dY_1 + I\alpha Y_1 - \alpha\gamma Y_1 - \alpha\beta K_1,\\ \frac{dK_1}{dt} &= -\frac{\pi^2}{4}dK_1 + IY_{1\tau} - \delta K_1 - \beta K_{1\tau},\\ \frac{dY_2}{dt} &= -\frac{9\pi^2}{4}dY_2 + I\alpha Y_2 - \alpha\gamma Y_2\gamma - \alpha\beta K_2,\\ \frac{dK_2}{dt} &= -\frac{9\pi^2}{4}dK_2 + IY_{2\tau} - \delta K_2 - \beta K_{2\tau},\\ & Y_{i\tau} = Y_i(x,t-\tau) \text{ and } K_{i\tau} = K_i(x,t-\tau) \text{ and } i = 1,2. \end{aligned} \tag{5}$$

Note that the series in (4) has been abbreviated at the two-term equation point because the two-term outcome provides sufficient accuracy. It also presents excellent outcomes compared to the PDE numerical scheme system. Moreover, the one-term system can be expressed as a couple of equations by assuming that $Y_2 = K_2 = 0$ for the ODEs in system (5).

We can utilize the equations in system (5) to explore the existence of the Hopf bifurcation points theoretically. These points are then used to determine a map showing the full stability analysis and any unstable and stable zones. The Hopf bifurcation denotes the periodic oscillation of the limit cycle in the neighbourhood of the steady state, which can cause a transition from a stable solution to an unstable solution. For more information, see [1, 22, 23, 31]. Hence, the points of the Hopf bifurcation can be displayed by utilizing the Taylor series for the steady-state value points; see [7, 29]. This result can be examined with

$$\begin{aligned} Y_i &= Y_{is} + \epsilon\chi_1 e^{-ut},\\ K_i &= K_{is} + \epsilon\chi_2 e^{-ut}, \quad \text{where } i = 1,2,\ \epsilon \ll 1. \end{aligned} \tag{6}$$

Hence, the expressions Y_i and K_i in (6) are inserted into the ODE system in (5). Afterwards, the steady-state values are linearized. Next, the Jacobian matrix of the eigenvalues considers a small system perturbation, which demonstrates the typical growth value u by placing $u = i\omega$ in the characteristic equation via dividing the characteristic equation by the real (RE) and imaginary (IM) equations. The next conditional equation then helps to determine the points in the Hopf bifurcation:

$$\frac{dY_i}{dt} = \frac{dK_i}{dt} = \text{RE} = \text{IM} = 0, \quad \text{where } i = 1,2. \tag{7}$$

4. Stability and the Hopf Bifurcation Maps

This section provides the Hopf bifurcation maps and the regions of stability for both the numerical simulations for the PDEs in (3) and the theoretical outcome for the ODEs in (5). The delay parameter τ and diffusion coefficient d are studied in conjunction with the adjustment coefficient for the production market and the investment parameters for the gross product and capital stock. At the end of this section, we present some numerical examples in order to show the accuracy of the analytical outcomes.

4.1. Effect of the Delay Parameter τ.

Figure 1 shows the maps of two different regions of the Hopf bifurcation for the delay parameter τ versus I (upper graph), β (middle graph), and α (lower graph). The analysis of the two-term solution (dashed line) and the numerical simulation for the PDEs (black crosses) are obtained in each case. Positive parameters are utilized in each graph, $\delta = 0.15$, $\gamma = 0.10$, and $d = 0.05$, where $\beta = 1$ and $\alpha = 5$ (upper figure), $\alpha = 3$ and $I = 0.2$ (middle figure), and $I = 0.2$ and $\beta = 1$ (lower figure). There is a unique curve in each figure dividing the stability regions: the region above the curve indicates the unstable zone, whereas the region below the curve indicates the stable zone. Note that when the investment delay τ is increased, the critical values of the Hopf bifurcation points for the adjustment coefficient for the production market α increase steadily. Moreover, the investment parameters for the gross product I and the capital product β also increase with an increase in the value of τ. When the delay investment parameter has a very small value, the solution of the business cycle model tends to become stable and reaches a steady state. It appears that the analytical prediction corresponds to the numerical simulation of the PDEs, with less than 1%

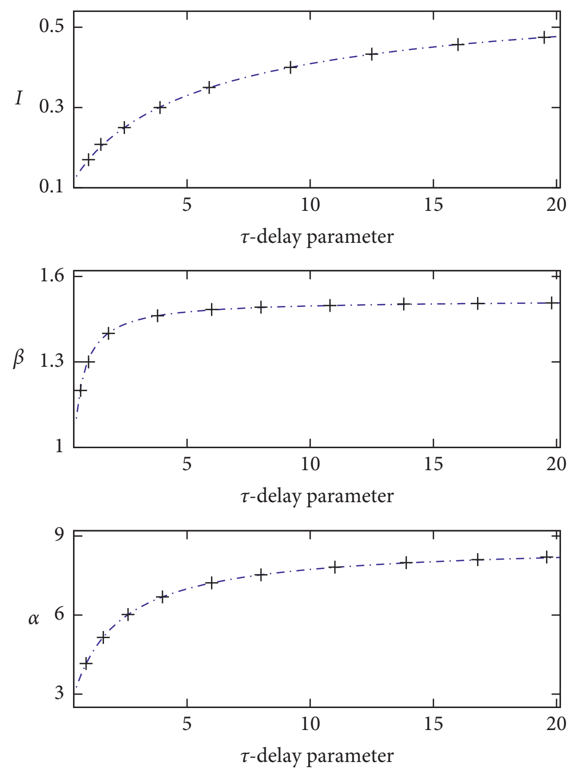

Figure 1: The regions produced by the Hopf bifurcation curves for the delay parameter τ versus I, β, and α. The analytical outcomes are indicated by the blue dashed lines, while the numerical simulation results for the PDE model are indicated by black crosses.

error reported for all values of τ. Therefore, the delay investment value τ can have a very crucial impact on the stability regions of the business cycle in terms of the investment function and can destabilize or stabilize the model. Moreover, it potentially has a significant influence on economic equilibrium and could assume a guiding role in investment activities.

Figures 2(a) and 2(b) explore the Hopf bifurcation maps on the $\alpha - \beta$ diagrams. Figure 2(a) shows both analytical ODE (blue dashed line) and numerical simulation for the PDEs (black crosses). Positive values are used in these figures, $\delta = 0.15$, $\gamma = 0.10$, $I = 0.2$, and $d = 0.3$. The stability regions are shown. This figure shows that, as the adjustment coefficient for the production market α increases, the value of the investment in the capital product β decreases. Furthermore, Figure 2(b) provides the analytical results for the two-term solution for five different values of the delay parameter τ, namely, $\tau = 1, 2, 3, 4$, and 5. At any selected fixed point of the adjustment coefficient for the production market α, the parameter for the investment in capital product β decreases as the delay investment parameter τ increases. Note that the resulting behaviour obtained in this figure is very similar to behaviours found in [1, 7]. Therefore, the investment delay term can also have a significant impact on Hopf bifurcation stability regions for this model.

Figures 3(a) and 3(b) present maps of the Hopf bifurcation regions for α against the investment parameter for gross production (I). Figure 3(a) shows the theoretical outcomes (blue dashed line) as well as the numerical results (black crosses). The positive values used here are $d = 0.05$, $\delta = 0.15$, $\gamma = 0.10$, and $\beta = 1$. As the adjustment coefficient of production market α increases, the Hopf bifurcation points for the investment parameter for the production rate I decrease slowly. The matchup between the numerical scheme for the PDEs and the theoretical results for the ODE system is excellent. In Figure 3(b), the two-term analytical solutions are shown for five different values of the delay parameter, namely, $\tau = 1, 2, 3, 4$, and 5. It can be seen that, as the adjustment coefficient for the production market parameter α increases, the unstable region becomes bigger than the stable area.

4.2. Effect of the Diffusion Coefficient Parameter d. Figure 4 presents the Hopf bifurcation maps for the diffusion coefficient in the $d - I$ plane (upper graph), $d - \beta$ plane (middle graph), and $d - \alpha$ plane (lower graph). In each figure, the two-term solution is shown with a red dashed line, while the black crosses indicate the numerical simulation results for the PDE model. The free parameters applied are $\beta = 1$ and $\alpha = 3$ (upper graph), $\alpha = 3$ and $I = 0.2$ (middle graph), and $I = 0.2$ and $\beta = 1$ (lower graph). The other parameters for all figures are $\tau = 1$, $\delta = 0.15$, and $\gamma = 0.10$. As in Figure 1, the graphs indicate the stable and unstable regions. Each graph indicates the results of the increases in the diffusion coefficient values d. As a result, the Hopf bifurcation points for the rate of the adjustment coefficient for the production market α have also increased considerably. Furthermore, the investment parameter rates I and β (for production and capital) also increase steadily

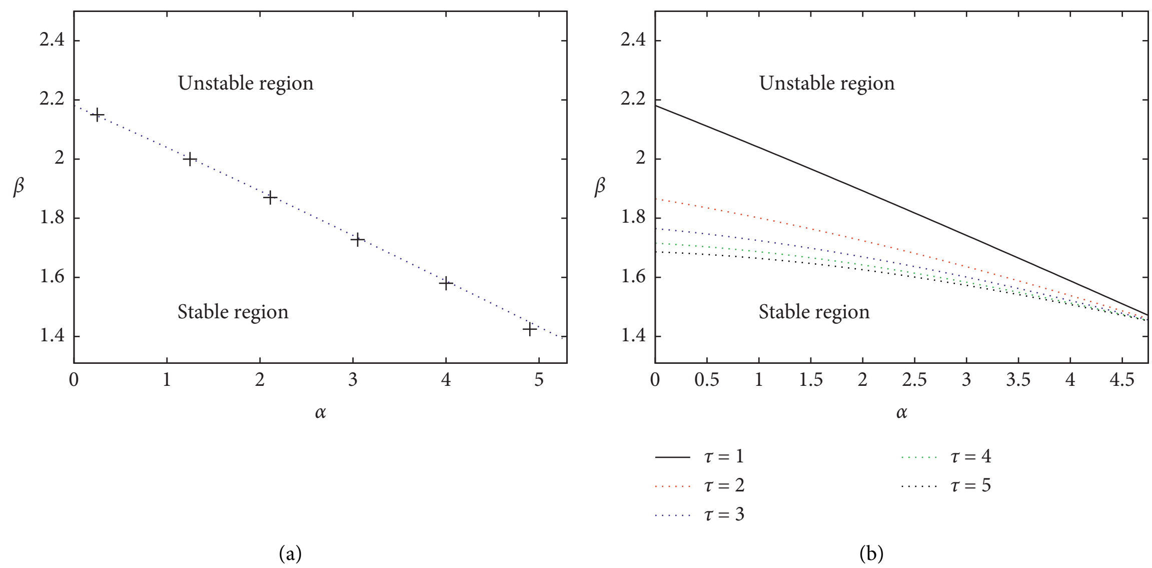

Figure 2: An exploration of the Hopf bifurcation maps in the $\alpha - \beta$ diagrams: (a) analytical and numerical simulation results and (b) analytical results for the two-term solution for five different values of τ.

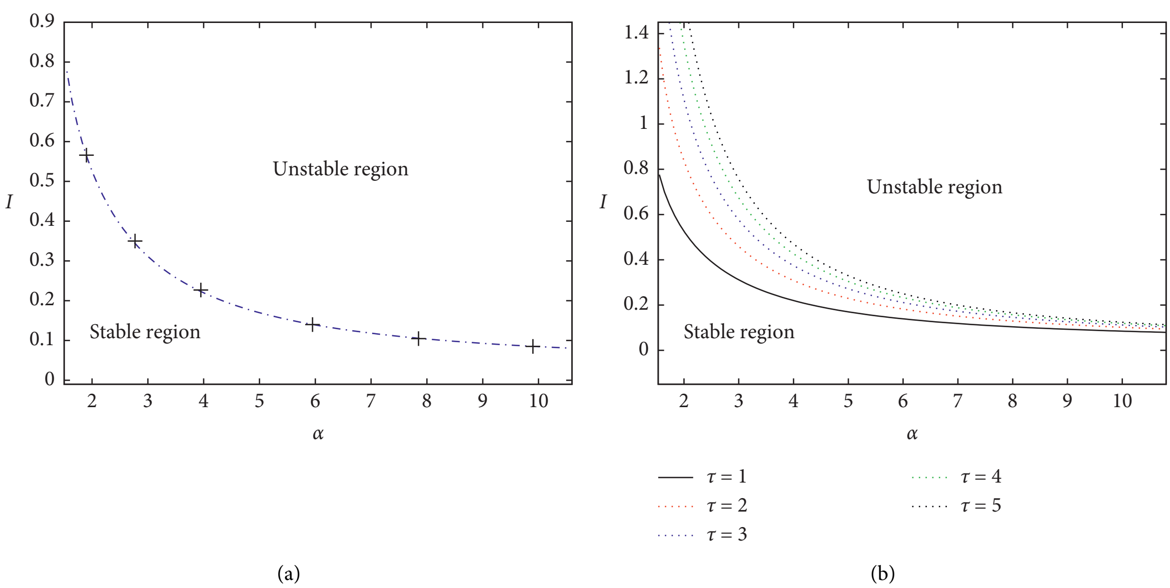

Figure 3: The two regions created by the Hopf bifurcation in the $\alpha - I$ and $\beta - I$ planes: (a) the two-term solutions and (b) the outcomes for five different values of τ.

against the increasing diffusion parameter d. Therefore, adding the diffusion coefficient d can have a significant effect on the stability of this model as it can change the stability of the model [1, 2].

Figure 5(a) presents the Hopf bifurcation maps on the $\alpha - \beta$ diagrams for the analytical (red dotted) and numerical simulation results (black crosses). The positive values used in Figure 5(a) are $\tau = 1$, $\delta = 0.15$, $\gamma = 0.10$, $I = 0.2$, and $d = 0.05$. Figure 5(b) shows plots of the analytical ODE results for five different values of the diffusion coefficient d: $0, 0.05, 0.10, 0.15,$ and 0.20. In both figures, the stability regions are provided. It can be shown that, at any fixed point of α, the parameter for the investment in the capital product β increases as the diffusion coefficient d increases. Note that the resulting behaviour obtained in this figure is very similar to behaviours found in [7]. The diffusion term can also have a huge impact on the bifurcation regions in the business cycle model.

Figure 6(a) determines the Hopf bifurcation maps in the $\tau - I$ plane, while the frequency of the periodic results for ω against τ is plotted in Figure 6(b). In both figures, we see the results for two cases: no diffusion term ($d = 0$; black dashed line) and a diffusion term ($d = 0.1$; red dashed line). The positive values used are $\alpha = 5$, $\beta = 1$, and $\gamma = \delta = d = 0.15$. In Figure 6(a), the diffusion rate causes the stabilization of the system utilizing the critical value of the investment rate I,

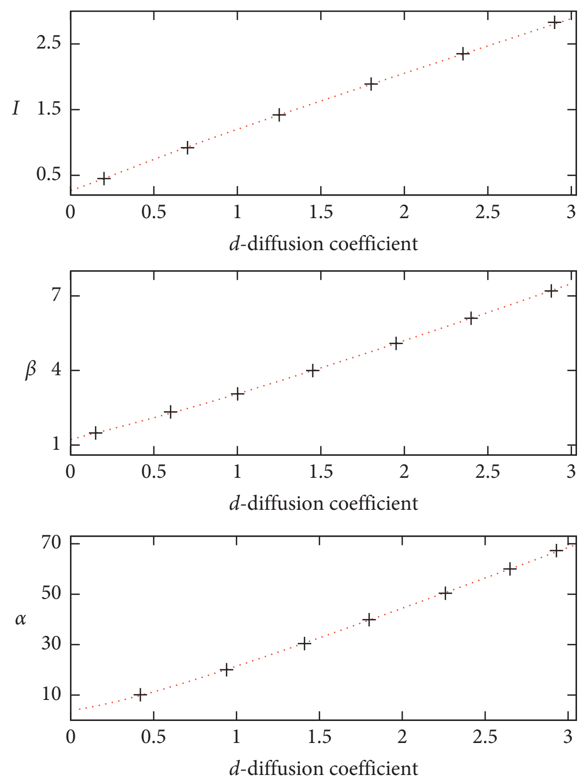

Figure 4: The Hopf bifurcation curves for $D-I$ (upper graph), $D-\beta$ (middle graph), and $D-\alpha$ (lower graph). In each case, the analytical (red dashed lines) and numerical simulation results (black crosses) are plotted.

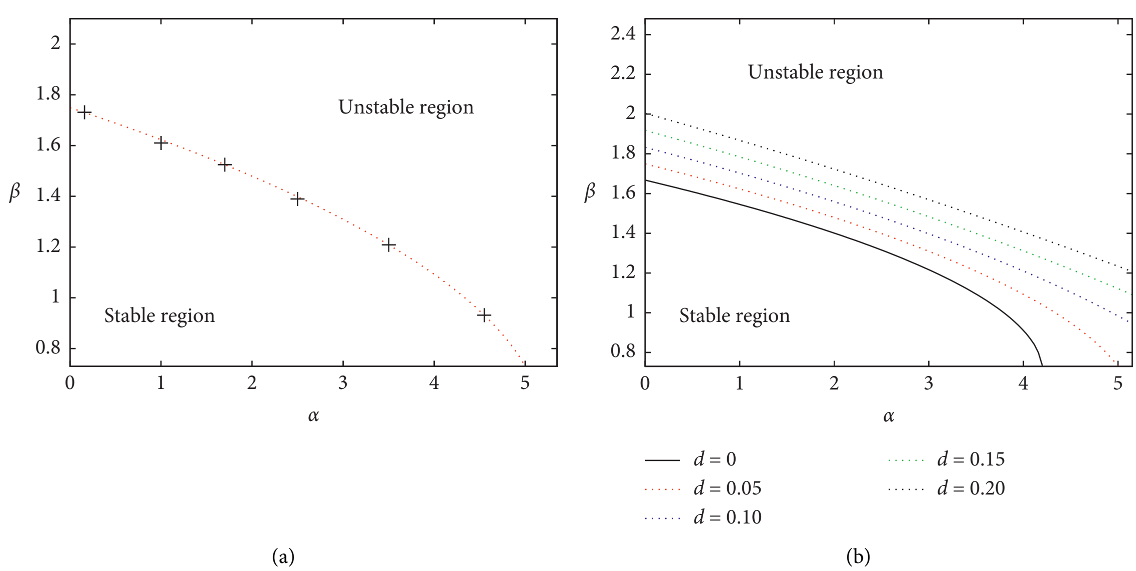

Figure 5: The Hopf bifurcation maps on the $\alpha-\beta$ diagrams: (a) an exploration of the analytical and numerical simulation results and (b) plots of the analytical ODE results for five different values of the diffusion coefficient d.

which increases where there is an assumed delay parameter τ. The Hopf bifurcation points decrease in shifting from the diffusion to the nondiffusion case. The frequency of the periodic result ω in Figure 6(b) increases steadily as τ increases. The differences between the frequency values for the periodic result ω in both cases are small, and the solutions have very similar predictions at large values of the delay parameter in this domain.

Figure 7 shows the Hopf bifurcation regions for the plot of the diffusion coefficient d versus τ (delay in investment). The two-term solution is shown as a red dashed line, while the black crosses indicate the numerical simulation results

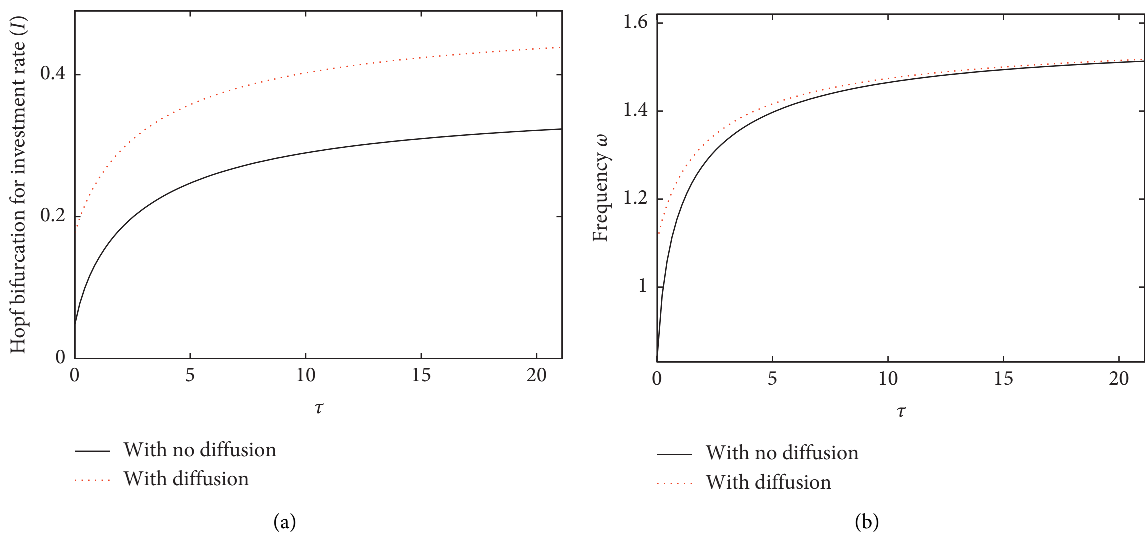

Figure 6: (a) The Hopf bifurcation maps in the $\tau - I$ plane and (b) the frequency of the periodic results for ω against τ. Here, we see results for two cases: $d = 0$ (no diffusion term) and $d = 0.1$ (diffusion term).

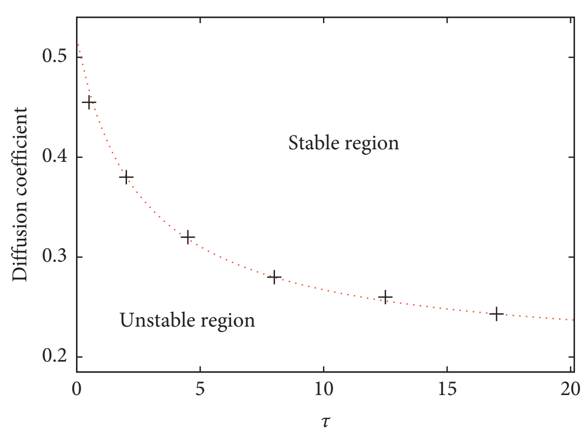

Figure 7: The Hopf bifurcation curve on the $\tau - d$ map. The analytical (red dotted line) and numerical simulation (black crosses) results are given.

for the PDEs. The parameters utilized here are $\delta = 0.15$, $\gamma = 0.10$, $I = 0.2$, $\alpha = 10$, and $\beta = 1$. It can be seen that, as the delay in investment τ increases, the Hopf bifurcation points for the diffusion coefficient value d decrease considerably. Furthermore, the results indicate that the relationship between the diffusion value and investment delay has a very significant impact on the stability of the business cycle model in terms of investment activity.

Figure 8 presents a map of the Hopf bifurcation regions in the plot of the β parameter against the investment parameter for gross production (I). The two-term numerical solutions are shown. The positive values used are $d = 0.05$, $\tau = 1$, $\delta = 0.15$, $\gamma = 0.10$, and $\alpha = 3$. In this figure, it was found that, as the parameter for the investment in the capital product β increases, the Hopf bifurcation points for the investment in the gross product value I increase slowly up until $\beta = 0.75$. Beyond this value, the Hopf bifurcation points for the investment switch from a high-conversion state to a minimum-conversion state for the gross product I and go down until $I = 0$ at $\beta \approx 1.74$. The comparisons in these figures show agreements between the analytical results for the ODEs and the simulations for the PDEs, with no more than 2% error for up to $\beta = 2$.

Lastly, a comparison is provided for the special parameter values $\tau = 15$, $\alpha = 2$, $\beta = 1$, and $\gamma = \delta = d = 0.15$. In this case, the points of the Hopf bifurcation of the investment parameter for gross production were examined for $I_c \simeq 2,055, 2.101$ for the analytical one- and two-term solutions, where $I_c \simeq 2.092$ is used for the numerical simulation of the PDE model. The prediction for the analytical ODE system agrees with the numerical predictions for the PDE system, with less than 1% error between them at this point. Hence, the theoretical ODE system provides reliable predictions regarding the Hopf bifurcation map as well as the stability regions.

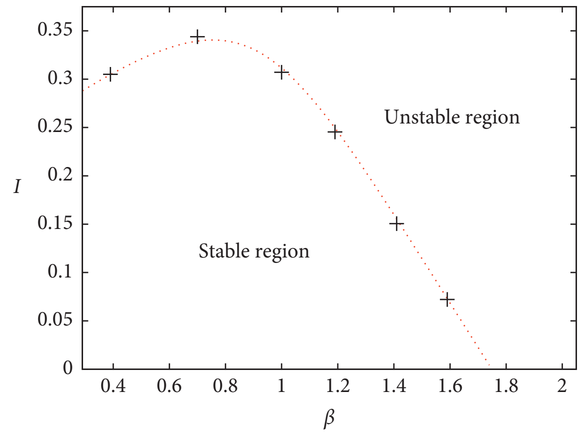

FIGURE 8: The Hopf bifurcation curves in the $\beta - I$ plane for the analytical (red dotted line) and numerical simulation (black crosses).

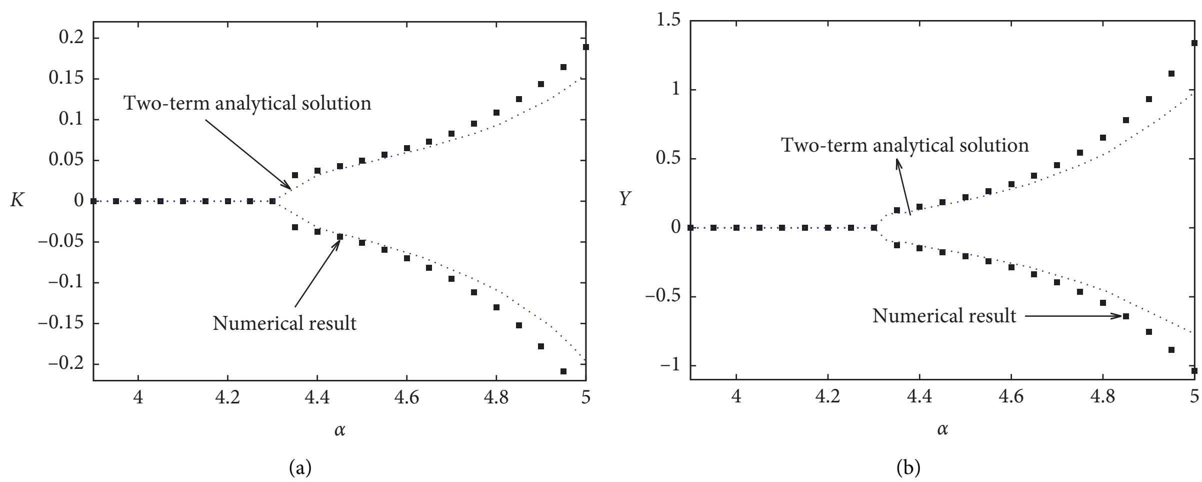

FIGURE 9: (a, b) The bifurcation diagrams for the capital Y and gross product K against the adjustment coefficient for the production market α. The two-term solutions and numerical results are shown.

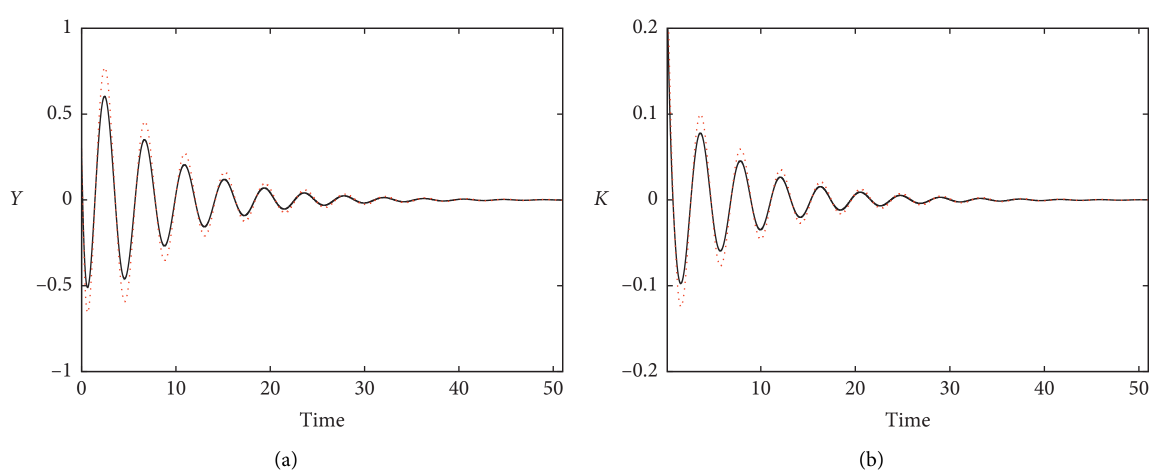

FIGURE 10: Continued.

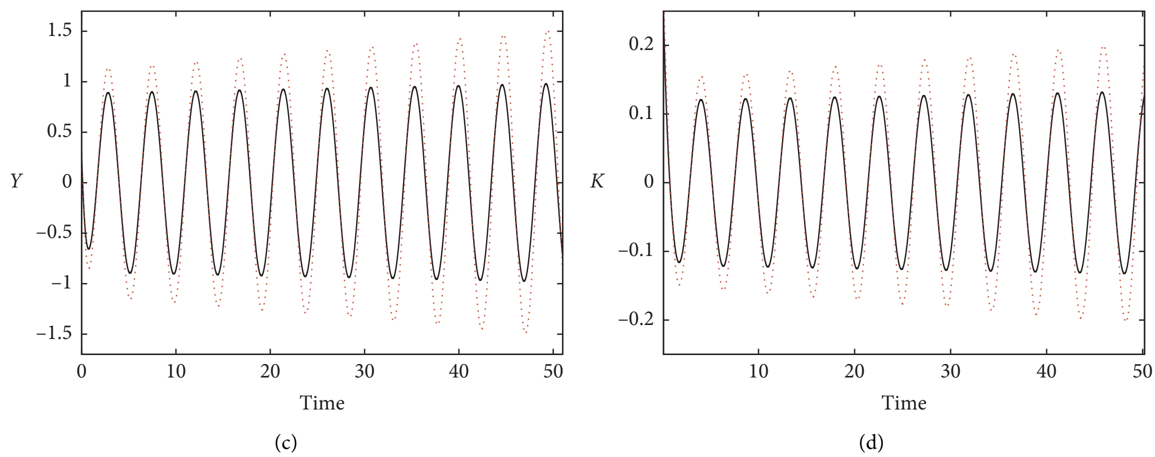

FIGURE 10: The business cycle of gross product Y and capital product K versus time t is plotted. The analytical outcome of the two terms and the numerical scheme of the PDE model are shown.

5. Bifurcation Diagrams and Periodic Oscillation Maps

This section focuses on the steady-state results as well as the bifurcation diagrams, periodic results, and 2D phase-plane map. In addition, the map of the bifurcation diagrams is considered of the domain in the centre $x = 0$.

Figures 9(a) and 9(b) plot the bifurcation diagrams for capital Y and gross product K with the adjustment coefficient for the production market α. The two-term solutions are shown as a blue dashed line, while the black dots indicated numerical simulation results. The parameters used are $\tau = 1$, $\delta = 0.15$, $\gamma = 0.10$, $\beta = 1$, $I = 0.2$, and $d = 0.05$. This example shows the importance of the investment delay in changing from a steady state to an unstable one, inducing limited cyclic solutions. In both cases, the analytical Hopf bifurcation point is $\alpha_c \simeq 4.33$. All of the results for $\alpha > \alpha_c \simeq 4.33$ are therefore unstable. After the Hopf bifurcation, the maximum amplitude over oscillation increases with growing α, while the minimum amplitude goes down. There are good matchups between the numerical PDE results and the analytical two-term solutions over the domain of the adjustment coefficient for the production market α.

Figure 10 presents the limits of the business cycle for the gross product $Y(t)$ and capital product $K(t)$ against time. The parameters used in Figures 10(a) and 10(b) are $\tau = 1$, $\delta = 0.15$, $\gamma = 0.10$, $\alpha = 10$, $\beta = 1$, $I = 0.2$, and $d = 0.50$ (from the stable region of Figure 7), while in Figures 10(c) and 10(d), $d = 0.4$ (from the unstable zone in Figure 7). In all these figures, the two-term solution is indicated by a black line, while the red dotted line refers to the numerical simulation. Note that the Hopf bifurcation point for the analytical outcomes in this example is $d_c \simeq 0.44 < 0.5$, where d is considered to be the bifurcation parameter. When $d_c \simeq 0.44 < 0.5$, the results become stable, as in Figures 10(a) and 10(b). However, at $0.4 < d_c \simeq 0.44$, the solution is unstable, as shown in Figures 10(c) and 10(d). The matchups between the analytical solutions and simulations in all of these figures are excellent.

6. Conclusions

This paper has provided a semianalytical outcome for the diffusive Kaldor–Kalecki model in the 1D geometry. The delay parameter was shown to exist for both gross product and capital stock functions. A system of ODEs was devolved using the Galerkin technique. The Hopf bifurcation points were found for dividing the graphs into two stability regions. Furthermore, we displayed full-map graphs for the delay parameter and diffusion coefficient values versus the parameters α, β, and I for a stability analysis of the system. The effects of these values, which can influence the stability of the model, were studied fully. The diffusion and investment delay values have different impacts on the bifurcation maps for the business cycle model. We found that the Hopf bifurcation points for the diffusion coefficient values decreased as the investment delay parameter τ increased. The results were examined by exploring several different numerical examples of the limit cycle and could help in the development of policy maker expectations and avoiding economic fluctuations. This method is therefore an extremely helpful, significant, and effective analytical technique for examining PDE models with delays. The technique provides good outcomes for all of the scenarios used in this work. In the future, we are planning to apply this method to the same model with an added delay feedback control term.

Data Availability

The data used to support the findings of this study are available upon request to the author.

Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

Authors' Contributions

The author carried out the proofs of the main results and approved the final manuscript.

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Research Article

Impact of Patent Infringement Compensation Rules on Patent Quality Problems

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Compensation rules for patent infringement greatly affect patent quality, which is closely related to R&D investments. In this study, A duopoly game model was developed to analyze innovative factories' R&D investment and patent licensing behavior, as well as the strategic choices of potential infringers under different compensation rules for patent infringement. Furthermore, a comparative analysis was conducted to analyze the patent quality under different scenarios, ultimately finalizing an optimal sequence rule for patent infringement compensation. The results show that patent quality is influenced by the invention height of patent and R&D efficiency, while the amount of patent infringement compensation has a great effect on potential infringement behavior. Patent quality can be effectively improved if the court adopts a proper sequence rule for patent infringement compensation according to the market circumstances.

1. Introduction

The patent for "Slide to Unlock" of Apple Inc. affords much food for thought. In 2014, a court jury in San Jose, California, convicted Samsung of infringing the patent of Apple Inc. for "Slide to Unlock" and "Fast Link," asking Samsung to pay $119.6 million to Apple Inc. as a compensation. In February 2016, the U.S. Circuit Court ruled that Apple's patent for "Slide to Unlock" was invalid because "Apple's so-called patented technology had appeared in an earlier technology patent." However, in October 2016, the U.S. Federal Circuit Court overturned the previous judgment and again ruled that Samsung had infringed Apple's patent. The judge decided that the patent for "Slide to Unlock" belonged to Apple. However, the attitudes toward this patent problem are different between different countries, e.g., the German and British courts declared the patent void.

As can be seen from this suspenseful case, the patent right, which has been regarded as a clearly defined property right for a long time, is not absolutely reliable and the validity is worthy of deep discussions (Jeon [1] integrated a series of events regarding patent infringement; it shows that roughly a half of litigated patents are found to be invalid). In recent years, some scholars have conducted a detailed analysis on the validity of patent rights, pointing out that the right property which has been clearly defined previously in practice is sometimes ambiguous; i.e., it is unclear whether the rights of a patent owner, after announcing to the public his/her ownership of a certain patent and obtaining the exclusive rights therein, exist in practice, Furthermore the scope of questionable patent is also unclear. These patents can be classified as questionable patents (patent review is in itself a process with strong subjective judgment because the patent examiner's personal knowledge has a great effect on the review results; more often than not, the patent examiner has an unclear understanding of the patented elements, so it is not at all surprising that the patent boundary is fuzzy).

Questionable patents are also called weak patents or probabilistic patents [2, 3]. In 2003, the U.S. Federal Trade Commission first proposed the concept of a "questionable patent" in *Promoting Innovation: An Appropriate Balance between Competition and Patent Laws and Policies.* A "questionable patent" is one that does not meet the patent licensing requirements or one that has an excessively wide scope of claims [4]. In recent years, due to the increasing complexity and diversity of inventions and creations, the number of questionable patents has increased rapidly, seriously affecting the normal operation of patent systems. This causes harm to legitimate competition and disrupts the social order of economic development (neem tree is a resource of great cultural significance in India; Indian farmers usually use the juice of neem tree seeds as a natural insecticide; in the early 1990s, researchers at W. R. Grace Company discovered a way to stabilize and activate azadirachtin and applied for a patent for this method; so far, Indian farmers have discovered that they are required to pay high user fees to use the resources they have depended on for generations; Grace Company took the lead in planting plants in India and continued to expand the market share of neem-based products [5]). Moreover, the innovation patent thicket may therefore be hindered. A large number of questionable patents have led to uncertainty in innovation revenue (Cohen et al. [6] provided the first large-sample evidence on the behavior and impact of nonpracticing entities (NPEs) in the intellectual property space; they found that NPE litigation had a real negative impact on innovation at targeted firms: firms' substantially reduced their innovative activity after settling with NPEs), thus weakening the motivating effect of the patent system on innovation.

The root cause for the presence of questionable patents is that the patent is not an enforceable right, and that the validity of the patent is often difficult to assess [7]. Other reasons include careless patent examination, the rapid increase of the number of patent applications, abuse of patent application right with the present system defects, and uncertain patient validity and defects in the governmental patent funding policies [8].

"Questionable patents" have aroused great attention from scholars, most of whom have explored the causes of "questionable patents" and put forward relevant countermeasures. Choi points out that owing to the lack of a rigorous examination process, many patent applications of questionable value have been approved, generally suppressing innovation rather than promoting innovation [9]. Considering that questionable patent holders lack the motivation to innovate, it is imperative to reform the patent system, strengthen third-party supervision, and replace expensive, time-consuming patent litigation with post-grant patent examination. Lemley and Shapiro [2] argue that the patent right is uncertain, while the patent system allows the patentee to hold the exclusive monopoly right for a certain period. Resources should be allocated for patent applications of greater commercial value in order to resolve the uncertainty of patent value.

In terms of the form, the presence of a "questionable patent" is defined as patent that is examined in a relaxed manner. However, in practice, the problem is caused by the inherent defects of patent systems. Some speculators take advantage of these defects to abuse the patent right. In fact, the patent right is not a natural right, but a legal right, which should be used judiciously. Farrell and Shapiro [10] argued that a "questionable patent" is caused by the relevant court's failure to fully examine the validity of the patent. In their game theory model, they proved that determining patent validity before patent granting is beneficial to social welfare. The impact of questionable patents on market entities depends largely on patent granting. Their presence may cause costly litigation and even hinder patent innovation. Inspired by the model built by Farrell and Shapiro, Encaonu and Lefouili [11] expressed a new view on questionable patents. On the one hand, they argued that a questionable patent may not necessarily involve small or micro innovations, while disruptive innovations may also lead to the presence of questionable patents; on the other hand, they ignored the hypothesis that the license contract provided by the patent owner must be accepted by all downstream vendors. They believed that questionable patents may be generated due to insufficient innovations or ambiguity in novelty. In addition, the presence of questionable patents is inevitable, so judicial departments should strengthen their supervision over questionable patents. Schuett [12] pointed out that a patent examiner's salary generally depends on the number of the patents examined by him/her; because he/she can save much more time when they pass a patent application than when they reject the application, patent examiners are more willing to grant a patent. This is also an important factor in the decline of patent quality. Kwon [13] proposed a new method to identify weak patents by using patent citation information in conjunction with the textual similarity between citing and cited patents. This method shows that 13% of U.S. patents filed from 2001 to 2010 are weak patents. He suggests that patent owners have an incentive to invest in maintaining and appropriating weak patents, and thus the current patent system is incapable of self-correcting weak patent issues.

Teece et al. [14] argued that because questionable patents have seriously affected the normal operation of the patent system, the reform of the patent system should focus on improving patent quality to facilitate innovations and high-quality inventions. Questionable patents have seriously affected patent quality. Love [15] pointed out that even though the patent offices have tried their best to improve the examination process, questionable patents still emerge in an endless stream. In this regard, expenses can be adjusted to reduce the number of patents granted, i.e., it is necessary to raise the maintenance cost of patents and cut down the cost of application for post-granting administrative proceedings. Lei and Wright [16] argued that the emergence of questionable patents is due to the lack of examination of patent applications. In other words, patent examiners ignore the objective validity of patents. Questionable patents have raised litigation-related social costs and reduced the social benefits of innovation incentives. Choi and Gerlach [17] analyzed patent pools and their effects on litigation incentives, overall royalty rates, and social welfare when patent rights are probabilistic and can be invalidated in court. The results show that patent pools with complementary patents reduce social welfare as they charge higher licensing fees and chilled subsequent innovation incentives if patents are sufficiently weak.

The above findings are concerned with the causes of questionable patents and their impact on innovation incentives. Most scholars believe that the number of questionable patents should be reduced by strengthening the examination process, increasing patent subsidies, and improving the patent system. However, most scholars do not consider the effects of patent infringement compensation rules on patent quality (the patent quality mentioned in this paper is an index parameter used to measure "questionable patents"; it represents the probability that a patent is deemed valid by the court after a patent litigation occurs). When patent infringement occurs, the court generally adopts the following two rules to cope with the act of infringement:

(1) *Profit Loss Rule.* This rule requires that the infringer should return the profit which originally belonged to the infringed to the infringed party as if infringement had not occurred (in this situation, the patent owner builds a factory independently and makes monopoly profits or licenses the patent to others), so that the infringed could gain the same profit as that prior to infringement.

(2) *Unjustified Enrichment Rule.* This rule requires that the infringer should return all profit obtained in its infringement act to the infringed.

As can be seen from the previous discussions, these two rules differ from each other in terms of operating mechanisms. The goal of the profit loss rule is to compensate the infringed for the loss of profit caused by infringement, while the goal of the unjustified enrichment rule is to prohibit the infringer from gaining profit in its act of infringement. The different ways adopted by the court in handling patent infringement may influence the interests of patent holders and potential infringer (Mazzeo et al. [18] used 340 patent infringement cases from 1995 to 2008 as a research sample and conducted a standardized study on related data; the results show that factors such as the calculation method of the compensation and the characteristics of the patent have a significant impact on the patent infringement damages), thereby affecting the behaviors of various market participants. As such, patent infringement compensation rules have an important effect on patent quality (Pincus [19] points out that after an infringement act is affirmed, the mechanism and calculation method by which the intellectual property holder obtains indemnity are important for giving full play to the role of the intellectual property protection system in remedying the intellectual property, stimulating knowledge innovation, and promoting economic development).

In this study, game theory has been adopted as the main research method to analyze the market behaviors of innovative firms and potential infringers from the perspective of endogenous patent quality. The effects of different patent infringement compensation rules on the market outcome are then analyzed. The following two issues are primarily discussed in this paper. On the one hand, what are the differences with respect to the effects of different patent infringement compensation rules on market outcome in terms of innovation incentives and potential infringers' behavior? What are the differences in patent quality and social welfare under different rules? On the other hand, can the patent system be further optimized? Specifically, because different patent infringement compensation rules have different effects on market participants, the patent quality under different rules must be different. Is it therefore possible to find a patent infringement compensation sequence rule that is best for patent quality (in international judicial practice, different countries have preference for different calculation methods; for example, the plaintiffs in the United States and the United Kingdom prefer the "profit loss rule," while the plaintiffs in Germany prefer the "unjust enrichment rule"; however, Japan is in the midst of changes, with the "profit loss rule" becoming increasingly popular; on 7 June 2019, the Grand Panel of the Intellectual Property High Court of Japan set a flexible and pro-patentee approach in determining patent infringement damages which may result in higher damage awards, assuming the criteria are satisfied; the prospect of Japanese courts being able to award higher patent infringement damage awards in the future using the calculation rules outlined in this milestone decision will contribute to the greater protection of patent rights in Japan [20]) ?

The research contribution of this paper lies in the introduction of the concept (to a certain extent, "questionable patents" have played an indispensable role in technological development; patent granting requires a certain innovation height, but since technological development is always progressive, the development of any new development must be based on the existing technology; to take out a patent for an invention, it must be "novel," "practical," and "non-obvious"; the innovation height is a comprehensive concept that includes the above three elements; a "questionable patent" is not one that is stale, but one that has an insufficient innovation height; for example, in the pharmaceutical industry, a new drug usually has to go through two processes, i.e., drug design and drug testing, before it is patented; although drug design may be completed early in many cases, drug testing generally takes ten years or several decades and needs hundreds of millions of dollars; from the perspective of patent examination, the completion of drug design can only indicate that the drug is "novel" and "non-obvious," but its "practicality" has not been proven, yet, so the drug cannot be patented owing to its insufficient innovation height; the "practicality" of this drug cannot be recognized unless more investment is made for drug testing to prove the drug is indeed effective; only then can this drug be considered to have a sufficient innovation height and patented) of "innovation height" to build an endogenous model of patent quality. Generally speaking, the higher the R&D investment is, the higher the invention height is. Moreover, higher invention height means higher patent quality. Thus, there exists a positive correlation between R&D investment and patent quality. If R&D investment is regarded as an exogenous variable, the invention height can be transformed into an endogenous variable to make patent quality endogenous. On this basis, we can further analyze the specific amount of compensation and its effects on innovative firms' behavior and patent quality under different patent infringement compensation mechanisms.

2. Model Assumption

We consider a Cournot duopoly competition model composed of Firm I and Firm E, which is similar to [21]. We assume that both firms produce a certain product at the same marginal cost $c(c < 1)$. The inverse demand function for this product is $p = 1 - (q^I + q^E)$. Suppose Firm I improves its production technology by means of R&D investment and has taken out a patent for the technology, thus decreasing the marginal cost of this product by Δc (for example, in the process of oil refining, one of the main steps is to remove phospholipids and free fatty acid from the crude oil; traditionally, the hydration and alkali refining technology is used to execute this step, but the method is time-consuming and costly; later, some researchers developed a powdery reagent with strong physical adsorption; added to the crude oil, the reagent can remove phosphorus and acid in a short time, thereby greatly reducing the oil refining cost; this technology has been patented; actually, other researchers had developed a similar product before this reagent appeared; however, the product failed to be patented because of the non-obvious effect, i.e., insufficient innovation height), which represents invention height. Suppose Firm I's R&D investment is $k = \theta\Delta c^2$, where θ represents the R&D efficiency. The higher θ is, the lower the R&D efficiency is and the higher the R&D investment is; conversely, the lower θ is, the lower the R&D investment is, suggesting that Firm I has relatively higher R&D efficiency.

Although Firm I has taken out a patent for the new technology, the patent may not be effective. Suppose its patent quality is $\rho \in [0, 1]$, where ρ also represents the probability of winning a patent infringement lawsuit for Firm I. In this paper, it is assumed that $\rho = \Delta c/\overline{c}$, where $\overline{c}$ represents significant invention height. To simplify the analysis, it is assumed that $\overline{c} = c$ in this paper. In other words, when Firm I's new technology reduces the marginal cost to zero, its patent must be effective.

The game in this paper consists of three stages, as shown in Figure 1. During the first stage, Firm I determines its R&D investment scale and patent license contract $[r, F]$, where r represents output commission and F represents a fixed fee.

During the second stage, Firm E decides whether to accept a patent license contract from Firm I. This results in one of the following three situations:

(i) Situation A: Firm E does not accept the patent license contract from Firm I and still uses the old production technology.

(ii) Situation B: Firm E accepts the patent license contract from Firm I and uses the new production technology.

(iii) Situation C: Firm E does not accept the patent license contract from Firm I but uses the new production technology by means of infringement. At this time, Firm I will file a lawsuit, and the probability of winning the lawsuit is ρ. If Firm I wins the lawsuit, Firm E will need to compensate Firm I for its loss. Otherwise, Firm E will not need to pay any fees if it wins the lawsuit.

The unjustified enrichment rule or profit loss rule is adopted for determining the amount of compensation for patent infringement. Under the unjust enrichment rule, if Firm I wins the lawsuit, then Firm E must transfer all the illegal profits to Firm I, such that Firm E's final profit becomes zero. Under the profit loss rule, Firm E should compensate Firm I for its actual loss, so that Firm I's final profit is the same as its due profit. Because both situation A and B can be regarded as equilibrium situations that "should have occurred" under the assumption of this paper, these two situations will be discussed separately.

At the third stage, either firm obtains its own benefits according to the previously selected strategy.

3. Analysis of Market Equilibrium in a Non-Infringement Situation

According to the assumption of this paper, Firm E will not infringe in situation A or situation B. The backward induction method in [21] will be used to analyze Firm I's R&D investment decision and either firm's profit gained in situation A and situation B. Specifically speaking, the firm's optimal pricing and profit are calculated first under the premise of a given invention height. Then, the optimal R&D investment level is determined for the innovative firm according to its R&D investment function while determining patent quality.

3.1. Situation A: Firm I Adopts New Technology, while Firm E Continues to Use the Old Production Technology.

First, the final stage of the game is analyzed. At this time, Firm I's R&D investment has been completed, so the invention height has been determined, as well. Therefore, the profit function for either firm in situation A is as follows:

$$\begin{cases} \pi^{\mathrm{AI}} = \left[1 - \left(q^{\mathrm{AI}} + q^{\mathrm{AE.}}\right) - c + \Delta c^{A}\right] q^{\mathrm{AI}} - k^{A}, \\ \pi^{\mathrm{AE}} = \left[1 - \left(q^{\mathrm{AI}} + q^{\mathrm{AE.}}\right) - c\right] q^{\mathrm{AE}}. \end{cases} \tag{1}$$

According to the conditions for profit maximization, either firm's profit can be revealed under the premise of undetermined innovation height by taking the first-order optimal conditions of q^{AI} and $q^{\mathrm{AE.}}$ for π^{AI} and π^{AE}, respectively:

$$\begin{cases} \pi^{\mathrm{AI}*} = \dfrac{(1 - c + 2\Delta c)^2}{9} - k, \\ \pi^{\mathrm{AE}*} = \dfrac{(1 - c - \Delta c)^2}{9}. \end{cases} \tag{2}$$

In situation A, since Firm E does not use the patented technology of Firm I, the second stage of the game needs not be analyzed. The first stage still needs to be analyzed though, i.e., Firm I's R&D investment decision needs to be analyzed.

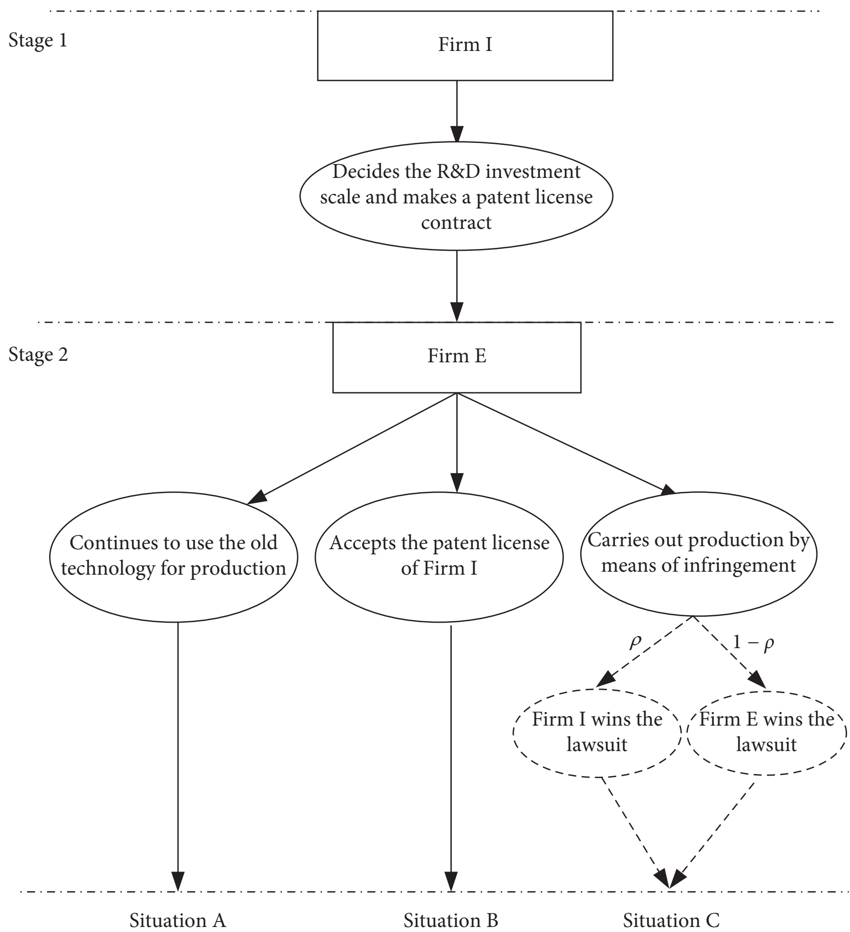

Figure 1: Game tree.

By substituting $k = \theta \Delta c^2$ into equation (2), we derive an objective function for Firm I in situation A, as follows:

$$\underset{\Delta c}{\text{Max}}\, \pi_{R\&D}^{\text{AI}*} = \frac{(1 - c + 2\Delta c)^2}{9} - \theta \Delta c^2. \tag{3}$$

The first-order optimal condition of Δc is taken for equation (3), revealing the optimal invention height of Firm I in situation A, as follows:

$$\Delta c^{A*} = \begin{cases} c, & \text{if } \theta \leq \dfrac{(2 + 2c)}{9c}, \\[2ex] \dfrac{2(1 - c)}{9\theta - 4}, & \text{if } \theta > \dfrac{(2 + 2c)}{9c}. \end{cases} \tag{4}$$

Equation (4) shows that when $\theta \leq (2 + 2c)/9c$, i.e., when is low, the R&D efficiency in the market is high. Moreover, Firm I's profit increases with its increase in R&D investment. Therefore, the optimal choice is to increase the innovation height to the highest level. At this time, Firm I is bound to provide a full-quality patent. Conversely, when $\theta > (2 + 2c)/9c$, owing to the low R&D efficiency in the market, it may be difficult to obtain satisfactory results with higher R&D investment. As such, Firm I may not invest enough R&D funds. As a result, its innovation is turned into a "questionable patent." With the innovation height being determined, either firm's optimal output can be identified by combining equation (2) with equation (4), as shown by equation (5) below:

$$q^{\text{AI}*} = \begin{cases} \dfrac{1 + c}{3}, & \text{if } \theta \leq \dfrac{2 + 2c}{9c}, \\[2ex] \dfrac{3\theta(1 - c)}{9\theta - 4}, & \text{if } \theta > \dfrac{2 + 2c}{9c}. \end{cases} \tag{5}$$

$$q^{\text{AE}*} = \begin{cases} \dfrac{1 - 2c}{3}, & \text{if } \theta \leq \dfrac{2 + 2c}{9c}, \\[2ex] \dfrac{(1 - c)(3\theta - 2)}{9\theta - 4}, & \text{if } \theta > \dfrac{2 + 2c}{9c}. \end{cases} \tag{6}$$

Based on the above analysis, either firms' profit (considering that either firm's output can never be negative, as can be seen from equation (6), when $\theta \leq (2 + 2c)/9c$, if $c \geq 1/2$, then $q^{\text{AE}**} = 0$; if $c > 1/2$, then $q^{\text{AE}**} > 0$; when $\theta > (2 + 2c)/9c$, if $\theta \leq 2/3$, then $q^{\text{AE}**} = 0$; if $\theta > 2/3$, then $q^{\text{AE}**} > 0$) in situation A can be revealed, as shown in Table 1.

Proposition 1 can be put forward as follows based on the above analysis.

Table 1: Profits of firms in situation A.

Profit	$c < 1/2$	$c \geq 1/2$
$\pi_{R\&D}^{AI*}$ $(\theta \leq 2 + 2c/9c)$	$(1 + c)^2/9 - \theta c^2$	$1/4 - \theta c^2$
$\pi_{R\&D}^{AI*}$ $(\theta > 2 + 2c/9c)$	$(1 - c)^2\theta/9\theta - 4$	$(1 - c)^2\theta/9\theta - 4$
π^{AE*} $(\theta \leq \max\{2/3, 2 + 2c/9c\})$	$(1 - 2c)^2/9$	0
π^{AE*} $(\theta > \max\{2/3, 2 + 2c/9c\})$	$(2 - 3\theta)^2 (1 - c)^2/(9\theta - 4)^2$	$(2 - 3\theta)^2 (1 - c)^2/(9\theta - 4)^2$

Proposition 1. *When Firm I uses the new technology while Firm E continues to use the old production technology, Firm I will provide a full-quality patent under the condition of high R&D efficiency, i.e.,* $\theta \leq (2 + 2c)/9c$*; Firm I will provide a questionable patent under the condition of low R&D efficiency, i.e.,* $\theta > (2 + 2c)/9c$*; if the R&D efficiency and marginal cost are both high, Firm E may be eliminated from the market.*

3.2. Situation B: Firm I Allows Firm E to Use the Patented Technology, and Both Firms Use the New Production Technology. Suppose Firm I provides a two-part patent license contract $[r, F]$, where r represents output commission and F represents a fixed fee. If Firm E accepts the contract, the duopoly firms' profit functions are shown as

$$\begin{cases} \pi^{BI} = \left[1 - \left(q^{BI} + q^{BE}\right) - c + \Delta c^B\right]q^{BI} + rq^{BE} + F, \\ \pi^{BE} = \left[1 - \left(q^{BI} + q^{BE}\right) - c + \Delta c^B\right]q^{BE} - rq^{BE} - F. \end{cases} \tag{7}$$

According to the conditions for profit maximization, the first-order optimal conditions of q^{BI} and q^{BE} are taken as π^{BI} and π^{BE},respectively, revealing either firm's profit under the premise of undetermined innovation height, as follows:

$$\begin{cases} q^{BI*} = \left(1 - c + r + \Delta c^B\right)/3, \\ q^{BE*} = \left(1 - c - 2r + \Delta c^B\right)/3. \end{cases} \tag{8}$$

When drafting a patent license contract, Firm I is bound to give priority to its own profit, but it should be noted that Firm E's profit is higher than Firm I's profit in situation A. Otherwise, Firm E will lose the economic value of using the patent. Firm I's R&D investment cost is also analyzed. By substituting equation (8) into equation (7), we derive an objective function for Firm E in situation B, as follows:

$$\begin{aligned} \pi^{BI*} &= \frac{c^2 - 5r^2 + 5r\left(1 + \Delta c^B\right) + \left(1 + \Delta c^B\right)^2 - \left(2 + 5r + 2\Delta c^B\right)c}{9} + F \\ \text{s.t. } \pi^{BE*} &\geq \pi^{AE**}. \end{aligned} \tag{9}$$

An optimal patent license contract can be developed for Firm I by taking the first-order condition of r for π^{BI} in equation (9), as follows:

$$\begin{cases} r^* = \dfrac{\left(1 - c + \Delta c^B\right)}{2}, \\ F^* = -\pi^{AE*}. \end{cases} \tag{10}$$

Now, by substituting equation (10) into equation (8), we obtain $q^{BE*} = 0$ and $q^{BI*} = r$. This shows that Firm I's optimal patent license contract must contain a very high patent output commission, but Firm E's output is decreased to zero. In addition, Firm I also needs to pay a fixed fee for patent licensing to Firm E. The fee is equal to Firm E's profit gained in situation A, so this shows that Firm I wants to expel Firm E from the market in order to monopolize the entire market (in reality, this phenomenon manifests itself in an advanced firm's acquisition or merger of a backward firm, e.g., Google's acquisition of Motorola, Microsoft's acquisition of Nokia, and so on). Situation B is a perfect monopoly market, while situation A is a duopoly market with certain competition. Therefore, the two firms' joint profit in situation A must be lower than that in situation B. According to the above analysis, Firm E has the same profit in situations A and B, so Firm I's profit in situation A is lower than that in situation B.

Using the same analysis process as situation A, it is easy to find the optimal invention height of Firm I in situation B, as shown in equation (11) below:

$$\Delta c^{B*} = \begin{cases} c, & \text{if } \theta \leq \dfrac{1}{4c}, \\ \dfrac{1 - c}{4\theta - 1}, & \text{if } \theta > \dfrac{1}{4c}. \end{cases} \tag{11}$$

Proposition 2 can be put forward based on the above analysis. Firm I's revenue in situation B can be revealed by combining (9), (10), and (11) together, as shown in equation (12) (since firm E's profit in situation B is the same as that in situation A, we will not give unnecessary details anymore here):

$$\pi_{R\&D}^{\mathrm{BI}*}=\begin{cases}\dfrac{1}{4}-\theta c^2-\pi^{\mathrm{AE}**}, & \text{if } \theta\leq\dfrac{1}{4c},\\ \dfrac{\theta(1-c)^2}{4\theta-1}-\pi^{\mathrm{AE}**}, & \text{if } \theta>\dfrac{1}{4c}.\end{cases} \tag{12}$$

Proposition 2. *When Firm I uses the new technology and Firm E accepts the patent license contract, Firm I will provide a full-quality patent as long as the R&D efficiency is high, i.e., $\theta\leq 1/4c$; Firm I will provide a "questionable patent" if the R&D efficiency is low, i.e.,$\theta>1/4c$. Firm I's optimal patent license contract must contain a high output commission, and it is bound to receive a negative fixed patent royalty from Firm E, thereby causing manufacturer E to withdraw from the market, while Firm I will monopolize the entire market. Firm I's final profit is not less than its profit gained in situation A.*

4. Analysis of Market Equilibrium in an Infringement Situation

4.1. Analysis of Market Equilibrium under the Unjust Enrichment Rule. At the last stage of the game, because the R&D cost has already incurred at the previous stage, there is only a sunk cost at the present stage, so Firm I does not consider the cost. Now, the two firms' expected profits are shown in the following equation:

$$\begin{cases}E\left(\pi_{\mathrm{UE}}^{\mathrm{CI}}\right)=\left[1-\left(q_{\mathrm{UE}}^{\mathrm{CI}}+q_{\mathrm{UE}}^{\mathrm{CE}}\right)-c+\Delta c_{\mathrm{UE}}^{C}\right]q_{\mathrm{UE}}^{\mathrm{CI}}+\rho_{\mathrm{UE}}^{C}\left[1-\left(q_{\mathrm{UE}}^{\mathrm{CI}}+q_{\mathrm{UE}}^{\mathrm{CE}}\right)-c+\Delta c_{\mathrm{UE}}^{C}\right]q_{\mathrm{UE}}^{\mathrm{CE}},\\ E\left(\pi_{\mathrm{UE}}^{\mathrm{CE}}\right)=\left(1-\rho_{\mathrm{UE}}^{C}\right)\left[1-\left(q_{\mathrm{UE}}^{\mathrm{CI}}+q_{\mathrm{UE}}^{\mathrm{CE.}}\right)-c+\Delta c_{\mathrm{UE}}^{C}\right]q_{\mathrm{UE}}^{\mathrm{CE}}.\end{cases} \tag{13}$$

The first-order optimal conditions of $q_{\mathrm{UE}}^{\mathrm{CI}}$ and $q_{\mathrm{UE}}^{\mathrm{CE}}$ are taken for $E(\pi_{\mathrm{UE}}^{\mathrm{CI}})$ and $E(\pi_{\mathrm{UE}}^{\mathrm{CE}})$, deriving equation (14), as follows:

$$\begin{cases}q_{\mathrm{UE}}^{\mathrm{CI}*}=\dfrac{\left(1-c+\Delta c_{\mathrm{UE}}^{C}\right)\left(1-\rho_{\mathrm{UE}}^{C}\right)}{3-\rho_{\mathrm{UE}}^{C}},\\ q_{\mathrm{UE}}^{\mathrm{CE}*}=\dfrac{1-c+\Delta c_{\mathrm{UE}}^{C}}{3-\rho_{\mathrm{UE}}^{C}}.\end{cases} \tag{14}$$

Either firm's optimal profit can be calculated by combining equation (13) with equation (14). A profit function can then be derived for Firm I at the first stage of the game, as shown in equation (15) below:

$$\pi_{\mathrm{UE}}^{R\&D}=E\left(\pi_{\mathrm{UE}}^{\mathrm{CI}}\right)^{*}-k=\frac{\left(1-c+\Delta c_{\mathrm{UE}}^{C}\right)^2}{\left(3-\rho_{\mathrm{UE}}^{C}\right)^2}-\theta\left(\Delta c_{\mathrm{UE}}^{C}\right)^2. \tag{15}$$

By substituting $\rho_{\mathrm{UE}}^{C}=\Delta c_{\mathrm{UE}}^{C}/c$ into the above equation and taking the first-order optimal condition of Δc for $\pi_{\mathrm{UE}}^{R\&D}$, we can reveal Firm I's optimal R&D investment level and then evaluate either firm's optimal profit and related market outcome. However, since the function is rather complicated, it is difficult to derive an intuitive form of expression for the optimal R&D investment function. To simplify analysis, Firm I's optimal innovation height and patent quality, as well as either firm's profit and market price, are calculated at different levels of c and θ based on a numerical example. For instance, given $c=0.2$ and $\theta=4$, $\rho_{\mathrm{UE}}^{C}=\Delta c_{\mathrm{UE}}^{C}/c=5\Delta c_{\mathrm{UE}}^{C}$ can be obtained, substituting $\rho_{\mathrm{UE}}^{C}=5\Delta c_{\mathrm{UE}}^{C}$ into equation (15) and taking the first-order optimal condition of $\Delta c_{\mathrm{UE}}^{C}$ for $\pi_{\mathrm{UE}}^{\mathrm{CI.stage1}}$. The optimal innovation height and patent quality of Firm I can be derived as $\Delta c_{\mathrm{UE}}^{C^*}=0.05$ and $\rho_{\mathrm{UE}}^{C^*}=0.25$. We can derive $\pi_{\mathrm{UE}}^{\mathrm{CI.stage1}*}=0.08$, $q_{\mathrm{UE}}^{\mathrm{CI}^*}=0.3$, and $q_{\mathrm{UE}}^{\mathrm{CE}^*}=0.25$ from substituting $\Delta c_{\mathrm{UE}}^{C^*},\rho_{\mathrm{UE}}^{C*}$ into equations (14) and (15), respectively. Finally, substituting $\Delta c_{\mathrm{UE}}^{C^*},\rho_{\mathrm{UE}}^{C*},q_{\mathrm{UE}}^{\mathrm{CI}*}$, and $q_{\mathrm{UE}}^{\mathrm{CE}*}$ into equation (13), we can get $E(\pi_{\mathrm{UE}}^{\mathrm{CE}})^*=0.063$. The results of other numerical calculation examples are shown in Table 2.

4.2. Analysis of Market Equilibrium under the Profit Loss Rule. Under the profit loss rule, the infringer must compensate the innovative firm for its loss of profit so that the latter's final profit should be the same as its due profit. Suppose Firm I's due profit is R after the court judges its patent valid. As such, either firm's profit function is as follows:

$$\begin{cases}E\left(\pi_{\mathrm{LR}}^{\mathrm{CI}}\right)=\left(1-\rho_{\mathrm{LR}}^{C}\right)\left[1-\left(q_{\mathrm{LR}}^{\mathrm{CI}}+q_{\mathrm{LR}}^{\mathrm{CE}}\right)-c+\Delta c_{\mathrm{LR}}^{C}\right]q_{\mathrm{LR}}^{\mathrm{CI}}+\rho_{\mathrm{LR}}^{C}R,\\ E\left(\pi_{\mathrm{LR}}^{\mathrm{CE}}\right)=\left[1-\left(q_{\mathrm{LR}}^{\mathrm{CI}}+q_{\mathrm{LR}}^{\mathrm{CE.}}\right)-c+\Delta c_{\mathrm{LR}}^{C}\right]q_{\mathrm{LR}}^{\mathrm{CE}}-\rho_{\mathrm{LR}}^{C}\left[R-\left(1-\left(q_{\mathrm{LR}}^{\mathrm{CI}}+q_{\mathrm{LR}}^{\mathrm{CE}}\right)-c+\Delta c_{\mathrm{LR}}^{C}\right)q_{\mathrm{LR}}^{\mathrm{CI}}\right].\end{cases} \tag{16}$$

The first-order optimal conditions of $\overset{\mathrm{CI}}{\mathrm{LR}}$ and $\overset{\mathrm{CE}}{\mathrm{LR}}$ are taken as $E(\pi_{\mathrm{LR}}^{\mathrm{CI}})$ and $E(\pi_{\mathrm{LR}}^{\mathrm{CE}})$, respectively, revealing either firm's expected profit and market price, as shown in the equation below:

Table 2: A numerical example of market equilibrium under the unjust enrichment rule.

c	θ	$\Delta c_{\mathrm{UE}}^{\mathrm{C}*}$	$\rho_{\mathrm{UE}}^{\mathrm{C}*}$	$\pi_{\mathrm{UE}}^{\mathrm{CI.stage1}*}$	$E(\pi_{\mathrm{UE}}^{\mathrm{CE}})^*$	$p_{\mathrm{UE}}^{\mathrm{C}*}$	$q_{\mathrm{UE}}^{\mathrm{CI}*}$	$q_{\mathrm{UE}}^{\mathrm{CE}*}$
0.1	0.1	0.1	1	0.133	0.071	0.366	0.367	0.267
0.1	0.5	0.1	1	0.129	0.071	0.366	0.367	0.267
0.1	1	0.1	1	0.124	0.071	0.366	0.367	0.267
0.1	4	0.056	0.563	0.101	0.079	0.381	0.338	0.281
0.1	10	0.021	0.209	0.094	0.086	0.393	0.314	0.293
0.2	0.1	0.2	1	0.156	0.04	0.4	0.4	0.2
0.2	0.5	0.2	1	0.14	0.04	0.4	0.4	0.2
0.2	1	0.2	1	0.12	0.04	0.4	0.4	0.2
0.2	4	0.05	0.25	0.08	0.063	0.45	0.3	0.25
0.2	10	0.019	0.093	0.074	0.068	0.461	0.279	0.26
0.3	0.1	0.3	1	0.179	0.018	0.434	0.433	0.133
0.3	0.5	0.3	1	0.143	0.018	0.434	0.433	0.133
0.3	1	0.28	0.933	0.098	0.02	0.44	0.w42	0.14
0.3	4	0.044	0.146	0.061	0.048	0.518	0.263	0.219
0.3	10	0.016	0.054	0.057	0.052	0.528	0.244	0.228
0.4	0.1	0.4	1	0.202	0.004	0.466	0.467	0.067
0.4	0.5	0.4	1	0.138	0.004	0.466	0.467	0.067
0.4	1	0.24	0.6	0.072	0.014	0.52	0.36	0.12
0.4	4	0.038	0.094	0.045	0.035	0.587	0.225	0.188
0.4	10	0.014	0.035	0.042	0.038	0.596	0.209	0.195
0.5	0.1	0.5	1	0.225	0	0.5	0.5	0
0.5	0.5	0.5	1	0.125	0	0.5	0.5	0
0.5	1	0.2	0.4	0.05	0.01	0.7	0.3	0
0.5	4	0.031	0.063	0.031	0.024	0.656	0.188	0.156
0.5	10	0.012	0.023	0.029	0.027	0.663	0.174	0.163
0.6	0.1	0.6	1	0.214	0	0.467	0.533	0
0.6	0.5	0.6	1	0.08	0	0.467	0.533	0
0.6	1	0.16	0.267	0.032	0.006	0.68	0.24	0.08
0.6	4	0.025	0.042	0.02	0.016	0.725	0.15	0.125
0.6	10	0.009	0.016	0.019	0.017	0.73	0.14	0.13
0.7	0.1	0.7	1	0.201	0	0.433	0.567	0
0.7	0.5	0.7	1	0.045	0	0.433	0.567	0
0.7	1	0.12	0.171	0.018	0.004	0.76	0.18	0.06
0.7	4	0.019	0.027	0.011	0.009	0.793	0.113	0.094
0.7	10	0.007	0.01	0.01	0.01	0.797	0.105	0.098
0.8	0.1	0.8	1	0.186	0	0.4	0.6	0
0.8	0.5	0.8	1	0.02	0	0.4	0.6	0
0.8	1	0.08	0.1	0.008	0.002	0.84	0.12	0.04
0.8	4	0.013	0.016	0.005	0.0039	0.862	0.075	0.063
0.8	10	0.005	0.006	0.005	0.0042	0.865	0.07	0.065

$$\begin{cases} p_{\mathrm{LR}}^{\mathrm{CI}*} = 1 - \dfrac{\left(1 - c + \Delta c_{\mathrm{LR}}^{C}\right)\left(2 - \rho_{\mathrm{LR}}^{C}\right)}{3 - \rho_{\mathrm{LR}}^{C}}, \\ E\left(\pi_{\mathrm{LR}}^{\mathrm{CI}*}\right) = \dfrac{\left(1 - c + \Delta c_{\mathrm{LR}}^{C}\right)^2\left(2 - \rho_{\mathrm{LR}}^{C}\right)}{\left(3 - \rho_{\mathrm{LR}}^{C}\right)^2} + \rho_{\mathrm{LR}}^{C} R, \\ E\left(\pi_{\mathrm{LR}}^{\mathrm{CE}*}\right) = \dfrac{\left(1 - c + \Delta c_{\mathrm{LR}}^{C}\right)^2}{\left(3 - \rho_{\mathrm{LR}}^{C}\right)^2} - \rho_{\mathrm{LR}}^{C} R. \end{cases} \quad (17)$$

The profit function for Firm I at the stage of R&D is $\pi_{\mathrm{LR}}^{R\&D} = \pi_{\mathrm{LR}}^{\mathrm{CI}*} - \theta(\Delta c_{\mathrm{LR}}^{C})^2$. By substituting $\rho = \Delta c/c$ into this equation and solving it together with equation (17), we get the following equation:

$$\pi_{\mathrm{LR}}^{R\&D} = \frac{c\left(1 - c + \Delta c_{\mathrm{LR}}^{C}\right)^2\left(c - \Delta c_{\mathrm{LR}}^{C}\right)}{\left(3c - \Delta c_{\mathrm{LR}}^{C}\right)^2} + \frac{\Delta c_{\mathrm{LR}}^{C}}{c} R - \theta\left(\Delta c_{\mathrm{LR}}^{C}\right)^2. \quad (18)$$

Firm I's optimal R&D investment level can be revealed by taking the first-order optimal condition of $\Delta c_{\mathrm{LR}}^{C}$ for $\pi_{\mathrm{LR}}^{R\&D}$. Because the functional form of the final result is rather complicated, it is difficult to observe the market outcome intuitively. To simplify analysis, the market outcome under the profit loss rule is calculated based on a numerical example. Considering that Firm I's profit obtained in both situations A and B can be regarded as its "due profit" under the assumption of this paper, both situations are analyzed in this paper. So, we need to analyze the both situations. For example, given $c = 0.2$ and $\theta = 4$, if the profit loss situation referred to by the court is situation A, it can be seen from Table 1 that $R = \pi^{\mathrm{AE}*} = (1-c)^2\theta/9\theta - 4$. Substituting $c = 0.2, \theta = 4$ and $R = 0.08$ into equation (18) and taking the first-order optimal conditions of $\Delta c_{\mathrm{LR}}^{C}$ for $\pi_{\mathrm{LR}}^{R\&D}$, the optimal innovation height and patent quality of Firm I can be derived as $\Delta c_{\mathrm{LR}}^{C*} = 0.23$. Then, the optimal profit of each firm can be obtained by combining these calculation results and formula (16). Similarly, if the profit loss situation referred to by the court is situation B, given that $c = 0.02$ and $\theta = 4$, from Table 1 and equation (12), we can calculate that $R = \pi^{\mathrm{BE}*} = 0.091$. The optimal invention height and profit of firm I can be derived from combining $R = 0.091$ and equation (18). The detailed results are shown in Tables 3 and 4.

5. Comparison and Optimization

5.1. Comparison of Innovation Incentives in Different Situations. According to the preceding analysis results, numerical examples can be obtained for patent quality in different situations, as shown by Table 3 (profit loss rule A means that the court refers to the profit loss in situation A when adopting the profit loss rule, while profit loss rule B means that the court refers to the profit loss in situation B when adopting the profit loss rule). As shown by the comparison of patent quality among the five situations in Table 3, the patent quality in none of the situations can always be maintained at the highest level. In the case of non-infringement, except $\rho^A \geq \rho^B$ when $\theta = 1$, the patent quality in situation A will never be better than that in situation B under other conditions. This is because situation A is a competitive market, while situation B is a monopolistic market. Different market structures have different incentive effects on firms. In the competitive market, Firm I innovates in order to gain a competitive edge. This reflects the incentive effects of competition on innovation. In the monopolistic market, Firm I innovates in order to cut down the costs for greater profit. This reflects the incentive effects of monopoly on innovation. When $\theta = 1$, competition has greater incentive effects on innovation, so the patent quality in situation A is higher; under other conditions, the monopoly has greater incentive effects on innovation, so the patent quality in situation B is higher.

Table 3: Numerical examples of patent quality in different situations.

c	θ	ρ^A	ρ^B	ρ^C_{UE}	ρ^C_{LR} (profit loss rule A)	ρ^C_{LR} (profit loss rule B)
0.1	0.1	1	1	1	0.74	0.85
0.1	0.5	1	1	1	0.71	0.83
0.1	1	1	1	1	0.67	0.8
0.1	4	0.563	0.6	1	0.46	0.59
0.1	10	0.209	0.231	1	0.31	0.37
0.2	0.1	1	1	1	0.84	0.92
0.2	0.5	1	1	1	0.77	0.84
0.2	1	1	1	1	0.7	0.73
0.2	4	0.25	0.267	1	0.23	0.29
0.2	10	0.093	0.103	0.12	0.1	0.125
0.3	0.1	1	1	1	0.87	0.94
0.3	0.5	1	1	1	0.69	0.78
0.3	1	0.933	0.778	1	0.447	0.56
0.3	4	0.146	0.156	0.14	0.117	0.143
0.3	10	0.054	0.06	0.05	0.047	0.057
0.4	0.1	1	1	1	0.903	0.94
0.4	0.5	1	1	1	0.615	0.673
0.4	1	0.6	0.5	1	0.293	0.37
0.4	4	0.094	0.1	0.07	0.065	0.078
0.4	10	0.035	0.038	0.025	0.025	0.03
0.5	0.1	1	1	1	0.92	0.92
0.5	0.5	1	1	1	0.514	0.514
0.5	1	0.4	0.333	0.232	0.184	0.226
0.5	4	0.063	0.067	0.04	0.038	0.044
0.5	10	0.023	0.026	0.016	0.016	0.016
0.6	0.1	1	1	1	0.93	0.892
0.6	0.5	0.667	0.667	1	0.392	0.338
0.6	1	0.267	0.222	0.122	0.113	0.135
0.6	4	0.042	0.044	0.023	0.023	0.027
0.6	10	0.016	0.017	0.01	0.01	0.01
0.7	0.1	1	1	1	0.936	0.861
0.7	0.5	0.429	0.429	0.193	0.261	0.199
0.7	1	0.171	0.143	0.067	0.067	0.076
0.7	4	0.027	0.029	0.014	0.014	0.016
0.7	10	0.01	0.011	0.006	0.006	0.006
0.8	0.1	1	1	1	0.936	0.825
0.8	0.5	0.25	0.25	0.09	0.136	0.101
0.8	1	0.1	0.083	0.035	0.036	0.039
0.8	4	0.016	0.017	0.0075	0.008	0.009
0.8	10	0.006	0.006	0.0025	0.003	0.004

In the case of infringement, the patent quality under the unjust enrichment rule is generally better than that of the profit loss rule. If it is for the purpose of improving patent quality, the profit loss rule may not be a good choice. This is because Firm I will not provide a full-quality patent in whichever situation a profit loss occurs. In particular, under profit loss rule A, the patent quality is at a suboptimal level no matter the condition. This is because the amount of infringement compensation under profit loss rule A is lower than that under profit loss rule B, so the latter has better incentive effects on innovation. However, neither situation performs better than other two situations. For example, situation B is better than other two situations only when $c = 0.2$ and $\theta = 10$. Therefore, the profit loss rule has a very limited effect in improving patent quality. Subsequently, Proposition 3 can be proposed as follows.

Proposition 3. *In the case of non-infringement, the patent quality in situation B is better than that in situation A under most circumstances. In the case of infringement, if the court prefers the profit loss rule, Firm I will not provide a full-quality patent in any situation where a profit loss occurs. Compared with the profit loss rule, the unjust enrichment rule can obtain better patent quality under most circumstances.*

5.2. Subgame Perfect Nash Equilibrium (SPNE). We adopt the reverse induction method to analyze SPNE. First, Firm I's decision at the final stage of the game is analyzed. Based on the previous analysis, numerical examples can be obtained for firm's final profit gained in different situations, as shown in Table 4.

Table 4: Numerical examples of Firm E's profit in different situations.

c	θ	π^{AE*}	π^{BE*}	$E(\pi_{UE}^{CE*})$	$E(\pi_{LR}^{CE*})$ (profit loss rule A)	$E(\pi_{LR}^{CE*})$ (profit loss rule B)
0.1	0.1	0.071	0.071	0	0.087	0.059
0.1	0.5	0.071	0.071	0	0.088	0.061
0.1	1	0.071	0.071	0	0.089	0.063
0.1	4	0.079	0.079	0	0.092	0.078
0.1	10	0.086	0.086	0	0.089	0.082
0.2	0.1	0.04	0.04	0	0.068	0.034
0.2	0.5	0.04	0.04	0	0.062	0.041
0.2	1	0.04	0.04	0	0.057	0.05
0.2	4	0.063	0.063	0	0.075	0.069
0.2	10	0.068	0.068	0.072	0.072	0.07
0.3	0.1	0.018	0.018	0	0.048	0.017
0.3	0.5	0.018	0.018	0	0.056	0.031
0.3	1	0.02	0.02	0	0.063	0.046
0.3	4	0.048	0.048	0.058	0.058	0.056
0.3	10	0.052	0.052	0.056	0.056	0.055
0.4	0.1	0.004	0.004	0	0.028	0.009
0.4	0.5	0.004	0.004	0	0.041	0.028
0.4	1	0.014	0.014	0	0.049	0.042
0.4	4	0.035	0.035	0.043	0.043	0.042
0.4	10	0.038	0.038	0.041	0.041	0.041
0.5	0.1	0	0	0	0.006	0.006
0.5	0.5	0	0	0	0.028	0.028
0.5	1	0.01	0.01	0.038	0.035	0.032
0.5	4	0.024	0.024	0.03	0.0295	0.0293
0.5	10	0.027	0.027	0.029	0.0285	0.0284
0.6	0.1	0	0	0	0.006	0.006
0.6	0.5	0	0	0	0.024	0.024
0.6	1	0.006	0.006	0.024	0.023	0.022
0.6	4	0.016	0.016	0.019	0.0188	0.0189
0.6	10	0.017	0.017	0.018	0.0183	0.0182
0.7	0.1	0	0	0	0.005	0.005
0.7	0.5	0	0	0.019	0.011	0.016
0.7	1	0.004	0.004	0.013	0.013	0.013
0.7	4	0.009	0.009	0.011	0.011	0.011
0.7	10	0.01	0.009	0.01	0.01	0.01
0.8	0.1	0	0	0	0.003	0.003
0.8	0.5	0	0	0.008	0.0073	0.0073
0.8	1	0.002	0.002	0.006	0.006	0.006
0.8	4	0.0039	0.0039	0.0047	0.005	0.0047
0.8	10	0.0042	0.0042	0.0045	0.005	0.0046

Proposition 4 can be put forth by comparing Firm E's profit in the five situations in Table 4.

Proposition 4

(1) *If the court prefers the unjust enrichment rule, equilibrium results will appear on the market as the original marginal cost and R&D efficiency change. If the original marginal cost is extremely low, e.g., $c < 0.1$, Firm E will accept the patent license contract from Firm I as the only SPNE, no matter what R&D efficiency is; as the original marginal cost increases and R&D efficiency decreases, e.g.,$c \geq 0.5$ and $\theta > 1$, Firm E will carry out production by means of infringement as the only SPNE.*

(2) *If the court prefers profit loss rule A, there exists the only SPNE, i.e., Firm E carries out production by means of infringement. If the court prefers profit loss rule B and the original marginal cost is very low, e.g., $c < 0.1$, Firm E will accept the patent license contract from Firm I as the only SPNE no matter what R&D efficiency is; as the original marginal cost increases and R&D efficiency decreases, e.g., $c \geq 0.2$ and $\theta > 1$, Firm E will be increasingly motivated to infringe patent rights. When the original marginal cost is high, i.e.,$c \geq 0.4$, Firm E will carry out production by means of infringement as the only SPNE no matter what R&D efficiency is.*

According to Proposition 4, compared with profit loss rule B, Firm E will be more likely to carry out production by means of infringement under profit loss rule A. The reason is that under profit loss rule A, Firm I's profit loss is confirmed by reference to the competitive profit, but under profit loss rule B, the firm's profit loss is confirmed by reference to the monopoly profit. Therefore, when Firm E is found guilty of infringement, if the court adopts profit loss rule A, Firm E will only need to *pay a small amount as compensation; on the contrary, if the court adopts profit loss rule B, firm E will have to pay a large amount as compensation. Therefore, Firm E has a stronger motive for infringement under profit loss rule A.*

5.3. Optimization of the Patent System. As can be seen from Table 3, in the case of non-infringement, the patent quality in situation B is better than that in situation A under most circumstances, so the court should promote conditions leading to situation B. Therefore, it should not interfere with Firm I's patent licensing act but let Firm I exercise its patent right to monopolize the market for further innovation.

In the case of infringement, if the court prefers the unjust enrichment rule, as shown by the comparison between π^{BE*} and $E(\pi_{UE}^{CE*})$, when it is easy to innovate (the R&D efficiency is high, or the original marginal cost is low, or both), e.g., the ultimate market equilibrium is also achieved in situation B, and Firm I can provide a high-quality patent. When it is difficult to innovate (the R&D efficiency is low, or original marginal cost is high, or both), e.g., when $\theta = 10$ and $c \geq 0.2$, $\pi^{BE*} \leq E(\pi_{UE}^{CE*})$.The ultimate market equilibrium is achieved in situation C.

As is noted, when it is difficult to innovate, under profit loss rule B, $\rho_{LR}^{C} \geq \rho_{UE}^{C}$ and $E(\pi_{LR}^{CE*}) \geq \pi^{BE*}$. If the court adopts profit loss rule B at this time, the ultimate equilibrium is achieved in situation C, but better patent quality is ensured (it is also difficult to achieve good results if profit loss rule B is used alone because when it is easy to innovate, the rule has very limited effect in improving patent quality; for example, when $\theta = 0.1$ and $c = 0.4$, the ultimate market equilibrium is achieved in situation C under profit loss rule B, and patent quality is 0.94; the ultimate market equilibrium is achieved in situation A under the unjust enrichment rule, and patent quality is 1). Therefore, when it is easy to innovate, the court should give priority to the unjust enrichment rule and achieve the ultimate market equilibrium of situation B; when it is difficult to innovate, the court should give priority to the profit loss rule to achieve the ultimate market equilibrium of situation C, so as to ultimately improve patent quality effectively.

When it is difficult to innovate, the court should give priority to profit loss rule B to achieve the ultimate market equilibrium of situation C so as to ultimately achieve effective patent quality optimization. If the court aims to optimize patent quality, it may be difficult to achieve ideal results under a single patent infringement compensation rule. The court needs to adopt different compensation rules for different situations. Concretely speaking, when it is easy to innovate, the unjust enrichment rule should be adopted first; when it is difficult to innovate, profit loss rule B should be adopted first.

6. Conclusions

The original intention of designing a patent system is to help innovators to obtain returns by commercializing their inventions, thus recovering their R&D costs and maintaining their motivation for innovation. However, the presence of "questionable patents" is obviously contrary to this original intention. A large number of low-quality patents have exerted great negative impacts on the normal operation of the patent systems. An endogenous model of patent quality was built in this paper to investigate the effects of different patent infringement compensation rules on patent quality.

The main conclusions are represented as the following three aspects. Firstly, in whatever situation, an innovative firm is likely to provide a questionable patent due to the strict requirements for a high-level innovation height or low R&D efficiency, compelling the innovative firm to bear a high investment cost if it wants to provide a full-quality patent. At this time, the profits brought by innovation cannot fully cover the R&D cost, leading the innovative firm to provide a "questionable patent." Therefore, the presence of "questionable patents" may not only be due to innovators' speculative behavior but also be due to the effects of specific market conditions on the innovators under many circumstances. Secondly, in the case of non-infringement, although the innovation incentives for an innovative firm are greater in the monopolistic market than in the competitive market, it can provide a higher-quality patent in the competitive market under certain conditions. In the case of infringement, the patent quality under the unjust enrichment rule is generally better than that under the profit loss rule. However, when it is very difficult to innovate, profit loss rule B can better motivate an innovative firm to innovate. Thirdly, if the court adopts a single patent infringement compensation rule, it will be difficult to optimize patent quality. Owing to the differences in their operating mechanism, different patent infringement compensation rules differ from one another in terms of innovation incentives for inventors. To improve patent quality, the court needs to adopt the correct patent infringement compensation rule depending on the circumstances. For example, when it is easier to innovate, the unjust enrichment rule should be adopted first; when it is difficult to innovate, the profit loss rule should be adopted first. Moreover, profit loss needs to reference the profit gained by the innovator under monopoly conditions.

It should be noted that this research can be expanded along different directions, which deserves further investigation. We consider the Cournot competition between different firms. If we further consider Bertrand competition between the firms, the conclusions may be different. Moreover, the research object of this innovation is cost-cutting innovation. If the research object is product innovation or quality ladder innovation, different conclusions may be drawn. It is worth mentioning that machine learning may be powerful in solving patent-related problems. As an emerging discipline, machine learning is a subfield of computer science that evolved from the study of pattern recognition and computational learning theory in artificial intelligence [22–24] and explores the study and construction of algorithms that can learn from and make predictions for complicated scenarios. If machine learning is applied to the process of patent examination, it may make the patent system more intelligent and efficient. At the same time, it can also increase the accuracy of patent examination results and help improve the patent quality greatly (Burk and Lemley [8] argued that "various inventions and innovations are totally different in nature; the difference in industry finds expression in the form of inventions and innovations; accordingly, there is a difference in patenting process").

Data Availability

All the data has been included in the manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Inventory and Ordering Decisions in Dual-Channel Supply Chains Involving Free Riding and Consumer Switching Behavior with Supply Chain Financing

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This study introduces a dual-channel supply chain including a supplier and a retailer with capital constraints, in which the retailer can apply for the trade credit financing from the supplier. This work investigates the effects of two typical behaviors, free riding behavior and consumer switching behavior, on inventory, ordering, and sales effort decisions in decentralized and centralized decision situations with stochastic demand. In order to achieve the optimal performance in the centralized system, this research designs a partial buyback contract to coordinate the supply chain. Furthermore, numerical analysis is provided to test the feasibility of the model. The results indicate that in the dual-channel supply chain with the above two behaviors, (1) the optimal sales effort level, optimal order quantity, the optimal offline, and online profits under the centralized decision-making are more than those under decentralized scenario, except for the optimal inventory level; (2) the increase of the offline consumer switching rate will lead to the reduction of the offline order quantity and the offline expected profit and raise the online inventory level and the online expected profit; (3) the increase of the online consumer switching rate will raise the offline order quantity and the offline expected profit but has no significant impact on the online inventory level and the online expected profit; (4) the increase of the free riding coefficient of the supplier, no matter whether in decentralized or centralized systems, will reduce the offline sales effort level, the offline expected profit, and the online expected profit and raise the inventory level. Finally, this work provides some managerial implication.

1. Introduction

As important contributors in economy, small- and medium-sized enterprises (SMEs) often confront with the problem of capital constraints, particularly in the stage of purchasing. Generally, commercial banks can provide financing solutions for SMEs. However, due to the small business scale, weak business capacity, low credibility, less assets, insufficient collateral, weak comprehensive strength, and other reasons, SMEs often cannot obtain the credit, and it is difficult for them to apply for financing [1]. Thus, capital constraints and financing difficulties have become the main problems hindering the development of SMEs [2]. Hence, trade credit financing is widely used in real transactions, which is usually provided by the core firms in the upstream of the supply chain [3]. For example, IBM provides short-term and long-term loans to customers through its wholly-owned subsidiary IBM Global Financing to help them to buy IBM software. Ford, through its wholly-owned subsidiary credit company, provided wholesale loans to dealers to purchase vehicles [4].

Furthermore, with the popularity of the new retail business and the development of e-commerce in the retailing industry, a growing body of companies, such as Apple, Nike, and Samsung, not only use traditional offline channels but sell products directly to customers by opening online channels as well [5, 6]. The existing dual-channel supply chain models can be divided into three types. The first is led by strong manufactures mastering core technology, such as Huawei and Apple in the mobile phone industry, and Intel and Qualcomm in the equipment manufacturing industry; the second is controlled by strong retailers, such as traditional large retailers represented by Suning and Gome, and large online retailers represented by Tmall and Jingdong; the third is vertical equilibrium; that is, manufactures and retailers have equal power, such as Starbucks and UNIQLO, which cooperate with Sephora (the global cosmetics retail authority) [7]. Online channels can help manufacturers reduce costs, better forecast customer's demand, and increase revenue [8]. In the dual-channel supply chain, consumer behavior will have two main impacts on the decision-making of supply chain members: consumer switching behavior and free riding across channels [9, 10]. Since the same product will be sold in online channel and offline channel, there exists the mutual substitution between two channels. And consumers will turn to the other channel to purchase products when the one channel is out of stock [11]. At the same time, with the introduction of online channels, manufacturers with no sales efforts will indirectly share one part of the increase of sales brought about by retailers' sales efforts [12]. Therefore, free riding will hinder retailers' sales efforts and affect their promotion strategies [13].

Finally, it is well-known that "the best performance" of supply chain members will be difficult to achieve without coordination, which means that the total performance cannot be best possible although the decisions of both sides are optimal [14]. Thus, the contract coordination is vital to coordinate and improve the profits of each partner in dual-channel supply chains, so as to alleviate the competition between channels and the pressure of financing to a certain extent. Based on our best knowledge, the existing study has less investigated the impacts of free riding and consumer switching behavior on the dual-channel supply chain performance with capital constraints.

Hence, this study aims to take free riding and consumer switching behavior into account, investigates their impacts on dual-channel supply chain performance, proposes the financing solution for the retailer with the capital constraint, and designs the contract coordination to help supply chain members achieve the global optimum.

This research contributes to the study of supply chain financing in the field of capital-constrained dual-channel supply chains with stochastic demand, conducts a deep investigation of two main impacts of consumer switching behavior and free riding on supply chain performance, and provides some scientific and reasonable support for decision makers.

The rest of this study is organized as follows. Sections 2 and 3 present the literature review and the problem and model description, respectively. Section 4, based on trade credit financing, free riding, and consumer switching behavior, analyzes the optimal solutions of inventory level, order quantity, and sales effort level in the decentralized and centralized supply chains. Section 5 proposes a partial buyback to coordinate the supply chain. Section 6 tests the feasibility of the model with a numerical example and provides the sensitivity analysis of the parameters. Finally, Section 7 concludes this study and puts forward some managerial implications.

2. Literature Review

In this section, the literature studies on supply chain financing, dual-channel supply chain, free riding, and supply chain coordination will be reviewed, respectively.

2.1. Supply Chain Financing. Supply chain financing (SCF) refers to promoting interorganizational capital flow through financing schemes provided by financial institutions, improving the supply chain management of cash flow, and ensuring the smooth implementation of transaction between supply chain members. [15]. SCF provides optimal financing conditions and sufficient funds, which can raise the supply chain members' performance, so as to ensure the long-term and effective operations of the supply chain [16]. Among them, bank loan and trade credit have been concerned by many scholars. A large number of literature studies have studied the problem that enterprises can ease the capital constraints through bank loans [17–21]. Among them, Dada and Hu [18] studied a newsboy model in which retailers with capital constraints can apply for financing through banks. Feng et al. [20] researched the optimal ordering strategy of the buyer under the bank financing and found that the buyer's order quantity and profit would raise with the increase of bank loan quota. Yan et al. [21] considered that the manufacturer provided credit guarantee for the retailer, investigated the influence of bank loan on retailer financing equilibrium and coordination. Trade credit is a kind of credit provided by the upstream enterprises to the downstream firms. By charging the loan interest, the downstream firms can purchase the product from the upstream enterprises in the case of delayed payment and pay back with the sales profit in the end of the sales cycle. Some scholars pointed out that retailers prefer trade credit than bank loans because of lower interest rates. For instance, Kouvelis and Zhao [22] found that, if providing an optimal structure of trade credit, retailers always preferred trade credit rather than bank financing, because risk neutral suppliers would always provide financing solutions for retailers with interest rate at most risk-free interest rate. Hua et al. [4] investigated a capital-constrained retailer ordering decision from suppliers through option contract by establishing a Stackelberg game model, and the retailer could apply for bank loans or trade credit financing from suppliers if needed. They also analyzed the financing problems in the supply chain and found that the retailer always tended to obtain financing from the supplier because of the low interest rate. Some scholars also claimed that, compared with bank loans, trade credit can reduce the double marginalization by risk sharing [23–25]. Among them, Jing and Seidmann [23] showed that trade credit, compared with bank loans, was more effective to alleviate double marginalization when the production cost was relatively low, because manufacturers and retailers shared the risk of low demand. Yang and Birge [25] suggested that trade credit enabled to raise the efficiency of the supply chain by sharing demand risk between retailers and suppliers. It can be found that most of the existing studies on SCF focused more on single-channel supply chains and less on dual-channel supply chains which consist of retailer's offline channel and supplier's online channel.

2.2. Dual-Channel Supply Chain. As the rapid development of e-commerce, the dual-channel supply chain has become one popular research topic in the last decade. It makes easier for many manufacturers to carry on online direct sales [5]. Most of researchers have studied the effect of pricing decisions on dual-channel supply chain. For instance, Chen et al. [26] considered manufacturer as the leader of Stackelberg game and retailer as the follower, studied the pricing decision and coordination by developing dual-channel supply chain model. Ma et al. [27] researched the pricing decision of dual-channel closed-loop supply chain by considering the government consumption subsidies and consumer channel preferences. Ding et al. [28] investigated the decision-making process of hierarchical pricing in different channel models and obtained the joint optimization strategy of offline retailer's sales price, online manufacturer's sales price, and wholesale price. Dai et al. [29] investigated the impact of retailers' fair concerning on the pricing decisions of the manufacture and the retailer by establishing the dual-channel supply chain model. Wang et al. [30] considered the sales effort and third-party product recovery, researched the optimal pricing of retail channel and direct channel of the dual-channel supply chain. Xu et al. [31] investigated the pricing decision and channel strategy of dual-channel supply chain under the manufacture had condition of sufficient and insufficient funds. Qin et al. [8] discussed the impact of a trade credit policy (delayed payment) on pricing decisions and alleviating conflicts arising on a dual-channel supply chain including one value-added retailer and one manufacturer and. In addition, inventory and ordering decisions are also one of the important problems for the supply chain members' decision. In contrast, few researchers have researched the inventory and ordering decisions in dual-channel supply chain. Among them, due to the mutual substitution of the same product between the two channels, customers usually switch to one channel to purchase when the other channel is out of stock, which leads to some studies on the problem of consumer switching behavior. For example, Chiang and Monahan [32] assumed that the demand was stochastic and developed a two-stage dual-channel inventory model, studied the inventory level decisions and control strategy where there was a shortage substitution between two different channels. Boyaci [33] established a newsboy model to analyze the optimal inventory decisions and revenues by considering the impact of consumer switching behavior. Geng and Mallik [34] considered the supplier's capacity shortage and investigated how the capacity constraint affected the manufacturer's optimal inventory allocation strategy, the retailer's order decision, and the equilibrium of the game under the consumer switching behavior and inventory competition. Yang et al. [35] studied the influence of delivery lead time and consumer switching behavior on the inventory decisions under the decentralized and centralized scenarios, discussed the inventory competition between online and offline channels, and found that at least one member would be overstocked in the decentralized system. Most of the above studies on the dual-channel supply chain assumed that members have no capital constraint and mainly focused on pricing decision if cash flow is limited. However, in real business, retailers, as the downstream SMEs in the supply chain, often face the problem of capital constraints. Hence, this work considers the retailer has shortage of capital, and combining with SCF, the inventory and ordering decisions in dual-channel supply chains are studied.

2.3. Free Riding. For another, there usually exists the free riding behavior based on sales effort in dual-channel supply chains [13]. When the offline retailers carry out various promotion activities (such as advertising and product experience), consumers can first enjoy the product brought by the promotion effect of offline retailing stores and then buy the product at a lower price by switching to online channels. Van Baal and Dach [36] found that in dual-channel supply chains, more than 20% of consumers have free riding behavior. He et al. [37] developed a dual-channel closed-loop supply chain and investigated the impact of free riding on carbon emissions in a product's life cycle. Zhou et al. [12] considered a two-echelon supply chain that manufacturers sold products through online and offline channels, in which retailers provided some presale service to customers, and researched the influence of free riding on pricing decision, service strategies, and profits of manufacturers and retailers based on consistent and inconsistent pricing. Chen and Chen [38] investigated the impact of free riding behavior on price matching strategy of physical retailers by developing a duopoly game using the Hotelling model. Zhang et al. [39] considered the supply chain including two kinds of manufacturers (i.e., free riding and green innovation), established a differential game model, and researched the dynamics of green innovation. Yan et al. [40] considered an online financing service for suppliers with capital constraint could be provided by an e-commerce platform and studied the effects of online financing and free riding on sales effort, optimal pricing, and order quantity. Thus, this study combines the free riding behavior with consumer switching behavior in the dual-channel supply chain.

2.4. Supply Chain Coordination. It is well known that the centralized decision can lead to the global optimum of the supply chain performance, but it does not provide specific profit allocation mechanisms. Hence, coordination mechanism is introduced to help each member in the supply chain with global optimum profit achieve Pareto-optimal. There exists some classic literature focusing on quantity discount, revenue sharing, buyback, quantity flexibility, effort cost sharing, and other contracts to coordinate supply chain [41–45]. After that, many scholars coordinate the supply chain by developing different contracts for specific situations. Among them, Xie et al. [46] proposed a bilateral buyback contracted to coordinate an intermodal transport system including one liner firm at a seaport and one railway transport firm at a dry port. Zhong et al. [47] analyzed the impact of revenue sharing contract on a three-stage logistics service supply chain, which composed of terminal distributors, express delivery companies, and e-commerce malls, and found that the contract could raise all members' profit, so as to get win-win situation. Xie et al. [48] investigated the impact of relative bargaining power and income uncertainty on the performance of buyback contract by developing a two-echelon supply chain including one seller and one buyer and considered that the buyer had uncertain demand and income. Zhong et al. [49] researched the coordination effect of unit delivery price, cost sharing, and revenue sharing contracts in the three semicentralized alliances by developing a three-stage supply chain composed of express company, e-commerce mall, and terminal distribution service provider based on Stackelberg game theory. Table 1 lists some key-related literature so as to illustrate the innovation and contribution of this work.

In summary, most of the existing studies mainly focused on single-channel supply chains, or dual-channel supply chains with sufficient funds, and less investigated the cases with capital constraints. Furthermore, in the dual-channel supply chains, most of research studies focus more on members' pricing decisions and less on inventory and ordering decisions. And there is little research taking into account the two main behaviors: consumer switching behavior and free riding behavior, and we discussed their influence on the optimal inventory level and ordering decisions.

Hence, this study considers consumer switching behavior and free riding behavior in a dual-channel supply chain, where the supplier sells directly through its own online channel and offline retailer channel. Furthermore, it investigates their impacts on the sales effort level of the retailer, ordering quantity and the supplier' inventory decisions with constrained capitals under the stochastic demand.

3. Problem and Model Description

3.1. Problem Description. This work considers a dual-channel supply chain system including a risk neutral retailer and a risk neutral supplier. The retailer and the supplier sell the same type of product through their own offline and online channel. At the beginning of the sales cycle, the retailer, as an SME in the downstream of the supply chain, has capital constraint. Its initial capital is enough to cover the cost of sales effort, but not sufficient to cover all purchasing cost. In this case, the supplier, as the core enterprise of supply chain, has enough capital and can provide trade credit financing solutions for the retailer through its own financial subsidiary corporation. Thus, the retailer can use financing capital to continuously purchase products from the supplier, which is not allowed to be used for another project investment [4]. At the end of the sales period, the retailer and the supplier deal with the unsold products at the residual price, respectively, and the retailer needs to repay the loan and financing interest to the supplier. Meanwhile, the problem considers the possibility of the retailer bankruptcy; that is, the retailer's sales profit may insufficient to pay all the loan and financing interest (Figure 1).

Furthermore, this study considers the influence of "free riding" behavior and consumer switching behavior on the supply chain decision and aims to maximize total supply chain performance. The feasibility of the model will be tested in the numerical analysis in Section 6.

Finally, the problem assumes that the order quantity and inventory level decisions are short-term strategies, and the sales effort level is a long-term strategy. Therefore, the sales effort decision should be determined before the inventory level and order quantity decisions. Under the decentralized decision, the retailer sets the sales effort level at first. Then, the supplier and the retailer make inventory level and order quantity decisions simultaneously (the Stackelberg game sequence). Under the centralized dual-channel supply chain, referring to Hua et al [6] and Yang et al. [35], this work uses the two-stage optimization to maximize the expected profit. First, the whole supply chain sets the sales effort level. Then, it makes inventory level decision and order quantity decision simultaneously.

3.2. Notation Definition. To formulate feasible models, some related notation is defined in Table 2.

3.3. Model Description. At the beginning of the sales cycle, the retailer has initial capital B, and the supplier provides credit loans with interest rate of I and wholesale price w for the retailer. The retailer sets sales effort level e at first. Then, the retailer determines the order quantity Q_r and the supplier decides the inventory level Q_s for the online channel simultaneously. And the retailer will apply for the financing amount $L = wQ_r + R(e) - B$ where $R(e) = \eta e^2/2$ is the cost of sales effort and η is the cost factor of sales effort [12, 50]. Then, the supplier produces products for its own online channel and offline channel at unit cost c_o and sells them in its own online channel with the price p_s. At the same time, the retailer buys the product from the supplier with the wholesale price w and sells the product to the customer via its offline channel at the retail price p_r. At the end of the sales period, the supplier and the retailer process the unsold products, respectively, at the price v, and the retailer has to pay back the loan and financing interest owed by the supplier. This study assumes that all prices are exogenous [35], and the risk-free interest rate is 0. To ensure the smooth progress of the transaction, this work also assumes that $v < c_o < w < w(1+I) < p_r, p_s$. Furthermore, the model sets a critical value of demand z, which implies that the critical point at the retailer's sales profit is enough to cover the supplier's loan and interest, i.e.,

$$z = \frac{\left(wQ_r + R(e) - B\right)(1+I) - vQ_r}{p_r - v}. \tag{1}$$

It means that, the retailer can only use its sales revenue to pay back when the sales revenue is not enough to repay all the outstanding loans and financing interest; otherwise, it needs to pay back the amount of $L(1+I)$ with interest and principal.

Note that $z = 0$ if the retailer's initial capital is sufficient. For another, the trade credits are not used for the retailer if $z > Q_r$. Then, the retailer applies for trade credit if $0 < z < Q_r$. Hence, this study assumes that $0 < z < Q_r$ [51].

Table 1: List of key-related literature.

Key-related studies	Decision variables	Financing type	Channel type	Contract strategy	Consumer switching	Free riding
Hua et al. (2019)	Supplier's interest rate; retailer's ordering; supplier's option price	Trade credit	Offline channel	Option contract	No	No
Kouvelis and Zhao (2012)	Retailer's ordering; credit guarantee coefficient	Bank financing; trade credit	Offline channel	Manufacturer's trade credit guarantee	No	No
Yang and Birge (2018)	Retailer's ordering; supplier's whole sale price	Bank financing; trade credit	Offline channel	Early-payment discount	No	No
Dai et al.(2019)	Online selling price; wholesale price; offline selling price	No	Dual-channel	Retailers' fairness concerns	No	No
Wang et al.(2020)	Online selling price; wholesale price; offline selling price; collection price	No	Dual-channel	No	No	No
Geng and Mallik (2007)	Retailer's ordering; manufacture's inventory	No	Dual-channel	Reverse revenue sharing	Yes	No
Yang et al. (2017)	Delivery lead time; retailer's ordering; manufacture's inventory	No	Dual-channel	No	Yes	No
Zhou et al. (2018)	Retailer's sales price; manufacture's sales price; retailer's service level	No	Dual-channel	Service-cost sharing	No	No
Qin et al. (2020)	Retailer's sales price; manufacture's sales price	Trade credit (delay payment)	Dual-channel	Trade credit contract	No	No
Chen and Chen (2019)	Brick-and-mortar retailer's sales price; online retailer's sales price	No	Dual-channel	No	No	No
Yan et al. (2020)	Offline price; online price	E-commerce platform finance	Dual-channel	No	No	No
This study	Retailer's ordering quantity and sales effort level; supplier's inventory level	Trade credit (supplier's financial subsidiary corporation)	Dual-channel	Partial buyback contract	Yes	Yes

To discuss consumer switching behavior and free riding behavior simultaneously, this research refers to the models of [11, 33] and establishes demand functions as follows:

Demand for the retailer: $D_r = d_r + (\alpha - \beta)e + K_s(d_s + \beta e - Q_s)^+$

Demand for the supplier: $D_s = d_s + \beta e + K_r(d_r + (\alpha - \beta)e - Q_r)^+$ where d_s and d_r are initial demands for the supplier's online channel and the retailer's offline channel, respectively, and they are both independent continuous random variables. The cumulative function and density function of d_s and d_r are $G(y)$ and $F(x)$, and $g(y)$ and $f(x)$, respectively. α is the elasticity coefficient of market demand under the given sales effort level; β $(0 < \beta < \alpha)$ is the degree of "free riding" behavior, which is used to measure the proportion of customers who enjoy free offline channel promotion service but transfer to online channels to purchase products. K_r, K_s are the switching rate of offline channel and online channel $(0 \le K_r, K_s < 1)$, respectively. That is, when the offline retail channel is out of stock, the consumer transfers to the online channel with probability K_r; when the online channel is out of stock, the consumer transfers to the offline channel with the probability K_s (Figure 2). It should be more favorable for the retailer and the supplier to satisfy the demand in their owned channel. Hence, the model assumes that $(p_r - v) > K_r(p_s - v)$ and $(p_s - v) > K_s(p_r - v)$ [35].

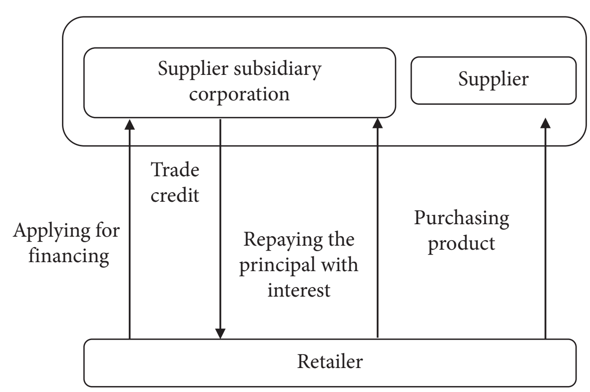

Figure 1: Dual-channel supply chain financing and trading process.

In the next section, the model derivation and analysis will be illustrated under the decentralized and centralized systems.

4. Model Analysis

4.1. Dual-Channel Supply Chain Model under the Decentralized Decision-Making. In this subsection, the supplier and the retailer make decisions so as to maximize their own profit.

Table 2: Notation definition.

Superscripts	$n \in \{d, c, u\}$	Decentralized (d), centralized (c), partial buyback contract (u)
Subscripts	$m \in \{r, s\}$	Retailer (r), supplier (s)
Decision variables	Q_m^n	Ordering quantity (r), inventory level (s)
	e^n	Sales effort level
Parameters	z^n	Critical value of demand
	p_m	Channel sales price
	K_m	Consumer switching rate
	η	Cost factor of sales effort
	β	Free riding coefficient of the supplier
	α	Elasticity coefficient of market demand response to the retailer's sales effort
	c_o	Production cost
	B	Initial funds of the retailer
	L	Financing amount of the retailer
	v	Residual value
	w	The supplier wholesale price
	u	Partial buyback ratio
	I	Interest rate of trade credit financing
	π_m^n	Profit under the decentralized system
	$\prod$	Profit under the centralized system
	d_m	Channel primary demands
	D_m	Channel total demand
	$f(x), g(y)$	Density function of demand
	$F(x), G(y)$	Cumulative density function of demand

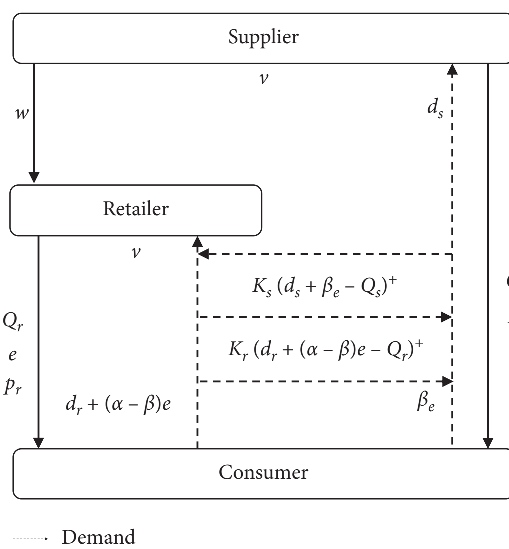

Figure 2: Dual-channel supply chain system.

The retailer's profit is defined as

$$V_r = -B + \begin{cases} p_r Q_r - L(1+I), & \text{if } d_r + (\alpha-\beta)e > Q_r, \\ p_r E\min(Q_r, D_r) + vE(Q_r - D_r)^+ - E\min\left[L(1+I), p_r E\min(Q_r, D_r) + vE(Q_r - D_r)^+\right], & \text{if } 0 < d_r + (\alpha-\beta)e < Q_r, d_s + \beta e > Q_s, \\ p_r D_r + vE(Q_r - D_r) - E\min\left[L(1+I), p_r D_r + vE(Q_r - D_r)\right], & \text{if } 0 < d_r + (\alpha-\beta)e < Q_r, 0 < d_s + \beta e < Q_s. \end{cases} \tag{2}$$

And the specific terms of the retailer profit except for $-B$ are as follows:

(1) The case of $d_r + (\alpha - \beta)e > Q_r$ means that the retailer's offline demand is more than the supply of the retailer no matter whether there exists demand transfer from the supplier's online channel. It implies that the retailer's sales profit is sufficient to cover all the outstanding loans and financing interest

$L(1+I)$. Hence, the retailer's expected profit expression can be written as

$$V_{r1} = \int_{Q_r-(\alpha-\beta)e}^{\infty} \left[p_r Q_r - \left(wQ_r + R(e) - B\right)(1+I)\right] f(x)\mathrm{d}x. \tag{3}$$

(2) The case of $0 < d_r + (\alpha-\beta)e < Q_r, d_s + \beta e > Q_s$ means that the offline demand is less than the supply of the retailer, but there exists demand transfer from the supplier's online channel. In this situation, the total offline demand of the retailer is more than the supply of the retailer if $D_r > Q_r$. When $D_r < Q_r$, the retailer's sales profit is insufficient to repay $L(1+I)$ if $D_r < z$, and the retailer should pay back the amount of $L(1+I)$ if $Q_r > D_r > z$. Therefore, the expected profit of the retailer under this condition is

$$\begin{aligned}
V_{r2} = {} & \int_{Q_s-\beta e}^{\left(Q_r-(\alpha-\beta)e\right)/K_s+Q_s-\beta e} \int_{z-(\alpha-\beta)e-K_s\left(y+\beta e-Q_s\right)}^{Q_r-(\alpha-\beta)e-K_s\left(y+\beta e-Q_s\right)} p_r\left(x+(\alpha-\beta)e+K_s\left(y+\beta e-Q_s\right)\right) f(x)g(y)\mathrm{d}x\,\mathrm{d}y \\
& + \int_{Q_s-\beta e}^{\left(\left(Q_r-(\alpha-\beta)e\right)/K_s\right)+Q_s-\beta e} \int_{z-(\alpha-\beta)e-K_s\left(y+\beta e-Q_s\right)}^{Q_r-(\alpha-\beta)e-K_s\left(y+\beta e-Q_s\right)} v\left(Q_r-x-(\alpha-\beta)e-K_s\left(y+\beta e-Q_s\right)\right) f(x)g(y)\mathrm{d}x\,\mathrm{d}y \\
& + \int_{Q_s-\beta e}^{\left(\left(Q_r-(\alpha-\beta)e\right)/K_s\right)+Q_s-\beta e} \int_{Q_r-(\alpha-\beta)e-K_s\left(y+\beta e-Q_s\right)}^{Q_r-(\alpha-\beta)e} p_r Q_r f(x)g(y)\mathrm{d}x\,\mathrm{d}y \\
& - \int_{Q_s-\beta e}^{\left(\left(Q_r-(\alpha-\beta)e\right)/K_s\right)+Q_s-\beta e} \int_{z-(\alpha-\beta)e-K_s\left(y+\beta e-Q_s\right)}^{Q_r-(\alpha-\beta)e} \left(\left(wQ_r+R(e)-B\right)(1+I)\right) f(x)g(y)\mathrm{d}x\,\mathrm{d}y.
\end{aligned} \tag{4}$$

(3) The case of $0 < d_r + (\alpha-\beta)e < Q_r, 0 < d_s + \beta e < Q_s$ means that the offline demand is less than the supply of the retailer, and there is no transfer from the supplier's online channel. In this case, the total offline demand for the retailer is more than the supply of the retailer if $D_r > Q_r$. When $D_r < Q_r$, if $D_r < z$, the retailer's sales profit is not enough to cover $L(1+I)$, and the retailer should pay back the amount of $L(1+I)$, if $Q_r > D_r > z$. Thus, the expected profit of the retailer is

$$\begin{aligned}
V_{r3} = {} & \int_0^{Q_s-\beta e} \int_{z-(\alpha-\beta)e}^{Q_r-(\alpha-\beta)e} p_r\left(x+(\alpha-\beta)e\right) f(x)g(y)\mathrm{d}x\,\mathrm{d}y \\
& + \int_0^{Q_s-\beta e} \int_{z-(\alpha-\beta)e}^{Q_r-(\alpha-\beta)e} v\left(Q_r-x-(\alpha-\beta)e\right) f(x)g(y)\mathrm{d}x\,\mathrm{d}y \\
& - \int_0^{Q_s-\beta e} \int_{z-(\alpha-\beta)e}^{Q_r-(\alpha-\beta)e} \left(\left(wQ_r+R(e)-B\right)(1+I)\right) f(x)g(y)\mathrm{d}x\,\mathrm{d}y.
\end{aligned} \tag{5}$$

Finally, the expression of the retailer's total expected profit can be taken as follows:

$$\begin{aligned}
\pi_r^d = {} & -B + V_{r1} + V_{r2} + V_{r3} \\
= {} & p_r Q_r - \left(wQ_r + R(e) - B\right)(1+I) - B \\
& - p_r Q_r \int_0^{Q_s-\beta e} \int_0^{Q_r-(\alpha-\beta)e} f(x)g(y)\mathrm{d}x\,\mathrm{d}y \\
& - p_r Q_r \int_{Q_s-\beta e}^{\left(\left(Q_r-(\alpha-\beta)e\right)/K_s\right)+Q_s-\beta e} \int_0^{Q_r-(\alpha-\beta)e-K_s\left(y+\beta e-Q_s\right)} f(x)g(y)\mathrm{d}x\,\mathrm{d}y \\
& + \int_{Q_s-\beta e}^{\left(\left(Q_r-(\alpha-\beta)e\right)/K_s\right)+Q_s-\beta e} \int_{z-(\alpha-\beta)e-K_s\left(y+\beta e-Q_s\right)}^{Q_r-(\alpha-\beta)e-K_s\left(y+\beta e-Q_s\right)} \left[vQ_r + \left(p_r - v\right)\left(x+(\alpha-\beta)e+K_s\left(y+\beta e-Q_s\right)\right)\right] f(x)g(y)\mathrm{d}x\,\mathrm{d}y \\
& + \int_0^{Q_s-\beta e} \int_{z-(\alpha-\beta)e}^{Q_r-(\alpha-\beta)e} \left[vQ_r + \left(p_r - v\right)\left(x+(\alpha-\beta)e\right)\right] f(x)g(y)\mathrm{d}x\,\mathrm{d}y \\
& + \left(wQ_r + R(e) - B\right)(1+I) \int_0^{Q_s-\beta e} \int_0^{z-(\alpha-\beta)e} f(x)g(y)\mathrm{d}x\,\mathrm{d}y \\
& + \left(wQ_r + R(e) - B\right)(1+I) \int_{Q_s-\beta e}^{\left(\left(Q_r-(\alpha-\beta)e\right)/K_s\right)+Q_s-\beta e} \int_0^{z-(\alpha-\beta)e-K_s\left(y+\beta e-Q_s\right)} f(x)g(y)\mathrm{d}x\,\mathrm{d}y.
\end{aligned} \tag{6}$$

And the retailer's expected repayment amount to the supplier is

$$
\begin{aligned}
V_{r4} &= \left(wQ_r + R(e) - B\right)(1+I) \\
&+ \int_{Q_s-\beta e}^{\left(\left(Q_r-(\alpha-\beta)e\right)/K_s\right)+Q_s-\beta e} \int_0^{z-(\alpha-\beta)e-K_s\left(y+\beta e-Q_s\right)} \left[vQ_r + \left(p_r - v\right)\left(x + (\alpha-\beta)e + K_s\left(y+\beta e - Q_s\right)\right)\right] f(x) g(y) \mathrm{d}x\, \mathrm{d}y \\
&+ \int_0^{Q_s-\beta e} \int_0^{z-(\alpha-\beta)e} \left[vQ_r + \left(p_r - v\right)\left(x + (\alpha-\beta)e\right)\right] f(x) g(y) \mathrm{d}x\, \mathrm{d}y \\
&- \left(wQ_r + R(e) - B\right)(1+I) \int_0^{Q_s-\beta e} \int_0^{z-(\alpha-\beta)e} f(x) g(y) \mathrm{d}x\, \mathrm{d}y \\
&- \left(wQ_r + R(e) - B\right)(1+I) \int_{Q_s-\beta e}^{\left(\left(Q_r-(\alpha-\beta)e\right)/K_s\right)+Q_s-\beta e} \int_0^{z-(\alpha-\beta)e-K_s\left(y+\beta e-Q_s\right)} f(x) g(y) \mathrm{d}x\, \mathrm{d}y.
\end{aligned}
\tag{7}
$$

Similarly, the supplier's profit is defined as

$$
V_s = -c_o\left(Q_r + Q_s\right) + B - R(e) + \begin{cases} p_s Q_s + E\min\left[L(1+I), p_r E\min\left(Q_r, D_r\right) + vE\left(Q_r - D_r\right)^+\right], & \text{if } d_s + \beta e > Q_s, \\ p_s E\min\left(Q_s, D_s\right) + vE\left(Q_s - D_s\right)^+ + L(1+I), & \text{if } 0 < d_s + \beta e < Q_s, d_r + (\alpha-\beta)e > Q_r, \\ p_s D_s + vE\left(Q_s - D_s\right) + E\min\left[L(1+I), p_r D_r + vE\left(Q_r - D_r\right)\right], & \text{if } 0 < d_s + \beta e < Q_s, 0 < d_r + (\alpha-\beta)e < Q_r. \end{cases}
\tag{8}
$$

And the specific terms of the supplier profit function except for $-c_o\left(Q_r + Q_s\right) + B - R(e)$ and V_{r4} are as follows:

(1) The case of $d_s + \beta e > Q_s$ means that the online demand of the supplier is more than the supply of the supplier whether or not there exists demand transfer from the offline channel. Thus, under this condition, the supplier's expected profit expression is

$$
V_{s1} = \int_{Q_s-\beta e}^{\infty} p_s Q_s g(y) \mathrm{d}y. \tag{9}
$$

(2) The case of $0 < d_s + \beta e < Q_s, d_r + (\alpha-\beta)e > Q_r$ means that the online demand of the supplier is less than its supply, but there exists demand transfer from the retailer's offline channel. In this case, the total online demand of the supplier is less than the supply of the supplier if $D_s < Q_s$. If $D_s > Q_s$, the total online demand of the supplier is more than the supply of the supplier. Hence, the supplier's expected profit expression is

$$
\begin{aligned}
V_{s2} &= \int_{Q_r-(\alpha-\beta)e}^{\left(\left(Q_s-\beta e\right)/K_r\right)+Q_r-(\alpha-\beta)e} \int_0^{Q_s-\beta e-K_r\left(x+(\alpha-\beta)e-Q_r\right)} p_s\left(y + \beta e + K_r\left(x + (\alpha-\beta)e - Q_r\right)\right) g(y) f(x) \mathrm{d}y\, \mathrm{d}x \\
&+ \int_{Q_r-(\alpha-\beta)e}^{\left(\left(Q_s-\beta e\right)/K_r\right)+Q_r-(\alpha-\beta)e} \int_0^{Q_s-\beta e-K_r\left(x+(\alpha-\beta)e-Q_r\right)} v\left(Q_s - y - \beta e - K_r\left(x + (\alpha-\beta)e - Q_r\right)\right) g(y) f(x) \mathrm{d}y\, \mathrm{d}x \\
&+ \int_{Q_r-(\alpha-\beta)e}^{\left(\left(Q_s-\beta e\right)/K_r\right)+Q_r-(\alpha-\beta)e} \int_{Q_s-\beta e-K_r\left(x+(\alpha-\beta)e-Q_r\right)}^{Q_s-\beta e} p_s Q_s g(y) f(x) \mathrm{d}y\, \mathrm{d}x.
\end{aligned}
\tag{10}
$$

(3) The case of $0 < d_s + \beta e < Q_s, 0 < d_r + (\alpha-\beta)e < Q_r$ means that the online demand of the supplier is less than its supply, and there is no transfer from the retailer's offline channel. In this case, the total online demand of the supplier is less than the supply of the supplier if $D_s < Q_s$. If $D_s > Q_s$, the total online demand of the supplier is more than the supply of the supplier. Thus, the supplier's expected profit expression is

$$V_{s3} = \int_0^{Q_r-(\alpha-\beta)e} \int_0^{Q_s-\beta e} p_s (y+\beta e) g(y) f(x) \mathrm{d}y\, \mathrm{d}x + \int_0^{Q_r-(\alpha-\beta)e} \int_0^{Q_s-\beta e} v(Q_s - y - \beta e) g(y) f(x) \mathrm{d}y\, \mathrm{d}x. \quad (11)$$

Finally, the expression of the supplier's total expected profit can be as follows:

$$\begin{aligned}
\pi_s^d &= -c_o (Q_r + Q_s) + B - R(e) + V_{s1} + V_{s2} + V_{s3} + V_{r4} \\
&= p_s Q_s + (wQ_r + R(e) - B)(1+I) - c_o (Q_r + Q_s) + B - R(e) \\
&\quad - (p_s - v) \int_0^{Q_r-(\alpha-\beta)e} \int_0^{Q_s-\beta e} (Q_s - y - \beta e) g(y) f(x) \mathrm{d}y\, \mathrm{d}x \\
&\quad - (p_s - v) \int_{Q_r-(\alpha-\beta)e}^{((Q_s-\beta e)/K_r)+Q_r-(\alpha-\beta)e} \int_0^{Q_s-\beta e-K_r(x+(\alpha-\beta)e-Q_r)} (Q_s - y - \beta e - K_r (x + (\alpha-\beta)e - Q_r)) g(y) f(x) \mathrm{d}y\, \mathrm{d}x \\
&\quad + \int_{Q_s-\beta e}^{((Q_r-(\alpha-\beta)e)/K_s)+Q_s-\beta e} \int_0^{z-(\alpha-\beta)e-K_s(y+\beta e-Q_s)} [vQ_r + (p_r - v)(x + (\alpha-\beta)e + K_s (y + \beta e - Q_s))] g(y) f(x) \mathrm{d}y\, \mathrm{d}x \\
&\quad + \int_0^{Q_s-\beta e} \int_0^{z-(\alpha-\beta)e} [vQ_r + (p_r - v)(x + (\alpha-\beta)e)] g(y) f(x) \mathrm{d}y\, \mathrm{d}x \\
&\quad - (wQ_r + R(e) - B)(1+I) \int_0^{Q_s-\beta e} \int_0^{z-(\alpha-\beta)e} g(y) f(x) \mathrm{d}y\, \mathrm{d}x \\
&\quad - (wQ_r + R(e) - B)(1+I) \int_{Q_s-\beta e}^{((Q_r-(\alpha-\beta)e)/K_s)+Q_s-\beta e} \int_0^{z-(\alpha-\beta)e-K_s(y+\beta e-Q_s)} g(y) f(x) \mathrm{d}y\, \mathrm{d}x.
\end{aligned} \quad (12)$$

In the following, the optimal solutions of the retailer and the supplier in the decentralized system will be analyzed by using the reverse derivation method. Firstly, for a given sales effort level of the retailer, the retailer's optimal order quantity and the supplier's optimal inventory level can be obtained. Then, the conditions of the retailer's optimal sales effort level are investigated.

With a given sales effort level $L(1+I)$, the first-order partial derivatives of the retailer Q_r^d and the supplier Q_s^d are as follows:

$$\begin{aligned}
F_r^d = \frac{\partial \pi_r^d}{\partial Q_r} &= p_r - w(1+I) - p_r \int_0^{Q_s-\beta e} \int_0^{Q_r-(\alpha-\beta)e} f(x) g(y) \mathrm{d}x\, \mathrm{d}y \\
&\quad - p_r \int_{Q_s-\beta e}^{((Q_r-(\alpha-\beta)e)/K_s)+Q_s-\beta e} \int_0^{Q_r-(\alpha-\beta)e-K_s(y+\beta e-Q_s)} f(x) g(y) \mathrm{d}x\, \mathrm{d}y \\
&\quad + v \int_{Q_s-\beta e}^{((Q_r-(\alpha-\beta)e)/K_s)+Q_s-\beta e} \int_{z-(\alpha-\beta)e-K_s(y+\beta e-Q_s)}^{Q_r-(\alpha-\beta)e-K_s(y+\beta e-Q_s)} f(x) g(y) \mathrm{d}x\, \mathrm{d}y \\
&\quad + v \int_0^{Q_s-\beta e} \int_{z-(\alpha-\beta)e}^{Q_r-(\alpha-\beta)e} f(x) g(y) \mathrm{d}x\, \mathrm{d}y \\
&\quad + w(1+I) \int_0^{Q_s-\beta e} \int_0^{z-(\alpha-\beta)e} f(x) g(y) \mathrm{d}x\, \mathrm{d}y \\
&\quad + w(1+I) \int_{Q_s-\beta e}^{((Q_r-(\alpha-\beta)e)/K_s)+Q_s-\beta e} \int_0^{z-(\alpha-\beta)e-K_s(y+\beta e-Q_s)} f(x) g(y) \mathrm{d}x\, \mathrm{d}y \\
&= 0.
\end{aligned} \quad (13)$$

$$\begin{aligned} F_s^d &= \frac{\partial \pi_s^d}{\partial Q_s} = p_s - c_o \\ &\quad - (p_s - v)\left[\int_0^{Q_r-(\alpha-\beta)e}\int_0^{Q_s-\beta e} g(y)f(x)\mathrm{d}y\,\mathrm{d}x \right. \\ &\quad \left. + \int_{Q_r-(\alpha-\beta)e}^{((Q_s-\beta e)/K_r)+Q_r-(\alpha-\beta)e}\int_0^{Q_s-\beta e-K_r(x+(\alpha-\beta)e-Q_r)} g(y)f(x)\mathrm{d}y\,\mathrm{d}x\right] \\ &\quad - (p_r - v)K_s\int_{Q_s-\beta e}^{((Q_r-(\alpha-\beta)e)/K_s)+Q_s-\beta e}\int_0^{z-(\alpha-\beta)e-K_s(y+\beta e-Q_s)} g(y)f(x)\mathrm{d}y\,\mathrm{d}x \\ &= 0. \end{aligned} \tag{14}$$

Proposition 1. *Under the decentralized decision, for any given sales effort level e, if $(p_r - v)K_s > w(1+I) - v$, the supplier's expected profit π_s and the retailer's expected profit π_r are strictly jointly concave in Q_s and Q_r.*

The proofs of Proposition 1, and the following propositions and lemmas are presented in Appendix. Proposition 1 proves that for any given sales effort level e, the optimal values of Q_s and Q_r can be found by using the first-order conditions.

Proposition 2. *The optimal sales effort level of the retailer in the decentralized scenario satisfies the following equation:*

$$\frac{\partial \pi_r^d}{\partial Q_r}\frac{\mathrm{d}Q_r(e)}{\mathrm{d}e} + \frac{\partial \pi_r^d}{\partial Q_s}\frac{\mathrm{d}Q_s(e)}{\mathrm{d}e} + \frac{\partial \pi_r^d}{\partial e} = 0. \tag{15}$$

Among them,

$$\frac{\mathrm{d}Q_r(e)}{\mathrm{d}e} = -\frac{1}{J}\begin{vmatrix} \dfrac{\partial F_r^d}{\partial e} & \dfrac{\partial F_r^d}{\partial Q_s} \\ \dfrac{\partial F_s^d}{\partial e} & \dfrac{\partial F_s^d}{\partial Q_s} \end{vmatrix} = -\frac{1}{J}\left(\frac{\partial^2 \pi_r^d}{\partial Q_r \partial e}\frac{\partial^2 \pi_s^d}{\partial Q_s^2} - \frac{\partial^2 \pi_r^d}{\partial Q_r \partial Q_s}\frac{\partial^2 \pi_s^d}{\partial Q_s \partial e}\right),$$

$$\frac{\mathrm{d}Q_s(e)}{\mathrm{d}e} = -\frac{1}{J}\begin{vmatrix} \dfrac{\partial F_r^d}{\partial Q_r} & \dfrac{\partial F_r^d}{\partial e} \\ \dfrac{\partial F_s^d}{\partial Q_r} & \dfrac{\partial F_s^d}{\partial e} \end{vmatrix} = -\frac{1}{J}\left(\frac{\partial^2 \pi_r^d}{\partial Q_r^2}\frac{\partial^2 \pi_s^d}{\partial Q_s \partial e} - \frac{\partial^2 \pi_r^d}{\partial Q_r \partial e}\frac{\partial^2 \pi_s^d}{\partial Q_s \partial Q_r}\right). \tag{16}$$

In the end, according to Proposition 1, the expressions of $Q_r^d(e)$ and $Q_s^d(e)$ can be obtained by integrating formulas (13) and (14) and then be taken into formula (15) based on Proposition 2, so as to get e^{d*}. Finally, Q_r^{d*} and Q_s^{d*} can be derived by taking e^{d*} into $Q_r^d(e)$ and $Q_s^d(e)$.

4.2. Dual-Channel Supply Chain Model under the Centralized Decision-Making

4.2. Dual-Channel Supply Chain Model under the Centralized Decision-Making. In the centralized system, supply chain members make decisions with the goal of optimal overall profit.

Hence, the overall expected profit of supply chain in the centralized system is

$$\begin{aligned}\prod &= \pi_r^d + \pi_s^d \\ &= (p_r - c_o)Q_r + (p_s - c_o)Q_s - \frac{\eta e^2}{2} \\ &\quad - (p_r - v)\int_0^{Q_s-\beta e}\int_0^{Q_r-(\alpha-\beta)e}(Q_r - x - (\alpha-\beta)e)f(x)g(y)\mathrm{d}x\,\mathrm{d}y \\ &\quad - (p_s - v)\int_0^{Q_r-(\alpha-\beta)e}\int_0^{Q_s-\beta e}(Q_s - y - \beta e)g(y)f(x)\mathrm{d}y\,\mathrm{d}x \\ &\quad - (p_r - v)\int_{Q_s-\beta e}^{((Q_r-(\alpha-\beta)e)/K_s)+Q_s-\beta e}\int_0^{Q_r-(\alpha-\beta)e-K_s(y+\beta e-Q_s)}(Q_r - x - (\alpha-\beta)e - K_s(y+\beta e - Q_s))f(x)g(y)\mathrm{d}x\,\mathrm{d}y \\ &\quad - (p_s - v)\int_{Q_r-(\alpha-\beta)e}^{((Q_s-\beta e)/K_r)+Q_r-(\alpha-\beta)e}\int_0^{Q_s-\beta e-K_r(x+(\alpha-\beta)e-Q_r)}(Q_s - y - \beta e - K_r(x+(\alpha-\beta)e - Q_r))g(y)f(x)\mathrm{d}y\,\mathrm{d}x.\end{aligned} \tag{17}$$

Under the centralized decision, with the given sales effort level e^c, the first-order partial derivatives of the overall profit of the supply chain with respect to Q_r^c and Q_s^c are as follows:

$$\begin{aligned}F_r^c = \frac{\partial \prod}{\partial Q_r} &= p_r - c_o \\ &\quad - (p_r - v)\left[\int_0^{Q_s-\beta e}\int_0^{Q_r-(\alpha-\beta)e} f(x)g(y)\mathrm{d}x\,\mathrm{d}y + \int_{Q_s-\beta e}^{((Q_r-(\alpha-\beta)e)/K_s)+Q_s-\beta e}\int_0^{Q_r-(\alpha-\beta)e-K_s(y+\beta e-Q_s)} f(x)g(y)\mathrm{d}x\,\mathrm{d}y\right] \\ &\quad - K_r(p_s - v)\int_{Q_r-(\alpha-\beta)e}^{((Q_s-\beta e)/K_r)+Q_r-(\alpha-\beta)e}\int_0^{Q_s-\beta e-K_r(x+(\alpha-\beta)e-Q_r)} g(y)f(x)\mathrm{d}y\,\mathrm{d}x \\ &= 0,\end{aligned} \tag{18}$$

$$\begin{aligned}F_s^c = \frac{\partial \prod}{\partial Q_s} &= p_s - c_o \\ &\quad - (p_s - v)\left[\int_0^{Q_r-(\alpha-\beta)e}\int_0^{Q_s-\beta e} g(y)f(x)\mathrm{d}y\,\mathrm{d}x + \int_{Q_r-(\alpha-\beta)e}^{((Q_s-\beta e)/K_r)+Q_r-(\alpha-\beta)e}\int_0^{Q_s-\beta e-K_r(x+(\alpha-\beta)e-Q_r)} g(y)f(x)\mathrm{d}y\,\mathrm{d}x\right] \\ &\quad - K_s(p_r - v)\int_{Q_s-\beta e}^{((Q_r-(\alpha-\beta)e)/K_s)+Q_s-\beta e}\int_0^{Q_r-(\alpha-\beta)e-K_s(y+\beta e-Q_s)} f(x)g(y)\mathrm{d}x\,\mathrm{d}y \\ &= 0.\end{aligned} \tag{19}$$

Proposition 3. *Under the centralized decision, the overall expected profit of centralized dual-channel supply chain $\prod$ is jointly concave in Q_r^c and Q_s^c, but not jointly concave in Q_r^c, Q_s^c and e^c.*

Proposition 4. *The optimal sales effort level of retailer in the centralized system satisfies the following equation:*

$$\begin{aligned}&\frac{\partial \prod}{\partial Q_r}\frac{\mathrm{d}Q_r(e)}{\mathrm{d}e} + \frac{\partial \prod}{\partial Q_s}\frac{\mathrm{d}Q_s(e)}{\mathrm{d}e} + \frac{\partial \prod}{\partial e} = 0, \\ &\frac{\mathrm{d}Q_r(e)}{\mathrm{d}e} = -\frac{1}{J}\left(\frac{\partial^2 \prod}{\partial Q_r \partial e}\frac{\partial^2 \prod}{\partial Q_s^2} - \frac{\partial^2 \prod}{\partial Q_r \partial Q_s}\frac{\partial^2 \prod}{\partial Q_s \partial e}\right), \\ &\frac{\mathrm{d}Q_s(e)}{\mathrm{d}e} = -\frac{1}{J}\left(\frac{\partial^2 \prod}{\partial Q_r^2}\frac{\partial^2 \prod}{\partial Q_s \partial e} - \frac{\partial^2 \prod}{\partial Q_r \partial e}\frac{\partial^2 \prod}{\partial Q_s \partial Q_r}\right).\end{aligned} \tag{20}$$

Based on Proposition 4, the following lemmas can be obtained.

Lemma 1. *Both Q_r^c and Q_s^c are monotone increasing functions of sales effort coefficient e^c under the centralized decision.*

To get more managerial implications, this work assumes that the market demand in two channels follow uniform distribution in the following lemma.

Lemma 2. *When the demand is uniformly distributed, $d_r \sim U(0,\theta), d_s \sim U(0,\theta)$, the expected profit $\prod$ of the whole supply chain is a strict concave function of the retailer's sales effort level e^c.*

Finally, the optimal sales effort level of the retailer can be obtained by Lemma 2 and can be expressed as $e^{c*} = ((p_r - c_o)(\alpha-\beta) + (p_s - c_o)\beta)/\eta$. Next, according to Proposition 3 and Lemma 2, bringing e^{c*} into formulas (18) and (19), the supplier's optimal inventory level Q_s^{c*} and the retailer's optimal order quantity Q_r^{c*} in the centralized system can be obtained by combining formulas (18) and (19).

It is known that centralized decision can achieve higher overall profit of supply chain than decentralized decision, but it does not provide some mechanism to allocate profit. Hence, it is fundamental to coordinate the supply chain with specific contracts in order to make the members of the dual-channel supply chain reach Pareto optimization.

5. Coordination Contract

This section proposes a coordination contract: the supplier partially buys back the retailer's surplus inventory with a certain proportion (u) at the wholesale price w. And the coordination method is based on the research of Zhong et al. [49].

In this case, $0 < u \le 1$, and the retailer's critical value of demand and expected profit of the retailer and the supplier can be expressed as follows:

$$
\begin{aligned}
z &= \frac{(wQ_r + R(e) - B)(1+I) - Q_r[(1-u)v + uw]}{p_r - uw - (1-u)v},\\
\pi_r^u &= p_rQ_r - (wQ_r + R(e) - B)(1+I) - B\\
&\quad - p_rQ_r\int_0^{Q_s-\beta e}\int_0^{Q_r-(\alpha-\beta)e} f(x)g(y)\mathrm{d}x\,\mathrm{d}y\\
&\quad - p_rQ_r\int_{Q_s-\beta e}^{((Q_r-(\alpha-\beta)e)/K_s)+Q_s-\beta e}\int_0^{Q_r-(\alpha-\beta)e-K_s(y+\beta e-Q_s)} f(x)g(y)\mathrm{d}x\,\mathrm{d}y\\
&\quad + \int_{Q_s-\beta e}^{((Q_r-(\alpha-\beta)e)/K_s)+Q_s-\beta e}\int_{z-(\alpha-\beta)e-K_s(y+\beta e-Q_s)}^{Q_r-(\alpha-\beta)e-K_s(y+\beta e-Q_s)} [((1-u)v+uw)Q_r + (p_r-(1-u)v-uw)(x+(\alpha-\beta)e\\
&\quad + K_s(y+\beta e-Q_s))]f(x)g(y)\mathrm{d}x\,\mathrm{d}y\\
&\quad + \int_0^{Q_s-\beta e}\int_{z-(\alpha-\beta)e}^{Q_r-(\alpha-\beta)e}[((1-u)v+uw)Q_r + (p_r-(1-u)v-uw)(x+(\alpha-\beta)e)]f(x)g(y)\mathrm{d}x\,\mathrm{d}y\\
&\quad + (wQ_r + R(e) - B)(1+I)\int_0^{Q_s-\beta e}\int_0^{z-(\alpha-\beta)e} f(x)g(y)\mathrm{d}x\,\mathrm{d}y\\
&\quad + (wQ_r + R(e) - B)(1+I)\int_{Q_s-\beta e}^{((Q_r-(\alpha-\beta)e)/K_s)+Q_s-\beta e}\int_0^{z-(\alpha-\beta)e-K_s(y+\beta e-Q_s)} f(x)g(y)\mathrm{d}x\,\mathrm{d}y,
\end{aligned}
$$

$$\begin{aligned}
\pi_s^u &= p_s Q_s + \left(wQ_r + R(e) - B\right)(1+I) - c_o\left(Q_r + Q_s\right) + B - R(e) \\
&-\left(p_s - v\right)\int_0^{Q_r-(\alpha-\beta)e}\int_0^{Q_s-\beta e}\left(Q_s - y - \beta e\right)g(y)f(x)\mathrm{d}y\,\mathrm{d}x \\
&-\left(p_s - v\right)\int_{Q_r-(\alpha-\beta)e}^{\left(\left(Q_s-\beta e\right)/K_r\right)+Q_r-(\alpha-\beta)e}\int_0^{Q_s-\beta e-K_r\left(x+(\alpha-\beta)e-Q_r\right)}\left(Q_s - y - \beta e - K_r\left(x + (\alpha-\beta)e - Q_r\right)\right)g(y)f(x)\mathrm{d}y\,\mathrm{d}x \\
&+\int_{Q_s-\beta e}^{\left(\left(Q_r-(\alpha-\beta)e\right)/K_s\right)+Q_s-\beta e}\int_0^{z-(\alpha-\beta)e-K_s\left(y+\beta e-Q_s\right)}\left[\left((1-u)v + uw\right)Q_r + \left(p_r - (1-u)v - uw\right)\left(x + (\alpha-\beta)e\right.\right. \\
&\left.\left.+K_s\left(y + \beta e - Q_s\right)\right)\right]f(x)g(y)\mathrm{d}x\,\mathrm{d}y \\
&+\int_0^{Q_s-\beta e}\int_0^{z-(\alpha-\beta)e}\left[\left((1-u)v + uw\right)Q_r + \left(p_r - (1-u)v - uw\right)\left(x + (\alpha-\beta)e\right)\right]f(x)g(y)\mathrm{d}x\,\mathrm{d}y \\
&-(uw - uv)\int_{Q_s-\beta e}^{\left(\left(Q_r-(\alpha-\beta)e\right)/K_s\right)+Q_s-\beta e}\int_0^{Q_r-(\alpha-\beta)e-K_s\left(y+\beta e-Q_s\right)}\left[Q_r - x - (\alpha-\beta)e - K_s\left(y + \beta e - Q_s\right)\right]f(x)g(y)\mathrm{d}x\,\mathrm{d}y \\
&-(uw - uv)\int_0^{Q_s-\beta e}\int_0^{Q_r-(\alpha-\beta)e}\left[Q_r - x - (\alpha-\beta)e\right]f(x)g(y)\mathrm{d}x\,\mathrm{d}y \\
&-\left(wQ_r + R(e) - B\right)(1+I)\int_0^{Q_s-\beta e}\int_0^{z-(\alpha-\beta)e}f(x)g(y)\mathrm{d}x\,\mathrm{d}y \\
&-\left(wQ_r + R(e) - B\right)(1+I)\int_{Q_s-\beta e}^{\left(\left(Q_r-(\alpha-\beta)e\right)/K_s\right)+Q_s-\beta e}\int_0^{z-(\alpha-\beta)e-K_s\left(y+\beta e-Q_s\right)}f(x)g(y)\mathrm{d}x\,\mathrm{d}y.
\end{aligned} \tag{21}$$

For the purpose of achieving coordination, the following conditions should be satisfied:

$$\begin{aligned}
\pi_r^u\left(Q_r^{c*}, e^{c*}\right) + \pi_s^u\left(Q_s^{c*}, e^{c*}\right) &= \prod\left(Q_r^{c*}, Q_s^{c*}, e^{c*}\right), \\
\pi_r^u\left(Q_r^{c*}, e^{c*}\right) &\geq \pi_r^d\left(Q_r^{d*}, e^{d*}\right), \\
\pi_s^u\left(Q_s^{c*}, e^{c*}\right) &\geq \pi_s^d\left(Q_s^{d*}, e^{d*}\right), \\
z^u &\geq 0.
\end{aligned} \tag{22}$$

Finally, the range of u can be obtained. Similarly, if the value of u is greater than 1, it means that the supply chain cannot be coordinated by a single partial buyback contract, and it needs to be coordinated with other contracts. However, the next numerical analysis shows that a single partial buyback contract can coordinate the dual-channel supply chain system.

6. Numerical Analysis

Referring to Yang et al. [33], the related parameters are assigned as follows: the potential market size of traditional retail channel and online channel is uniformly distributed, $d_r \sim U(0,\theta), d_s \sim U(0,\theta)$. Retailer's initial capital is $B = \$50{,}000$. Trade credit rate $I = 0.05$. Unit product price of traditional retail channel $p_r = \$650$. Unit product price of online channel $p_s = \$645$. Supplier's unit production cost $c_o = \$350$. The wholesale price of supplier's unit product $w = \$480$. The residual value of remaining inventory $v = \$200$. Elasticity coefficient of market demand to sales effort level of offline channel $\alpha = 20$. Cost coefficient of sales effort $\eta = 1000$. Supplier free riding coefficient $\beta = 10$. Consumer switching rate of the retailer's offline channel $K_r = 0.2$. Consumer switching rate of the supplier's online channels $K_s = 0.2$. In this case, according to Proposition 1, it holds for $|J| = (\partial^2\pi_r^d/\partial Q_r^2)(\partial^2\pi_s^d/\partial Q_s^2) - (\partial^2\pi_r^d/\partial Q_r\partial Q_s)(\partial^2\pi_s^d/\partial Q_s\partial Q_r) > 0$. That is, for any given sales effort level e^d, the supplier's total expected profit π_s^d and the retailer's total expected profit π_r^d are jointly concave in Q_s^d and Q_r^d.

Hence, based on the above theoretical analysis, the optimal order quantities in the decentralized and centralized systems are $Q_r^{d*} = 348.1519$ and $Q_r^{c*} = 569.5954$; the corresponding optimal inventory levels are $Q_s^{d*} = 566.2159$ and $Q_s^{c*} = 564.5006$; the corresponding optimal sales effort levels are $e^{d*} = 1.3905$ and $e^{c*} = 5.95$; the corresponding optimal expected profit is $\pi_r^d = \$25087.16$ and $\pi_s^d = \$138395.26$, and the optimal total expected profit is $\prod = \$181434.60$.

6.1. Sensitivity Analysis. Referring to [33, 35] and combining with the innovation points of this study, this section mainly investigates the impacts of the supplier's wholesale price, offline sales price, online sales price, consumer switching rate, and free riding on the optimal sales effort level, the optimal order quantity, the optimal inventory level, the optimal expected profit of the retailer and the supplier in the decentralized system, and the optimal total expected profit, respectively.

Table 3 shows that (1) with the increase of the supplier's wholesale price$w$, the optimal sales effort level e^{d*}, the optimal order quantity Q_r^{d*}, and the expected offline retailer profit π_r^d under the decentralized decision-making will decrease, while the optimal inventory level Q_s^{d*} and expected online supplier profit π_s^d will increase; (2) for a given wholesale price w, the optimal total expected profit, the optimal sales effort level, and the optimal order quantity in the centralized system are all superior to those in the decentralized system; and (3) with the increase of the whole sale price$w$, the optimal online inventory level Q_s^{d*} under the decentralized scenario will raise gradually and exceed the optimal inventory level Q_s^{c*} under the centralized scenario.

From Table 4, it can be found that (1) under the decentralized decision-making, with the increase of offline sales price p_r, the optimal sales effort e^{d*}, the optimal order quantity Q_r^{d*}, the expected offline retailer profit π_r^d, and the optimal online supplier profit Q_s^{d*} will increase, while the optimal inventory level decreases; (2) under centralized decision-making, with the increase of offline sales price p_r, the optimal order quantity Q_r^{c*}, the optimal sales effort level e^{c*}, and total expected supply chain profit will rise gradually, while the inventory level Q_s^{c*} decreases; and (3) For a given offline sales price p_r, the total expected supply chain profit, the optimal sales effort level, and the optimal order quantity in centralized system are all more than those in decentralized system, while the optimal inventory level in centralized system is less than that in the decentralized system.

It can be observed from Table 5 that (1) with the raise of the online sales price p_s in the decentralized system, the optimal order quantity Q_r^{d*} and the optimal offline profit π_r^d will reduce slightly, while the optimal inventory level Q_s^{d*} and the optimal online expected profit π_s^d will increase; (2) with the raise of the online sales price p_s in the centralized system, the optimal sales effort level e^{c*}, the optimal inventory level Q_s^{c*}, and total expect profit $\prod$ will increase, while the optimal offline order quantity Q_r^{c*} decreases; and (3) for a given online sales price p_s, the total expected supply chain profit, the optimal sales effort level, and the optimal order quantity under the centralized decision-making are all higher than those under the decentralized decision-making, while the optimal online inventory level Q_s^{c*} under the centralized decision-making is less than Q_s^{d*} under the decentralized decision-making.

Table 6 suggests that (1) in the decentralized system, with the increase of K_r, the optimal order quantity Q_r^{d*}, and the optimal offline profit π_r^d will decrease slightly, while the optimal inventory level Q_s^{d*} and the optimal online profit π_s^d will increase; (2) in the centralized system, with the increase of K_r, the optimal online inventory level Q_s^{c*} and the total expected supply chain profit $\prod$ will increase, while the optimal offline inventory Q_r^{c*} will decrease; and (3) for a given offline consumer switching rate K_r, the total expected supply chain profit, the optimal sales effort level, the optimal order quantity, and the optimal inventory level in the centralized supply chain are all higher than those in the decentralized supply chain.

It can be concluded from Table 7 that (1) with the raise of K_s in the decentralized supply chain, the optimal order quantity Q_r^{d*}, the optimal offline profit π_r^d, and the optimal online profit π_s^d all increase; (2) with the raise of K_s in the centralized supply chain, the optimal order quantity Q_r^{c*} and the total expected supply chain profit both increase, but the optimal inventory level Q_s^{c*} decreases; and (3) for a given online consumer switching rate K_s, the total expected supply chain profit, the optimal sales effort level, and the optimal order quantity under the centralized decision-making are all higher than those under the decentralized decision-making, while the optimal online inventory level Q_s^{c*} under the centralized decision-making is less than Q_s^{d*} under the decentralized decision-making.

Table 8 demonstrates that (1) under the decentralized scenario, with the increase of free riding β, the optimal order quantity Q_r^{d*}, the optimal sales effort level e^{d*}, the optimal offline profit π_r^d and the optimal online profit π_s^d will decrease, while the optimal online inventory level Q_s^{d*} will increase; (2) under the centralized scenario, with the increase of β, the optimal sales effort level e^{c*}, the optimal order quantity Q_r^{c*}, and the total expected supply chain profit will decrease, while the optimal online inventory level Q_s^{c*} will increase; and (3) for a given free riding coefficient β, the total expected supply chain profit, the optimal sales effort level, and the optimal order quantity under the centralized are more than those under the decentralized scenario.

6.2. Coordination Analysis. It is well known that the centralized decision-making cannot provide a mechanism to share the total expected profit for each supply chain member. This subsection develops one partial buyback contract so as to make the supplier and the retailer achieve the Pareto optimization. The supplier partially buys back the retailer's surplus inventory according to a certain proportion (u) at the wholesale price w.

To achieve the coordination, the following constraints should be satisfied:

$$\begin{aligned} \pi_r^u\left(Q_r^{c*}, e^{c*}\right) + \pi_s^u\left(Q_s^{c*}, e^{c*}\right) &= \prod\left(Q_r^{c*}, Q_s^{c*}, e^{c*}\right), \\ \pi_r^u\left(Q_r^{c*}, e^{c*}\right) &\geq \pi_r^d\left(Q_r^{d*}, e^{d*}\right), \\ \pi_s^u\left(Q_s^{c*}, e^{c*}\right) &\geq \pi_s^d\left(Q_s^{d*}, e^{d*}\right), \\ z^u &\geq 0. \end{aligned} \tag{23}$$

Hence, it is easy to obtain that $0.622426 < u < 0.873072$. Table 9 lists the offline retailer and online supplier expected profits with some values of partial buyback rate u, and Figure 3 shows the impact of u on the change rate of the offline and online profits.

It can be seen that the increase of the supplier's partial buyback rate u will raise the growth rate of the offline retailer's profit and reduce the growth rate of the online supplier's profit. Hence, the partial buyback contract can stimulate the offline retailer to cooperate with the online supplier. The final value of partial buyback rate depends on their agreement.

7. Conclusion and Managerial Implications

This study develops a dual-channel supply chain model, which includes an online supplier with sufficient funds and an offline retailer with capital constraints, and the supplier provides trade credit financing to the retailer. Based on it, this work investigates the influence of "free riding" behavior and consumer switching behavior on the retailer's ordering decision and the supplier's inventory decision with the stochastic demand. Subsequently, this research analyzes the impacts of the supplier's wholesale price, online and offline sales prices, consumer switching behavior, and free riding behavior on sales effort level, inventory level, order quantity, and the offline and the online profits under the decentralized and centralized decision-making, respectively. Then, it analyzes the optimal sales effort level, the optimal inventory level, and optimal order quantity, and the optimal offline and

Table 3: Sensitivity analysis of wholesale price w.

w	e^{d*}	e^{c*}	Q_r^{d*}	Q_r^{c*}	Q_s^{d*}	Q_s^{c*}	π_r^d	π_s^d	$\prod$
500	1.19	5.95	302.02	569.60	570.65	564.50	18990.23	139354.81	181434.60
480	1.39	5.95	348.15	569.60	566.22	564.50	25087.16	138395.29	181434.60
460	1.59	5.95	387.48	569.60	563.52	564.50	31861.89	135332.49	181434.60
440	1.79	5.95	422.64	569.60	561.97	564.50	39269.87	130711.38	181434.60
420	1.99	5.95	455.25	569.60	561.24	564.50	47304.32	124796.02	181434.60
400	2.19	5.95	486.38	569.60	561.12	564.50	55981.77	117705.30	181434.60

Table 4: Sensitivity analysis of offline retailer channel sales price p_r.

p_r	e^{d*}	e^{c*}	Q_r^{d*}	Q_r^{c*}	Q_s^{d*}	Q_s^{c*}	π_r^d	π_s^d	$\prod$
660	1.49	6.05	364.37	578.28	564.79	563.31	27877.33	140186.00	185590.93
650	1.39	5.95	348.15	569.60	566.22	564.50	25087.16	138395.29	181434.60
640	1.30	5.85	330.13	560.52	567.99	565.72	22387.88	136437.34	177318.86
630	1.20	5.75	309.89	551.01	570.20	566.98	19793.62	134261.27	173246.10
620	1.10	5.65	286.89	541.04	572.96	568.28	17323.13	131793.97	169218.92
610	1.01	5.55	260.37	530.57	576.44	569.64	15001.85	128927.26	165240.27
600	0.91	5.45	229.26	519.54	580.89	571.05	12865.41	125495.33	161313.40

Table 5: Sensitivity analysis of online sales price p_s.

p_s	e^{d*}	e^{c*}	Q_r^{d*}	Q_r^{c*}	Q_s^{d*}	Q_s^{c*}	π_r^d	π_s^d	$\prod$
655	1.39	6.05	347.93	568.42	572.38	573.41	25038.97	142319.59	185570.04
645	1.39	5.95	348.15	569.60	566.22	564.50	25087.16	138395.29	181434.60
635	1.39	5.85	348.39	570.80	559.77	555.18	25138.92	134494.49	177341.09
625	1.39	5.75	348.65	572.05	553.01	545.40	25194.60	130618.95	173292.04
615	1.39	5.65	348.93	573.34	545.92	535.14	25254.60	126770.59	169290.25
605	1.39	5.55	349.23	574.69	538.47	524.35	25319.36	122951.54	165338.85
595	1.39	5.45	349.56	576.10	530.65	512.98	25389.40	119164.13	161441.35

Table 6: Sensitivity analysis of consumer switching rate of the retailer's offline channel K_r.

K_r	e^{d*}	e^{c*}	Q_r^{d*}	Q_r^{c*}	Q_s^{d*}	Q_s^{c*}	π_r^d	π_s^d	$\prod$
0.8	1.39	5.95	345.57	395.81	650.24	683.13	24535.64	158236.33	193195.89
0.7	1.39	5.95	345.93	436.89	636.12	649.01	24612.46	155226.90	190580.98
0.6	1.39	5.95	346.32	470.91	622.04	623.31	24695.42	152096.07	188296.43
0.5	1.39	5.95	346.74	500.24	608.00	603.28	24784.46	148845.61	186276.64
0.4	1.39	5.95	347.18	526.04	594.02	587.42	24879.50	145477.36	184479.33
0.3	1.39	5.95	347.65	549.01	580.09	574.72	24980.43	141993.26	182873.52
0.2	1.39	5.95	348.15	569.60	566.22	564.50	25087.16	138395.29	181434.60

Table 7: Sensitivity analysis of consumer switching rate of the supplier's online channel K_s.

K_s	e^{d*}	e^{c*}	Q_r^{d*}	Q_r^{c*}	Q_s^{d*}	Q_s^{c*}	π_r^d	π_s^d	$\prod$
0.9	1.39	5.95	363.93	756.61	567.67	309.94	28506.45	140093.56	197633.33
0.8	1.39	5.95	361.98	698.17	565.53	375.17	28080.44	139968.15	194155.49
0.7	1.39	5.95	359.89	659.84	563.96	421.59	27622.86	139800.62	191266.35
0.6	1.39	5.95	357.66	631.78	563.02	458.98	27138.89	139591.65	188776.66
0.5	1.39	5.95	355.34	610.31	562.76	490.70	26635.18	139343.12	186596.15
0.4	1.39	5.95	352.95	593.51	563.20	518.34	26119.56	139058.05	184669.91
0.3	1.39	5.95	350.54	580.21	564.35	542.75	25600.62	138740.49	182959.33
0.2	1.39	5.95	348.15	569.60	566.22	564.50	25087.16	138395.29	181434.60
0.1	1.39	5.95	345.82	561.09	568.75	583.98	24587.64	138027.76	180071.36

Table 8: Sensitivity analysis of free riding β.

β	e^{d*}	e^{c*}	Q_r^{d*}	Q_r^{c*}	Q_s^{d*}	Q_s^{c*}	π_r^d	π_s^d	$\prod$
17.5	0.35	5.91	337.76	524.88	557.83	608.47	24260.30	134134.44	181212.17
15	0.70	5.93	339.84	539.72	562.29	593.88	24425.31	135807.62	181286.16
12.5	1.04	5.94	343.30	554.63	565.09	579.22	24700.72	137228.26	181360.30
10	1.39	5.95	348.15	569.60	566.22	564.50	25087.16	138395.29	181434.60
7.5	1.74	5.96	354.38	584.63	565.68	549.72	25585.48	139307.22	181509.05
5	2.09	5.98	362.00	599.72	563.49	534.88	26196.77	139962.15	181583.66
2.5	2.43	5.99	371.00	614.88	559.63	519.97	26922.39	140357.74	181658.42

Table 9: Coordination analysis.

u	π_r^u	π_s^u	$\prod$
0.65	25982.23	155452.37	181434.60
0.7	27744.06	153690.53	181434.60
0.75	29711.44	151723.15	181434.60
0.8	31922.57	149512.03	181434.60
0.85	34425.73	147008.86	181434.60

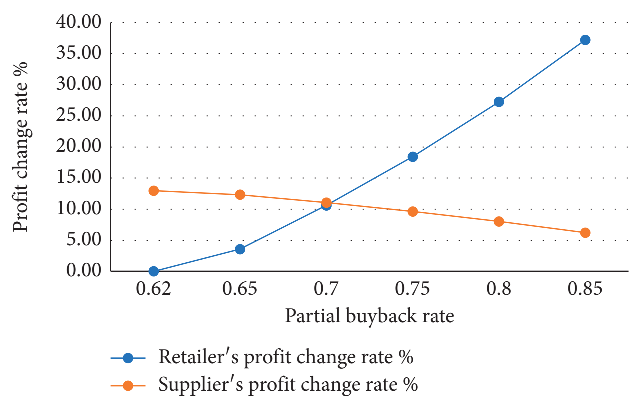

Figure 3: Sensitivity of partial buyback contract.

online profits under the decentralized and the centralized decision-makings. Finally, this work proposes a partial buyback contract to coordinate the two channels so as to achieve the win-win status.

Furthermore, this study has the following conclusions and the corresponding managerial implications:

(1) In the dual-channel supply chain involving free riding and consumer switching behavior, the optimal sales effort level, optimal order quantity, and the optimal offline and online profits under the centralized decision-making are more than those under decentralized decision-making, except for the optimal inventory level. Hence, it is fundamental and important to centralize the dual-channel supply chain.

(2) The supplier's wholesale price has negative impact on the optimal sales effort level, the optimal order quantity, and the offline profit in the decentralized system, only has positive impact on the online profit in the decentralized system, and raises the inventory level. Hence, it is vital to keep an appropriate wholesale price so as to stimulate the sales effort level and the offline retailer's order quantity and provide a trade-off between the offline and the online profits.

(3) No matter whether in decentralized or centralized supply chain, the offline sales price is positively related to the optimal sales effort level, the optimal order quantity, the offline and the online profits. It can be seen that, the influence of offline sales price on online profit under the decentralized decision-making is different with the result in [35], which is negatively related to the online profit. This shows that, with the higher sales price in offline channel, the risk of bankruptcy of the retailer will reduce, and the impact of price on repayment for the supplier is greater than that on sales loss. Therefore, it implies that the offline retailer is recommended to keep a relatively high sales price if the offline demand is not significantly affected by the price.

(4) The increase of supplier's online sales price will encourage the supplier to keep relatively high inventory level so as to achieve more online profit but has no significant impact on the retailer's offline

profit, which is same as the result in [35]. And it also has no significant impact on the retailer's sales effort level. Thus, it is reasonable to keep a relatively high online sales price if the online demand is not significantly affected by the price.

(5) The increase of the offline consumer switching rate will lead to the decrease of the offline order quantity and the offline expected profit and raise the online inventory level and the online expected profit, which is consist with the result in [35]. For another, the increase of the online consumer switching rate will raise the offline order quantity and the offline expected profit but has no significant impact on the online inventory level and the online expected profit.

(6) The increase of the free riding coefficient of the supplier, no matter whether in decentralized or centralized systems, will reduce the offline sales effort level, the offline expected profit, and the online expected profit and raise the inventory level. Hence, it is critical to introduce some coordination mechanism to reduce the free riding behavior, so as to achieve the win-win status.

(7) Partial buyback contract can coordinate the dual-channel supply chain members and help them to join the cooperation and achieve the Pareto optimization. The growth rate of each member's profit depends on the partial buyback rate, which is usually determined by their bargaining power and agreements.

In addition, there exist some limitation in this study. (1) This work assumes that demand is mainly affected by free riding behavior and consumer switching behavior and is not significantly affected by the price. (2) It also assumes that both the online supplier and the offline retailer are risk neutral. Hence, the future research will investigate the impact of different risk preferences on the financing decision in dual-channel supply chain taking the price factor into demand function.

Appendix

Proof . of Proposition 1. In order to determine the optimal value of profit with respect to Q_r^d and Q_s^d, the following Hessian matrix is obtained:

$$
\begin{gathered}
H=\begin{pmatrix} \dfrac{\partial^2 \pi_r^d}{\partial Q_r^2} & \dfrac{\partial^2 \pi_r^d}{\partial Q_r \partial Q_s} \\[2ex] \dfrac{\partial^2 \pi_s^d}{\partial Q_s \partial Q_r} & \dfrac{\partial^2 \pi_s^d}{\partial Q_s^2} \end{pmatrix}, \\
\frac{\partial^2 \pi_r^d}{\partial Q_r^2} = -(p_r - v)\int_0^{Q_s-\beta e} [f(Q_r-(\alpha-\beta)e)]g(y)\mathrm{d}y \\
-(p_r-v)\int_{Q_s-\beta e}^{((Q_r-(\alpha-\beta)e)/K_s)+Q_s-\beta e} [f(Q_r-(\alpha-\beta)e-K_s(y+\beta e-Q_s))]g(y)\mathrm{d}y \\
+[w(1+I)-v]\int_0^{Q_s-\beta e}\left[f(z-(\alpha-\beta)e)\frac{w(1+I)-v}{p_r-v}\right]g(y)\mathrm{d}y \\
+[w(1+I)-v]\int_{Q_s-\beta e}^{\frac{Q_r-(\alpha-\beta)e}{K_s}+Q_s-\beta e}\left[f(z-(\alpha-\beta)e-K_s(y+\beta e-Q_s))\frac{w(1+I)-v}{p_r-v}\right]g(y)\mathrm{d}y,
\end{gathered}
\tag{A.1}
$$

$$\begin{aligned}
\frac{\partial^2 \pi_r^d}{\partial Q_r \partial Q_s} &= -(p_r - v)K_s \int_{Q_s-\beta e}^{((Q_r-(\alpha-\beta)e)/K_s)+Q_s-\beta e} [f(Q_r - (\alpha-\beta)e - K_s(y + \beta e - Q_s))] g(y) \mathrm{d}y \\
&\quad + [w(1+I) - v]K_s \int_{Q_s-\beta e}^{((Q_r-(\alpha-\beta)e)/K_s)+Q_s-\beta e} [f(z - (\alpha-\beta)e - K_s(y + \beta e - Q_s))] g(y) \mathrm{d}y, \\
\frac{\partial^2 \pi_s^d}{\partial Q_s^2} &= -(p_s - v)\left[\int_0^{Q_r-(\alpha-\beta)e} g(Q_s - \beta e) f(x) \mathrm{d}x + \int_{Q_r-(\alpha-\beta)e}^{((Q_s-\beta e)/K_r)+Q_r-(\alpha-\beta)e} g(Q_s - \beta e - K_r(x + (\alpha-\beta)e - Q_r)) f(x) \mathrm{d}x\right] \\
&\quad + (p_r - v)K_s \int_0^{z-(\alpha-\beta)e} g(Q_s - \beta e) f(x) \mathrm{d}x \\
&\quad - (p_r - v)K_s^2 \int_{Q_s-\beta e}^{((Q_r-(\alpha-\beta)e)/K_s)+Q_s-\beta e} f(z - (\alpha-\beta)e - K_s(y + \beta e - Q_s)) g(y) \mathrm{d}y, \\
\frac{\partial^2 \pi_s^d}{\partial Q_s \partial Q_r} &= -K_r(p_s - v) \int_{Q_r-(\alpha-\beta)e}^{((Q_s-\beta e)/K_r)+Q_r-(\alpha-\beta)e} g(Q_s - \beta e - K_r(x + (\alpha-\beta)e - Q_r)) f(x) \mathrm{d}x \\
&\quad -[w(1 + I) - v]K_s \int_{Q_s-\beta e}^{((Q_r-(\alpha-\beta)e)/K_s)+Q_s-\beta e} f(z - (\alpha-\beta)e - K_s(y + \beta e - Q_s)) g(y) \mathrm{d}y.
\end{aligned} \tag{A.2}$$

It is obvious that $(\partial^2 \pi_r^d / \partial Q_r^2) < 0$, $(\partial^2 \pi_s^d / \partial Q_s^2) < 0$, $(\partial^2 \pi_r^d / \partial Q_r \partial Q_s) < 0$, $(\partial^2 \pi_s^d / \partial Q_s \partial Q_r) < 0$.

In addition,

$$J = \begin{vmatrix} \dfrac{\partial^2 \pi_r^d}{\partial Q_r^2} & \dfrac{\partial^2 \pi_r^d}{\partial Q_r \partial Q_s} \\ \dfrac{\partial^2 \pi_s^d}{\partial Q_s \partial Q_r} & \dfrac{\partial^2 \pi_s^d}{\partial Q_s^2} \end{vmatrix} = \frac{\partial^2 \pi_r^d}{\partial Q_r^2} \frac{\partial^2 \pi_s^d}{\partial Q_s^2} - \frac{\partial^2 \pi_r^d}{\partial Q_r \partial Q_s} \frac{\partial^2 \pi_s^d}{\partial Q_s \partial Q_r}. \tag{A.3}$$

It is found that, if $(p_r - v)K_s > w(1 + I) - v$, then $|\partial^2 \pi_r^d / \partial Q_r^2| > |\partial^2 \pi_r^d / \partial Q_r \partial Q_s|$, $|\partial^2 \pi_s^d / \partial Q_s^2| > |\partial^2 \pi_s^d / \partial Q_s \partial Q_r|$, and $|J| = (\partial^2 \pi_r^d / \partial Q_r^2)(\partial^2 \pi_s^d / \partial Q_s^2) - (\partial^2 \pi_r^d / \partial Q_r \partial Q_s)(\partial^2 \pi_s^d / \partial Q_s \partial Q_r) > 0$. Thus, for any given sales effort level e^d, if $(p_r - v)K_s > w(1 + I) - v$, the supplier's total expected profit π_s^d and the retailer's total expected profit π_r^d are strictly jointly concave in Q_s^d and Q_r^d. Otherwise, π_s^d and π_r^d are jointly concave in Q_s^d and Q_r^d if $|J| = (\partial^2 \pi_r^d / \partial Q_r^2)(\partial^2 \pi_s^d / \partial Q_s^2) - (\partial^2 \pi_r^d / \partial Q_r \partial Q_s)(\partial^2 \pi_s^d / \partial Q_s \partial Q_r) > 0$ □

Proof. of Proposition 2. The optimal sales effort level e^{d*} can be obtained by calculating the first derivative of the retailer's expected profit with respect to the sales effort level and making it equal to zero and combining with the implicit function theorem.

Among them,

$$\begin{aligned}
\frac{\mathrm{d}Q_r(e)}{\mathrm{d}e} &= -\frac{1}{J} \begin{vmatrix} \dfrac{\partial F_r^d}{\partial e} & \dfrac{\partial F_r^d}{\partial Q_s} \\ \dfrac{\partial F_s^d}{\partial e} & \dfrac{\partial F_s^d}{\partial Q_s} \end{vmatrix} = -\frac{1}{J}\left(\frac{\partial^2 \pi_r^d}{\partial Q_r \partial e} \frac{\partial^2 \pi_s^d}{\partial Q_s^2} - \frac{\partial^2 \pi_r^d}{\partial Q_r \partial Q_s} \frac{\partial^2 \pi_s^d}{\partial Q_s \partial e}\right), \\
\frac{\mathrm{d}Q_s(e)}{\mathrm{d}e} &= -\frac{1}{J} \begin{vmatrix} \dfrac{\partial F_r^d}{\partial Q_r} & \dfrac{\partial F_r^d}{\partial e} \\ \dfrac{\partial F_s^d}{\partial Q_r} & \dfrac{\partial F_s^d}{\partial e} \end{vmatrix} = -\frac{1}{J}\left(\frac{\partial^2 \pi_r^d}{\partial Q_r^2} \frac{\partial^2 \pi_s^d}{\partial Q_s \partial e} - \frac{\partial^2 \pi_r^d}{\partial Q_r \partial e} \frac{\partial^2 \pi_s^d}{\partial Q_s \partial Q_r}\right),
\end{aligned} \tag{A.4}$$

$$\begin{aligned}
\frac{\partial^2 \pi_r^d}{\partial Q_r \partial e} &= (p_r - v)[(\alpha-\beta) + K_s\beta] \int_{Q_s-\beta e}^{((Q_r-(\alpha-\beta)e)/K_s)+Q_s-\beta e} [f(Q_r - (\alpha-\beta)e - K_s(y+\beta e - Q_s))] g(y)\mathrm{d}y \\
&\quad + (p_r - v)(\alpha-\beta)\int_0^{Q_s-\beta e} [f(Q_r - (\alpha-\beta)e)] g(y)\mathrm{d}y \\
&\quad + [w(1+I) - v]\left[\frac{\eta e(1+I)}{p_r - v} - (\alpha-\beta)\right]\int_0^{Q_s-\beta e} [f(z-(\alpha-\beta)e)] g(y)\mathrm{d}y \\
&\quad + [w(1+I) - v]\left[\frac{\eta e(1+I)}{p_r - v} - (\alpha-\beta) - K_s\beta\right]\int_{Q_s-\beta e}^{((Q_r-(\alpha-\beta)e)/K_s)+Q_s-\beta e} [f(z-(\alpha-\beta)e - K_s(y+\beta e - Q_s))] g(y)\mathrm{d}y, \\
\frac{\partial^2 \pi_s^d}{\partial Q_s \partial e} &= (p_s - v)\left[\beta\int_0^{Q_r-(\alpha-\beta)e} g(Q_s - \beta e) f(x)\mathrm{d}x + (\beta + K_r(\alpha-\beta))\right. \\
&\quad \left. \cdot \int_{Q_r-(\alpha-\beta)e}^{((Q_s-\beta e)/K_r)+Q_r-(\alpha-\beta)e} g(Q_s - \beta e - K_r(x + (\alpha-\beta)e - Q_r)) f(x)\mathrm{d}x\right] \\
&\quad - \beta(p_r - v)K_s\int_0^{z-(\alpha-\beta)e} g(Q_s-\beta e) f(x)\mathrm{d}x \\
&\quad - (p_r - v)K_s\left[\frac{\eta e(1+I)}{p_r - v} - (\alpha-\beta) - K_s\beta\right]\int_{Q_s-\beta e}^{((Q_r-(\alpha-\beta)e)/K_s)+Q_s-\beta e} f(z-(\alpha-\beta)e - K_s(y+\beta e - Q_s)) g(y)\mathrm{d}y,
\end{aligned} \tag{A.5}$$

$$\begin{aligned}
\frac{\partial \pi_r^d}{\partial Q_s} &= -(p_r - v)K_s\int_{Q_s-\beta e}^{((Q_r-(\alpha-\beta)e)/K_s)+Q_s-\beta e}\int_{z-(\alpha-\beta)e-K_s(y+\beta e-Q_s)}^{Q_r-(\alpha-\beta)e-K_s(y+\beta e-Q_s)} f(x)g(y)\mathrm{d}x\,\mathrm{d}y, \\
\frac{\partial \pi_r^d}{\partial e} &= -\eta e(1+I) + (p_r - v)(\alpha-\beta+K_s\beta)\int_{Q_s-\beta e}^{((Q_r-(\alpha-\beta)e)/K_s)+Q_s-\beta e}\int_{z-(\alpha-\beta)e-K_s(y+\beta e-Q_s)}^{Q_r-(\alpha-\beta)e-K_s(y+\beta e-Q_s)} f(x)g(y)\mathrm{d}x\,\mathrm{d}y \\
&\quad + (p_r - v)(\alpha-\beta)\int_0^{Q_s-\beta e}\int_{z-(\alpha-\beta)e}^{Q_r-(\alpha-\beta)e} f(x)g(y)\mathrm{d}x\,\mathrm{d}y \\
&\quad + \eta e(1+I)\int_0^{Q_s-\beta e}\int_0^{z-(\alpha-\beta)e} f(x)g(y)\mathrm{d}x\,\mathrm{d}y \\
&\quad + \eta e(1+I)\int_{Q_s-\beta e}^{((Q_r-(\alpha-\beta)e)/K_s)+Q_s-\beta e}\int_0^{z-(\alpha-\beta)e-K_s(y+\beta e-Q_s)} f(x)g(y)\mathrm{d}x\,\mathrm{d}y.
\end{aligned} \tag{A.6}$$

□

Proof . of Proposition 3.

In order to determine the optimal value of the overall profit of the supply chain with respect to Q_r and Q_s, the following Hessian matrix is obtained:

$$\widehat{H} = \begin{pmatrix} \dfrac{\partial^2 \prod}{\partial Q_r^2} & \dfrac{\partial^2 \prod}{\partial Q_r \partial Q_s} \\ \dfrac{\partial^2 \prod}{\partial Q_s \partial Q_r} & \dfrac{\partial^2 \prod}{\partial Q_s^2} \end{pmatrix}. \tag{A.7}$$

Furthermore,

$$\begin{aligned}
\frac{\partial^2 \prod}{\partial Q_r^2} &= -[p_r - v - K_r(p_s - v)]\int_0^{Q_s-\beta e}[f(Q_r-(\alpha-\beta)e)]g(y)\mathrm{d}y \\
&\quad - (p_r - v)\int_{Q_s-\beta e}^{((Q_r-(\alpha-\beta)e)/K_s)+Q_s-\beta e}[f(Q_r-(\alpha-\beta)e-K_s(y+\beta e-Q_s))]g(y)\mathrm{d}y \\
&\quad - K_r^2(p_s - v)\int_{Q_r-(\alpha-\beta)e}^{((Q_s-\beta e)/K_r)+Q_r-(\alpha-\beta)e} g(Q_s-\beta e-K_r(x+(\alpha-\beta)e-Q_r))f(x)\mathrm{d}x, \\
\frac{\partial^2 \prod}{\partial Q_s^2} &= -[p_s - v - K_s(p_r - v)]\int_0^{Q_r-(\alpha-\beta)e} g(Q_s-\beta e)f(x)\mathrm{d}x \\
&\quad - (p_s - v)\int_{Q_r-(\alpha-\beta)e}^{((Q_s-\beta e)/K_r)+Q_r-(\alpha-\beta)e} g(Q_s-\beta e-K_r(x+(\alpha-\beta)e-Q_r))f(x)\mathrm{d}x \\
&\quad - (p_s - v)K_s^2\int_{Q_s-\beta e}^{((Q_r-(\alpha-\beta)e)/K_s)+Q_s-\beta e} f(Q_r-(\alpha-\beta)e-K_s(y+\beta e-Q_s))g(y)\mathrm{d}y, \\
\frac{\partial^2 \prod}{\partial Q_r \partial Q_s} = \frac{\partial^2 \prod}{\partial Q_s \partial Q_r} &= -K_r(p_s - v)\int_{Q_r-(\alpha-\beta)e}^{((Q_s-\beta e)/K_r)+Q_r-(\alpha-\beta)e} g(Q_s-\beta e-K_r(x+(\alpha-\beta)e-Q_r))f(x)\mathrm{d}x \\
&\quad - K_s(p_r - v)\int_{Q_s-\beta e}^{((Q_r-(\alpha-\beta)e)/K_s)+Q_s-\beta e} f(Q_r-(\alpha-\beta)e-K_s(y+\beta e-Q_s))g(y)\mathrm{d}y.
\end{aligned} \tag{A.8}$$

In addition,

$$\widehat{J} = \begin{vmatrix} \dfrac{\partial^2 \prod}{\partial Q_r^2} & \dfrac{\partial^2 \prod}{\partial Q_r \partial Q_s} \\ \dfrac{\partial^2 \prod}{\partial Q_s \partial Q_r} & \dfrac{\partial^2 \prod}{\partial Q_s^2} \end{vmatrix} = \frac{\partial^2 \prod}{\partial Q_r^2}\frac{\partial^2 \prod}{\partial Q_s^2} - \frac{\partial^2 \prod}{\partial Q_r \partial Q_s}\frac{\partial^2 \prod}{\partial Q_s \partial Q_r} > 0. \tag{A.9}$$

Because $(p_r - v) > K_r(p_s - v)$ and $(p_s - v) > K_s(p_r - v)$, it is easy to prove that $(\partial^2 \prod/\partial Q_r^2) < 0$, $(\partial^2 \prod/\partial Q_s^2) < 0$, $(\partial^2 \prod/\partial Q_r \partial Q_s) < 0$, $(\partial^2 \prod/\partial Q_s \partial Q_r) < 0$, and $|\widehat{J}| = (\partial^2 \prod/\partial Q_r^2)(\partial^2 \prod/\partial Q_s^2) - (\partial^2 \prod/\partial Q_r \partial Q_s)(\partial^2 \prod/\partial Q_s \partial Q_r) > 0$. Therefore, under the centralized scenario, the overall expected profit of centralized dual-channel supply chain $\prod$ is strictly jointly concave in Q_r^c and Q_s^c.

However, there is no more evidence to make sure that

$$\widetilde{J} = \begin{vmatrix} \dfrac{\partial^2 \prod}{\partial Q_s^2} & \dfrac{\partial^2 \prod}{\partial Q_s \partial e} \\ \dfrac{\partial^2 \prod}{\partial e\, \partial Q_s} & \dfrac{\partial^2 \prod}{\partial e^2} \end{vmatrix} > 0. \tag{A.10}$$

Thus, $\prod$ is indefinite with respect to Q_s^c and e^c. Therefore, $\prod$ is not jointly concave in Q_r^c, Q_s^c, and e^c. □

Proof of Proposition 4. The optimal sales effort level e^{c*} can be obtained by calculating the first derivative of the retailer's expected profit with respect to the sales effort level and making it equal to zero and combining with the implicit function theorem. □

Proof of Lemma 1

$$\frac{\partial^2 \prod}{\partial Q_r \partial e} = (\alpha-\beta)(p_r - v)\int_0^{Q_s-\beta e}[f(Q_r-(\alpha-\beta)e)]g(y)\mathrm{d}y$$
$$+(\alpha-\beta+K_s\beta)(p_r-v)\int_{Q_s-\beta e}^{((Q_r-(\alpha-\beta)e)/K_s)+Q_s-\beta e}[f(Q_r-(\alpha-\beta)e-K_s(y+\beta e-Q_s))]g(y)\mathrm{d}y$$
$$-(\alpha-\beta)K_r(p_s-v)\int_0^{Q_s-\beta e} f(Q_r-(\alpha-\beta)e)g(y)\mathrm{d}y$$
$$+[\beta+K_r(\alpha-\beta)]K_r(p_s-v)\int_{Q_r-(\alpha-\beta)e}^{((Q_s-\beta e)/K_r)+Q_r-(\alpha-\beta)e} g(Q_s-\beta e-K_r(x+(\alpha-\beta)e-Q_r))f(x)\mathrm{d}x,$$
$$\frac{\partial^2 \prod}{\partial Q_s \partial e} = \beta(p_s-v)\int_0^{Q_r-(\alpha-\beta)e} g(Q_s-\beta e)f(x)\mathrm{d}x$$
$$+[\beta+K_r(\alpha-\beta)](p_s-v)\int_{Q_r-(\alpha-\beta)e}^{((Q_s-\beta e)/K_r)+Q_r-(\alpha-\beta)e} g(Q_s-\beta e-K_r(x+(\alpha-\beta)e-Q_r))f(x)\mathrm{d}x$$
$$-\beta K_s(p_r-v)\int_0^{Q_r-(\alpha-\beta)e} g(Q_s-\beta e)f(x)\mathrm{d}x$$
$$+[(\alpha-\beta)+K_s\beta]K_s(p_r-v)\int_{Q_s-\beta e}^{((Q_r-(\alpha-\beta)e)/K_s)+Q_s-\beta e} f(Q_r-(\alpha-\beta)e-K_s(y+\beta e-Q_s))g(y)\mathrm{d}y, \tag{A.11}$$

$$\frac{\partial \prod}{\partial e} = -\eta e+(\alpha-\beta)(p_r-v)\int_0^{Q_s-\beta e}\int_0^{Q_r-(\alpha-\beta)e} f(x)g(y)\mathrm{d}x\,\mathrm{d}y$$
$$+\beta(p_s-v)\int_0^{Q_s-\beta e}\int_0^{Q_r-(\alpha-\beta)e} f(x)g(y)\mathrm{d}x\,\mathrm{d}y$$
$$+(p_r-v)[(\alpha-\beta)+K_s\beta]\int_{Q_s-\beta e}^{((Q_r-(\alpha-\beta)e)/K_s)+Q_s-\beta e}\int_0^{Q_r-(\alpha-\beta)e-K_s(y+\beta e-Q_s)} f(x)g(y)\mathrm{d}x\,\mathrm{d}y$$
$$+(p_s-v)[\beta+K_r(\alpha-\beta)]\int_{Q_r-(\alpha-\beta)e}^{((Q_s-\beta e)/K_r)+Q_r-(\alpha-\beta)e}\int_0^{Q_s-\beta e-K_r(x+(\alpha-\beta)e-Q_r)} g(y)f(x)\mathrm{d}y\,\mathrm{d}x. \tag{A.12}$$

Hence,

$$\frac{\mathrm{d}Q_r(e)}{\mathrm{d}e} = -\frac{1}{\hat{J}}\left(\frac{\partial^2\prod}{\partial Q_r\partial e}\frac{\partial^2\prod}{\partial Q_s^2} - \frac{\partial^2\prod}{\partial Q_r\partial Q_s}\frac{\partial^2\prod}{\partial Q_s\partial e}\right) = (\alpha-\beta) > 0,$$
$$\frac{\mathrm{d}Q_s(e)}{\mathrm{d}e} = -\frac{1}{\hat{J}}\left(\frac{\partial^2\prod}{\partial Q_r^2}\frac{\partial^2\prod}{\partial Q_s\partial e} - \frac{\partial^2\prod}{\partial Q_r\partial e}\frac{\partial^2\prod}{\partial Q_s\partial Q_r}\right) = \beta > 0. \tag{A.13}$$

□

Proof . of Lemma 2.

When the demand is uniformly distributed, $d_r \sim U(0,\theta), d_s \sim U(0,\theta)$, it can be obtained as follows:

$$\frac{\partial\prod}{\partial Q_r}\frac{\mathrm{d}Q_r(e)}{\mathrm{d}e} + \frac{\partial\prod}{\partial Q_s}\frac{\mathrm{d}Q_s(e)}{\mathrm{d}e} + \frac{\partial\prod}{\partial e} = (p_r - c_o)(\alpha-\beta) - \eta e + \beta(p_s - c). \tag{A.14}$$

And it is obvious that $(\mathrm{d}^2\prod/\mathrm{d}^2 e) = -\eta < 0$, which means that the expected profit $\prod$ of the whole supply chain is a strict concave function of the retailer's sales effort level e^c. □

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Market Premium and Macroeconomic Factors as Determinants of Industry Premium: Evidence from Emerging Economies

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In this study, we examine the equity (industry) premium of seventeen nonfinancial sectors covering sample 306 firms using monthly data from January 2002 to December 2018. Two-stage least square (2SLS) method is applied to estimate the macro-based multifactor model. It is found that the market premium and the interest rate factors are significantly affecting the industry equity premium of all the nonfinancial sectors. However, there exists a positive effect of other macroeconomic variables such as money supply, foreign direct investment, and industrial production which is different for the different sectors based on its nature of product and services they offered. The industries based on their product development which are linked to particular macroeconomic variables have more effect than others such as increase in money supply which cannot increase the sale of pharmaceutical products until needed. Similarly, an interesting insight reveals that industries producing seasonal goods, e.g., food producing, are not very much affected by macroeconomic variables but the change in seasons and similar results also revealed for tobacco industry.

1. Introduction

Since asset pricing can be viewed in terms of per share expected discounted cash flows and the required rate of returns, macroeconomic variables that effect future cash flows or required rates of return should also influence asset pricing. Therefore, its impact on historical returns is an important component to study for planning of future investment decision. In the current situation, one of the most contemporary issues in advance corporate finance and financial economics is the magnitude of equity premium in the total returns of an investment. The equity premium is the additional return that investors necessitate from investing in riskier stocks rather than risk-free securities. Equity (risk) premium drives the total expected stock returns and is a key determinant of the cost of equity. In this study, we calculate the sectoral premium by using [1] a method to form each sector portfolio and calculate the sector premium.

Equity risk premium is the essential element of every risk and return model in finance and is a major input into estimating costs of equity and cost of capital in both economics and corporate finance valuation models [2]. In the standard mathematical technique to calculate the equity risk premiums, the researcher used historical returns with the difference in annual returns on stocks and risk-free securities such as bonds and bills over a long time period, comprising the expected equity premium. The investments in risky stocks are expected to produce higher expected returns than those investment opportunities which have very low or even no risk. It is usually discussed in the existing literature that the equity risk premium is high in developing markets than in developed countries' stock markets [3, 4]. This is because investing in emerging markets is usually apparently to be more risky, which has to be rewarded in terms of a high expected return.

Equity risk premium is estimated in many asset pricing models such as APT, three-factor model, and multifactor models [5]. [6] Research work by Markowitz was the first study to lay down the base line for this kind of analysis. Markowitz theory was further developed and constructed into capital asset pricing model (CAPM) by [7–12]. The CAPM has been extensively used by the financial research experts. It is adopted in the portfolio management as a standard of rating the performance of portfolio managers.

The "capital asset pricing model" is explained by the following equation:

$$E(R_i) = R_f + \beta\left[E(R_m) - R_f\right], \quad (1)$$

where $E(R_i)$ is the expected return on industry i where $i = 1$–17, R_f is the risk-free interest rate, $E(R_m)$ is the expected return of the market, and β is the measure of market risk. Expression in the square brackets is the equity risk premium.

The equity premium has always been under the severe pressure during the period of any financial crises and its magnitude always depends upon the stable market. When the market return decreases, the magnitude of the premium becomes near to zero or even negative. During the Asian financial crisis (1997 Asian economic crises), the volatility in the global stock markets also increased. When equity returns have more volatility, the market systematic risk (β) is also more likely to be increased. The stocks having more disclosure to the sources of risk will have more equity price reactions than the rest of the firms. Similarly, scholars study the risk and return relationship in six Asian stock markets which were affected by the 1997 Asian economic crisis. Their conclusions showed that market equity risk (β) steadily increased and the expected average returns dropped significantly after the start of the economic crisis and led to considerable drop in the equity premium. Choudhry and Wu [13] provided a study of the effects of the Asian crisis on the beta of Malaysian and Taiwanese firms. The results show a rise in the systematic risk (β) during the economic crisis, especially in the case of Malaysian stock market. Similarly, recently, Bellelah et al. [14] explored how the global financial crises affect the equity premium. Several studies conclude that the financial crises lead to volatility which increases the systematic risk coefficient. Increase in the systematic risk causes increase in the expected rate of return.

The equity risk premium is calculated through two general ways: the use of historical stock market data and the use of estimate for future projections. To calculate the equity risk premium one must know about the market rate of return and the risk-free asset of the particular country. The equity risk premium can be calculated for any time period. However, the best results are generated for longer period of data. The United States capital markets data exist back as late as 1800s. While calculating the equity premium, one should consider the benchmark market of the country under consideration. A standard practice has been observed while studying the literature that most of the studies cite only the United States and European markets experience. However, the US source remains the most widely used citation. The historical record of data availability exceeded more than 100 years.

1.1. Significance of Pakistan Stock Exchange. KSE100 index is the standard benchmark of the Pakistan Stock Exchange (PSX) to compare price over the period of time to decide the representative of higher market capitalization of the PSX listed companies. Pakistan Stock Exchange is an emerging capital market and studied extensively by both practitioners and academicians [15–19]. They studied different dimensions starting from the performance of stock market, its determinants, and applicability of different financial models. This study is raising question regarding the calculation of sector equity premium and its determinants of nonfinancial listed firms in Pakistan Stock Exchange (PSX). Besides other factors, investment analyst also greatly relies on the equity risk premium while making portfolio asset allocation decision and calculating the cost of equity and equity premium is affected by many variables as well as the time frame of the investments which further agitates the total expected return of assets. In Pakistan, a number of related literature [19–23] among others is available about stock market return, its implications, determinants, and interrelation with global markets. However, as per the best knowledge of the authors, very limited studies have been found on market premium and no study found on firm sector equity premium. In order to reduce this gap in Pakistan Stock Exchange, this research is of the most importance.

1.2. Significance of the Study. Previously, many research studies have explored the effect of economic factors and stock market returns. This study is an effort to investigate the relationship among industry level equity premium and macroeconomic determinants which is scant in the literature. This study will examine the impact of macroeconomic variables on the industry level equity premium. Furthermore, the study has been motivated by a number of factors. In Pakistan, plenty of researches have been done on stock market return, economic growth, and its determinants, for example, Zeeshan et al. [19, 23–25] studied the relationship between macroeconomic variables and KSE100 index and found that GDP, exchange rate, and inflation are positively related to stocked prices while negatively related to interest rate. Similarly, company factors and stock return have also been studied in many stock markets [2, 12, 26]. The previous works done were mostly based on stock return rather than considering an important factor of industry level equity premium. Therefore, there is still room for examining the macroeconomic variables and industry level equity premium. To the author's knowledge, no specific study has been done for estimating equity premium determinants in

Pakistan and it is also difficult to know about the size of historical equity premium of Pakistani capital market though it is the net return (market return less risk-free interest rate) and one of the main components of total returns.

1.3. Macroeconomic Factors as Drivers of Equity Premium. Macroeconomic factors such as interest rate, inflation, industrial production, and other factors severely affect the stock returns which translated into equity premium. The equity premium is lower in economies where the macroeconomic variables are more volatile. Lettau et al. [27] explored that change in equity premium in US capital market is mainly caused by volatility of macroeconomic variables [28, 29]; these studies examine the relationship among inflation and equity premiums and found very little or no correlation. However, Brandt et al. [30, 31] discussed that positive news about change in inflation rate dominates news about real economic and financial growth in determining risk aversion and risk premiums. They present support that equity risk premiums be inclined to boost if inflation is higher than expected and will decline when it is lower than expected. The latest study by Wang [32] indicates that increase in inflation causes increase in ERP. Kizys and Spencer [33] opined that macroeconomic influence on the US and Japanese stock returns showed a positive relation with industrial production and a negative relation with inflation and interest rate. However, Japanese stocks were negatively related to the money supply, while US stocks had no significant relation. Lamont [34] is of the view that portfolios developed to follow the growth rates of real income (GDP) and consumption and labour income earned abnormal positive expected returns.

Neely et al. [35] explored that inflation rate has strong correlation with changes in risk premium. According to Kizys and Spencer [33], long-term government bonds can explain perception of investors about inflation much clearer than short-term interest rate and also inflation is more influential in long-term investment periods than the short periods. Chou et al. [36] conducted a study related to macroeconomic factors and equity premium which have been done in the developed financial markets. However, the literature available in developing economies such as Pakistan is limited. In the current research, we are considering a set of macroeconomic factors as determinant on firm level equity risk premium in Pakistan. More recently, Imran et al. [5, 37, 38] conclude that along with economic and financial factors, noneconomic factors also cause volatility of stock return and equity premium. They consider terrorism and political instability in Pakistan as major noneconomic factors of volatility in Pakistan stock market.

1.4. Research Objectives. The study analyses the effects of macroeconomic and sectoral premium of PSX. We are considering seventeen different nonfinancial sectors that how different macroeconomic variables affect the equity premium of different sectors. For this purpose, an extended version of the macro-based multifactor model is used for estimating equity premium which includes the set of macroeconomic variables which are most relevant to nonfinancial sectors. Moreover, we attempt to broaden the techniques used in the previous studies and thus discussed the contribution of this research which is to expand previous analyses of the expected market premium to industry level equity premium.

The following Section 2 presents the detailed literature review followed by model description in Section 3. Section 4 provides the estimated results and discussion, and finally Section 5 concludes the research paper.

2. Literature Review

The most popular funds allocation and investment decision were based on mean-variance analysis. Markowitz [6] and Tobin [39] introduced the mean-variance rule. Perhaps, this was the first most used investment allocation tool under any uncertainty in economics and finance. This has been broadly used by academics and investment practitioners in the past. The same mean-variance analysis framework is the base of [8, 9] capital asset pricing model (CAPM), which is the cornerstone of today's modern economics and finance and other theoretical models.

According to Damodaran [2], high equity premium is witnessed by many authors but usually their estimates are based on long period of historical data of almost 100 years (Ibbotson associate data bank starting from 1926). Several studies concluded that the equity returns and equity premium could be better for a longer period. As far as the long period is concern, it is obvious that the return will be higher in the long period as compared to the short time period. According to Elton and Gruber [40], equity premium is one of the most significant pillars of modern portfolio theory with the condition that most of the investors are risk averse and like to have return with less risk. Therefore, the investment over the long period produced higher returns. This fact can be supported by literature of Goetzmann and Ibbotson [41]. Elton and Gruber [40, 42] wrote that investors want high return from the less risky investment. However, this could be true to have higher return from less risky investment only if you invest in a bearish trend.

In an equity premium survey report by Fernandez et al., [43] considerable variation in equity premiums across economic analysts within the same stock market was made. In the United States, for example, they recorded that the average equity risk premium across analysts was 5.8%. However, the numbers produced by different academic and economic experts ranged from 3.2% to 10.5%. More recently, Imra et al. [5, 37, 38] disclosed the noneconomic variables influence the stock market returns and firm level equity premium. The current study analyses the impact of macroeconomic variables on industry-level equity premium to check that which industries are more vulnerable to change in macroeconomic factors.

2.1. Selection of Variables. The preference of the macroeconomic variables is not random. It is motivated by number of research articles that have investigated the matter in detail and received worldwide appreciation. Roll and Ross [44] investigated macroeconomic influences on stock price (as well as risk premium) and proved that gross domestic product (GDP) and inflation do influence risk premium. Arnott and Henriksson [45] in their research study about historical risk premium in the United States of America pointed out that inflation and GDP growth have had big influence on risk premium value in the USA during 1802–2002. Lettau et al. [27] opined that equity risk premium used the term "macroeconomic risk," which is volatility of the aggregate economy. They pointed out that changes in GDP were the most important factors in economic changes, which in its turn influenced risk premium. Neely et al. [35] also found that inflation rate has strong correlation with changes in risk premium. According to Kizys and Spencer [33], long-term government bonds can explain the perception of investors about inflation much clearer than short-term interest rate and also inflation is more influential in long-term investment horizons than the short one. A study of macroeconomic influences on the US and Japanese stock returns showed a positive relation with industrial production and a negative relation with inflation and interest rate. However, Japanese stocks were negatively related to the money supply, while the US stocks had no significant relationship. According to [36, 46], a set of macroeconomic variables has an effect on stock prices that lead to change in equity premium and translated in total expected returns. Recently, Churchill et al. [47] reviewed 87 research studies on the effect of government expenditure on economic development and growth. In the high income countries, there is negative effect of government expenditure and GDP.

Lamont [34] explored that portfolios developed to follow the growth rates of industrial production, consumption, and labour income to earned abnormal positive returns, while opposite is true with interest rate and inflation. Similarly, Bai [48] developed and proposed a macroeconomic index that explained short-term disparity in future equity returns with more predicting capacity than the historical average returns. A significant cyclical pattern was marked with time-varying macroeconomic conditions.

3. Model

3.1. Theoretical Background Framework. The theoretical work relevant to equity premium started since 1952. The earliest theory of risk and return model was capital asset pricing model (CAPM). While extending this tremendous work of Markowitz, the arbitrage pricing theory (APT) came with more good results followed by three-factor model and multifactor model of Fama and French. Similarly, relevant to the different degrees of risk, macro-based and-micro based risk factor models were also developed accordingly. However, there is still room to investigate the industry equity premium and its determinants using macro-based multifactor model.

3.2. Macro-Based Risk Factor Model. We calculate the equity risk premium for sector portfolios rather than market premium as examined in earlier studies. The sector level equity premium differentiates this research from other studies conducted. We extend the macro-based model [49, 50] for a set of more relevant macroeconomic variables according to Pakistani scenario and to explore how these macroeconomic variables affect the sector level equity premium in Pakistan's capital market. This will be the first study to be conducted on sector level premium, and we used the modified version of macro-based multifactor model, and can be expressed as:

$$\begin{aligned}\left(R_{st}-R_{ft}\right) = \alpha_i + \beta_{i1}\left(R_{mt}-R_{ft}\right) + \beta_{i2}\left(\text{InterestRate}_t\right) \\ + \beta_{i3}\left(\text{Inflation}_t\right) + \beta_{i4}\left(\text{FDI}_t\right) \\ + \beta_{i5}\left(\text{MoneySupply}_t\right) + \beta_{i6}\left(\text{GDP}_t\right) + \varepsilon_{it}.\end{aligned} \tag{2}$$

The macro-based multifactor model is only used for capturing the impact of macroeconomic variables and equity premium in Pakistan Stock Exchange. Ewijk et al. [51] examined that the equity risk premium tends to increase in more economic volatility and changing of economic policies. The author witnessed negative effect of the interest rate on equity risk premium. This indicates that the total return on stock cannot be calculated by adding a stable equity risk premium to a time-varying short or long-term risk-free interest rate. The risk-free rate of return on equity premium has its own determinants which is partly correlated with the dynamics of the interest rate and equity risk premium.

3.3. Data Collection. There are 654 listed stocks at Pakistan Stock Exchange (PSX) as of December 2018. The focus of this study is on the nonfinancial sectors listed in PSX. It excludes the financial sector of Pakistan. The main reason is that there exists a difference in the financial mix and other regulatory requirements of financial and nonfinancial sectors. This study selected 306 companies from the nonfinancial sectors. The data for the study were collected from Pakistan Stock Exchange (PSX) official website (http://www.kse.gov.pk), business recorder, economic survey of Pakistan, and International Finance Statistics (IFS). The number of firms from each sector is provided in Table 1 in the appendix of this paper.

3.4. Research Methodology. The study uses the assumption of continuous returns for KSE100 index and the asset prices of each firm. The continuously compounded returns formula is expressed as follows:

$$\text{future value} = \text{present value} \times e^{in}. \tag{3}$$

Continuously compounded returns are computed for each asset by using the following formula:

$$R_t = \ln\left(P_t/P_{t-1}\right). \tag{4}$$

After calculating the returns of KSE100 index and sector's average returns, now the data are ready to calculate each sector equity premium by taking the difference of sector return and risk-free interest rate following the Fama and French [26]; Damodaram [12] method:

$$ER_i = R_m - R_f. \quad (5)$$

To analyse our data, we use two-stage least square method.

3.5. Two-Stage Least Square Method. Two-stage least squares (TSLS) is a particular case of instrumental variables regression. As the name suggests, there are two discrete stages in two-stage least squares. In the first stage, TSLS finds the portions of the endogenous and exogenous variables that can be attributed to the instruments. This stage involves estimating an ordinary least square (OLS) regression of each variable in the model on the set of instruments. The second stage is a regression of the original equation, with all of the variables replaced with their instruments. The coefficients of this regression are the two-stage least square estimates.

The standard regression model is

$$y = X\beta + \varepsilon, \quad (6)$$

where "y" is the "T" dimensional vector containing observations of the dependent variable, X is a $T\times\ k$ matrix of independent variables, β is a k-vector of coefficient, and ε is a T-vector of disturbances. T is the number of observations and k is the number of right hand side regressor.

The least squares regression coefficient b is computed by the standard OLS formula:

$$b_{\mathrm{OLs}} = (X'X)^{-1}X'y. \quad (7)$$

Let Z be the matrix of instruments, and let y and X be the dependent explanatory variables. The linear TSLS objective function is given by

$$\Psi(\beta) = (y - X\beta)'Z\left(Z^{'Z}\right)^{-1}Z'(y - X\beta). \quad (8)$$

Then, the coefficients computed in two-stage least square are given by

$$b_{\mathrm{TSLS}} = X'Z(Z'Z)^{-1}Z'^{X^{-1}}X'Z(Z'Z)^{-1}Z'y, \quad (9)$$

and the standard estimated covariance matrix of these coefficients may be computed using

$$\widehat{\sum}\mathrm{TSLS} = \c{S}^2\left(X'Z(Z'Z)^{-1}Z'X\right)^{-1}X'Z(Z'Z)^{-1}Z'Y, \quad (10)$$

where $\c{S}^2$ is the estimated residual variance (square of the standard error of the regression).

The following assumptions must be testified before performing two-stage least square method. The variance of error term for all variables must be homoskedastic, i.e., equal $\mathrm{Var}(v_{ij}) = \sigma^2$. Error terms must be normally distributed, i.e., $v_{ij} \sim N(0, \sigma^2)$.

Model should be properly and correctly defined.

It is assumed that observation should be independent of each other.

It is also assumed that unusual observations, i.e., outliers, is removed from the dataset.

The dataset for the macroeconomic variables and sector premium consists of time series data. The frequency of this dataset is monthly. Two-stage least square (2SLS) method is used for the analysis and estimation for this dataset.

4. Empirical Analysis of Macroeconomic Variables

Table 2 contains the summary statistics for the macroeconomic variables used in this study, which may help in the interpretation of the coefficient estimates by providing the scale of the relevant variables (see Appendix Table 2).

Table 3 in the appendix contains the summary statistics of the market premium of each sector used in this study (see Appendix Table 3.

Table 4 in the appendix shows the results of the correlation matrix which indicate that there is no serious correlation issue. The sector equity premium is considered as dependent variable. To assess the normality of dependent variable, i.e., industry equity premium, Kolmogorov–Smirnov test is applied. The results are presented in Table 5 (in appendix). The results demonstrate that p value of Kolmogorov–Smirnov test is insignificant which suggests that sector premium is normal. The same normality trend is also observed by constructing a histogram.

4.1. Sectorwise Estimated Results. To estimate our model, we have applied two-stage least square (2SLS) method. The estimation of model is not appropriate by using the simple ordinary least square method as the problem of possible endogeneity of the variables can cause to be the least squares estimators biased and contradictory. Endogeneity is expected to occur mainly due to reveres causality between the independent variables such as inflation and money supply; these likely same nature variables are therefore likely to be correlated with the error term. To find reliable parameter estimates in panel data, we apply two-stage least square estimation technique [52]. This technique is based on the standard of variables which are used as instruments under the theoretical assumption that, although there may be correlation between explanatory variables and the error term, such correlation does not exists between the lagged variables and the error term (rather than using changes in lagged U__ as instruments, we can use lagged levels of U__. For example, choosing (U_, _6_, U_, _6_) __ instrument at time t is no less efficient than the procedure that uses (ΔU_,_6_), as the latter is a linear combination of the former 52).

To overcome for the likelihood of cross-sectional hetroskedasticity, which also affects the effectiveness of the estimators and the strength of the hypothesis testing and inference, the models are estimated by using white cross-sectional standard errors and covariance. The correction for hetroskedasticity improves the statistical significance of the regressors.

The industrywise estimated results are discussed as follows. These results are good for the practical implication for each sector analysis. The company management can take necessary measures for any change in the macroeconomic variables. On the other hand, the investors can change their investment decision apropos to certain change in the monetary and fiscal policy which leads to change in the macroeconomic variables. Some variables affect one industry different from others; therefore, this analysis is very important in that respect. The interpretation of estimated results is presented below.

4.2. Automobile and Parts. Table 6A(refer to Table 6, in the appendix; 6A refers to column A in "Table 6.". Each column presents separate sector results of this study) presents the estimated results of automobile sector with macroeconomic variables. The estimated results are according to theoretical expectations. The coefficient on market premium is positive and statistically significant which indicates that one percent increase in market premium will increase equity risk premium in automobile sector by 0.99 percent. This result is consistent with [26]. The statistically significant negative coefficient on T-Bill rate indicates that one percent increase in interest rate decreases equity risk premium in the automobile sector by 0.03 percent. Also, the negative and statistically significant coefficients of inflation indicate that one percent increase in inflation causes 0.07 percent decrease in firm level equity premium. The statistical significant value of industrial production is consistent with the theoretical expectations that increase in industrial growth causes increase in the equity risk premium. This indicates that one percent increase in industrial growth will increase equity risk premium in the automobile sector by more than 0.12 percent. The coefficient of money supply variable is negative but statistically insignificant, which implies that money supply does not affect equity risk premium in the automobile sector. These results are consistent with result by Ferreira [53]. Just like money supply, the effect of foreign direct investment on equity risk premium is also statistically insignificant. It implies that FDI does not affect equity premium in the automobile sector (Appendix Table 6).

The value of coefficient of determination (R^2) indicates that more than 42 percent variation in the model is explained by the explanatory variables. Similarly, the value of adjusted-R^2 implies that more than 40 percent variation in equity risk premium is explained by the explanatory variables. The value of F-statistics is highly statistically significant, which indicates that the model fitted the data well. The value of the Durban Watson (DW) test is close to the standard value of 2, which implies that there is no serious problem of autocorrelation in the data. To verify the autocorrelation issue, we have also applied Lagrange Multiplier (LM) serial correlation test. Unlike the DW-statistic for AR(1) errors, the LM test may be used to test for higher order auto regressive moving average (ARMA) errors and is appropriate whether there are lagged dependent variables or not. Therefore, we recommend its use (in preference to the DW-statistic) whenever we are concerned with the possibility that our errors exhibit autocorrelation. The null hypothesis of the LM test is that there is no serial correlation up to lag order p, where p is a prespecified integer. The local alternative is ARMA(r, q) error, where the number of lag terms $p = \max(r, q)$. Note that this alternative includes both AR(p) and MA(p) error processes so that the test may have power against a variety of alternative autocorrelation structures. The LM test statistic is asymptotically distributed as a $\chi^2(p)$ and is computed as the number of observation (n) times the (uncentered) R^2. From the test regression, i.e., $\chi^2(p) = n.R^2$, insignificant value of LM statistics also confirms the absence of autocorrelation problem. Moreover, to test the validity of the instrument, the J-statistics, which is also as the Sargan statistic, for over-identifying restrictions is used. Under the null hypothesis that the over-identifying restrictions are valid, the Sargan statistic is distributed as $\gamma(p - k)$, where k is the number of estimated coefficients and p is the instrument rank. The high insignificant p values of the J-statistics indicate that the instruments are valid.

4.3. Engineering Sector. Table 6B in the appendix presents the estimated results of engineering sector with macroeconomic variables. The estimated results are consistent with the theoretical expectations. The coefficient on market premium is positive and statistically significant which indicates that one percent increase in market premium will increase equity risk premium in the engineering sector by 0.60 percent. The statistically significant negative coefficient on T-Bill rate indicates that one percent increase in interest rate decreases equity risk premium in the engineering sector by 0.04 percent. The coefficient of inflation is not according to expectation. Theoretically, the impact of inflation on equity returns is negative. However, in our results, the coefficient is positive but statistically insignificant. Just like inflation, the coefficient of money supply, industrial production index, and foreign direct investment are statistically insignificant, which implies that these variable do not affect equity risk premium in the engineering sector.

The value of coefficient of determination (R^2) indicates that more than 30 percent variation in the model is explained by the explanatory variables. Similarly, the value of adjusted-R^2 implies that more than 27 percent variation in equity premium is explained by the model. The value of F-statistics is highly statistically significant, which implies that the model fits the data well. The value of the DW test is almost equal to the desired value of 2, which shows that there is no autocorrelation problem in the data. Insignificant value of LM statistics also confirms that there is no serious problem of autocorrelation in the data. Moreover, the high insignificant value of J-statistics indicates that the instruments used are valid.

4.4. Beverages. Table 6C in the appendix presents the estimated results of beverages sector with macroeconomic variables. The estimated results are not consistent with the theoretical expectations. None of the coefficients is statistically significant, except T-Bill rates. The statistically significant but negative coefficient of T-Bill indicates that one percent increase in interest rate decreases equity premium in the engineering sector by 0.05 percent. The rest of the variables in the model do not have any significant impact on the beverages sector. The possible reason may be the seasonal consumption pattern of beverages. Regardless of inflation, money supply, etc., people tend to use beverages in the summer and avoid in the winters.

The value of coefficient of determination (R^2) indicates that more than 12 percent variation in the model is explained by the explanatory variables. Similarly, the value of adjusted-R^2 implies that only 8 percent variation in equity premium is explained by the model. The value of F-statistics is statistically significant, which implies that the model fits the data well. Insignificant value of LM statistics indicates the absence of autocorrelation problem. In order to confirm the validity of the instrument, we find the value of J-statistics. The insignificant value of J-statistics shows that the instruments used in the analysis are valid.

4.5. Chemicals. Table 6D in the appendix presents the estimated results of chemical sector with macroeconomic variables. The estimated results are according to the theoretical expectations. The coefficient on market premium is positive and highly significant which indicates that one percent increase in market premium will increase equity premium in the chemical sector by 0.76 percent. The statistically significant negative coefficient on T-Bill rate indicates that one percent increase in interest rate decreases equity premium in the chemical sector by 0.02 percent. The negative and statistically significant coefficient of inflation indicates that one percent increase in inflation will decrease equity premium by 0.04 percent of chemical industry. This is consistent with the previous studies [54]. The statistically significant coefficients of industrial production and FDI indicate that for one percent increase in IDI and foreign direct investment, the equity premium of chemical sector will increase by 0.07 percent and 0.001 percent, respectively. The results are consistent with [23]. The negative statistically insignificant coefficient of money supply indicates that it does not have any statistically significant impact on the chemical sector.

The value of coefficient of determination (R^2) indicates that more than 61 percent variation in the model is explained by the explanatory variables. Similarly, the value of adjusted-R^2 implies that more than 59 percent variation in equity premium is explained by the model. The value of F-statistics is highly statistically significant, which implies that the data are well fitted in the model. The value of the DW test is close to the expected value of 2, which confirms that there is serious problem of autocorrelation in the data. Insignificant value of LM statistics also confirms the absence of autocorrelation problem. Moreover, the highly statistically insignificant value of J-statistics indicates that the instruments used are valid.

4.6. Electrical and Engineering Goods. Table 6E in the appendix presents the estimated results of electrical and engineering sector with macroeconomic variables. The coefficient of market premium is positive, however, statistically insignificant, which indicates that the market premium does not affect the electrical and engineering sector. The statistically highly significant negative coefficient on T-Bill rate indicates that one percent increase in interest rate decreases equity premium in the electrical and engineering sector by 0.09 percent. The negative and statistically significant coefficient of inflation indicates that one percent increase in equity premium of electrical and engineering sector decreases by 0.08 percent. The rest of the variables used in the model are not statistically significant. During the last one decade, the electrical and engineering sector was performing low because of the severe shortfall off energy in the country. This might be one of the reasons the macroeconomic variable is not showing any significant relationship with EE sector.

The value of coefficient of determination (R^2) indicates that more than 9 percent variation in the model is explained by the explanatory variables. Similarly, the value of adjusted-R^2 implies that more than 6 percent variation in equity premium is explained by the model. The value of the DW test is close to the desired value of 2, which indicates the absence of autocorrelation problem. Insignificant value of LM statistics also confirms the absence of autocorrelation problem. Moreover, the high insignificant value of J-statistics shows that the instruments used in the analysis are valid.

4.7. Electricity. Table 6F in the appendix presents the estimated results. The coefficient on market premium is positive and highly statistically significant which indicates that one percent increase in market premium will increase equity premium in the electrical industry by 0.90 percent. The statistically significant negative coefficient on T-Bill rate indicates that one percent increase in interest rate decreases equity premium in the chemical sector by 0.04 percent. The inflation has negative and statistically significant coefficients which indicate that one percent increase in inflation decreases equity premium of the electricity sector. This is consistent with the previous studies [54]. The statistical significant value of industrial production is consistent with the theoretical expectations that increase in industrial production causes an increase in the equity premium of electricity sector. One percent increase in industrial production increases ERP by 0.22 percent. The effect of FDI on equity premium is positive but statistically insignificant. Coefficient of money supply variable is also statistically insignificant, which implies that money supply does not affect equity premium in the electricity sector.

The value of coefficient of determination (R^2) indicates that more than 29 percent variation in the model is explained by the explanatory variables. Similarly, the value of adjusted-R^2 implies that more than 26 percent variation in equity premium is explained by the model. The value of F-statistics is statistically significant, which implies that it is well fitted in the model. The value of both DW test and LM statistics indicates the absence of autocorrelation problem. Insignificant value of LM statistics also confirms the absence of autocorrelation problem. Insignificant value of J-statistics indicates that the instruments used are valid.

4.8. Food Producers. Table 6G presents the result for the food producer sector. The coefficient on market premium is positive and statistically significant which indicates that one percent increase in market premium will increase equity premium in the food industry by 0.40 percent. The statistically significant negative coefficient on T-Bill rate indicates that one percent increase in interest rate decreases equity premium in the food producer sector by 0.05 percent. The positive and statistically significant coefficients of foreign direct investment indicate one percent increase in FDI increases equity premium of the food producer sector by 0.05 percent. The inflation, industrial production, and money supply variables are statistically insignificant, which implies that these variables do not affect equity premium in the food producer sector.

The value of coefficient of determination (R^2) indicates that more than 9 percent variation in the model is explained by the explanatory variables. Similarly, the value of adjusted-R^2 implies that around 6 percent variation in equity premium is explained by the model. The values of the DW test and LM statistics indicate the absence of autocorrelation problem. Moreover, highly insignificant value of J-statistics shows that the instruments used in the analysis are valid.

4.9. Fixed Line Telecommunication. Table 6H in the appendix presents the estimated result of fixed line telecommunication sector. The coefficient on market premium is positive and statistically significant which indicates that one percent increase in market premium will increase equity premium in the electrical industry by 0.02 percent. The statistically significant negative coefficient on T-Bill rate indicates that one percent increase in interest rate decreases equity premium in fixed line telecommunication sector by more than 0.05 percent. The positive and statistically significant coefficients of foreign direct investment indicate that one percent increase in FDI increases the equity premium of fixed line telecommunication sector by 0.05 percent. The inflation, industrial production, and money supply variables are statistically insignificant, which implies that these variables do not affect equity premium of the fixed line telecommunication sector.

The value of coefficient of determination (R^2) indicates that more than 9 percent variation in the model is explained by the explanatory variables. Similarly, the value of adjusted-R^2 implies that around 5 percent variation in equity premium is explained by the model. The values of the DW test and LM statistics indicate the absence of autocorrelation problem. Moreover, the highly insignificant value of J-statistics indicates that the instruments used in the analysis are valid.

The results and discussion for the next eight sectors are provided in the Appendix Section 2 and can be described in similar way.

5. Conclusion

Dynamics of equity premium are ranging from microlevel to macrolevel and proceeding further to some noneconomics phenomena. Awareness of the size of equity premium is an important number for the efficient allocation of funds. The statistics of equity premium for a particular security or a particular set of portfolio can be used for evaluating cost of equity as well as expected return. This part of the total returns has been extensively studied in developed as well as emerging equity markets. However, very limited literature is available for developing counties such as Pakistan, especially no study focused on Industry level equity premium. The author took a series of paper in this area to analyse and reached to forecast a suitable model. This part of the study explores the sectorial equity premium and macroeconomic variables as its determinants. We calculate the sector premiums for sixteen nonfinancial sectors.

Analyses are conducted using monthly equity prices data for the period of January 2001 to December 2018. As we know that macroeconomic are not controllable by the firms, however, change in these variables affects stock prices and the equity premium. The macroeconomic variables included in this study are interest rate, money supply, income (industrial production index), foreign direct investment, and inflation (consumer price index). Interest rate is the major component that greatly and directly affects the equity premium. Increase in interest rate leads to decrease in the equity premium as the equity premium is the difference between market return and risk-free rate of return. In this study, we use 3-month T-Bill rate (interest rate) as risk-free rate to calculate the equity premium.

For the analysis purpose, we proposed the extended version of macro-based multifactor model develop by [49] which includes more macroeconomic variables than the previous studies and we expand the estimation technique from simple regression to two-stage least square method. The model includes the market premium and five more macroeconomic variables which are more related to the capital market in general and to the nonfinancial sector in particular.

The impact of these macroeconomic variables also been examined on the equity premium of each nonfinancial sector. Due to the possible presence of endogeneity issue in the variables, we use two-stage least square (2SLS) method for estimation. The estimated results reveal that each single stock and each industry follow the bullish trend of the KSE100 index. If the market (KSE100 index) moves upward, regardless of the industry, most of the stock prices go up and increase the premium size which provides better returns than expected. The average equity premium of this study period ranges from −0.15 percent to 22.8 percent for nonfinancial sectors listed in PSX. The market premium is positive and highly significant in 14/16 sectors. The sectors which do not follow the market trend are beverages, food producing industry, and tobacco and the intuition is that these three industries are related to seasonal products. The sale of beverages increases in summer regardless of the market trend. Similarly, different food producing firms have peak sales in different seasons. Therefore, it does not have statistically significant relation with the market premium. Among the selected group of macroeconomic variables, change in interest rate effects all sector premium negatively followed by inflation in specific manufacturing sector. The industrial production, money supply, and foreign direct investment are positively related to different sectors according to the nature of their products and services.

Overall, based on these findings, we can formulate the investors must examine the size of equity premium and change in macroeconomic variables. Similarly, the investors need to invest in seasonal goods and services industries accordingly. Stable interest rate provides better returns. More foreign direct investments create healthy returns from investments in the stock market. The policy makers need to oversee the financial and economic policy to encourage investment in the stock market.

5.1. Practical and Theoretical Implications. Pakistan Stock Exchange is one the is emerging and changing behaviour markets with respect to the changes in macroeconomics and fiscal policies. The investors need to use a model which can capture the effect of company fundamental variables, macroeconomics behaviours, and noneconomic factors such as terrorism, political instability, and other related factors. For this purpose, we used macro-based multifactor model proposed for macroeconomic variables for examining the relationship of each or all variables. This can help to explain the variation of equity premium in Pakistan Stock Exchange. The investor also needs to examine the macroeconomic variables and its importance in investment decision. Interest rate, inflation, industrial production, money supply, and foreign direct investment are the variables that should be considered in asset pricing and investment decisions. The macro-based multifactor model used in this study can help the investor and institutions in examining the fluctuation in macroeconomics which leads to change in industry premium.

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Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Additional Points

Limitations of the Study. The scope of the study is limited only to the nonfinancial sector firms listed on Pakistan Stock Exchange. Pakistan Stock Exchange is an emerging south Asian capital market and the results are not compared with other emerging markets in the region. Financial structures of financial and nonfinancial firms are not the same; therefore, we consider only nonfinancial firms. Another limitation of the study is data constraint, as long-term data needed for the study are not available electronically. Hence, the study period is limited to 18 years only.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Supplementary Materials

The appendixes contain all the resulted tables of the study. (*Supplementary Materials*)

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Research Article

Understanding the Complex Adoption Behavior of Cloud Services by SMEs Based on Complexity Theory: A Fuzzy Sets Qualitative Comparative Analysis (fsQCA)

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To survive in a competitive environment, small and medium enterprises (SMEs) have had to adapt to the digital environment in order to adjust to customer needs globally, particularly in the post-COVID-19 world. The advantages of cloud computing (e.g., flexibility, scalability, and low entry cost) provide opportunities for SMEs with a restricted budget and limited resources. To understand how SMEs adopt cloud computing in a complex digital environment, this study examines how antecedents combine with each other to explain the high adoption of cloud computing. From the perspectives of holism and set theory, we draw on complexity and configuration theories, present a conceptual model including seven antecedents based on the technology-organization-environment framework, and conduct an asymmetric fuzzy-set qualitative comparative analysis. Through an empirical study with 123 Chinese companies, we identify nine combinations (configurations) of determinant antecedents that lead to the high adoption of cloud computing. The results show that none of the factors are indispensable to explain a high adoption on their own; instead, they are insufficient but necessary parts of the causal combinations that explain a high adoption. This study contributes to the literature on cloud computing adoption by extending current knowledge on how antecedents combine to increase the adoption and identify specific patterns of SMEs for whom these factors are essential and greatly influence their adoption.

1. Introduction

Small and medium enterprises (SMEs) use digital technologies in the current digital era, such as artificial intelligence, smart technologies, and cloud technology, to grow their online businesses alongside their offline operations. The digital environment provides numerous opportunities for entrepreneurs who start and run SMEs to impact and grow their businesses. To survive in a turbulent competitive environment, SMEs have had to adapt to the digital environment to adjust to customer needs globally, particularly in a post-COVID-19 world. Therefore, there is a strong need for digital technologies to improve the business performance, cost advantages, and competitive advantages with a restricted budget and limited resources.

As a representative emerging digital technology, cloud computing has become an important information technology (IT) development trend in recent years. Cloud computing is considered a transformation of IT resources and the service delivery paradigm, and promises to deliver IT resources as a utility, similar to water, electricity, gas, and telephony services [1]. An increasing number of well-known IT service providers have begun to provide cloud services, such as Amazon (Elastic Computing Cloud), Google (App Engine), and Microsoft (Azure). Cloud computing can transform business processes, reduce IT expenditures, deliver real-time applications, provide access to ubiquitous storage, and have unlimited computing power and the potential for market information mobilization. It has therefore been used in various fields such as e-commerce, e-government, and customer relationship management [2–6].

The advantages of cloud computing services (e.g., flexibility, scalability, and low entry cost) also provide opportunities for SMEs. These opportunities can enable SMEs to improve IT capability with relatively low transaction and switching costs, and to formulate quality IT strategies allowing SMEs to develop within the new technological paradigm shift [7]. Small businesses can improve their operations and productivity enormously by moving to the cloud. Doing so will increase their revenue, thereby setting them ahead of the competition. In addition, the governments of many countries have issued relevant policies to encourage domestic enterprises to use cloud services. For example, the State Council of China issued its "Opinions on Promoting the Innovative Development of Cloud Computing and Cultivating New Types of Information Industry" in January 2015. Although the adoption of cloud services can bring about many benefits to SMEs, not all SMEs are eager to adopt cloud services and are still on the sidelines owing to various challenges, such as privacy and data security issues, a lack of uniform standards for the cloud services industry, and an inadequate regulation of cloud services [8–11]. In particular, the size and structure of SMEs often make them face specific challenges. Although the adoption of cloud services can increase their competitive advantage, it also involves the consumption of funds. Therefore, SMEs need to be extremely cautious when making decisions on the adoption of cloud services [12]. Therefore, in response to the call of the country to encourage enterprises to adopt cloud services, thereby accelerating the digital transformation of enterprises and promoting the development of the cloud computing industry, it is important to explore ways to encourage SMEs to adopt cloud computing and take relevant targeted measures.

Numerous studies in this area have used conventional regression-based quantitative methods, such as multiple regression analysis and structural equation modeling, to explore the factors that affect the adoption of cloud services by an enterprise. These methods assume that relations between variables are symmetric, and adopt an isolated analytical perspective on variables, focusing on exploring the marginal "net effect" of a single variable or a few variables on the adoption of cloud services. It is difficult to explain the interdependence of variables and the complex cause–effect relationships on how variables' configurations affect the results. However, as in real life, it is a common phenomenon that the conditions occurring in management practice are interdependent rather than independent. There are few studies on the complex cause–effect relationship between each antecedent variable (e.g., interdependence) or on the different casual configurations required for enterprises to adopt cloud services.

To address such gaps in the literature, we start from the perspectives of holism and set theory, taking 123 SMEs with a high degree of informatization as the empirical research object, using the qualitative comparative analysis method initiated by Ragin [13] to study the configurations of determinants for enterprises adopting cloud services, and to explore the conditions under which enterprises are more inclined to adopt such services. The results of this research will improve theories on cloud service adoption and promote the application of qualitative comparative analysis in the field of information systems (IS). At the same time, theoretical guidance for SMEs to formulate better IT strategies and cloud service providers to provide products that better meet market needs, formulate specific sales strategies, and formulate more scientific policies to promote the development of the cloud computing industry is provided. At the same time, it provides theoretical guidance for SMEs, cloud service providers, and government to formulate better IT strategies, provide products that better meet market needs, and make more scientific policies to promote the development of the cloud computing industry, respectively.

2. Literature Review

2.1. Cloud Services and Their Adoption. Cloud computing is defined as "a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction" by the National Institute of Standards and Technology (NIST) [14]. Cloud computing refers to both applications delivered as services over the Internet and hardware and systems software in a data center that provide such services [2].

Cloud computing can bring about many benefits to an enterprise and is an innovative computing model that enables SMEs to obtain complex technologies without investing much money. Enterprises can take advantage of the flexibility of cloud computing to increase computing resources as demand increases, which enables enterprises to plan far ahead for provisioning [15, 16]. Computational resources are stored in the resource pool, and users can access these scalable and adjustable resources virtually [15]. These computing resources can be used automatically, and their use does not require any organizational interaction [14, 15]. However, not all enterprises are willing to adopt cloud services owing to various challenges, such as privacy and data security issues, a lack of uniform standards for the cloud services industry, and inadequate regulations [8–11]. Therefore, to accelerate the development of the cloud computing industry, numerous studies have used technology adoption theories to explore the determinants of intention and behavior to adopt cloud services. Table 1 lists the empirical studies on cloud service adoption over the past 10 years.

As shown in Table 1, the existing literature mainly uses a regression analysis and structural equation modeling to study the independent effects of factors, such as technology, organization, and environment, on the adoption and assimilation of cloud services in enterprises and medical and educational industries. Few studies have investigated the interdependence between multiple factors. However, to further reveal the influence mechanism of the adoption of cloud services by an enterprise, it is necessary to explore the complex interactions of multiple factors from a holistic perspective. To fill in this gap, we adopt a fuzzy-set

Table 1: Empirical research on cloud service adoption.

Resources	Theory basis	Methodology	Adoption (DV)	Determinants (IV)
[17]	No specific theory is used	PLS	Intention to adopt CC	Perceived accessibility, perceived scalability, perceived cost-effectiveness, perceived lack of security
[18]	TAM	PLS	Behavioral intention	Social influence, attitude toward mobile innovation, perceived benefits, perceived usefulness, perceived ease of use, behavioral intention, marketing efforts, security, and trust
[19]	TOE, DOI, INT	No specific methodology is used.	Intention to adopt cloud	Availability, reliability, security, privacy, trust, relative advantage, compatibility, complexity, top management support, organization size, technology readiness, compliance with regulations, competitive pressure, trading partner pressure, physical location
[5]	TOE	Regression analysis	CC adoption	Relative advantage, complexity, compatibility, top management support, firm size, technology readiness, competitive pressure, trading partner pressure
[20]	TAM3	Path analysis	Actual usage of CC	Access to software, ease of travel, personal innovativeness, technology anxiety, instructor support, reliability, usefulness, ease of use
[21]	TOE	SEM	Intention to adopt CC	Cloud security, compatibility, reliability and availability, extendibility of existing APPs to cloud, compliance policy, lack of IT standards, business scalability, cost flexibility, market adaptability, hidden complexity, share best practices, adopter's style
[22]	No specific theory is used	PLS	Usage and adoption of CC	Reliability, ease of use and convenience, cost reduction, sharing and collaboration, security and privacy
[23]	TOE, DOI	SEM	CC adoption	Relative advantage, complexity, compatibility, security concerns, cost savings, technology readiness, top management support, firm size, competitive pressure, regulatory support
[24]	TOE	Analysis of variance	The adoption decision of CC	CIO innovativeness, perceived technical competence, data security, complexity, compatibility, cost, relative advantage, top management's support, adequate resource, benefits, government policy, perceived industry pressure
[25]	TOE	SEM	Cloud adoption intention	Perceived benefits, business concerns, IT capability, external pressure
[26]	TOE	Semistructured interviews	Intention to adopt cloud	Availability, reliability, security, privacy, trust, relative advantage, compatibility, complexity, top management support, organization size, technology readiness, compliance with regulations, competitive pressure, trading partner pressure, physical location
[27]	TOE	SEM	Attitude toward SaaS, intention to use SaaS	IT infrastructure, top management support, relative advantage, simplicity, compatibility, experience ability, competitor pressure, partner pressure
[28]	TOE	PLS	CC adoption	Relative advantage, complexity, compatibility, management support, vendor lock, data concern, government regulation, peer pressure
[29]	TOE, DOI	Binomial test, fuzzy AHP	SaaS adoption	Relative advantage, competitive pressure, security and privacy, sharing and collaboration culture, social influence, compatibility, IT resource, observability, complexity, trialability

Table 1: Continued.

Resources	Theory basis	Methodology	Adoption (DV)	Determinants (IV)
[7]	TOE	SEM	Cloud service transformation intention	Reliability, information security, institutional pressure, structure assurance, vendor scarcity, size, international scope, IT competence, entrepreneurship
[30]	No specific theory is used	Hierarchical multiple regression analysis	Cloud service adoption intention	Relative advantage, compatibility, observability, trialability, perceived complexity, subjective norms, new technology self-efficacy, network externality
[31]	TOE	Analysis of variance, PLS	A firm's intention to adopt CC services	Relative advantage, ease of use, compatibility, trialability, observability; security, firm size, global scope, financial costs, satisfaction with existing IS, competition intensity, regulatory environment
[32]	TAM	Quantitative research	Respondents' intention to use CC	Perceived ease of use, personal innovativeness, threat and high scores in respondents' challenge, self-efficacy, openness to experience, computer competence, and in social media use
[33]	No specific theory is used	Structural-equations model	Adoption on public CC	Alignment, adaptation, security, cost-effectiveness, operational risk, IT compliance, management/controlling power
[34]	SLA, DOI, trust theory, TAM	Descriptive analysis, CFA, correlation analysis, fsQCA, SEM	Cloud service adoption intention	Trust of firms concerning cloud services, perceived usefulness of loud service, trust in cloud service, foundation characteristics specific to cloud service, perceived compatibility regarding cloud service, perceived relative advantage regarding cloud services
[35]	DOI, TAM	SEM	Intention to adopt CC, actual usage of CC	Awareness, cost-effectiveness, risk, data security, infrastructure, relative advantage, compatibility, complexity, observability, trialability, results demonstrable, ease of use, usefulness, sociocultural
[36]	TOE, DOI, INT	PLS	Three stage of SaaS diffusion: Intention, adoption, routinization	Relative advantage, compatibility, complexity, technology competence, top management support, coercive pressures, normative pressures, mimetic pressures
[15]	No specific theory is used	SEM, EFA, CFA	CC adoption	Security, need, cost saving, supplier availability, integration, maintenance, virtualization, reliability, performance
[37]	TOE, INT, PVT	SEM	The intention to adopt SaaS, the adoption of SaaS	Representation capability of SaaS, reach capability of SaaS, monitoring capability of SaaS, technology competence, top management support, coercive pressure, normative pressure, mimetic pressures
[38]	DOI, TAM	SPSS, SEM	The intent to adopt CC, actual usage of CC	Awareness, upfront cost saving, running cost, risk, data security, availability of good information and communications technology infrastructure, relative advantage, compatibility, complexity, observability, trialability, results demonstrable, ease of use, usefulness, sociocultural factors, the age of the university, the size of the university, the location of the university, the age of university information and communications technology experts and decision-makers
[39]	TAM	SEM	Behavioral intention to use	Perceived usefulness, perceived ease of use, top management support, training, communication, technological complexity, organization size

Table 1: Continued.

Resources	Theory basis	Methodology	Adoption (DV)	Determinants (IV)
[40]	No specific theory is used	SEM, CFA	The level of CC adoption	R&D institutions over an organization, the influence of technology providers, public administration on a given organization, managers' awareness of killer applications based on cloud computing, managers' awareness of success cases in cloud computing
[41]	TOE, grounded theory	Coding	E-Government cloud adoption	Comparative advantage, technological concern, cloud provider characteristic, cloud provider competence, cloud provider presence, top management support, organization inertia, the scale and complexity of information resource, policy and regulation, industry standards, competition pressure, requirement of citizen, best practice, financial fund, initial trust, perceived benefit-based trust
[42]	TOE	SEM, artificial neural network	CC adoption	Perceived IT security risk, risk analysis, technology innovation, usage of technology, industry usage, trust, management style
[43]	TOE	PLS	SaaS adoption	Coercive pressures, normative pressures, mimetic pressures, technology competence, top management support
[12]	TOE, DOI	Quantitative analysis, logistic regression	CC adoption	Manager cloud computing expertise, employee's know-how, perceived business benefit, cost reduction, security and privacy, cooperation with cloud providers, the government support, employee's information access, manager's innovation capacity, trialability

CC, Cloud computing; DV, Dependent Variable; IV, Independent Variable; SEM, Structural-equations model; EFA, Exploratory factor analysis; CFA, Confirmatory factor analysis; PLS, Partial Least Squares; TAM, Technology Acceptance Model; TOE, Technology-Organization-Environment; DOI, Diffusion of Innovation; INT, Institutional Theory; PVT, Process Virtualization Theory.

qualitative comparative analysis (fsQCA) method based on the set theory to study the main configuration of determinants of cloud service adoption by SMEs, and analyze the joint action and interaction mechanism of various factors on the cloud service adoption by SMEs both comprehensively and systematically.

2.2. TOE Framework. The technology-organization-environment (TOE) framework was proposed to explain the innovation process in the context of an organization [44]. It considers three contexts that influence the adoption of innovation by an organization: technology, organization, and environment context [44]. The TOE framework has been applied to research on the adoption of various technologies [43, 45, 46]. It has been applied many times to study cloud service adoption at the enterprise level [5, 25, 31, 47]. The technology context refers to the internal and external technologies related to the organization [5, 23, 36] and technologies that affect the adoption process [31]. Organizational context refers to the descriptive characteristics of an enterprise, such as enterprise size, management structure, degree of centralization, and quality of human resources [5, 23, 31, 36, 44, 48]. The environment context includes market elements, competitors, regulatory environments, and government policies [5, 23, 36, 44]. The TOE framework is consistent with the Diffusion of Innovation (DOI) proposed by Roger et al. The DOI takes the five technical characteristics of relative advantage, complexity, compatibility, observability, and trialability, as determinants of innovation adoption [49–51]. Some researchers in the IS field believe that the institutional (INT) theory can strengthen the environmental context of the TOE framework [48, 52–54]. The INT theory defines different institutional pressures, such as the coercive pressure, normative pressure, and mimetic pressure [55]. Institutional pressure has proven to be an essential determinant of innovation adoption, particularly in remote systems such as SaaS [43, 56]. However, the DOI and INT theories only consider unilateral factors that affect the process of innovation adoption. Combining DOI, INT theory, and the TOE framework can compensate for this deficiency and further improve the explanatory capability of the model [23]. Many previous studies have adopted integrated models to explore the adoption of various innovations [12, 23, 36].

3. Research Model and Antecedents of Cloud Service Adoption

3.1. Research Model. Although previous studies have demonstrated that various factors can influence cloud service adoption, almost all factors can be classified into technological, organizational, or environmental contexts. Moreover, with the development of cloud services, and an understanding of what they provide, an increasing number of cloud service providers have been adjusting and improving their related technologies to attract enterprises to adopt such services [40]. Moreover, with an increasing number of enterprises adopting cloud services, cloud service providers are emerging in the market. The characteristics of cloud service providers will also influence other antecedents to a certain extent. For example, the technical and management service capabilities of cloud service providers can influence the relative advantages of cloud services. Therefore, provider factors are also essential factors for enterprises to consider when making cloud service adoption decisions [41]. Based on the above analysis, combining the characteristics of cloud services and expanding on the three dimensions of technology, organization, and environment that have been clearly defined in the TOE framework, we propose a cloud service adoption model of SMEs with four different dimensions, namely, technology-organization-environment-provider, and empirically test the relevant antecedents. The research model is shown in Figure 1.

3.2. Antecedents of Cloud Service Adoption

3.2.1. Technology Context. The two-factor theory of technology adoption recently appeared in the IS field, which is the inheritance and development of Herzberg's two-factor theory of motivation [57–60]. The two-factor theory divides the factors that affect the user's will into promoting factors (motivators) and inhibiting factors (hygiene) [59]. In the IS field, promoting factors refer to factors that promote users to adopt a specific product or service, whereas inhibiting factors refer to factors that hinder users from adopting them [59, 60]. The two-factor theory states that promoting and inhibiting factors are not opposed to each other, and independently affect the user's will [59, 61]. The adoption of cloud services by enterprises is an act of adopting new technologies or services, and technical characteristics are the key factors that influence the adoption of innovative technologies by organizations. As an innovative technology, the relative advantage of cloud services can bring competitiveness to an enterprise. However, because of security issues, enterprises can also be exposed to certain risks. Therefore, based on the two-factor theory, enterprises need to consider both the relative advantages and perceived security risks of cloud services in terms of technical characteristics when making cloud service adoption decisions.

(i) Relative Advantage. The relative advantage is defined as "the degree to which an innovation is perceived as being better than its precursor" [62]. Existing studies suggest a positive correlation between relative advantage and IT adoption [28, 29, 31]. When enterprises perceive that an innovative technology has relative advantages, the possibility of adopting this technology will increase [63, 64]. Cloud services provide many advantages for adopters, including flexibility, scalability, a low entry cost, pay-per-use, portability, ease of installation and maintenance, and run analyses through the Internet [2, 3, 25]. Enterprises are usually willing to adopt new technologies with the advantage of improving the business performance and efficiency. Therefore, the relative advantages of cloud services are considered essential variables for their adoption by an enterprise.

(ii) Perceived Security Risk. Perceived security risk refers to the risk that users perceive when they believe that cloud service adoption will hinder an organization's performance [42, 65]. Cloud services are the integration of storage and computing in a shared multi-user environment. Because they cannot fully understand and determine potential security risks, enterprises add security considerations when deciding whether to adopt a cloud service [66–68]. The main security risks perceived by an enterprise in using a cloud service come from data security issues, including a malicious manipulation of private data, a risk of disclosure of private information, and a reduced auditability of the enterprise data. These security risks will cause economic losses to an enterprise and lead to a decline in its prestige and trust from the public to a certain extent. Therefore, we believe that the perceived security risks that cloud services bring to an enterprise will affect an enterprise with its intention to adopt a cloud service.

3.2.2. Organization Context. Organizational factors include the organizational characteristics and the support of available resources within the organization, which is an internal situational condition that promotes or restricts the adoption of innovative technologies within the organization. As an innovative technology, whether an enterprise adopts a cloud service and includes it in its management decision depends mostly on the top management's attitude and actions inside the enterprise. At the same time, IT competency of an enterprise also promotes or restricts its interest to adopt cloud services to a certain extent. Therefore, this study takes top management support and IT competence as essential variables that influence the adoption of cloud services by an enterprise at the organizational level.

(i) Top Management Support. Top management support has proven to be a necessary condition for overcoming organizational resistance to change and ensuring a successful IT implementation [69]. Top management support is the vision, support, and commitment provided by top management to create an ideal environment for adopting a cloud service [70]. Top management support is particularly crucial for the adoption of technology in SMEs, where the CEO or equivalent personnel often has the final say over the organization's information and communications technology strategy and resulting investments [39, 71]. When top management recognizes the advantages of cloud services, it may allocate necessary resources for adopting a cloud service and encourage its use by the employees; conversely, when top management does not recognize the benefits of cloud services to the enterprise, it will refuse to adopt such services [23]. Therefore, top management support is also considered an essential factor influencing the adoption of cloud services by an enterprise.

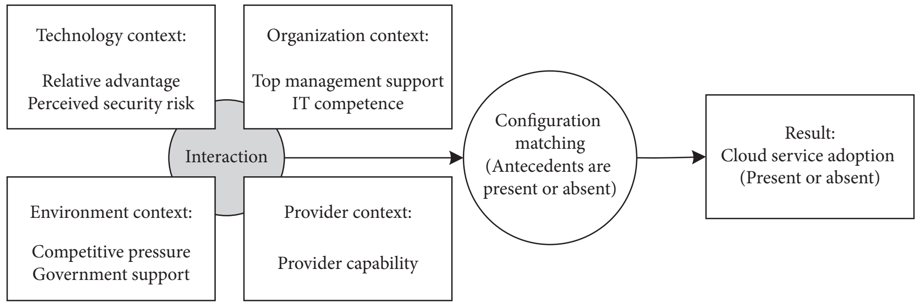

Figure 1: Research model.

(ii) IT Competence. IT competence refers to the technologies available in the organization, such as IT infrastructure and IT professionals [72]. IT infrastructure refers to installed platforms that can complement or be replaced by a new technology solution [23, 37]. IT professionals are employees who have the expertise required to implement cloud services [36]. Existing studies have found that it is an essential factor influencing IT adoption [36, 37, 43]. To improve the IT performance, SMEs with weaker IT competence may have more incentives to adopt cloud services. Therefore, we believe that the IT competence of an enterprise will affect its willingness to adopt a cloud service.

3.2.3. Environment Context. Environmental factors refer to external constraints and feasible conditions for organizations to adopt innovative technologies. Any decision made by an enterprise will be affected by the social environment in which the enterprise is located. We believe that two factors at the environmental level—competitive pressure and government support—affect the cloud service adoption decisions of an enterprise.

(i) Competitive Pressure. Competitive pressure refers to the pressure that enterprises experience from competitors in the industry [5, 73, 74] and has been proven to be an essential factor in technology diffusion in the literature on innovation diffusion [23]. SMEs are largely available, have weak funds, and have poor risk resistance, and thus are more likely to feel pressure from competitors and follow them in the use of new technologies. By adopting cloud services, enterprises can better understand market visibility, collect data more accurately, and achieve a higher operational efficiency, which will lead to more profits for the enterprise [5, 75]; therefore, enterprises can better continue to operate in industry competition. We believe that competitive pressure is an essential variable for enterprises adopting cloud services.

(ii) Government Support. Government support means that the government plays a promotional role in the strategic plan and business operations of an enterprise by providing political, economic, and social resources [76]. It includes direct investment, the establishment of relevant funds, the formulation of privilege policies, and the provisioning of specific guidance. SMEs have weak funds, poor fund-raising capabilities, and poor risk resistance, whereas government support can be regarded as a form of social capital that can help enterprises overcome problems such as resource shortages [77]. To accelerate the development of science and technology, many countries have issued relevant policies to promote the development of the cloud computing industry and provide financial support for some cloud computing projects. For example, the State Council of China issued the "Opinions on Promoting the Innovative Development of Cloud Computing and Cultivating New Types of Information Industry" in January 2015, and the Ministry of Industry and Information Technology issued the "Three-year Action Plan for Cloud Computing Development (2017–2019)" in April 2017. Some enterprises that have successfully adopted cloud computing will be rated as benchmark enterprises, with improved social reputation and social status, as well as receiving more political, economic, and social resources [78]. Therefore, with the government's support, companies can establish a good corporate image by adopting cloud services, and to a certain extent, gain more economic and social benefits. Given this, government support is considered an essential factor that influences enterprises to adopt cloud services.

3.2.4. Provider Context. With the development of cloud services and an understanding of cloud services of an enterprise, an increasing number of cloud service providers have been adjusting and improving their related technologies to attract enterprises to adopt cloud services [40]. Furthermore, as an increasing number of enterprises adopt cloud services, cloud service providers are emerging in the market. Therefore, we also consider the factors of the cloud providers and believe that their capability is also an essential factor for enterprises to consider when making cloud service adoption decisions.

(i) Provider Capability. Cloud provider capabilities refer to the technical service capabilities of the provider and the management service capabilities required to virtually complete work tasks in specific areas, such as computing capabilities, the ability to reasonably take security measures and disaster recovery measures, and the ability to standardize service standards [41, 63, 79, 80]. Cloud service providers with higher capabilities can usually better protect the private data of an enterprise and achieve higher technological advancement and service standardization. In the

face of such cloud service providers, enterprises will be more inclined to adopt cloud services to improve the operational efficiency, the security of enterprise data, and the standardization of business processes, and reduce costs in all aspects of the enterprise. Therefore, we believe that the capabilities of cloud providers affect the adoption of cloud services by an enterprise.

4. Methodology

4.1. Data Collection. The variables in this study were measured using a 5-point Likert scale. To ensure the reliability and validity of the scale, the measurements of the variables should refer to existing mature scales as much as possible, while comprehensively considering the context of Chinese enterprises adopting cloud services. Because some of the reference items were originally in English, according to the translation and back-translation procedures, the students of this major translated the English items into Chinese, and then several master's students back-translated the items into English. This process ensured the accuracy of the questionnaire translation through a comparison. We contacted organizations such as the Shandong CIO Union to invite their members to help us fill out the questionnaires. These enterprises have a relatively high degree of informatization, and 240 questionnaires were distributed to enterprises in China through an online survey by Wenjuanxing (http://www.wenjuan.com). The questionnaires were filled out by grassroots/middle-level/senior managers of the enterprise information department. A total of 123 valid questionnaires were returned, with an effective recovery rate of 51.25%. The descriptive statistics of the sample are shown in Table 2.

4.2. Reliability and Validity Measures. We used Smart PLS software (version 3.0) to conduct a partial least squares analysis on the data. Reliability describes the internal consistency of the measurement results. Reliability testing was measured using Cronbach's α (CA) and composite reliability (CR). Through a calculation, the CA and CR values of each variable are greater than 0.7, and 0.8, respectively, indicating that each variable has good internal consistency and that the measurement model has good reliability. Validity includes content validity and construct validity, and construct validity is measured by convergent and discriminant validity. Convergent validity is used to judge whether different observed variables can be used to measure the same latent variable. The criterion is the average variance extracted (AVE) of the latent variable and the factor loading of the construct. Through the calculation, all AVE values and factor loading values are greater than 0.5, and 0.7, respectively, indicating that the measurement model has a good convergent validity. Discriminant validity refers to whether there are significant differences between latent variables. If the square root of the average variance extracted from a variable is greater than the correlation coefficient between the variable and the other variables, the discriminant validity of this variable is good. The calculation shows that the measurement model has high discriminant validity.

4.3. QCA and Data Analysis. Traditional statistical methods (e.g., regression analysis) mainly study the net effect of independent variables on dependent variables, and it is difficult to explain the interdependence between independent variables. With a qualitative comparative analysis (QCA), which is a case-study-oriented method, it is believed that the result occurs based on the interaction of related elements. The combination of each element is called the configuration [81–84]. A QCA is divided into two methods: a clear-set QCA and a fuzzy-set QCA. The value of a variable in a clear-set QCA is zero or 1, and in a fuzzy-set QCA, it is a real number between these same values. Because fsQCA is more distinguishable than a clear-set QCA, fsQCA was used in this study [83]. Similar to the significance level and coefficient of determination in a regression analysis, fsQCA uses the consistency and coverage proposed by Ragin to test the relationship between independent and dependent variables. Consistency can be used to determine whether an independent variable is a sufficient or necessary condition for a dependent variable [82]. When the consistency is greater than 0.8, the independent variable X is considered a sufficient condition for the dependent variable Y, and when the consistency is greater than 0.9, the independent variable X can be considered as a necessary condition for the dependent variable Y. Coverage reflects the explanatory degree of the model. Based on this, we select the relative advantage, perceived security risk, top management support, IT capability, competitive pressure, government support, and provider capability to study the interaction mechanism between variables. A complete QCA analysis process includes a theoretical analysis and the extraction of antecedents, data collection, variable recalibration, selection of case frequency and consistency thresholds, construction of a truth table, a standardized QCA, and the reporting of results using QCA symbols.

We first need to calibrate the measured variables and convert them into sets [81]. The calibration of variables requires three thresholds to be set based on theoretical knowledge and actual conditions: a full-membership threshold, an intermediate membership threshold, and a full nonmembership threshold. The eight variables selected in this study were measured using 2–4 items. The score of each variable for each item was obtained according to the 5-point Likert scale scoring standard, and the average score of each variable was calculated as the final score. We set the maximum and minimum scores of each variable as the full-membership threshold and full nonmembership threshold, respectively. The mean values of the scores were set as the intermediate membership threshold for variables with little difference between the mean and median scores. The mean and median scores of some variables were significantly different, whereas the median scores were 4.33, the samples with a score of 4.33 are more than 20% of the total sample. Therefore, the intermediate membership thresholds of these variables need to be set to 4.32–4.34. If the intermediate membership threshold of these variables is set to 4.32, it will lead to a calibrated data distribution. Therefore, the intermediate membership threshold of these variables was set to 4.34. By setting the three thresholds, fsQCA converts the scores of these variables into fuzzy scores between zero and 1.

Table 2: Descriptive statistics.

Characteristic		Frequency	Percentage
Position	CIO/CTO/IT department manager	67	54.47
	Other managers of the IT department	56	45.53
Industry	Mining industry	21	17.07
	Electricity, heat, gas, and water production and supply	5	4.07
	Real estate	1	0.81
	Construction business	1	0.81
	Transportation, storage, and postal industry	7	5.69
	Financial industry	7	5.69
	Wholesale and retail	11	8.94
	Water conservancy, environment, and public facilities management industry	2	1.63
	Culture, sports, and entertainment industry	2	1.63
	Information transmission, software and information technology service industry	59	47.97
	Manufacturing	5	4.07
	Leasing and business services	1	0.81
	Scientific research and technical service industry	1	0.81
Enterprise size	21–50	10	8.13
	51–100	18	14.63
	100–200	35	28.46
	More than 200	60	48.78
Enterprise age	2–5	21	17.07
	6–10	47	38.21
	11–20	43	34.96
	More than 20	12	9.76
Annual turnover (RMB)	1010000–5000000	7	5.69
	5010000–10000000	14	11.38
	10010000–50000000	34	27.64
	50010000–100000000	29	23.58
	100000000–300000000	15	12.20
	300000000–500000000	11	8.94
	500000000–1000000000	4	3.25
	More than 1000000000	4	3.25
	Inconvenient to disclose	5	4.07
Number of IT staff	Less than 5	9	7.32
	5–10	33	26.83
	11–20	30	24.39
	More than 20	51	41.46
IT annual investment budget	Less than 1000000	19	15.45
	1000000–10000000	75	60.98
	10000000–100000000	16	13.00
	More than 100000000	5	4.07
	Inconvenient to disclose	7	5.69
	Not clear	1	0.81

After the data calibration, fsQCA 3.0 was used to analyze the truth table. After deleting the cases with frequencies of zero and 1, and a consistency of less than 0.8, 76% of the samples were retained, and a standardized analysis was used to identify the antecedent configuration of enterprises adopting the cloud services. The QCA analysis results report three solutions: complex, intermediate, and parsimonious solutions. The conditions that appear in both the parsimonious and intermediate solutions are the core conditions, whereas the conditions that only exist in the intermediate solution are peripheral. In addition, variables with a consistency of greater than 0.9 are necessary conditions, and must be the core conditions. The core condition has a strong causal relationship with the outcome, and the peripheral condition has a weaker relationship.

5. Results and Discussion

5.1. Analysis of Necessity. We tested the necessary conditions for the presence of cloud service adoption. For cloud service adoption, the consistency values range between 0.41 and 0.87 for both the presence and negation of the casual conditions.

No single condition on its own leads to cloud service adoption because none of the casual conditions exceeds a value of 0.9. Thus, we proceed with a fuzzy-set analysis to identify sufficient combinations of casual conditions that explain the cloud service adoption. The results of the analysis of the necessary conditions are presented in Table 3.

Table 3: Analysis of necessary conditions.

	Consistency	Coverage
fzRA	0.827	0.765
~fzRA	0.481	0.688
fzPSR	0.603	0.749
~fzPSR	0.775	0.795
fzTMS	0.846	0.824
~fzTMS	0.535	0.709
fzIT	0.865	0.851
~fzIT	0.524	0.686
fzCP	0.810	0.834
~fzCP	0.540	0.666
fzGS	0.786	0.792
~fzGS	0.556	0.704
fzPA	0.875	0.750
~fzPA	0.412	0.671

5.2. Analysis of Sufficiency. The findings from fsQCA on the configurations for cloud service adoption by SMEs are presented in Table 4.

The solutions were grouped according to the core conditions. Every combination in the solution can explain the same outcome at a specific amount. Consistency values are presented in Table 4 for each solution as well, with all values being higher than the recommended threshold (>0.75). Consistency shows the degree to which the relationship has been approximated, and coverage evaluates the empirical relevance of a consistent subset. The overall consistency was similar to the correlation showing the robustness of the solution. The overall solution coverage indicates the extent to which a high satisfaction may be determined from the existing configurations and is comparable to the R-square value reported in traditional regression analyses. The overall solution coverage of 0.74 indicates that the six solutions explain 74% of the outcome.

Furthermore, fsQCA computes the empirical relevance for each solution by calculating the raw and unique coverage. The raw coverage describes the amount of the outcome explained by a certain alternative solution, whereas the unique coverage describes the amount of the outcome that is exclusively explained by an alternative solution. The coverage of each configuration was greater than zero. Thus, all configurations are empirically relevant.

For cloud service adoption by SMEs, solutions 1–6 present combinations for which the examined factors may be present or absent, depending on how they combine with each other.

5.2.1. Solution 1. In configurations 1a–1c, government support is the core condition and is present, which means that enterprises with political, economic, and social resources provided by the government are more inclined to adopt cloud services. Moreover, in configurations 1a–1c, top management support, IT capability, and competitive pressure are peripheral conditions and are absent, indicating that government support is particularly important for enterprises with unclear support of the top management, incomplete IT technology, and no significant pressure from competitors in the same industry to adopt cloud services. In addition, the relative advantage and provider capability in configuration 1a are peripheral conditions and absent, whereas perceived security risk is an irrelevant condition. In configuration 1b, perceived security risk is a core condition and is present, and the provider capability is a peripheral condition and absent, and a relative advantage is an irrelevant condition. For configuration 1c, perceived security risk is a peripheral condition and is present, and a relative advantage is a peripheral condition and is absent, whereas the provider capability is an irrelevant condition. It can be seen from configurations 1a–1c that government support has a significant influence on the decision of an enterprise to adopt cloud services. For enterprises supported by the government, even if other conditions affecting the adoption of cloud services are incomplete, it is easier for them to incorporate cloud services into the decision of the enterprise operation and management. These solutions explain the cloud service adoption of SMEs at rates of 23.5%, 23.7%, and 27.2%.

5.2.2. Solution 2. In configurations 2a and 2b, relative advantage, IT capability, and provider capability are the core conditions. This means that the feeling regarding a cloud service can bring about a relative advantage, having a complete IT capability, and for cloud providers with high technology and management service capabilities, enterprises are more inclined to adopt their services. Cloud services, enterprises, and cloud providers, as the three central bodies, all play a vital role in the process of enterprise adoption of cloud services. Only when the three complement and cooperate with each other can they further encourage enterprises to adopt cloud services. Furthermore, in configurations 2a and 2b, government support is the peripheral condition and is absent, indicating that as long as the relative advantages of the cloud services are sufficient, the IT capability of the enterprise is sufficient, and the cloud provider's capability is sufficient to support the provisioning of high-quality cloud services. Even if there is no government financial support, enterprises will also adopt cloud services because of the high performance, versatility, and high efficiency of the cloud platform. In addition, in configuration 2a, top management support is a peripheral condition and is present, and the perceived security risk is a peripheral condition and is absent. In addition, the competitive pressure is an irrelevant condition; in configuration 2b, perceived security risk is a peripheral condition and is present, and top management support and competitive pressure are peripheral conditions and are absent. It can be seen from configurations 2a and 2b that the relative advantages of cloud services and cloud service provider capabilities significantly impact the adoption of cloud services

Table 4: FsQCA analysis results.

	Cloud service adoption by SMEs								
	1			2		3	4	5	6
	1a	1b	1c	2a	2b				
RA	⊗		⊗	●	●	●	⊗	●	⊗
PSR		●	●	⊗	●		⊗	●	●
TMS	⊗	⊗	⊗	●	⊗	●	⊗	●	●
IT	⊗	⊗	⊗	●	●	●	⊗	●	●
CP	⊗	⊗	⊗		⊗	●	⊗	⊗	⊗
GS	●	●	●	⊗	⊗	●	⊗	⊗	●
PA	⊗	⊗		●	●	●	●	⊗	⊗
Consistency	0.786	0.833	0.861	0.946	0.952	0.982	0.883	0.932	0.945
Raw coverage	0.235	0.237	0.272	0.418	0.269	0.558	0.254	0.210	0.208
Unique coverage	0.004	0.004	0.008	0.033	0.013	0.185	0.008	0.013	0.005
Solution coverage					0.740				
Solution consistency					0.842				

Black circles ("●") indicate the presence of a condition, and circles with a cross-out ("⊗") indicate the absence of a condition. Furthermore, large circles indicate core conditions, and small circles indicate peripheral conditions. Blank spaces indicate a "do not care" situation in which the causal condition may be either present or absent.

by enterprises. Therefore, cloud service providers should strive to improve their service capabilities and make enterprises deeply feel the relative advantages of cloud services, such that more enterprises will willing adopt cloud services. These solutions explain the cloud service adoption of SMEs at rates of 41.8% and 26.9%, respectively.

5.2.3. Solution 3. In configuration 3, the relative advantage, IT capability, government support, and provider capability are core conditions and are present, top management support and competitive pressure are peripheral conditions and are present, and perceived security risk is an irrelevant condition. This configuration shows that for enterprises with relatively complete IT capabilities, the government support, higher cloud service provider capabilities, and perceived advantages of cloud services will make enterprises more willing to adopt cloud services. In the discussion of configuration 1, it can be seen that government support can promote enterprises to adopt cloud services; in the discussion of configuration 2, it can be seen that the relative advantages of cloud services, the IT capabilities of enterprises, and the capabilities of cloud providers can jointly promote the adoption of cloud services by enterprises. Therefore, if an enterprise with relatively complete IT capability chooses a cloud service provider with strong technical service capabilities and management service capabilities and feels the relative advantages of cloud services, it will undoubtedly make a decision to adopt cloud services with the strong support of the government. This configuration further illustrates the vital role that the government plays in promoting the adoption of cloud services by an enterprise. In addition, top management support and competitive pressure in configuration 3 are peripheral conditions and are present, which means that full understanding and trust of cloud services from top management, the resources allocated to cloud services, and the pressure brought by industry competitors will promote the adoption of cloud services by enterprises to a certain extent. This solution explains cloud service adoption of SMEs at a rate of 55.8%.

5.2.4. Solution 4. In configuration 4, provider capability is the core condition and is present, and the relative advantage, perceived security risk, top management support, IT capability, competitive pressure, and government support are peripheral conditions and are absent. This indicates that as long as the technical services and management services capability of the cloud service provider are mature and sufficiently trustworthy, even if there are no other conditions that promote the adoption of cloud services by an enterprise, the enterprise will also be willing to entrust the cloud service provider with the implementation of work related to cloud services, deploy websites and systems to the cloud service platforms, and allow cloud service providers to provide service deployment, service choreography, cloud service management, and security and privacy protection for the enterprise. In addition, perceived security risk is the peripheral condition and is absent, indicating that enterprises do not perceive that cloud services will bring risks to the organizational performance under the condition of strong cloud service providers, which will further promote enterprises to adopt cloud services. This solution explains cloud service adoption of SMEs at a rate of 25.4%.

5.2.5. Solution 5. In configuration 5, relative advantage and IT capability are core conditions and are present; perceived security risk and top management support are peripheral conditions and are present; and competitive pressure, government support, and provider capability are peripheral conditions and are absent, indicating that for enterprises with complete IT capabilities, if they feel that the cloud service will bring relative advantages for the enterprise, they will tend to adopt such services. Top management support is a peripheral condition and is present, indicating that enterprises with top management who support cloud service adoption decisions will be more willing to adopt cloud services. Compared with configuration 2b, it can be seen that even if the enterprise is not overly confident in the technical service ability and management serviceability of the cloud service provider, it is possible to adopt cloud services to take advantage of its relative advantages to improve their business performance and operating efficiency. This is because the top management can feel that the cloud service will bring advantages to the enterprises and be willing to actively participate in the development of the cloud services strategy. Other peripheral conditions indicate that, regardless of whether the enterprise feels competitive pressure, receives government support, perceives the risks that cloud services will bring, or has a capable cloud service provider, as long as the cloud service brings obvious relative advantages to the enterprise, which has relatively strong IT capability, it will adopt the services. This solution explains the cloud service adoption of SMEs at a rate of 21%.

5.2.6. Solution 6. In configuration 6, IT capability and government support are core conditions and are present, and perceived security risk and top management support are peripheral conditions and are also present. Relative advantage, competitive pressure, and provider capability are peripheral conditions and are absent, indicating that the IT capability of the enterprise is relatively complete. The enterprise is supported by the political, economic, and social resources of the government for adopting cloud services, and will adopt the cloud services. Top management support is a peripheral condition and is present, indicating that the top management is willing to allocate resources to implement cloud services and encourage employees to use cloud services, which will further promote the adoption of cloud services by an enterprise. Other peripheral conditions indicate whether the enterprise perceives the relative advantages or security risks that the cloud services will bring, whether it feels competitive pressure, and whether the capabilities of the cloud service providers are complete; in addition, as long as the enterprise has high IT capabilities and is supported by the government, it will be confident to adopt cloud services owing to the “cloud service coupons” (financial cloud service subsidies) issued by the government. This solution explains the cloud service adoption of SMEs at a rate of 20.8%.

6. Conclusion

To survive in a competitive environment, SMEs have had to adapt to the digital environment and adjust to customer needs globally, particularly in a post-COVID-19 world. The advantages of cloud computing (e.g., flexibility, scalability, and low entry cost) provide opportunities for SMEs with a restricted budget and limited resources. Small businesses can improve their operations and productivity enormously by moving to the cloud. Doing so will increase their revenue, thereby setting them ahead of the competition. To accelerate the digital transformation of SMEs and promote the development of the cloud computing industry, it is of great significance to explore ways to encourage SMEs to adopt cloud computing and make relevant and targeted measures.

SMEs need to consider multiple factors when incorporating cloud service adoption into their business management decisions. We argue that different combinations (or configurations) of multiple antecedents can explain SMEs’ adoption of cloud services. To identify such combinations, we build on complexity and configuration theories, propose a conceptual model that includes seven antecedents (i.e., relative advantage, perceived security risk, top management support, IT competence, competitive pressure, government support, provider capability), and use fsQCA (asymmetric) to identify nine configurations for the adoption of cloud service.

The findings show that government support is present in three out of six solutions and always as a core factor, suggesting that it plays a critical role in driving SMEs to adopt cloud services. The Chinese government, particularly local governments, can significantly influence the business decisions of an enterprise. The government usually formulates policies conducive to a particular business in specific regions and industries, or issues policies for enterprises of a specific size and ownership type. If necessary, the government may even provide financial support to enterprises to encourage them to comply with government guidelines. Cai et al. [76] proposed that government support can promote enterprises to integrate the supply chain information, reflecting the influence of government support on enterprise decision-making.

Our findings also show that provider capability is present in three out of six solutions and always as a core factor, indicating that the strong technical service capabilities and management service capabilities of a cloud service provider can encourage an SME to adopt its cloud services. Indeed, Liang et al. [41] proposed that the capability of a cloud provider can affect the cloud provider support and thus the adoption of an e-government cloud, but it has not proven to have a significant promoting effect. Fu et al. [85] pointed out that the ability of a cloud service provider will affect the adoption of cloud computing by an enterprise, although research results have shown that this is not an extremely important factor. However, in this study, provider capability is present as the core condition in the three configurations, indicating that this factor has an essential effect on the adoption of cloud services of an SME.

In addition, our findings show that a relative advantage is present in three out of six solutions and is always a core factor. Many studies prove that the relative advantage can significantly promote the adoption of cloud services by an enterprise [23, 28]. The results of this study confirm this conclusion. Therefore, cloud service providers should continuously strive to improve the quality of their services, and thus enterprises can further feel the relative advantages of cloud services, such as flexibility, scalability, low entry, and computing cost.

Finally, our findings show that IT competence is present in four out of six solutions and is always as a core factor, suggesting that it plays a critical role in driving SMEs to adopt cloud services. Oliveira et al. [23] and Martins et al. [36] proposed and proved that technology competence could significantly positively influence SaaS adoption by enterprises. The results of this study further indicate that the IT capabilities of an enterprise play an essential role in promoting the adoption of cloud services. Enterprises should strive to improve their own IT capabilities, increase investment in IT hardware and software, and improve the quality of the IT staff to prepare for the adoption of cloud services at any time.

6.1. Theoretical Implications. In the context of the country using cloud computing as a development strategy, we need to increase our understanding of SME adoption and investigate internal factors and how they lead to more adoptions. Our findings identify multiple combinations that explain cloud service adoption in SMEs and offer two main contributions.

This study systematically sorted the latest research on the factors that affect cloud service adoption through a literature review. After such sorting, it was found that the existing literature mostly uses the TOE framework, DOI theory, and technology acceptance model as the theoretical basis when proposing research models, and mostly uses partial least squares (PLS), regression analysis, and structural equation modeling (SEM) as research methods. In recent years, after some theoretical frameworks have become more mature, and more research methods have gradually emerged, no research has specifically reviewed the latest studies on the factors affecting cloud service adoption. The combined effort in the study can help scholars find the research gap in this type of research, explore more factors that affect the adoption of cloud services, establish a more scientific and systematic research model based on existing research, and conduct innovative research in this field.

Another theoretical implication of this study lies in the innovative use of new research methods. We use fsQCA in the research field of factors that influence enterprises to adopt cloud services. Existing studies have mostly used PLS, regression analysis, and SEM to explore the factors affecting the adoption of cloud services of an enterprise. These methods assume that the relations between variables are symmetric [86, 87], but the relations can also be asymmetric in real life. These methods are also dedicated to studying the independent effects of independent variables on dependent variables, although the relationship between independent variables in real life is often interdependent, and they will work together to lead to specific results. This situation occurs when SMEs make cloud service adoption decisions. They often need to consider multiple factors to decide whether to adopt a cloud service, and these factors often exist simultaneously and affect the decision-making. In addition, the research of relevant scholars also shows that there is a causal asymmetry in an enterprise adoption of cloud services; for example, Tashkandi and Al-Jabri [28] pointed out that the relative advantage of cloud services has a significant positive impact on cloud service adoption, whereas Low et al. [5] verified a significant negative impact. Building on complexity and configuration theories, fsQCA can capture the causal asymmetry between many factors and the adoption of cloud services by an enterprise, resulting in new research models and theories. Based on the TOE framework, this study uses fsQCA to study the joint effects of the relative advantage, perceived security risk, top management support, IT capability, competitive pressure, government support, and provider capability on the adoption of cloud services, and identifies nine paths that lead an enterprise to adopt cloud services. This study innovatively uses the fsQCA to expand the conclusions of existing research, and at the same time, will provide researchers with a new way to think and operate tools to continuously enrich the research in this field.

In addition, this research enriches the application of QCA in the field of management. In the management area, existing studies have used the QCA method in human resource management, innovation management, international business, entrepreneurial management, knowledge management, corporate governance, social responsibility, stakeholder management, strategic management, organizational design, project management, and marketing management; however, no scholars have used the QCA method in the field of enterprise adoption of cloud services. This study uses fsQCA to explore the nine paths that will lead enterprises to adopt cloud services, which opens up new areas for applying the QCA method, further enhancing the understanding of this method for management scholars, and promoting the development of management theory.

6.2. Practical Implications. The results of this study have important guiding significance and enlightenment for enterprise management practitioners. With the in-depth development of cloud computing technology, cloud service providers have landed and officially commercialized both at home and abroad, and the term “cloud” has become the norm for corporate development. Particularly since the outbreak of COVID-19 in early 2020, the Ministry of Industry and Information Technology of China has required the use of cloud computing and other technologies to help enterprises resume work and production. Cloud services can drive process and business innovations and become a new profit growth point for enterprises. However, in the face of the state promotion of enterprises to adopt cloud services and the benefits that cloud services can bring to them, some enterprises have still refused to adopt cloud services owing to a weak awareness and the security issues of cloud services. This study identified nine paths that lead enterprises to adopt cloud services. The results will provide relevant practical guidance for governments, cloud service providers, and enterprises to promote the adoption of cloud services, thereby enhancing the leading position and firm competitiveness of the cloud computing industry in China.

First, the research results show that government support is present as a core factor in three out of six solutions, indicating that it plays a vital positive role in the adoption of cloud services by enterprises. Therefore, to promote the use of cloud computing to accelerate the digitalization, networking, and intelligent transformation of enterprises, and to promote the development of the cloud computing industry, governments at all levels should correctly and rationally understand the development path of cloud services and scientifically promote the adoption of cloud services by enterprises. Thus, we propose two specific suggestions for governments.

On the one hand, the government should strengthen the infrastructure of cloud services, formulate more preferential policies, and increase support for enterprises to adopt cloud services. At present, to promote the coordinated development of industries and maximize the creation of corporate value, China has successively formulated and promulgated the "Industrial Internet Plat-form Construction and Promotion Guidelines," "Promoting Enterprise Cloud Implementation Guidelines (2018–2020)," and other policy documents to help SMEs adopt cloud services. In the future, the government should strictly implement the content of the document and put forward more innovative opinions. Meanwhile, the government can set up a team of experts to provide policy interpretation services and legal support to enterprises.

On the other hand, the government should give priority support to enterprises that lack complete IT capabilities and top management support for cloud service adoption, providing them with relevant policy guidance and technical support. This is due to IT capability, and top management support is a peripheral condition and is absent in configuration 1. An expert team can also be organized to provide training to the IT employees of such enterprises, such as educating them on how to comprehend and use cloud services, or how to choose cloud service providers. Furthermore, cloud service "coupons" should be issued to these enterprises to fully promote the application of cloud services and give full-play to the positive role of such services in enterprise operation and management.

Second, provider capability is present in three out of six solutions and is always as a core factor, suggesting that it is an essential subject in the process of enterprises adopting cloud services. Therefore, cloud service providers can not only help enterprises improve their IT architecture and achieve business growth but also reduce the pressure on enterprise operation and maintenance through high-quality services. To attract more SMEs to adopt cloud services, cloud service providers should continuously improve their technical service capabilities and management service capabilities and achieve higher technological advancement and service standardization, thereby improving the stability, security, and availability of the cloud platform infrastructure. These measures can further enhance their relative advantages. They should enhance their own ability to protect user data security by building a data security capability scale, full life cycle security capability requirements, and data security capability dimensions; thus, enterprises can safely outsource their work related to cloud services to cloud service providers. At the same time, the providers should provide good after-sales services to enterprises that have already adopted cloud services to increase their satisfaction with cloud services and form a word-of-mouth effect.

Third, because IT capability is a core condition and is present in four out of six solutions, enterprises should focus on building their own IT capabilities, increase investment in IT hardware and software, deploy a good IT environment and essential software and hardware facilities, attach importance to the development of IT departments, and form excellent IT teams to support enterprises in applying cloud services better, thereby promoting the construction of enterprise informatization. At the same time, top management of the enterprises should promote and popularize cloud services, actively participate in the formulation of the cloud service vision and strategy, improve the ability of employees to accept new technologies, and focus on the promotion of IT department managers. This will provide a solid foundation for enterprises to deploy cloud services, accelerate innovation, and reduce costs to ensure that enterprises remain competitive in the wave of industry adoption of cloud services.

6.3. Limitations and Directions for Future Work. As a limitation of this study, the number of factors considered was relatively small. Only seven factors were studied on the joint effect of enterprise adoption of cloud services. In addition, the research object of this study was only SMEs in China. Because the sample selection is restricted by region and scale, the universality of the nine configurations that can enable enterprises to adopt cloud services obtained in this study needs to be further explored and analyzed. Based on this research, in the future, we will use the QCA method to study other factors that lead enterprises to adopt cloud services and expand the scope of research objects to enterprises in Asia, further increasing the breadth and depth of this research.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Research Article

Spatial Spillover Effect of Government Public Health Spending on Regional Economic Growth during the COVID-19 Pandemic: An Evidence from China

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The COVID-19 pandemic, which was first reported at the end of 2019, has had a massive impact on the Chinese economy and society. The pandemic has seriously tested the emergency management capabilities of the Chinese government regarding public health. Based on the panel data of 31 provinces in China for the period of 2006–2019, this paper examines the impacts of government public health spending on regional economic growth. Furthermore, the possibility of spatial spillover effects of government public health spending is investigated through spatial econometric analysis. Government public health spending and regional economic growth have significant positive spatial correlation and spatial agglomeration effects. The indicator of government public health spending significantly promotes regional economic growth. In addition, it significantly promotes the economic growth of neighboring areas through certain spatial spillovers.

1. Introduction

The COVID-19 pandemic was first reported in Wuhan, Hubei Province, China, in December 2019 and has subsequently placed pressure on both economic and social conditions. The resulting recession could be the deepest since World War II. Economic growth has weakened due to trade tensions between the US and China that preceded the transmission of COVID-19 [1]. The pandemic also poses a serious threat to human health and life, resulting in negative economic growth in the first quarter for the entirety of China. As of 19 June 2020, the number of COVID-19 confirmed cases was 83,299. The pandemic has also tested the Chinese public disease prevention and control system. The Chinese government has launched a first-level emergency plan to address this disaster. A large number of medical staff and large quantities of medical instruments were sent to Hubei Province and the city of Wuhan. There are many similarities between COVID-19 and SARS in 2003. Both are highly contagious diseases that can be transmitted by respiratory droplets [2]. Both diseases have also affected the formulation of public health policies. Thus, it is important to establish a strong public health and epidemic prevention system to address public health emergencies and ensure that the economy is running well.

Despite the initial responses, several disadvantages remain after the outbreak of the pandemic. The mechanism of reporting the disease was not smooth at the beginning of the pandemic. Preventive and health care measures remain imperfect. Government public health spending is unreasonable, and institutions are not well prepared with medical supplies. Nonetheless, some traditional economically powerful provinces, such as Jiangsu, Zhejiang, and Guangdong, implemented first-level responses to public health emergencies during the first outbreak to improve the cure rate, reduce the mortality rate, and resume production and work. The formulation and implementation of public health policy are related to the improvement of people's livelihood and the increase of people's physical well-being, which affects the level of national education and skills [3]. In the last decade, China has become the second-largest economy in the world. Its comprehensive national strength has significantly improved, and life expectancy has increased. Government public health spending has played an important role in Chinese economic growth and in building a well-off society. The policy "Healthy China 2030 Plan Outline," released by the Fifth Plenary Session of the 18th Central Committee of the CPC, puts forward the strategic theme of coconstruction/sharing and national health to comprehensively improve the health level of all the nation's people and promote the accumulation of healthy human capital in China. In the ongoing COVID-19 pandemic, it is currently very meaningful to study the impact of public health expenditure on economic growth.

In this paper, we focus on the key points: whether the government public health spending of provincial regions in China has changed, whether the contribution to regional economic growth has significantly improved, and whether there is a spatial spillover effect of government public health spending.

2. Literature Review

Against the background of the Chinese new normal economy, the promotion of sound and rapid economic development has been studied from different perspectives. From the perspective of industrial capital, public health spending, fixed asset investment, and technological innovation are conducive to the formation of industrial agglomeration, which promotes economic development. From the perspective of human capital, the reasonable distribution of medical and health resources can effectively promote human health quality and indirectly improve labor production efficiency, which improves the economic growth rate. From the macroeconomic level, the health factor is the catalyst of economic growth. Barro [4] established a health demand model based on the three elements of health factors, education investment, and material capital and analyzed the role of these factors in promoting economic growth. Grossman [5] introduced health capital as an endogenous variable into the health demand model and analyzed the contribution of health as a utility function and a production function in the model. From the microeconomic level, government spending on health care can well control the level of human capital. Newhouse [6] confirmed that government spending on public health has played a significant role in GDP growth. Mushkin [7] proposed that increasing public health spending easily forms healthy human capital, thus forming high-efficiency economic output.

From the perspective of empirical analysis, Narayan et al. [8] used panel data of Asian countries from 1974 to 2007 to conduct cointegration analysis on government public health spending and GDP growth, indicating that government public health spending significantly promotes per capita GDP growth. Du et al. [9] established the distribution lag model of government health expenditure and concluded that the influence coefficient of government health input on the national economy is 0.42% and that government health input makes a clear contribution to economic growth. Bernet and Singh [10] built models of operating efficiencies for 5 core public health activities to analyze economies of scale. They concluded that consolidation or regionalization might lower the cost per unit for select public health activities, which can further improve the public's health. Man et al. [11] introduced a time series model that used per capita GDP and per capita total health expenditure from 214 countries and regions in the world. The empirical analysis indicated that the influencing factors of per capita GDP should be more detailed. Mujtaba et al. [12] used panel data from 28 OECD economies from 2002 to 2018 to test the influence of environmental pollutants, economic growth, and public health. They concluded that investment in renewable energy can improve healthcare and promote economic growth. Moti and Goon [13] examined the intricate balance between health and the economy during the breakout of the COVID-19 pandemic with an econometric model. Based on the results, they gave some policy options and strategies to implement to protect health and promote economic recovery. Aisa and Pueyo [14] established an endogenous growth model and confirmed, with relevant data from developed countries, that government public health spending has a significant negative effect on economic growth. Eggoh et al. [15] selected data from typical Asian countries and used a dynamic panel model to construct a growth model. They found that government health expenditure is not conducive to promoting economic growth and, in fact, has a reverse effect on economic growth. Liu and Zhang [16] constructed a panel data model to empirically analyze data from 31 provinces in China and concluded that the indirect production expenditure in public health input has a negative effect on economic growth. In the selection of econometric models, most studies use the ordinary panel data model and fail to refine the indicators of public health spending when selecting explanatory variables. Some studies are measured by the total volume. However, the factors of economic growth cannot completely rely on total volume, and the influence of per capita factors should be considered. Moreover, the formulation of government public health policies is also affected by population factors. There is a spatial spillover effect on the surrounding provinces. Based on the above analysis, this paper intends to refine some indicators and investigate the spatial effect of public health spending on economic growth.

Tao and Wang [17] analyzed the mechanism of government public health spending and economic growth and pointed out that government public health spending directly and indirectly affects the level of economic development by improving the quality of workers, increasing social fixed capital investment, and improving the abilities of scientific and technological innovation. Therefore, government public health spending not only reflects the attention of the local government to medical care and health but also, to a certain degree, reflects the level of medical service and residents' health awareness [18]. This paper examines the impact of public health input factors on economic growth, including the following three issues: whether there is spatial autocorrelation between public health spending and economic growth, whether the spatial spillover effect of public health spending on economic growth is significant, and which factors related to national health quality exert a significant impact on economic growth.

3. Methodology

3.1. Model Specification. Most of the existing studies consider an ordinary panel data model to construct their methodology, although some also consider a dynamic panel data model with a lag effect. The traditional panel data model usually assumes that the data from different sectors should be independent. However, this assumption is not true for the research object of this paper. There is a spatial dependence between public health spending and economic growth, so it is necessary to introduce a spatial econometric model. The advantage of this approach is that the estimation result is more effective if the spatial-temporal characteristics are fully considered. There is obvious path dependence between government public health spending and regional economic growth [19]. Therefore, to accurately grasp the impact of government public health spending on regional economic growth, it is necessary to choose the spatial econometric model. The formula of spatial econometrics can be expressed as follows:

$$Y_{i,t} = \rho WY_{i,t} + X_{i,t}\beta + WX_{i,t}\theta + \mu_i + \gamma_t + \varepsilon_{i,t}. \quad (1)$$

In this formula, ρ is the spatial autocorrelation coefficient, W is the spatial weight matrix, WY, WX are spatial lag terms, and $\varepsilon_{i,t}$ is the error term satisfying $\varepsilon_{i,t} \sim N(0, \sigma^2 I_n)$. There are three types of spatial econometric models: the spatial autoregressive model (SAR), spatial error model (SEM), and spatial Durbin model (SDM).

3.2. Variable Selection. Per capita GDP is an important indicator to measure the level of economic growth and is selected as the explained variable. According to the results of the existing literature [20–23], to quantify the emphasis of government on public health, this paper selects government public health spending as an explanatory variable. Furthermore, as noted by Hazwan [24], there are many ways to capture human capital. For example, Barro [4] used a combination of the enrollment rate, life expectancy, and birth rate as proxies for human capital. Li and Huang [25] pointed out that human resources related to public health must be considered. They suggested using the number of medical staff as a proxy for human capital. As an important factor of the economic system, the birth rate has a long-term, stable relationship with economic development. The increase in birth rate can optimize the Chinese population structure and improve the overall quality of the whole population [26]. Before the full liberalization of the Chinese two-child policy in 2015, most research conclusions showed a negative correlation between birth rate and economic development. However, with the adjustment of population policy, the demographic dividend has transformed again into the engine of economic growth, thereby promoting economic growth. At the same time, the continuous promotion of urbanization has resulted in increasingly substantial investment in infrastructure construction in China. Such investment directly affects the national physical quality, education level, and scientific and technological innovation, which indirectly affect the development of the regional economy. Some results have shown that the urbanization rate plays a clear role in promoting economic growth [27]. To fully reflect healthy resources, following [20, 24, 28], fixed investment, human capital, medical scale, urbanization, and population size are chosen as control variables. The symbols and descriptions of each variable are shown in Table 1.

3.3. Data Sources. The original panel data of 31 provinces in China from 2006 to 2019 are chosen from the *China Science and Technology Statistical Yearbook*, *China Health and Family Planning Statistical Yearbook*, *China Statistical Yearbook*, and the *National Economic and Social Development Statistical Bulletin* (due to the lack of statistical data, Hong Kong, Macao, and Taiwan are not included in the research). To eliminate the influence of currency, GDP data are adjusted based on 2005. Considering the influence of dimensionality and heteroscedasticity on the model, the corresponding data are processed with a natural logarithm. For missing data, we use the method of local polynomial interpolation. The summary statistics of all variables are shown in Table 2.

3.4. Spatial Autocorrelation Indicators. To test whether the public health spending of 31 provinces in China is suitable for the spatial econometric model, it is necessary to test the spatial correlation of variables. Moran's I in econometrics is used in this paper. The formula of global Moran's I at the national level is given as follows:

$$I_G = \frac{n \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} (x_i - \overline{x})(x_j - \overline{x})}{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} \sum_{j=1}^{n} (x_i - \overline{x})^2}. \quad (2)$$

In formula (2), I_G represents the global Moran's I; n is the number of regions; x_i and x_j represent, respectively, the values of region i and region j; and w_{ij} is the spatial weight matrix. The value of Moran's I changes from −1 to 1. If Moran's I is positive, it shows a positive spatial correlation. If Moran's I is negative, it shows a negative spatial correlation [29]. To further study the spatial agglomeration effect in different regions, the local Moran's I is used. The formula for the local Moran's I is given in the following:

$$I_L = \frac{n (x_i - \overline{x}) \sum_{j=1}^{n} w_{ij} (x_j - \overline{x})}{\sum_{j=1}^{n} (x_i - \overline{x})^2}. \quad (3)$$

In formula (3), I_L represents the local Moran's I, and the other variables are the same as those in formula (2). A local

Table 1: Variable descriptions.

Variable	Reaction factor	Symbol	Description	Unit
Explained variable	Level of economic development	pgdp	GDP per capita	Thousand yuan
Explanatory variable	Public health expenditure	pph	Government spending on public health	Billion yuan
	Fixed investment	fi	Fixed asset investment	10 billion yuan
Control variable	Human capital	hc	Average of health technical staff	—
	Medical scale	mc	Average of medical beds	—
	Urbanization	ur	Urbanization rate	%
	Population size	rp	Birth rate	‰

Table 2: Summary statistics of all variables.

Variable	Max	Min	Mean	Std. dev	Obs
pgdp	164.22	5.75	43.92	26.70	434
pph	15.65	0.07	2.71	2.37	434
Fi	59.07	0.23	13.16	12.01	434
Hc	15.46	2.10	5.47	1.93	434
Mc	7.65	1.69	4.51	1.39	434
Ur	89.60	21.13	53.66	14.28	434
Rp	17.89	5.36	11.37	2.71	434

Moran scatter diagram intuitively expresses local spatial autocorrelation. A two-dimensional graph is drawn to express the relationship between a spatial unit and its surrounding spatial units [30]. The first quadrant comprises a fully positive correlation, and the third quadrant comprises a fully negative correlation. The second quadrant indicates that a region has a low indicator, while its neighbors have a high indicator. The fourth quadrant represents that a region has a high indicator, while its neighbors have a low indicator [31]. In this paper, we select the adjacent space weight matrix. If region i and region j have common edges or vertices, then $w_{ij} = 1$; otherwise, $w_{ij} = 0$.

We use the STATA 15 software to test the global Moran's I of pgdp of 31 provinces in China from 2006 to 2019 and report the results in Table 3. Moran's I is greater than 0 and significant at the 1% level. This result indicates that the data are subject to significant positive spatial correlation and have spatial agglomeration effects. Hence, it is necessary to consider a spatial econometric model for explanatory and explained variables for its own and neighborhood variables. The Chinese economy was affected by the global financial crisis from 2007 to 2010, which greatly affected both Chinese investment and import/export trade and the healthy development of the economy due to the existence of domestic economic structural contradictions. From 2011 to 2013, the Chinese economy began to recover from the global financial crisis. By expanding domestic demand, adjusting the economic structure, and developing high-tech industries, the country has achieved regional economic growth. In 2011, China became the second-largest economy in the world. From 2014 to 2019, the Chinese economy converted from a high-speed growth stage to a high-quality development stage. In the process of building a modern economic system, we should not only pay attention to the development of the real economy but also pay attention to the construction of public utilities such as the public health system.

Table 3: Global Moran's I results for pgdp

Year	pgdp
2006	0.406 (4.189)***
2007	0.399 (4.080)***
2008	0.405 (4.072)***
2009	0.403 (4.030)***
2010	0.414 (4.100)***
2011	0.410 (4.044)***
2012	0.394 (3.891)***
2013	0.381 (3.678)***
2014	0.362 (3.598)***
2015	0.360 (3.576)***
2016	0.371 (3.696)***
2017	0.398 (3.948)***
2018	0.388 (3.851)***
2019	0.330 (3.403)***

***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. The z statistic is in parentheses.

Figure 1 shows local Moran scatter diagrams of pgdp and pph in 2015 and 2019. Most scatter plots are located in the first and third quadrants, indicating that spatial distributions of government public health spending and regional economic growth are not randomly distributed but display a clear spatial agglomeration. In addition, the eastern coastal areas of Shanghai, Jiangsu, Zhejiang, Shandong, Beijing, Tianjin, Fujian, and other provinces show a "high-high" agglomeration trend.

3.5. Direct and Indirect Effects. In this subsection, we further decompose the model by introducing the method of direct, indirect, and total effects. We rewrite formula (1) in the form of a matrix equation:

$$Y = \rho WY + X\beta + WX\theta + \alpha + \varepsilon. \quad (4)$$

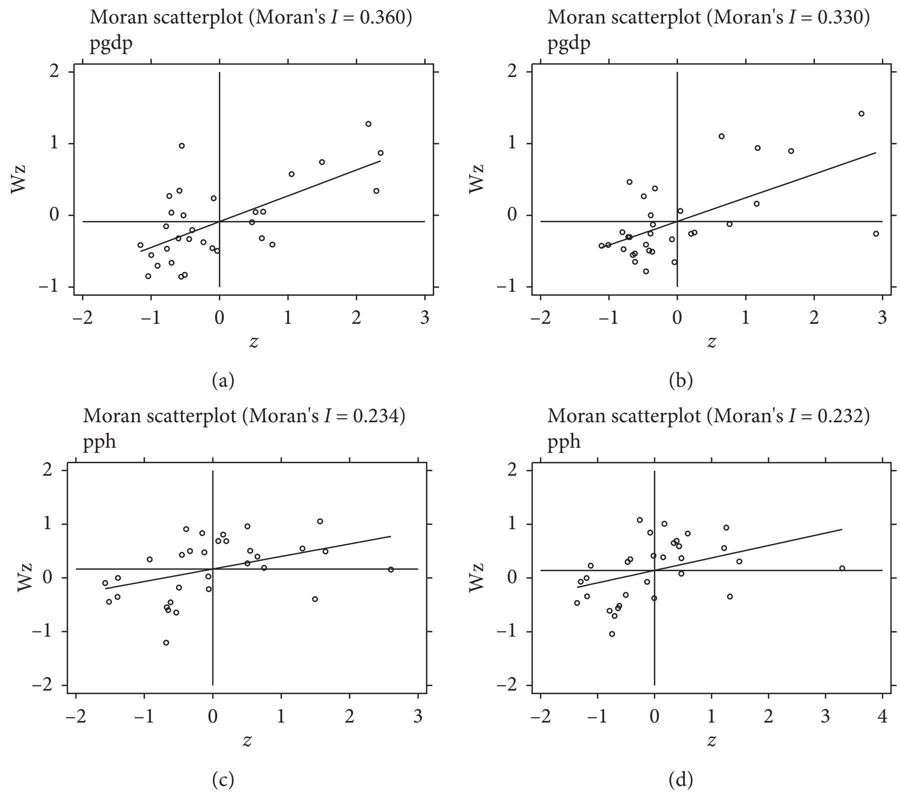

Figure 1: Local Moran scatter diagrams of pgdp and pph. (a) 2015 pgdp. (b) 2019 pgdp. (c) 2015pph. (d) 2019 pph.

The matrix equation (4) is transformed into the inverse matrix equation as follows:

$$Y = (I - \rho W)^{-1}\alpha + (I - \rho W)^{-1}(X\beta + WX\theta) + (I - \rho W)^{-1}\varepsilon. \tag{5}$$

Taking the derivative of vector X on both sides of formula (5), we obtain a partial differential matrix equation as follows:

$$\begin{bmatrix} \frac{\partial Y}{\partial X_{1k}} & \cdots & \frac{\partial Y}{\partial X_{nk}} \end{bmatrix} = \begin{bmatrix} \frac{\partial Y_1}{\partial X_{1k}} & \cdots & \frac{\partial Y_n}{\partial X_{1k}} \\ \cdots & \cdots & \cdots \\ \frac{\partial Y_n}{\partial X_{1k}} & \cdots & \frac{\partial Y_n}{\partial X_{nk}} \end{bmatrix} = (I - \rho W)^{-1} \begin{bmatrix} \beta_k & W_{12}\theta_k & \cdots & W_{1n}\theta_k \\ W_{21}\theta_k & \beta_k & \cdots & W_{2n}\theta_k \\ \cdots & \cdots & \cdots & \cdots \\ W_{n1}\theta_k & W_{n2}\theta_k & \cdots & \beta_k \end{bmatrix}. \tag{6}$$

The mean value of the diagonal elements of the right matrix is defined as a direct effect, and the mean value of the sum of nondiagonal elements in each row or each column is defined as an indirect effect (also known as a spillover effect). The sum of the direct effect and indirect effect is the total effect, which is the comprehensive effect of the explanatory variable on the explained variable.

4. Empirical Analysis

4.1. Estimation of Nonspatial Panel Data. First, to choose a suitable econometric model, we operate pool ordinary least squares (OLS) regression with nonspatial panel data. The regression results of the nonspatial model are shown in Table 4.

As seen in Table 4, the result of the F test with spatial fixed effects and time fixed effects is significant at the 1% level, implying that there are spatial and time fixed effects in the model. Therefore, SDM is chosen to analyze the spatial panel data.

4.2. Estimation of SDM at National Level. Next, we test to estimate SDM at the national level. To verify whether SDM can be simplified to SAR and SEM, we should report the

Table 4: Estimation results of nonspatial panel data.

Variable	Classification of fixed effect models			
	Pool OLS	Spatial fixed effects	Time fixed effects	Spatial-time-fixed effects
lnpph	0.1699*** (0.0325)	0.3220*** (0.0160)	−0.1153*** (0.0338)	−0.0875** (0.0358)
lnfi	−0.0032 (0.0290)	0.1713*** (0.0200)	0.1413*** (0.0264)	0.1295*** (0.0278)
lnhc	0.6816*** (0.0973)	0.1107* (0.0619)	0.8126*** (0.0815)	0.7579*** (0.0852)
lnmc	0.0009 (0.0822)	0.0031 (0.0527)	−0.4054*** (0.0747)	−0.4718*** (0.0810)
lnur	1.0168*** (0.0871)	0.4527*** (0.1250)	0.9390 (0.7283)	1.0274*** (0.0775)
lnrp	0.1215** (0.0539)	−0.0204 (0.0473)	−0.0058*** (0.04622)	0.0217 (0.0471)
R^2	0.8559	0.9721	0.8166	0.9062
F statistic	429.53***	115.58***	115.58***	11.15

***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. The numbers in the coefficient parentheses are standard errors.

results of the Wald and LR tests of the model. The null hypotheses of the Wald test and LR test are H_0^1: $\theta = 0$ and H_0^2: $\theta + \rho\beta = 0$, respectively [32]. To determine the fixed effect model or random effect model, the Hausman test should be implemented. The results of the Wald, LR, and Hausman tests are listed in Table 5.

Both the Wald and the LR tests reject the null hypotheses, indicating that SDM should be recommended. According to the Hausman test, $\text{chi}^2 = 26.52 > 0$ and passes the significance test at the level 1%, implying that the fixed effect model is superior to the random effect model. According to the above statements, SDM with fixed effects is the best model to analyze the spatial panel data in this paper. The fixed effect model is divided into spatial fixed effects, time fixed effects, and spatial-time-fixed effects. To select a better model, we test three models individually and report the results in Table 6.

Table 6 shows that the significance of rho and the variables of the time fixed effect model are higher than those of the other models. In other words, a time fixed effect model is recommended to investigate the impact of government public health spending on regional economic growth. The SDM results show that the spatial agglomeration of government public health spending exerts a significant influence on regional economic growth. The explanatory variable pph has a significant positive impact on local economic growth. The elasticity coefficient is 0.1671. This result implies that, for every 1% increase in government public health spending, economic growth will increase by 0.1671%. The control variable rp exerts a significant negative impact on local economic growth. In addition, the spatial autoregression coefficient (rho) reveals that it has a significant positive correlation with regional economic growth. Moreover, the R^2 of the SDM is larger than that of the pool OLS model, indicating that the spatial econometric model is more suitable for this paper.

Table 5: Result of Wald, LR, and Hausman tests.

Test	Statistics	p-value
Wald spatial lag	26.93	0.000
Wald spatial error	30.97	0.000
LR spatial lag	16.39	0.018
LR spatial error	32.87	0.000
Hausman	26.52	0.001

4.3. Spillover Effects. Furthermore, Xu and Wang [30] pointed out that, in SDM, the regression coefficient of the explanatory variable cannot directly reflect its effects on the explained variable. Therefore, it is necessary to employ spatial effect decomposition. We show the decomposition result of spatial effects under time fixed effects in Table 7.

As shown in Table 7, the direct effects of all variables are significant at the 5% level, which indicates that the core indicators pph, fi, hc, and ur can significantly promote regional economic growth. Against the background of the new normal of the Chinese economy, the factors related to the health of human capital become increasingly important. Without healthy human capital, there is no motivating force to transform into economic growth, which also shows that economic growth contains the recognition of health awareness as well as scientific and technological innovation. Although the birth rate (rp) has a clear reverse effect on the growth of the regional economy, the coefficient of its spatial lag term is significantly positive at the 1% level, indicating that the excessive population base in the current period hinders economic growth. However, the lag effect will be transformed into a positive effect over time. Therefore, the birth rate will indirectly promote economic growth.

For the spatial spillover effects in Table 7, the effects of variables pph, hc, and ur are significantly positive, which

Table 6: Estimation result of SDM at national level.

	Classification of fixed effect models		
	Spatial fixed effects	Time fixed effects	Spatial-time-fixed effects
Lnpph	0.3015*** (0.0221)	0.1671*** (0.0323)	0.1615*** (0.0331)
Lnfi	0.1329*** (0.0193)	0.1350*** (0.0235)	0.1436*** (0.0202)
Lnhc	0.1371** (0.0570)	0.8791*** (0.0731)	0.1130* (0.0586)
Lnmc	−0.0560 (0.0519)	−0.4021*** (0.0772)	0.0017 (0.0514)
Lnur	0.3812*** (0.1098)	0.7664*** (0.0787)	0.3222*** (0.1087)
Lnrp	0.0109 (0.0447)	−0.1415** (0.0606)	0.0408 (0.0445)
W^*lnpph	−0.1676*** (0.0317)	0.2457** (0.0587)	−0.0162 (0.0360)
W^*lnfi	0.0120 (0.0349)	−0.1284*** (0.0463)	0.1363** (0.0555)
W^*lnhc	−0.2353** (0.1179)	−0.1184 (0.1433)	−0.1640 (0.1288)
W^*lnmc	0.2240** (0.1033)	−0.0677 (0.1462)	0.1850* (0.1063)
W^*lnur	−0.1236 (0.1982)	0.0148 (0.0771)	−0.6481*** (0.2233)
W^*lnrp	−0.1078 (0.0770)	0.2931*** (0.0692)	−0.0316 (0.0925)
Rho	0.4324***	0.2581***	0.2108
R^2	0.9752	0.8719	0.9702
Log-likelihood	567.6973	465.3824	610.6094

***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. The numbers in the coefficient parentheses are standard errors.

Table 7: Direct, indirect, and total effects of SDM with time fixed effects.

Variable	Direct effect	Indirect effect	Total effect
Lnpph	0.0542 (−4.55)***	0.2528 (3.28)***	0.3070 (1.07)
Lnfi	0.1283 (5.25)***	−0.1172 (−2.00)**	0.0111 (0.16)
Lnhc	0.8916 (12.58)***	0.1470 (2.11)**	1.0386 (5.40)***
Lnmc	−0.4168 (−6.03)***	−0.2194 (−1.28)	−0.6362 (−3.79)***
Lnur	0.7760 (10.06)***	0.2620 (2.74)***	1.0380 (7.29)***
Lnrp	−0.1249 (−2.20)**	0.3222 (4.46)***	0.1973 (2.86)***

***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. The numbers in the coefficient parentheses are the t statistics.

indicates that these indicators not only significantly promote regional economic growth in the region but also have some spillover effects. However, the total effect of explanatory pph does not pass the significance test. The direct, indirect, and total effects of control variable ur all pass the significance test at the 1% level. To develop the local economy, the government needs a considerable amount of land. In the case of a shortage of industrial land in the city, it begins to expand to the periphery of the city and drives investment and funding of major municipal construction, which promotes local economic development. Generally, the size of health care is related to the number of health technicians. If there is a high level of medical technology in a city, it tends to attract residents from surrounding areas to seek medical treatment. This phenomenon is common in big cities. Moreover, we also see that the coefficient of mc is negative but not significant, indicating that the number of medical beds does not necessarily hinder economic growth at the national level.

4.4. Robustness Test. In this subsection, we present the robustness test of the model. From the above analysis, we know that the SDM with time period fixed effects is the best for the panel data. Therefore, we should again operate the SDM by converting the spatial weight matrix into geographical distance and economic distance. The conversion results are listed in Table 8, which shows that, for the geographical

Table 8: Robustness test of public health spending on regional economic growth.

Variable	Geographical distance matrix		Economic distance matrix	
	Coefficient	t value	Coefficient	t value
Lnpph	0.0884**	−2.45	0.1394***	−6.02
Lnfi	0.0891***	3.44	0.0829***	4.52
Lnhc	0.6741***	7.33	0.5296***	9.78
Lnmc	−0.1943**	−2.19	−0.1337***	−2.67
Lnur	0.7610***	10.26	0.7148***	14.97
Lnrp	−0.1385**	−2.40	0.1343***	4.18
W*lnpph	0.2932***	3.31	0.1907**	−2.42
W*lnfi	−0.1126*	−1.73	−0.0645	−1.33
W*lnhc	−0.0778	−0.41	−0.3664**	−1.99
W*lnmc	−0.1072	−0.60	−1.999	−1.38
W*lnur	0.8693***	3.13	2.7241***	11.01
W*lnrp	0.4261***	3.62	0.5031***	4.70
Rho	0.0372*	1.79	0.0768*	1.89
R^2	0.9442		0.9628	
Log-likelihood	154.1253		303.5903	

***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. The numbers in the coefficient parentheses are standard errors.

distance matrix and economic distance matrix, the result is the same as the adjacent spatial weight matrix. This result implies that government public health spending has significant spatial agglomeration and a significant positive impact on regional economic growth. In other words, the results of this paper are robust.

4.5. Estimation of SDM at Subnational Level. Due to the vast territory of China, heterogeneity among regions is prominent with respect to the natural environment, humanistic background, and location advantage. To understand the relationship between public health spending and economic growth in more detail, following concepts in the existing literature [20, 23], we divide the national sample into three subsamples according to geographical location: eastern (including Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan), central (including Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei, and Hunan), and western (including Sichuan, Chongqing, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, Tibet, Xinjiang, Guangxi, and Inner Mongolia). The SDM model is again used to test the relationship between government public health expenditure and regional economic growth, and the regression results are shown in Table 9.

The results in Table 9 show that the values of R^2 and log-likelihood are ideal. All the spatial autocorrelation coefficients are positive, implying that there is a spatial agglomeration effect of government public health spending and regional economic growth for the three subsamples. Regarding the significance of the explanatory variable, there are positive effects in the eastern and central regions, while the western region does not pass the significance test. Regarding the control variables, the coefficient of fixed asset investment in the eastern, central, and western regions is positive and passes the significance test, indicating that it promotes regional economic growth. The coefficient of the urbanization rate in the central and western regions is positive and passes the significance test, whereas it fails the significance test in the eastern region. Judging by birth rate has significantly hindered economic growth in the western region, which may be related to the rapid growth of the population in the west. Excessive population growth leads to

Table 9: SDM estimation results at the subnational level.

Variable	Eastern	Central	Western
lnpph	0.3183*** (0.0367)	0.1669*** (0.0717)	0.0792 (0.0587)
lnfi	0.1670*** (0.0366)	0.1079*** (0.0372)	0.1750*** (0.0337)
lnhc	0.1151 (0.0949)	−0.1732 (0.1467)	0.3482*** (0.1072)
lnmc	−0.0578* (0.0900)	0.1418 (0.1218)	0.0562 (0.0818)
Lnur	0.1121 (0.2991)	0.3924* (0.2323)	0.3141** (0.1407)
Lnrp	0.0294 (0.0804)	0.1483** (0.0741)	−0.1300* (0.0722)
W*lnpph	−0.0059 (0.0705)	−0.1475* (0.0773)	0.0688 (0.0627)
W*lnfi	0.0872 (0.0959)	0.1322* (0.0679)	−0.0609 (0.0518)
W*lnhc	−0.1492* (0.1482)	−0.0032 (0.1660)	−0.3677*** (0.1433)
W*lnmc	0.2270 (0.1550)	0.1478 (0.1440)	0.1731 (0.1270)
W*lnur	−0.3246 (0.0.4162)	−0.4516 (0.2776)	−0.4492** (0.2075)
W*lnrp	−0.2155 (0.1097)	−0.2187** (0.0893)	0.0492 (0.1346)
Rho	0.0211 (0.0874)	0.4959*** (0.0682)	0.4734*** (0.0750)
R^2	0.9648	0.9763	0.9853
Log-likelihood	188.3498	161.7663	256.0567

***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. The numbers in the coefficient parentheses are standard errors.

uncoordinated development with economic growth, reduces the amount of wealth per capita, and exacerbates the contradiction between the labor force and employment opportunities [33].

5. Conclusions and Suggestions

This study uses panel data of 31 provinces in China to study the impact of government public health spending on regional economic growth. The results show that there is a clear spatial agglomeration effect of government public health spending on regional economic growth. Furthermore, government public health spending has significant promotion and spillover effects on regional economic growth. The explanatory variable shows significant spatial spillover effects. In addition, the population birth rate shows a significant negative correspondence with economic growth. However, over time, the birth rate maintains the same direction as economic growth.

Government public health spending influences people's physical fitness to guide them to obtain a high-quality education. These policies can improve the medical environment and health, municipal facilities, and other physical conditions. Additionally, cities can attract more high-level and high-quality talent and improve the technology of local regions, which can enhance technological innovation capabilities and comprehensive competitiveness to promote rapid economic growth. The Chinese economy has adjusted to the new normal. The government no longer leads the development of the market, but instead stimulates market vitality through optimization and reasonable spatial layout. With the aging of China's population, the increasing rate of the number of laborers has decelerated, and the structure of talent is unreasonable. The demand for high-quality professional and technical personnel has increased. In this environment, the Chinese economy has made a new transition from the traditional high-speed growth stage to the high-quality development stage, especially during the COVID-19 pandemic, which has severely tested the emergency response capabilities of the Chinese government and prompted the government's attention to improve public health mechanisms.

In the future, policies should be adjusted. It is necessary to expand health resources to cover the population and improve the number and professional quality of health institutions. Additionally, the government should establish the division of labor and cooperation between professional health institutions and community health institutions. Furthermore, complementary resources should be established to improve the service efficiency and level of health institutions. As the process of urbanization accelerates, it is necessary to establish sound coverage of the basic public health service system and increase the number of health technicians in the grassroots community. Government spending on public health should follow the principles of prebudget, in-process, and postaudit supervision. Such spending should be guaranteed by legal supervision, which can improve the quality of government public health construction and public health early warning mechanisms and expand the coverage of health care institutions. There is great love in the face of the catastrophe. Donations from social groups and overseas Chinese during the pandemic have played an important role in winning the battle against COVID-19. Therefore, in future medical and health reforms, public health funds should be established for public health promotion, health funding, and assistance to vulnerable groups. Social groups and overseas Chinese should be encouraged to donate appropriately. Despite the great challenges posed by this pandemic, public health institutions have made outstanding contributions. In the future, we should increase spending on public health institutions and strengthen the training of professional and technical personnel.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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