

Understanding Low Carbon Sustainable Development Behaviour and Its Complexity

Lead Guest Editor: Wei Zhang

Guest Editors: Yuan Jiang and Charbel José Chiappetta Jabbour





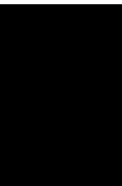
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

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Research Article

How Technological Innovation Influences Environmental Pollution: Evidence from China

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Technological innovation has an important impact on environmental pollution. In this paper, first, we analyze the influence mechanism of technological innovation on environmental pollution and then design the index system of technological innovation. Then, we use the entropy method to calculate the technological innovation level of different regions in China based on provincial panel data from 2004 to 2016. Finally, the panel vector autoregression model (PVAR) is adopted, and taking the discharge of sewage, solid waste, and exhaust gas as the research objects, the impact of technological innovation on them is empirically analyzed. The results show that China's technological innovation level is steadily improving, but there are significant differences in the impact of technological innovation on wastewater, waste gas, and solid waste. Specifically, technological innovation can contribute to an increase in wastewater and solid waste emissions. However, the impact of this technological innovation on them is not equal. Secondly, the impact of technological innovation on exhaust emissions is to inhibit exhaust emissions in the short term and promote exhaust emissions in the long term. Finally, there are clear differences between them in terms of the specific impact of changes in wastewater, solid waste, and exhaust emissions. Changes in wastewater discharges and solid waste generation are largely derived from their own effects, while the role of technological innovation is supportive and insignificant. The change in exhaust emissions is initially influenced by itself, but in the long run, the influence of technological innovation gradually increases and eventually exceeds its own influence. Based on these research results, this paper puts forward corresponding policy suggestions to speed up environmental pollution control.

1. Introduction

A rapid development of the economy is important to increase employment opportunities, improve people's living standards, and promote social stability. However, during any developmental process, environmental pollution is prone to occur, which has attracted the attention of governments and academics worldwide to avoid a deterioration of the environment. As the largest developing country, China has experienced rapid economic growth since the reform and opening-up policies in 1978. By 2019, China's gross domestic product (GDP) had reached 14.5 trillion dollars. China's rapid economic development, however, came at the cost of massive resource input and ecological destruction [1]. According to statistics, the annual economic loss in China

due to environmental pollution is approximately 2% to 3% of the GDP [2]. In order to alleviate the environmental pollution caused by economic development, China has made great efforts to develop science and technology in the hope of promoting the transformation and upgrading of economic development through the development of science and technology and ultimately alleviating environmental pollution. Therefore, how the development of technological innovation affects the emission of environmental pollutants has become a topic of general concern.

The Porter hypothesis represents the most prominent research on the relationship between technological innovation and environmental pollution. It states that appropriate environmental regulation can encourage innovative activities and, in turn, improve the productivity of

enterprises to offset the costs caused by environmental protection [3]. Since then, much research has involved empirical tests of the Porter hypothesis, which proposes environmental regulation as a way to enhance the innovation ability of enterprises [4–6]. Other studies support the compliance cost theory, which suggests that environmental regulation increases the manufacturer's production costs, weakening technological advances [7, 8]. Generally, these studies focus on analyzing the impact of environmental regulation on technological innovation, especially those focusing on carbon dioxide emissions. Most of these studies are performed in both dynamic and static aspects [9]. Among these studies, Fan et al. and Kumar and Managi found that technological innovation in developed countries can reduce carbon dioxide emissions. In developing countries, these emissions have increased [10, 11]. Mao et al. analyzed the impact of technological innovation on water pollution intensity and found that technological innovation has different effects on pollution reduction under different levels of water pollution intensity [12]. Wang and Luo analyzed the impact of technological innovation on environmental pollution from the perspective of foreign direct investment (FDI) quantity and quality. The study found that when the FDI level was low, the scientific and technological innovation ability aggravated the degree of environmental pollution, while when the FDI level crossed a higher threshold, the scientific and technological innovation ability improved the environmental quality [13]. In addition, many scholars have paid attention to the dynamic relationship between technological innovation and pollutant emissions [14]. Since environmental pollution often involves multiple media (i.e., air, water, and solid waste), few studies have analyzed the actual impact of technological innovation on different types of environmental pollution. Therefore, we first analyze the influencing mechanisms of technological innovation on environmental pollution, and then, based on the provincial panel data of China, utilize the panel vector autoregressive model (PVAR) model to analyze its impact on wastewater discharge, exhaust emission, and solid waste discharge. This study provides the following contributions: on the one hand, it enriches the available research on the impact of technology on pollution control; on the other hand, as the largest developing country, China's experience will provide abundant lessons for other developing countries.

This paper is structured as follows: Section 2 analyzes the theory behind the influencing mechanisms of technological innovation on environmental pollution. Section 3 illustrates the methods and data sources, followed by the research results in Section 4. Section 5 presents the conclusions, including policy implications.

2. Influence Mechanism of Technological Innovation on Environment Pollution

From Figure 1, we can clearly find how technological innovation affects the emission of environmental pollution. Next, we explain Figure 1 in detail. Based on existing research, technological innovation affects environmental pollution through the following three paths: changing energy consumption, industrial structure, and technology

application to environmental governance. Firstly, the industrial structure is not only an important carrier of economic activities but also a factor with an important impact on the ecological environment. It has the dual function of being a resource converter and an environmental regulator [15]. In modern society, compared with primary and tertiary industries, the secondary industry has the greatest impact on environmental pollution. In China, for example, energy consumption is mainly concentrated in the industrial sector, which also produces the most waste gas emissions, wastewater, and residues in the economic sector [16]. Studies have found that technological innovation has an important impact on upgrading the industrial structure and changes in structure in a unified and strict legal market environment, decreasing the intensity of pollutant emissions [17–19] (see Figure 1). Secondly, technological innovation can affect energy consumption efficiency [20]. At present, China's energy consumption is still dominated by coal and oil, which are significant sources of environmental pollution and are often wasted during consumption [21]. Finally, technological innovation often means that the corresponding scientific and technological achievements can be used to control environmental pollution [22]. For example, Cinderby and Forrester applied a geographic information system (GIS) to control air pollution and found that GIS not only promotes local governance to be more responsible for improving air quality but also strengthens the interactive relationship among local governments, environmental scientists, and the public [23]. Furthermore, the application of technology can facilitate the reporting of environmental damage behavior of enterprises by the public on a real-time basis, thereby strengthening the capacity of government regulation in environmental pollution. Therefore, the application of technological innovations to the field of environmental governance can change the ability to control environmental pollution and ultimately have a profound impact on the sustainability of the environment [24].

3. Model Settings and Data Description

3.1. Design of a Comprehensive Index System of Technological Innovation. The direct manifestation of the level of technological innovation is its effectiveness, which is determined by the environment, inputs, and outputs. Therefore, based on existing research and considering the availability of data [25–27], we selected 15 indicators (the proportion of the economically active population with a junior college degree or above, GDP per capita, the proportion of funding for science and technology in financial funding, the Internet penetration rate, and so on) [28, 29], based on environmental technological innovation (TECINN), investment in TECINN, output of TECINN, and achievements of TECINN to construct an index system for technological innovation (see Table 1).

3.2. Model of Comprehensive Level of Technological Innovation. Firstly, the raw data is standardized to eliminate the impact of different units and dimensions of the index, as follows:

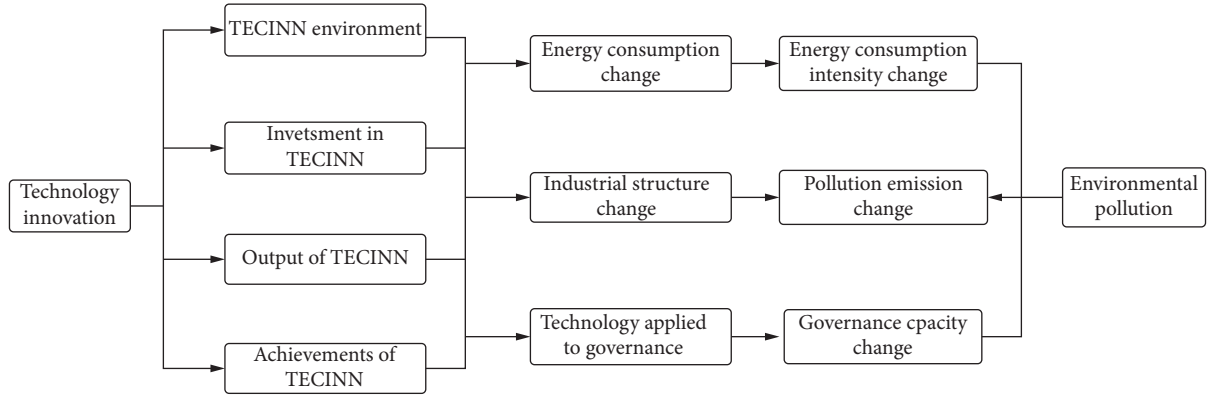


FIGURE 1: The influence mechanism of technological innovation (TECINN) on environmental pollution.

TABLE 1: Comprehensive index system of technological innovation.

| The total system | First-level index | The secondary index |
|---------------------------------|---|--|
| Technological innovation system | The environment of technological innovation | The proportion of the economically active population with a junior college degree or above (%), GDP per capita (%), the proportion of funding for science and technology in financial funding (%), the Internet penetration rate (%) |
| | Investment in technological innovation | Full-time equivalent of R&D personnel per 10,000 people, proportion of R&D expenditure to GDP (%), proportion of enterprises with R&D institutions (%), internal expenditure of R&D, expenditure of large and medium-sized high-tech enterprises (ten thousand yuan) |
| | Output of technological innovation | Number of scientific and technological papers (papers), number of patent authorization (items), technology market turnover (100 million yuan) |
| | Achievements of technological innovation | Sales income of new products (10,000 yuan), export of high-tech products accounting for delivery value (100 million yuan), energy consumption per unit GDP (tons of standard coal/10,000 yuan), labor productivity (10,000 yuan/person) |

$$\text{Positive indexes: } y_{ij} = \frac{[\max(x_{ij}) - x_{ij}]}{[\max(x_{ij}) - \min(x_{ij})]}, \quad (1)$$

$$\text{Negative indexes: } y_{ij} = \frac{[x_{ij} - \min(x_{ij})]}{[\max(x_{ij}) - \min(x_{ij})]}, \quad (2)$$

where the x_{ij} represents the sample value, $\max(x_{ij})$ and $\min(x_{ij})$ represents the maximum and minimum values of the sample data, respectively.

Secondly, the index weight is calculated. There are two different methods for the calculation of index weight, a subjective and objective weighting method. In this paper, the entropy method as the objective weighting method is adopted to calculate the weight of each index, as follows:

$$p_{ij} = \frac{y_{ij}}{\sum_{i=1}^n y_{ij}}, \quad (3)$$

$$e_j = \left[-\frac{1}{\ln(n)} \right] \sum_{i=1}^n p_{ij} \ln p_{ij},$$

$$w_j = \frac{(1 - e_j)}{\sum_{i=1}^n (1 - e_i)}. \quad (4)$$

Finally, the comprehensive level of technological innovation (U_T) is calculated by the following formula:

$$U_T = \sum_{j=1}^m w_j y_j, \quad (5)$$

$$\sum_{j=1}^m w_j = 1.$$

3.3. Panel-Data Vector Autoregressive Model. The single-dimensional vector autoregression model (VAR), established by Sims in 1980, was used to describe the impact of variables on a specific variable [30]. However, the VAR model did not support panel data; therefore, Holtz-Eakin, Newey, and Rosen extended it to a panel data structure [31]. Compared with the VAR model, the panel-data vector autoregressive model (PVAR) can lower the requirements for data volume and form and effectively control the estimation bias caused by spatial and individual heterogeneity [32]. To investigate the relationship between technological innovation and environmental pollution, this paper constructs a panel vector autoregressive model (PVAR) for empirical tests, as follows:

$$Y_{it} = \gamma_0 + \alpha_i + \beta t + \sum_{j=1}^p \gamma_j Y_{i,t-j} + \varepsilon_{it}, \quad (6)$$

$$(i = 1, 2, 3, \dots, N, t = 1, 2, 3, \dots, T),$$

where the subindexes i refer to the province, t refers to time. Y_{it} is the endogenous variable that changed over time, and region, γ_0 and γ_j indicate the estimated coefficients of the constant term and lagged endogenous variable, respectively; p is the lag period, α_i is a vector of individual effects, which indicates the otherness of the cross-sectional.

β_t is a time effect vector used to explain the temporal characteristics of variables. ε_{it} is the random disturbance item.

3.4. Variable Selection and Data Sources. We used the entropy method to measure the level of technological innovation in different regions of China, and the discharge status of environmental pollutants is selected from the three indicators of solid waste generation, sulfur dioxide discharge, and wastewater discharge. This study uses a yearly panel dataset of 30 provinces and cities in mainland China, except Tibet, from 2004 to 2016. The data were sourced from China Science and Technology Statistical Yearbook (2005–2017), China Statistical Yearbook (2005–2017), and China Environmental Statistics Yearbook (2005–2017).

4. Results

4.1. Comprehensive Level of Technological Innovation. According to formula (1)–(5), the comprehensive level of technological innovation in China from 2004 to 2016 can be calculated. Table 2 shows the specific comprehensive level. The mean of the comprehensive level of technological innovation in different regions shows the overall trend of technological innovation in China from 2004 to 2016 (Figure 2).

It can be seen from Table 2 and Figure 2 that the level of China's technological innovation has increased since 2004. In 2004, the average comprehensive level of technological innovation was just 0.13, but after decades of development, this level has reached 0.827 in 2016, which shows that China's efforts to promote technological progress by increasing the investment and training of personnel have been effective. However, we found significant regional differences in the level of Chinese technological innovation. In 2016, a lower level of technological innovation of 0.6–0.8 is observed in Inner Mongolia, Guangxi, Guizhou, Yunnan, Gansu, and Qinghai, the economic level of these areas is also relatively backward. By contrast, Beijing, Tianjin, Shanghai, Jiangsu, and Guangdong, which are relatively developed regions in China, had a higher level of 0.8. Based on the results in different regions of China, we analyzed the specific impact of technological innovation progress on the emission of environmental pollutants.

4.2. Impact of Technological Innovation on the Emission of Environmental Pollutants

4.2.1. Panel Unit Root Test. Before using the PVAR model to analyze the impact of technological innovation on the emission of wastewater, solid waste, and exhaust gas, unit root testing must be used to test the stability of various variables. For the unit root test of panel data, the Levin, Lin & Chu (LLC test), Im, Pesaran and Shin W-stat (IPS test), AdF-Fisher Chi-Square (ADF test), and PPFisher Chi-Square (PP test) were adopted [33]. The test results are shown in Table 3. According to the results, it can be found that the original data of technological innovation, wastewater, solid waste, and exhaust gas become a stationary sequence after a first-order difference, which shows that they can be tested for cointegration.

4.2.2. Cointegration Test. According to the cointegration test method proposed by Baltagi and Kao and Pedroni [34, 35], this study cointegrated the data of technological innovation at comprehensive level, wastewater discharge, solid waste, and exhaust emissions, and the results are shown in Table 4. According to the results of the cointegration test, there is a cointegration relationship between the comprehensive level of technological innovation and the data on environmental pollution emission (Table 5).

4.2.3. PVAR Model Regression Analysis. The optimal lag order of the model needs to be determined to test the PVAR model [36]. The existing literature is mainly selected by Akaike's information criterion (AIC), Bayesian information criterion (BIC), Hannan and Quinn information criterion (HQIC) to judge the optimal lag order [37, 38]. The test results are shown in Table 4. According to the order with the most passes of all inspection values as the criterion for determining the optimal lag order, we can find that in technological innovation-wastewater and technological innovation-solid waste, the optimal lag period is 1, while the lag period of technological innovation and exhaust gas is 4.

4.2.4. Impulse Response Analysis. Impulse response analysis can help analyze how technological innovation affects pollutant emissions. This study sets the number of responses to 10 periods and Monte Carlo simulations to 1000 times to analyze the impulse impact of technological innovation on wastewater discharge, solid waste generation, and exhaust gas emissions. The results are shown in Figure 3. In Figure 3, the abscissa represents the lag period, the ordinate represents the degree of impulse response, the two curves at the top and bottom represent the upper and lower bounds of the 95% confidence interval, respectively, and the intermediate curve stands for the value of the impulse response.

Figure 3(a) shows the response of wastewater discharge to technological innovation. Figure 3(a) shows that after receiving a standard deviation impulse from technological innovation, the wastewater discharge remains with a positive response in the 0th period until reaching a peak in the 5th lag

TABLE 2: Comprehensive level of technological innovation in 30 provinces.

| Area | Year | | | | | | | | | | | | |
|----------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 |
| Beijing | 0.101 | 0.157 | 0.240 | 0.339 | 0.375 | 0.423 | 0.533 | 0.581 | 0.660 | 0.651 | 0.745 | 0.832 | 0.891 |
| Tianjin | 0.134 | 0.183 | 0.229 | 0.275 | 0.240 | 0.284 | 0.399 | 0.447 | 0.622 | 0.653 | 0.762 | 0.889 | 0.924 |
| Hebei | 0.127 | 0.169 | 0.183 | 0.222 | 0.258 | 0.374 | 0.471 | 0.463 | 0.615 | 0.671 | 0.698 | 0.765 | 0.943 |
| Shanxi | 0.053 | 0.096 | 0.168 | 0.220 | 0.289 | 0.367 | 0.367 | 0.429 | 0.556 | 0.803 | 0.749 | 0.773 | 0.818 |
| Inner Mongolia | 0.151 | 0.248 | 0.241 | 0.180 | 0.247 | 0.291 | 0.384 | 0.421 | 0.603 | 0.614 | 0.570 | 0.642 | 0.667 |
| Liaoning | 0.318 | 0.282 | 0.311 | 0.301 | 0.324 | 0.419 | 0.554 | 0.532 | 0.595 | 0.599 | 0.626 | 0.676 | 0.847 |
| Jilin | 0.290 | 0.229 | 0.259 | 0.242 | 0.227 | 0.360 | 0.355 | 0.363 | 0.441 | 0.588 | 0.617 | 0.698 | 0.797 |
| Heilongjiang | 0.159 | 0.249 | 0.205 | 0.264 | 0.271 | 0.374 | 0.488 | 0.477 | 0.613 | 0.603 | 0.619 | 0.788 | 0.765 |
| Shanghai | 0.035 | 0.164 | 0.317 | 0.324 | 0.335 | 0.516 | 0.585 | 0.573 | 0.621 | 0.631 | 0.713 | 0.778 | 0.887 |
| Jiangsu | 0.060 | 0.100 | 0.133 | 0.190 | 0.222 | 0.353 | 0.514 | 0.566 | 0.733 | 0.799 | 0.828 | 0.901 | 0.970 |
| Zhejiang | 0.055 | 0.155 | 0.270 | 0.304 | 0.329 | 0.345 | 0.460 | 0.496 | 0.596 | 0.663 | 0.697 | 0.765 | 0.874 |
| Anhui | 0.049 | 0.070 | 0.101 | 0.135 | 0.152 | 0.230 | 0.378 | 0.428 | 0.534 | 0.704 | 0.774 | 0.842 | 0.918 |
| Fujian | 0.158 | 0.195 | 0.156 | 0.203 | 0.325 | 0.380 | 0.495 | 0.486 | 0.614 | 0.683 | 0.646 | 0.733 | 0.760 |
| Jiangxi | 0.091 | 0.138 | 0.216 | 0.279 | 0.196 | 0.302 | 0.371 | 0.352 | 0.418 | 0.606 | 0.643 | 0.721 | 0.840 |
| Shandong | 0.074 | 0.117 | 0.166 | 0.235 | 0.314 | 0.350 | 0.522 | 0.543 | 0.620 | 0.734 | 0.746 | 0.780 | 0.837 |
| Henan | 0.065 | 0.149 | 0.171 | 0.236 | 0.228 | 0.277 | 0.403 | 0.464 | 0.565 | 0.708 | 0.731 | 0.773 | 0.871 |
| Hubei | 0.077 | 0.108 | 0.138 | 0.196 | 0.225 | 0.298 | 0.437 | 0.446 | 0.543 | 0.658 | 0.726 | 0.783 | 0.871 |
| Hunan | 0.087 | 0.092 | 0.135 | 0.213 | 0.254 | 0.277 | 0.383 | 0.404 | 0.536 | 0.692 | 0.742 | 0.815 | 0.867 |
| Guangdong | 0.068 | 0.075 | 0.155 | 0.207 | 0.275 | 0.338 | 0.476 | 0.469 | 0.561 | 0.682 | 0.668 | 0.842 | 0.959 |
| Guangxi | 0.154 | 0.209 | 0.221 | 0.205 | 0.234 | 0.287 | 0.434 | 0.449 | 0.528 | 0.666 | 0.670 | 0.608 | 0.721 |
| Hainan | 0.123 | 0.127 | 0.214 | 0.229 | 0.391 | 0.386 | 0.477 | 0.544 | 0.600 | 0.699 | 0.624 | 0.752 | 0.857 |
| Chongqing | 0.109 | 0.147 | 0.187 | 0.210 | 0.260 | 0.244 | 0.390 | 0.404 | 0.450 | 0.605 | 0.678 | 0.702 | 0.884 |
| Sichuan | 0.177 | 0.198 | 0.223 | 0.261 | 0.218 | 0.294 | 0.326 | 0.345 | 0.585 | 0.559 | 0.653 | 0.760 | 0.750 |
| Guizhou | 0.125 | 0.133 | 0.223 | 0.171 | 0.217 | 0.348 | 0.391 | 0.413 | 0.424 | 0.505 | 0.581 | 0.677 | 0.749 |
| Yunnan | 0.232 | 0.188 | 0.178 | 0.192 | 0.197 | 0.217 | 0.369 | 0.325 | 0.513 | 0.604 | 0.575 | 0.686 | 0.736 |
| Shaanxi | 0.214 | 0.143 | 0.162 | 0.198 | 0.207 | 0.289 | 0.359 | 0.383 | 0.513 | 0.559 | 0.612 | 0.669 | 0.771 |
| Gansu | 0.135 | 0.184 | 0.231 | 0.240 | 0.287 | 0.388 | 0.394 | 0.470 | 0.550 | 0.648 | 0.720 | 0.787 | 0.776 |
| Qinghai | 0.183 | 0.181 | 0.194 | 0.232 | 0.283 | 0.451 | 0.355 | 0.544 | 0.587 | 0.536 | 0.582 | 0.637 | 0.755 |
| Ningxia | 0.082 | 0.107 | 0.146 | 0.223 | 0.208 | 0.314 | 0.401 | 0.492 | 0.593 | 0.522 | 0.580 | 0.718 | 0.812 |
| Xinjiang | 0.225 | 0.126 | 0.135 | 0.257 | 0.304 | 0.300 | 0.522 | 0.537 | 0.543 | 0.561 | 0.591 | 0.675 | 0.682 |
| Mean | 0.130 | 0.157 | 0.197 | 0.233 | 0.263 | 0.336 | 0.433 | 0.462 | 0.564 | 0.640 | 0.672 | 0.749 | 0.827 |

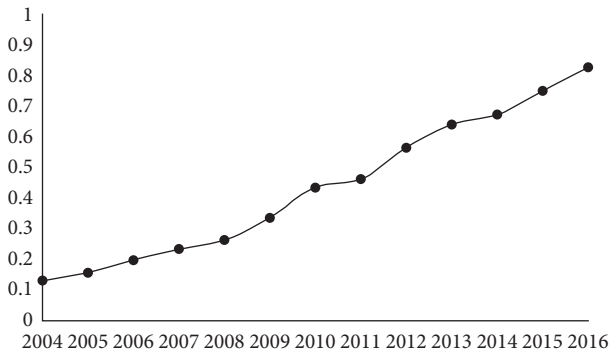


FIGURE 2: China's comprehensive level of technological innovation from 2004 to 2016.

phase, eventually, technological innovation has a positive effect that leads to an increase in wastewater discharge. Figure 3(b) indicates that technological innovation has an initial positive impulse on solid waste discharge, which gradually weakens over time. Figure 3(c) shows a negative response of the exhaust gas, but over time, however, in the long term, technological innovation promotes the increase in exhaust emissions. These findings are consistent with the study by Kumar and Managi, who found that technological

innovation in developing countries promotes rather than curbs CO₂ emissions [11].

4.2.5. Variance Decomposition. Impulse response analysis cannot be used to evaluate the importance of different impulses to specific variables [33]. Therefore, a variance decomposition is utilized to analyze the contribution of various structural impulses to the fluctuation of environmental pollution. The results are shown in Table 6.

Table 6 reflects that in the 1st period, 100% of the explanatory power of the change in wastewater comes from itself, but as time passes, the impact of wastewater discharge on itself gradually decreases, and the impact of technological innovation on wastewater discharge gradually increases. By the 12th period, 97.2% of the change in wastewater discharge can be explained by itself, and the contribution of technological innovation to it reaches 2.8%. Based on the above structure of variance decomposition, it can be concluded that the change of China's wastewater discharge is mainly affected by itself, and the influence of technological innovation on wastewater discharge is not significant. In the discharge of solid waste, the explanatory power of the change in solid waste is 100% in the 1st period. With the passage of time, the impact of solid waste emissions on its own shows a

TABLE 3: Results of unit root test.

| Variable | LLC-test | IPS-test | ADF-test | PP-test | Result |
|----------------------|-------------|-------------|-------------|-------------|------------|
| Wastewater | -14.9361*** | -7.25428*** | -5.32203*** | -5.21888*** | Smooth |
| Δ wastewater | -18.4038*** | -10.9611*** | -9.05958*** | -11.1499*** | Smooth |
| Solid waste | -0.49884 | 4.37137 | 4.10015 | 5.35996 | Not smooth |
| Δ solid waste | -13.304*** | -6.18938*** | -6.37182*** | -8.14711*** | Smooth |
| Exhaust gas | -13.246 *** | -8.20254*** | -6.71452*** | -9.14431*** | Smooth |
| Δ exhaust gas | -12.472*** | -8.0203*** | -7.2352*** | -11.1865*** | Smooth |
| TECINN | -4.8807*** | 0.92277 | 56.1363 | 54.2141 | Not smooth |
| Δ TECINN | -17.4002*** | -9.52198*** | 186.539*** | -12.9367*** | Smooth |

Note. ***, **, and * shows significance at the 1% level, 5% level, and 10% level, respectively. Δ represents the 1st order difference.

TABLE 4: Results of the optimal lag order test.

| Variable | Lag | AIC | BIC | HQIC |
|--------------------|-----|--------|--------|--------|
| TECINN-wastewater | 1 | 19.51* | 20.25* | 19.80* |
| | 2 | 19.612 | 20.45 | 19.95 |
| | 3 | 19.91 | 20.87 | 20.29 |
| | 4 | 19.88 | 20.98 | 20.32 |
| TECINN-solid waste | 1 | 15.04* | 15.78* | 15.34* |
| | 2 | 15.24 | 16.08 | 15.58 |
| | 3 | 15.77 | 16.73 | 16.16 |
| | 4 | 16.17 | 17.27 | 16.61 |
| TECINN-exhaust gas | 1 | 8.47 | 9.20 | 8.76 |
| | 2 | 8.81 | 9.66 | 9.151 |
| | 3 | 7.47 | 8.43 | 7.86 |
| | 4 | 6.30* | 7.41* | 6.75* |

TABLE 5: Results of cointegration root test.

| Variable | Test statistics | Test result | Conclusion |
|---------------------|---------------------|-------------|-----------------------------------|
| TECINN-wastewater | Panel v-Statistic | 2.61*** | Cointegration relationship exists |
| | Panel rho-Statistic | -0.19 | |
| | Panel PP-Statistic | -5.99*** | |
| | Panel ADF-Statistic | -0.66 | |
| | Group rho-Statistic | 2.43 | |
| | Group PP-Statistic | -5.92*** | |
| | Group ADF-Statistic | -1.21 | |
| TECINN-solid waste | Panel v-Statistic | 5.01*** | Cointegration relationship exists |
| | Panel rho-Statistic | -0.14 | |
| | Panel PP-Statistic | -0.60 | |
| | Panel ADF-Statistic | -3.30*** | |
| | Group rho-Statistic | 2.06 | |
| | Group PP-Statistic | -0.82 | |
| | Group ADF-Statistic | -1.50 | |
| TECINN -exhaust gas | Panel v-Statistic | 5.53*** | Cointegration relationship exists |
| | Panel rho-Statistic | -5.03*** | |
| | Panel PP-Statistic | -10.32*** | |
| | Panel ADF-Statistic | -8.59*** | |
| | Group rho-Statistic | -1.71** | |
| | Group PP-Statistic | -10.91*** | |
| | Group ADF-Statistic | -9.59*** | |

Note. *** means $p < 0.01$; ** means $p < 0.05$; and * means $p < 0.1$.

gradual downward trend, and the impact of technological innovation on it shows a gradually enhancing trend. By the 12th period, 99.6% of the change in solid waste emissions can be explained by itself, and technological innovation contributes 0.4% to solid waste. Similar to the conclusion on

wastewater discharge, the change in China's solid waste discharge is mainly influenced by itself, while technological innovation has little impact on it. In the case of the emission change of exhaust gas, the explanatory power of the change in exhaust gas is 100% in the 1st period. However, with the

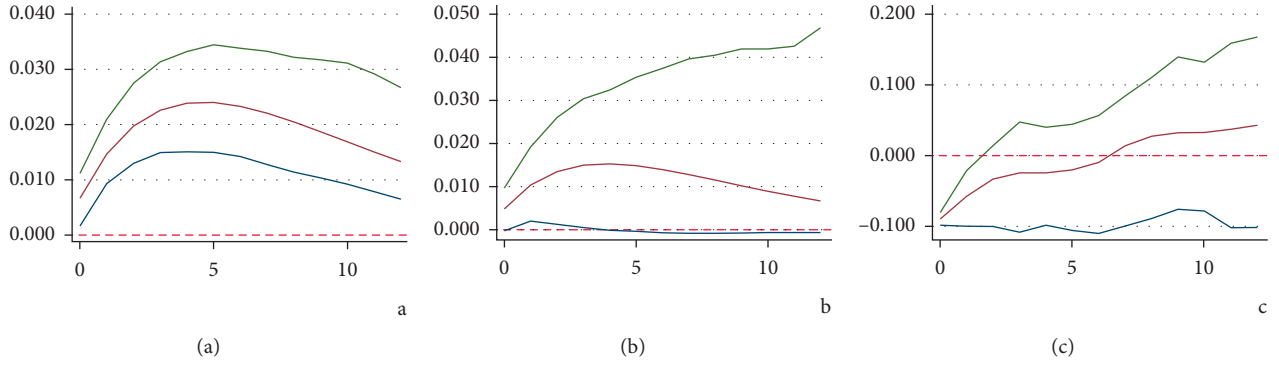


FIGURE 3: Impulse response results of technological innovation to environmental pollution: (a) impulse response of wastewater to TECINN, (b) impulse response of waste solid to TECINN, and (c) impulse response of exhaust gas to TECINN.

TABLE 6: Variance decomposition.

| Variable period | Wastewater | | Solid waste | | Exhaust gas | |
|-----------------|------------|--------|-------------|--------|-------------|--------|
| | Wastewater | TECINN | Solid waste | TECINN | Exhaust gas | TECINN |
| 1 | 1.000 | 0.000 | 1.000 | 0.000 | 1.000 | 0.000 |
| 2 | 0.998 | 0.002 | 1.000 | 0.000 | 0.871 | 0.129 |
| 3 | 0.996 | 0.004 | 0.999 | 0.001 | 0.686 | 0.314 |
| 4 | 0.992 | 0.008 | 0.999 | 0.001 | 0.544 | 0.456 |
| 5 | 0.989 | 0.011 | 0.998 | 0.002 | 0.474 | 0.526 |
| 6 | 0.985 | 0.015 | 0.998 | 0.002 | 0.431 | 0.569 |
| 7 | 0.982 | 0.018 | 0.997 | 0.003 | 0.398 | 0.602 |
| 8 | 0.979 | 0.021 | 0.997 | 0.003 | 0.358 | 0.642 |
| 9 | 0.977 | 0.023 | 0.997 | 0.003 | 0.341 | 0.659 |
| 10 | 0.975 | 0.025 | 0.996 | 0.004 | 0.339 | 0.661 |
| 11 | 0.973 | 0.027 | 0.996 | 0.004 | 0.337 | 0.663 |
| 12 | 0.972 | 0.028 | 0.996 | 0.004 | 0.337 | 0.663 |

passage of time, the impact of exhaust gas emissions on itself shows a gradual decrease, while the impact of technological innovation increases. However, it is worth noting that by the 12th period, 33.7% of the variation in exhaust gas can be explained by itself, and 66.3% of this change was attributable to technological innovation. According to the results, China's exhaust gas emissions are initially affected by itself, but in the long term, they are mainly influenced by technological innovation.

5. Conclusion

5.1. Conclusion and Policy Implications. Based on provincial panel data of China from 2004 to 2016, this study analyzes the impact mechanisms of technological innovation on environmental pollution and then empirically analyzes how China's technological innovation affects the discharge of wastewater, solid waste, and waste gas. This is the biggest difference between this study and the existing literature, which failed to analyze different pollutant emissions.

In conclusion, the level of technological innovation in China has been rising steadily. However, technology plays a promoting rather than inhibiting role in the discharge of wastewater, solid waste, and waste gas emissions, which is consistent with existing research. For example, Yu and Du

found that China's independent technological innovation activities would accelerate CO₂ emissions, especially when the speed of economic growth slows down [9]. Kumar and Managi indicated that developing countries tend to promote CO₂ emissions while technologically advancing [11]. In addition, Li et al. have found that technological progress in central and western China has increased the discharge of water pollutants [39]. The fundamental reason why technological innovation has promoted the emission of pollutants is that, in the development process, China focused on improving economic effectiveness while ignoring environmental benefits. As a result the environmental costs in China were low, or in some cases, nonexistent. Meanwhile, a lack of environmental awareness has caused pollution. We can expect that with the slowdown of economic growth, technological innovation will further promote the emission of pollutants [9]. We also found that the changes in China's wastewater discharge and solid waste production are mainly due to their own influence. However, variations in exhaust emissions, in the short term, are mainly influenced by themselves. In the long term, the influence of technological innovation on exhaust emissions gradually amplify and eventually surpass the influence of its own.

We propose that the government should further improve the system and policies for environmental pollution control,

which are needed to establish strict discharge standards and protection laws. In addition, China must invest in the development of environmentally friendly technology, even when facing an economic recession. In this case, to achieve the coordinated development of the economy and the environment, it is essential to decrease the negative impact of pollution emissions and promote sustainable economic development.

5.2. Research Limitation and Prospect. In the context of increasingly serious global environmental pollution and the continuous development of technology, this study takes China as an example to empirically analyze the impact of technological innovation on pollutant emissions. A limitation of this study is that we adopted the entropy method and the PAVR model. Future research could use other approaches to analyze the complex relationship between technological innovation and environmental pollutant emissions. In addition, due to the significantly uneven development of economic levels, technological innovation, and energy consumption among different regions in China, it is necessary to further broaden the research objects and data sources in the future to enrich and improve the conclusions of this paper.

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 financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' Contributions

Xin Duan contributed to the methodology and investigation. Zhi Sheng Zhang contributed to modifying and improving the paper. Jiahui Sun contributed to the investigation and formal analysis.

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Research Article

The Green Product's Pricing Strategy in a Dual Channel considering Manufacturer's Risk Attitude

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This paper develops a two-echelon green supply chain that consists of one green manufacturer and one retailer. The green manufacturer has both online direct and offline retail channels. Considering manufacturer's risk attitude and product's green level, the paper constructs centralized and decentralized game models when the online channel's demand is uncertain. Furthermore, this paper analyzes the impacts of a set of factors, including consumer environmental awareness (CEA), product green level, and risk attitude on decision-making in the supply chain. Finally, we present numerical examples. The main findings are as follows: the manufacturer and the retailer will benefit from the improvement of CEA; hence, they could invest more to obtain more profits by improving CEA; manufacturer's risk attitude has a negative impact on the pricing and profits of the supply chain; as such, the members of the supply chain should improve the accuracy of their demand forecast, so as to minimize risks and losses resulting from uncertainty in demand.

1. Introduction

Many manufacturers have begun to produce environmentally friendly products (green products) facing the government regulations as well as international green barriers. Now consumers are more willing to pay for the green product. An empirical survey demonstrates that 62% of consumers are willing to buy high-star appliances, and half of the consumers are willing to pay \$67.6 more for purchasing air conditioners with a high energy efficiency level in India [1, 2].

At the same time, with the convenience of online sales, many green product manufacturers develop their own online channels to directly sell their products to the end consumers [3], such as Dell, Media, and Haier. However, introducing the online channel may not mean that the manufacturer's utility will increase because of the channel competition and fluctuation of the online channel demand [4]. Therefore, whether the green manufacturer will benefit from the online channel and how risk attitude affects the dual-channel pricing decision are the questions calling for studies.

Our research is motivated by the household appliances industry. Take Haier as an example, Haier produces a variety of energy-saving air conditioners and refrigerators. At the same time, Haier introduces the online direct channel. Media and Dell are other good examples. With the practice of these green products, it is important to explore the optimal decisions for the manufacturers and retailers. This study focuses on how a manufacturer that sells a green product can take advantage of both the traditional retail channel and the direct online channel.

The demand of the online channel could be affected by some nonproduct or service-related factors such as Internet accessibility and consumers' acceptance that may be difficult to observe [5]. With the uncertain demand, the risk attitude suggested by prior studies is an important factor affecting a firm's decision [6]. Hence, with the uncertainty of the online demand, in this paper, we will explore the price strategies changes when the manufacturer's risk attitude is different.

Specifically, we investigate the following research questions: (1) How the manufacturer and the retailer decide the online direct price and the retail price to mitigate

channel conflict? (2) How the demand uncertainty and manufacturer's risk attitude influence manufacturer and retailer's decisions?

To answer these questions, we consider a dual-channel green supply chain, where one manufacturer produces a green product and sells the product through a retail channel and its own direct channel to maximize his profit. Considering CEA and the demand uncertainty, we give the demand functions of the online channel and retail channel. In the Stackelberg game, we assume that the manufacturer is the leader and the retailer is the follower, and we discuss the scenarios when the manufacturer is risk neutral and risk averse in the centralized model and decentralized model, respectively. In the centralized model, the manufacturer and the retailer as a whole decide the green product's online channel price and retail channel price. In the decentralized model, the dominant manufacturer decides the wholesale price and online channel price; then the retailer decides the retail price. We use the backward induction to solve the problem. In addition, we conduct numerical studies to observe the profit changes with respect to key parameters. Finally, we give the main managerial implications.

The rest of the paper is organized as follows. In Section 2, we present the literature review. In Sections 3 and 4, we establish the centralized model and decentralized model when the manufacturer is risk neutral and risk averse. Section 5 presents the numerical examples. We conclude this study in Section 6.

2. Literature Review

There are some literature related to green supply chain, dual channel, and risk attitude, and we here primarily review the most related two research streams: dual channel and risk attitude.

The first stream focuses on how the manufacturer or the retailer coordinates the two channels to mitigate the channel competition. Tsay and Agrawal [7] developed a model that captured key attributes of such a setting, including various sources of inefficiency. Yao and Liu [8] considered the price competition between these two channels under two market game settings: the Bertrand and the Stackelberg price competition models. Yue and Liu [9] analyzed the benefits of sharing demand forecast information in a manufacturer-retailer supply chain. Cai et al. [10] evaluated the impact of price discount contracts and pricing schemes with the dual-channel supply chain competition. Dan et al. [11] evaluated the impacts of retail services and the degree of customer loyalty to the retail channel on the manufacturer and retailer's pricing behaviors in a centralized and a decentralized dual-channel supply chain. Chen and Bell [12] examined how a firm that faces customer returns can enhance profit by using different customer returns policies, full-refund and no-returns, as a device to segment its market into a dual-channel structure. Cao et al. [13] developed an analytical framework to study the impact of an "online-to-store" channel on the demand allocations and profitability of a retailer who sells products to customers through multiple distribution channels. Li et al. [14] examined a dual-channel

supply chain in which the manufacturer makes green products for the environmental consciousness. Jamali and Rasti-Barzoki [1] focused on the pricing and determination of the degree of greenness of a product in competition with a nongreen product. Barzinpour and Taki [15] proposed a mathematical model in this paper that identifies locations of productions and shipment quantity by exploiting the trade-off between costs and emissions for a dual-channel supply chain network. Yang et al. [16] modeled the environmental responsibility behaviors of both manufacturer and consumers to study the dual-channel structure strategy of a green manufacturer and further examines its environmental performance under fuzzy uncertainties. Ranjan and Jha [17] investigated the pricing strategies and coordination mechanisms considering the green quality and sales effort. Li et al. [18] constructed a dual-channel value chain composed of one altruistic manufacturer and one altruistic retailer, where the manufacturer makes green innovation input for green products and sells its green products to its customers through both the direct channel and the traditional channel, and the retailer provides channel service for customers and sells green products through the traditional channel. Liang and Sun [19] considered service free-riding and channel price difference in a green product dual-channel supply chain with a manufacturer and a retailer. Li et al. [20] studied a dynamic price game model in a dual-channel green supply chain considering firm's innovation input of green products and channel service. Lou et al. [21] explored the issues concerning green subsidies of government and optimal decisions of a manufacture and dual-channel retailers in a two-echelon dual-channel supply chain.

The above literature works mainly discuss the pricing for the dual channel, but the uncertainty of the online channel is not considered. This paper will explore the impacts of the uncertainty of online demand on dual-channel pricing.

The second stream focuses on how the supply chain member's risk attitude affects the manufacturer's and retailer's decisions. In the single-channel sales model, Zand et al. [22] studied the profit division of the supply chain members considering their risk attitude and bargaining power through asymmetrical Nash bargaining. Ni et al. [23] analyzed the risk of the manufacturer and the supplier in a scenario in which an upstream supplier and a downstream manufacturer transacting an intermediate product via direct bilateral contracting and futures market channels with differentiated products. Wan et al. [24] focused on uncertain demand from the merchant and agency mode perspectives. In the dual-channel model, Xu et al. [25] investigated the impact of establishing a dual-channel supply chain coordinating contract when the supply chain agents are risk aversion under a mean-variance model. Li et al. [26] explored the effects of the retailer's risk indicator on the retail price, the ordering quantities of the e-channel and traditional channel and the profits of the supplier and the retailer, and the total profits of the supply chain. Zhu et al. [27] measured the risk attitude with Conditional Value-at-Risk (CVaR) approach and assumed that the manufacturer is risk neutral and the retailer is risk averse in a dual-channel supply chain including a direct channel and a traditional

channel. Zhang and Wang [4] studied the retailer's risk attitude under the condition that a retailer sells short-life-cycle product and uses the online channel as a supplement to its traditional channel. Rahmani and Yavari [28] investigated the demand disruption management in a dual-channel supply chain producing and selling green products. Wang and Song [29] investigated the pricing policies for dual-channel supply chain under uncertain demand but assumed that the manufacturer is risk neutral, the manufacturer sells green products by the direct channel, and the retailer sells nongreen products.

Most above literature discussed the traditional product's price strategy with retailer's risk attitude, but in this paper, we assume that the online direct channel and the retail channel sell the green product and discuss the scenario when the manufacturer is risk neutral or risk averse.

3. Assumptions and the Model

3.1. Problem Description. Assume that a two-echelon green supply chain consists of one manufacturer and one retailer. We assume that the manufacturer produces a green product with green quality e . The manufacturer sells the product to the retailer with the wholesale price and sells the product directly to consumers by online direct channel. The retailer sells the product to consumers by retail channel. Consumers choose the sale channel to purchase the product based on their channel preference.

The structure of the dual-channel supply chain is illustrated in Figure 1.

3.2. Assumptions. Compared with the ordinary product, the green product has green quality such as the low carbon emission, energy saving, or the high recycling rate. We denote the green quality of the green product as the green level of the product. We consider the impacts of the CEA and green level of the product on the market demand. As the CEA and the green level of the product increase, the green product's demand increases [22]. And the demand decreases with the retail price. Because the demand of the online channel has much higher uncertainty than the offline channel, hence we assume that the online channel demand is uncertain. Further, we study the risk attitude of the manufacturer in the model.

Similar to [30, 31], we assume that the green product's demand functions for the offline sales and direct sales channels are as follows, respectively:

$$\begin{aligned} D_r &= a_1 - p_r + \theta(p_d - p_r) + \tau e, \\ D_d &= a_2 - p_d + \theta(p_r - p_d) + \tau e + \varepsilon, \end{aligned} \quad (1)$$

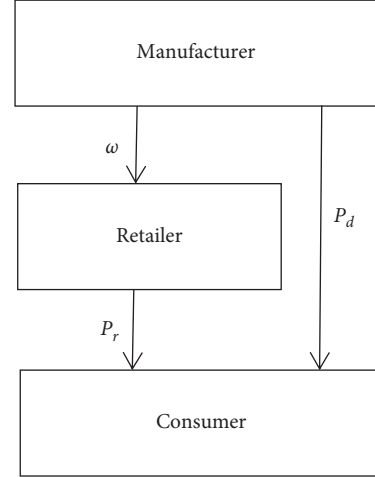


FIGURE 1: Dual-channel supply chain structure.

where ε is the random demand and follows a truncated normal distribution in $[-A, A]$, $E(\varepsilon) = 0$, and $\text{Var}(\varepsilon) = \sigma^2$. And, we assume that $\tau e \geq A$ to ensure that the online channel's demand is positive.

Assume that the manufacturer is responsible for the R&D and manufacturing costs of the green product in the supply chain. Similar to Zhu and He [32] and Reimann et al. [33], the manufacturer's R&D cost in the green product is $(1/2)ze^2$, where z is the R&D influence coefficient. With the direct sale channel, the marketing cost for the manufacturer is c_{sm} .

We use η_m to denote the risk attitude of the manufacturer; $\eta_m = 0$ indicates that the manufacturer is risk neutral and a higher η_m value indicates that the manufacturer is more risk averse. The parameters and decision variables are presented in Table 1.

Based on the above assumptions, the profit functions for the manufacturer and retailer are derived as follows:

$$\pi_m = \omega D_r + (p_d - c_{sm})D_d - \frac{1}{2}ze^2, \quad (2)$$

$$\pi_r = (p_r - \omega)D_r.$$

The manufacturer's expected profit function is

$$\begin{aligned} E(\pi_m) &= E\left\{\omega D_r + (p_d - c_{sm})D_d - \frac{1}{2}ze^2\right\} \\ &= \omega[a_1 - p_r + \theta(p_d - p_r) + \tau e] + (p_d - c_{sm})[a_2 - p_d + \theta(p_r - p_d) + \tau e] - \frac{1}{2}ze^2. \end{aligned} \quad (3)$$

TABLE 1: Model parameters and decision variables.

| Parameters | Definition |
|---------------------------|--|
| e | Green level of product |
| c_{sm} | Unit marketing cost of manufacturer |
| τ | CEA ($\tau > 0$) |
| a_i | Market demand of channel i ($a_i > 0$) |
| z | R&D cost coefficient |
| η_m | Manufacturer's risk attitude ($\eta_m \geq 0$) |
| ε | Uncertainty in demand ($\varepsilon \sim N(0, \sigma^2)$) |
| σ^2 | Mean squared error of demand |
| θ | Cross price elasticity coefficient between traditional sales channel and direct sales channel ($\theta > 0$) |
| I | $i = r$ or m represents the manufacturer or the retailer |
| π_i | The profit of i |
| $E(\pi_i); U(\pi_i)$ | The expected profit and the utility of i |
| <i>Decision variables</i> | |
| ω | Manufacturer's wholesale price |
| p_r | Retailer's retail price |
| p_d | Manufacturer's direct sale price |

In addition, superscript c denotes the centralized decision-making model, and superscript d denotes the decentralized decision-making model. Subscripts 1 and 2 denote whether the manufacturer is risk neutral or risk averse, respectively; subscript d denotes the direct sale channel; and subscript c denotes the supply chain.

As the manufacturer is risk averse, based on the mean-variance theory [34] and the impacts of profit and variance, the manufacturer's expected utility is

$$\begin{aligned}
U(E(\pi_m)) &= E(\pi_m) - \eta_m \text{Var}(\pi_m) \\
&= E(\pi_m) - \eta_m E[\pi_m - E(\pi_m)]^2 = \omega[a_1 - p_r + \theta(p_d - p_r) + \tau e] \\
&\quad + (p_d - c_{sm})[a_2 - p_d + \theta(p_r - p_d) + \tau e] \\
&\quad - \frac{1}{2}ze^2 - \eta_m(p_d - c_{sm})^2\sigma^2.
\end{aligned} \tag{4}$$

4. Centralized Decision Model

In the centralized model, the manufacturer and the retailer are as a whole, and the goal is to maximize the utility of the

supply chain. On this basis, we discuss the two scenarios in which the manufacturer is either risk neutral or risk averse.

In the centralized model, the expected utility of the supply chain is as follows:

$$\begin{aligned}
U(E\pi_c^c) &= U(E\pi_m) + U(\pi_r) \\
&= (p_d^c - c_{sm})[a_2 - p_d^c + \theta(p_r^c - p_d^c) + \tau e] - \frac{1}{2}ze^2 \\
&\quad - \eta_m(p_d^c - c_{sm})^2\sigma^2 + p_r^c[a_1 - p_r^c + \theta(p_d^c - p_r^c) + \tau e].
\end{aligned} \tag{5}$$

4.1. Manufacturer Is Risk Neutral. In this section, we study the supply chain's pricing strategy under the centralized decision model when the manufacturer is risk neutral. In

this scenario, $\eta_m = 0$; then, the utility functions of the manufacturer and the supply chain can be derived as follows:

$$U(E\pi_{m1}^c) = \omega_1^c [a_1 - p_{r1}^c + \theta(p_{d1}^c - p_{r1}^c) + \tau e] + (p_{d1}^c - c_{sm}) [a_2 - p_{d1}^c + \theta(p_{r1}^c - p_{d1}^c) + \tau e] - \frac{1}{2} z e^2, \quad (6)$$

$$U(\pi_{c1}^c) = (p_{d1}^c - c_{sm}) [a_2 - p_{d1}^c + \theta(p_{r1}^c - p_{d1}^c) + \tau e] - \frac{1}{2} z e^2 + p_{r1}^c [a_1 - p_{r1}^c + \theta(p_{d1}^c - p_{r1}^c) + \tau e]. \quad (7)$$

Theorem 1. *In the centralized decision model, when the manufacturer is risk neutral, the optimal green supply chain pricing strategies for the manufacturer and retailer are as follows:*

$$p_{d1}^c = \frac{a_2 + (a_1 + a_2)\theta + (1 + 2\theta)(c_{sm} + \tau e)}{2(2\theta + 1)}, \quad (8)$$

$$p_{r1}^c = \frac{a_1 + (a_1 + a_2)\theta + (1 + 2\theta)\tau e}{2(2\theta + 1)}. \quad (9)$$

Proof of Theorem 1 is shown in Appendix A.

From Theorem 1, we can see that the manufacturer's direct sale price and the retailer's retail price are correlated with market demand, the market share of the offline sales channel, CEA, and product green level. From this theorem, Propositions 1–3 can be derived.

Proposition 1. *In the centralized decision model, when the manufacturer is risk neutral, both p_{d1}^c and p_{r1}^c increase with CEA τ .*

Proposition 2. *In the centralized decision model, when the manufacturer is risk neutral, both p_{d1}^c and p_{r1}^c increase with the product green level e .*

Proposition 1 shows that, with CEA, the manufacturer's and the retailer's channel prices increase; Proposition 2 shows that when the manufacturer increases investment in the R&D to improve the green level of the green product, both the manufacturer's direct sales price and the retailer's retail price increase.

Proof of Propositions 1 and 2 is shown in Appendix C.

4.2. Manufacturer Is Risk Averse. In this subsection, we study green product's pricing strategies in the centralized decision model when the manufacturer is risk averse. With the uncertain demand of the online channel, the manufacturer's risk attitude may be averse. In this scenario, $\eta_m > 0$, and the utility function of the supply chain is

$$\begin{aligned} U(E\pi_{c2}^c) &= (p_{d2}^c - c_{sm}) [a_2 - p_{d2}^c + \theta(p_{r2}^c - p_{d2}^c) + \tau e] \\ &\quad - \frac{1}{2} z e^2 - \eta_m (p_{d2}^c - c_{sm})^2 \sigma^2 + p_{r2}^c [a_1 - p_{r2}^c \\ &\quad + \theta(p_{d2}^c - p_{r2}^c) + \tau e]. \end{aligned} \quad (10)$$

Theorem 2. *In the centralized decision model, when the manufacturer is risk averse, the optimal pricing strategies for the dual channels of the green supply chain are as follows:*

$$p_{d2}^c = \frac{a_2 + (a_1 + a_2)\theta + (1 + 2\theta)(c_{sm} + \tau e) + 2(1 + \theta)c_{sm}\eta_m\sigma^2}{2(2\theta + \eta_m\sigma^2 + \theta\eta_m\sigma^2 + 1)}, \quad (11)$$

$$p_{r2}^c = \frac{a_1 + (a_1 + a_2)\theta + (1 + 2\theta)\tau e + (\theta c_{sm} + a_1 + \tau e)\eta_m\sigma^2}{2(2\theta + \eta_m\sigma^2 + \theta\eta_m\sigma^2 + 1)}. \quad (12)$$

Proof of Theorem 2 is shown in Appendix B.

Different from Theorem 1, the prices of both channels in Theorem 2 are related to the variable of the random demand. From this Theorem 2, Propositions 3–5 can be derived.

Proposition 3. *In the centralized decision model, when the manufacturer is risk averse, both p_{d1}^c and p_{r1}^c increase with CEA τ .*

Proposition 4. *In the centralized decision model, when the manufacturer is risk averse, both p_{d2}^c and p_{r2}^c increase with the product green level e .*

Similar to Propositions 1 and 2, we could obtain Propositions 3 and 4.

Proposition 5. *In the centralized decision model, when the manufacturer is risk averse, p_{d2}^c and p_{r2}^c decrease with the manufacturer's risk averse level η_m .*

Proposition 5 means that the higher the manufacturer's risk averse level, the lower the direct sale price and the retail price. It is interesting that the retail price of the offline channel also decreases with η_m .

Proof of Propositions 3 and 4 is shown in Appendix C and proof of Proposition 5 is shown in Appendix D.

5. Decentralized Decision Model

In this model, both the manufacturer and the retailer try to maximize their own utility. In the Stackelberg game, we assume that the manufacturer is the leader and the retailer is the follower. The manufacturer's decision variables are the

wholesale price ω and direct sale price p_d ; the retailer needs to decide the retail price p_r . We use the backward induction method to determine the optimal solutions. The manufacturer's utility function and retailer's profit function are as follows:

$$U(E\pi_m^d) = \omega^d [a_1 - p_r^d + \theta(p_d^d - p_r^d) + \tau e] + (p_d^d - c_{sm}) [a_2 - p_d^d + \theta(p_r^d - p_d^d) + \tau e] - \frac{1}{2}ze^2 - \eta_m(p_d^d - c_{sm})^2 \sigma^2, \quad (13)$$

$$\pi_r^d = (p_r^d - \omega^d)D_r = (p_r^d - \omega^d) [a_1 - p_r^d + \theta(p_d^d - p_r^d) + \tau e].$$

5.1. Manufacturer Is Risk Neutral. In this subsection, we study the pricing strategy under the decentralized decision model when the manufacturer is risk neutral; that is, $\eta_m = 0$.

Then the utility functions of the manufacturer, retailer, and the whole supply chain can be derived as follows:

$$U(E\pi_m^d) = \omega_1^d [a_1 - p_{r1}^d + \theta(p_{d1}^d - p_{r1}^d) + \tau e] + (p_{d1}^d - c_{sm}) [a_2 - p_{d1}^d + \theta(p_{r1}^d - p_{d1}^d) + \tau e] - \frac{1}{2}ze^2, \quad (14)$$

$$U(\pi_{r1}^d) = (p_{r1}^d - \omega_1^d) [a_1 - p_{r1}^d + \theta(p_{d1}^d - p_{r1}^d) + \tau e], \quad (15)$$

$$U(E\pi_{c1}^d) = (p_{d1}^d - c_{sm}) [a_2 - p_{d1}^d + \theta(p_{r1}^d - p_{d1}^d) + \tau e] - \frac{1}{2}ze^2 + p_{r1}^d [a_1 - p_{r1}^d + \theta(p_{d1}^d - p_{r1}^d) + \tau e]. \quad (16)$$

Theorem 3. In the decentralized decision model, when the manufacturer is risk neutral, the optimal pricing strategies for

the green supply chain for the manufacturer and retailer are as follows:

$$p_{d1}^d = \frac{a_2 + (a_1 + a_2)\theta + (1 + 2\theta)(c_{sm} + \tau e)}{2(2\theta + 1)}, \quad (17)$$

$$\omega_1^d = \frac{a_1 + (a_1 + a_2)\theta + (1 + 2\theta)\tau e}{2(2\theta + 1)}, \quad (18)$$

$$p_{r1}^d = \frac{2\theta(1 + \theta)(a_1 + a_2) + a_1(3 + 4\theta) + \theta c_{sm}(1 + 2\theta) + [3 + 4\theta(2 + \theta)]\tau e}{8\theta^2 + 12\theta + 4}. \quad (19)$$

Proof of Theorem 3 is shown in Appendix E.

Theorem 3 indicates that, in the decentralized decision model, when the manufacturer is risk neutral, the wholesale price, direct sales price, and retail price are correlated with market demand, the market share of the offline sales channel, CEA, and product green level. From Theorem 3, Propositions 6 and 7 can be derived.

Proposition 6. In the decentralized decision model, when the manufacturer is risk neutral, p_{d1}^d , ω_1^d , and p_{r1}^d increase with CEA.

Proposition 7. In the decentralized decision model, when the manufacturer is risk neutral, p_{d1}^d , ω_1^d , and p_{r1}^d increase with product green level.

Proof of Propositions 6 and 7 is shown in Appendix H.

Propositions 6 and 7 indicate that high CEA motivates the manufacturer to increase input into R&D and manufacturing of the green product; a high green level requires higher-quality raw materials and more input into advertising and marketing. The extra costs will eventually be shifted to consumers, driving up the price.

5.2. Manufacturer Is Risk Averse. In this subsection, we consider supply chain pricing strategies in the decentralized decision model when the manufacturer is risk averse ($\eta_m > 0$). Then the utility functions of the manufacturer, retailer, and the whole supply chain can be derived as follows:

$$U(E\pi_{m2}^d) = \omega_2^d [a_1 - p_{r2}^d + \theta(p_{d2}^d - p_{r2}^d) + \tau e] + (p_{d2}^d - c_{sm}) [a_2 - p_{d2}^d + \theta(p_{r2}^d - p_{d2}^d) + \tau e] - \frac{1}{2} z e^2 - \eta_m (p_{d2}^d - c_{sm})^2 \sigma^2, \quad (20)$$

$$U(\pi_{r2}^d) = (p_{r2}^d - \omega_2^d) D_r = (p_{r2}^d - \omega_2^d) [a_1 - p_{r2}^d + \theta(p_{d2}^d - p_{r2}^d) + \tau e]. \quad (21)$$

The expected utility of the supply chain is

$$U(E\pi_{c2}^d) = (p_{d2}^d - c_{sm}) [a_2 - p_{d2}^d + \theta(p_{r2}^d - p_{d2}^d) + \tau e] - \frac{1}{2} z e^2 + p_{r2}^d [a_1 - p_{r2}^d + \theta(p_{d2}^d - p_{r2}^d) + \tau e] - \eta_m (p_{d2}^d - c_{sm})^2 \sigma^2. \quad (22)$$

Theorem 4. *In the decentralized decision model, when the manufacturer is risk averse, the optimal pricing strategies for the green supply chain are as follows:*

$$p_{d2}^d = \frac{a_2 + (a_1 + a_2)\theta + (1 + 2\theta)(c_{sm} + \tau e) + 2(1 + \theta)c_{sm}\eta_m\sigma^2}{2(2\theta + \eta_m\sigma^2 + \theta\eta_m\sigma^2 + 1)}, \quad (23)$$

$$\omega_2^d = \frac{a_1 + (a_1 + a_2)\theta + (1 + 2\theta)\tau e + (\theta c_{sm} + a_1 + \tau e)\eta_m\sigma^2}{2(2\theta + \eta_m\sigma^2 + \theta\eta_m\sigma^2 + 1)}, \quad (24)$$

$$p_{r2}^d = \frac{a_1(4\theta + 3) + 2\theta(1 + \theta)(a_1 + a_2) + \theta(1 + 2\theta)c_{sm} + (3 + 8\theta + 4\theta^2)\tau e + 3(1 + \theta)[\theta c_{sm} + a_1 + \tau e]\eta_m\sigma^2}{4(\theta + 1)(2\theta + \eta_m\sigma^2 + \theta\eta_m\sigma^2 + 1)}. \quad (25)$$

Proof of Theorem 4 is shown in Appendix F.

Theorem 4 indicates that, under the decentralized decision model, when the manufacturer is risk averse, the direct sales price, the wholesale price, and the retail price are correlated with market demand, the market share of the offline sales channel, CEA, and the manufacturer's risk averse level. Different from Theorem 3, the prices in Theorem 4 are affected by the random demand variable. From Theorem 4, Propositions 8–10 can be derived.

Proposition 8. *In the decentralized decision model, when the manufacturer is risk averse, p_{d2}^d , ω_2^d , and p_{r2}^d increase with CEA.*

Proposition 9. *In the decentralized decision model, when the manufacturer is risk averse, p_{d2}^d , ω_2^d , and p_{r2}^d increase with the product green level.*

Proof of Propositions 8 and 9 is shown in Appendix G.

Similar to the situations in Propositions 8 and 9, stronger CEA and a high product green level motivate the manufacturer to increase input into R&D and the procurement of

higher-quality green materials. The increases in costs will increase the wholesale price, direct sales price, and retail price.

Proposition 10. *In the decentralized decision model, when the manufacturer is risk averse, p_{d2}^d , ω_2^d , and p_{r2}^d decrease with the manufacturer's risk averse level η_m .*

Proof of Proposition 10 is shown in Appendix H.

Proposition 10 indicates that the manufacturer will reduce the investment of the R&D of the green product as the risk averse level increases; hence, the wholesale price and the direct sales price decrease; then the retailer follows the manufacturer's pricing strategy and reduces the offline sales price.

6. Numerical Analysis

In this section, we will present the change trends of the manufacturer's and retailer's profits as market share of the offline sales channel, CEA, product green level, and manufacturer's risk aversion level when the manufacturer is risk

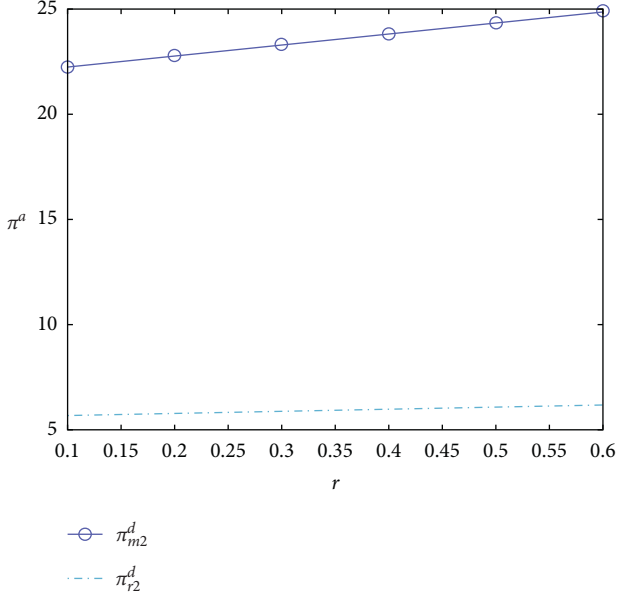


FIGURE 2: Impacts of CEA on profits in the centralized and decentralized decision models.

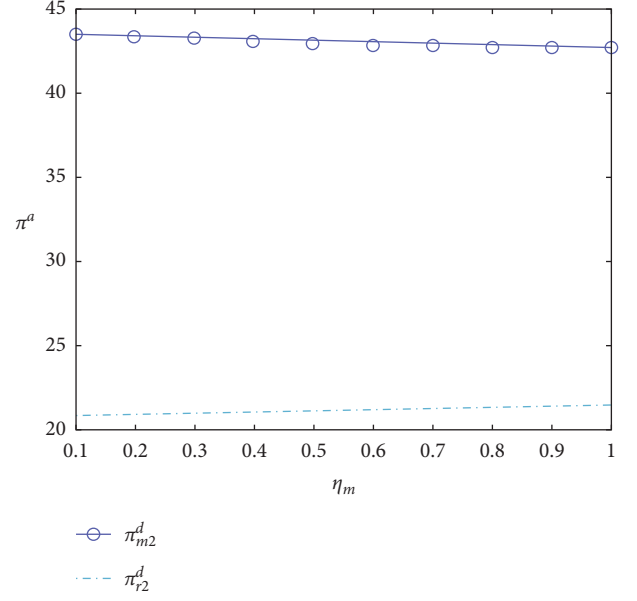


FIGURE 4: Impacts of manufacturer's risk averse level on profits in the centralized and decentralized decision models.

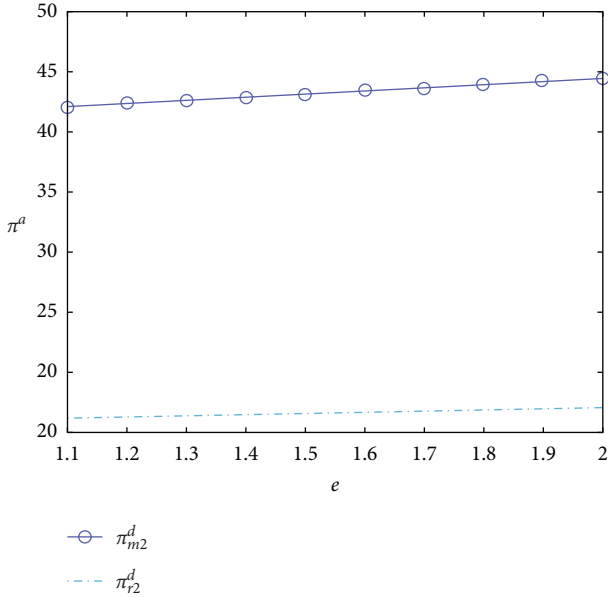


FIGURE 3: Impacts of green level of the product on profits in the centralized and decentralized decision models.

averse in the decentralized model. Because of the complexity of the profits' expressions, we could not give the proofs of the change trends, but we also could obtain some interesting results from the numerical examples. Assume that $c_{sm} = 3$, $z = 0.1$, $\sigma = 2$, and $\theta = 0.4$. These parameters are consistent with our assumptions and industrial practices.

6.1. Impacts of CEA and Green Level of the Product. In this subsection, we explore the impacts of consumers' environmental awareness τ and green level of the product e on the manufacturer's and retailer's profits. Let $a_1 = a_2 = 10$, $e = 1$, and $\eta_m = 0.5$, and other parameters are as assumed at the beginning of this section. Figure 2 shows that the manufacturer's and retailer's profits continue to increase with CEA. Figure 3 shows that the manufacturer's and retailer's profits continue to increase with CEA.

Propositions 2, 4, 7, and 9 show that the wholesale price, direct sales price, and retail price increase with e . Let $a_1 = a_2 = 10$, $\tau = 0.5$, and $\eta_m = 0.5$; we study the green level of the product e on the manufacturer's and retailer's profits. Figure 3 shows that the manufacturer's and retailer's profits continue to increase with e . This means that increasing input into green products is profitable, as the profits to members of the supply chain outweigh their input into green products.

6.2. Impact of the Manufacturer's Risk Aversion Level. In this subsection, we explore the impact of manufacturer's risk aversion level η_m on the manufacturer's and retailer's profits. Assume $a_1 = a_2 = 10$, $\tau = 0.5$, and $e = 1$, and other parameters are as assumed at the beginning of this section. Figure 4 shows the change trends of the manufacturer's and retailer's profits in centralized and decentralized models. Figure 4 shows that the manufacturer's and retailer's profits decrease with η_m in the centralized model; and the manufacturer's profit decreases but the retailer's profit increases with η_m in the decentralized model.

7. Conclusions

This paper develops centralized and decentralized decision models in a two-echelon green supply chain that consists of one manufacturer and one retailer. Assume that the manufacturer could open the online direct sale channel and the online demand is uncertain; we analyze the impacts of manufacturer's risk attitude towards the online demand uncertainty on the prices and manufacturer's and retailer's profits. Further, we explore the impacts of the market share of the offline channel, CEA, green level of the product, and manufacturer's risk aversion level. This paper gives the following management insights: manufacturer's high-risk averse level towards the uncertain demand decreases green product's retail price and direct sale price; further, the manufacturer's profit decreases with manufacturer's risk averse level, but retailer's profit may increase with manufacturer's risk averse level. Hence, it may not be a good news to introduce the online channel for the manufacturer when the online channel demand is uncertain and the manufacturer is risk averse. Increasing CEA or green level of the product will bring more profits for the manufacturer and the retailer, thus the manufacturer and the retailer could invest more money on R&D or advertisement on green product to increase CEA or green level of the product.

This paper only studies a two-echelon green supply chain that consists of one manufacturer and one retailer. In future, we could consider the competition of the manufacturers and retailers. In addition, the differences between the online channel and retail channel are not included. Future research could consider the sale service difference into the model. And the channel coordination contract is another research orient.

Appendix

A. Proof of Theorem 1

The following is calculated based on equation (7):

$$\begin{aligned}\frac{\partial U(\pi_{c1}^c)}{\partial p_{r1}^c} &= 2(p_{d1}^c - p_{r1}^c)\theta - 2p_{r1}^c - \theta c_{sm} + a_1 + \tau e, \\ \frac{\partial U(\pi_{c1}^c)}{\partial p_{d1}^c} &= (1 + \theta)c_{sm} + 2(p_{r1}^c - p_{d1}^c)\theta + a_2 - 2p_{d1}^c + \tau e.\end{aligned}\quad (A.1)$$

The Hessian matrix of p_{r1}^c and p_{d1}^c is $H = \begin{bmatrix} -2\theta - 2 & 2\theta \\ 2\theta & -2\theta - 2 \end{bmatrix}$. Because $\theta > 0$, $|H| = 8\theta + 4 > 0$; furthermore, because $-2\theta - 2 < 0$, $U(\pi_{c1}^c)$ is the concave function of p_{r1}^c and p_{d1}^c . p_{r1}^c and p_{d1}^c have optimal solutions that maximize the utility function of the supply chain.

Let $(\partial U(\pi_{c1}^c)/\partial p_{r1}^c) = 0$ and $(\partial U(\pi_{c1}^c)/\partial p_{d1}^c) = 0$; the simultaneous equations are solved to arrive at the optimal solutions of p_{d1}^c and p_{r1}^c which are equations (8) and (9). Theorem 1 is proved.

B. Proof of Theorem 2

The following is calculated based on equation (10):

$$\begin{aligned}\frac{\partial U(\pi_{c2}^c)}{\partial p_{r2}^c} &= 2\theta(p_{d2}^c - p_{r2}^c) - 2p_{r2}^c - \theta c_{sm} + a_1 + \tau e, \\ \frac{\partial U(\pi_{c2}^c)}{\partial p_{d2}^c} &= a_2 - 2p_{d2}^c + (1 + \theta)c_{sm} + 2(p_{r2}^c - p_{d2}^c)\theta + \tau e \\ &\quad + 2(c_{sm} - p_{d2}^c)\eta_m\sigma^2.\end{aligned}\quad (B.1)$$

The Hessian matrix of $U(\pi_{c2}^c)$ with respect to p_{r2}^c and p_{d2}^c is $H = \begin{bmatrix} -2\theta - 2 & 2\theta \\ 2\theta & -2\eta_m\sigma^2 - 2\theta - 2 \end{bmatrix}$. Because $\theta > 0$, $|H| = 4(2\theta + 1) + 4(1 + \theta)\eta_m\sigma^2 > 0$; additionally, because $-2\theta - 2 < 0$, H is a negative definite matrix, and $U(\pi_{c2}^c)$ is the concave function of p_{r2}^c and p_{d2}^c ; therefore, p_{r2}^c and p_{d2}^c have optimal solutions that maximize the utility function of the supply chain. Let $(\partial U(\pi_{c2}^c)/\partial p_{r2}^c) = 0$ and $(\partial U(\pi_{c2}^c)/\partial p_{d2}^c) = 0$. The simultaneous equations are solved to arrive at the optimal solutions of p_{d2}^c and p_{r2}^c , which are equations (11) and (12). Theorem 2 is proved.

C. Proofs of Propositions 1–4

We can obtain Propositions 1–4 by solving the first partial derivative. So we omit the proofs.

D. Proof of Proposition 5

The following is calculated based on equations (11) and (12):

$$\begin{aligned}\frac{\partial p_{d2}^c}{\partial \eta_m} &= -\frac{(1 + \theta)\sigma^2 [a_2 + (a_1 + a_2)\theta + (1 + 2\theta)(\tau e - c_{sm})]}{2(\eta_m\sigma^2 + \theta\eta_m\sigma^2 + 2\theta + 1)^2} < 0, \\ \frac{\partial p_{r2}^c}{\partial \eta_m} &= -\frac{\theta\sigma^2 [a_2 + (a_1 + a_2)\theta + (1 + 2\theta)(\tau e - c_{sm})]}{2(\eta_m\sigma^2 + \theta\eta_m\sigma^2 + 2\theta + 1)^2} < 0.\end{aligned}\quad (D.1)$$

Therefore, p_{d2}^c and p_{r2}^c are decreasing functions of η_m ; namely, with the increase in η_m , p_{d2}^c and p_{r2}^c decrease. Proposition 5 is proved.

E. Proof of Theorem 3

The following is calculated based on equation (15):

$$\frac{\partial U(\pi_{r1}^d)}{\partial p_{r1}^d} = \theta(p_{d1}^d - p_{r1}^d) - p_{r1}^d + a_1 + \tau e - (p_{r1}^d - \omega_{r1}^d)(\theta + 1).\quad (E.1)$$

The second-order partial derivative of $U(\pi_{r1}^d)$ with respect to p_{r1}^d is $-2\theta - 2 < 0$; therefore, there is an optimal solution to p_{r1}^d that maximizes (14).

Let $(\partial U(\pi_{r1}^d)/\partial p_{r1}^d) = 0$; the following can be derived:

$$p_{r1}^d = \frac{\theta p_d + \lambda(a_1 + a_2) + \tau e + \omega(\theta + 1)}{2(\theta + 1)}. \quad (E.2)$$

Substituting the above equation to equation (14), we have

$$\begin{aligned} \max U(\pi_{m1}^d) &= \frac{1}{2} \omega_1^d [p_{d1}^d \theta - (1 + \theta) \omega_1^d + a_1 + \tau e] - \frac{1}{2} z e^2 \\ &+ \frac{(p_{d1}^d - c_{sm}) [2(a_1 + a_2)(1 + \theta) - 2a_1 - 2(1 + 2\theta)p_{d1}^d + (\omega_1^d - p_{d1}^d)\theta^2 + (\omega_1^d - a_1)\theta + (2 + 3\theta)\tau e]}{2(\theta + 1)}. \end{aligned} \quad (E.3)$$

Taking the first-order partial derivative of the above equation with respect to p_{d1}^d and ω_1^d and rearranging the equation, we have

$$\begin{aligned} \frac{\partial U(\pi_{m1}^d)}{\partial p_{d1}^d} &= \frac{2a_2 + 2(a_1 + a_2)\theta + 2(1 + 2\theta)(c_{sm} - 2p_{d1}^d) + (c_{sm} - 2p_{d1}^d + 2\omega_1^d)\theta^2 + (2\omega_1^d - a_1)\theta + (2 + 3\theta)\tau e}{2(\theta + 1)}, \\ \frac{\partial U(\pi_{m1}^d)}{\partial \omega_1^d} &= \theta p_{d1}^d - (1 + \theta) \omega_1^d + \frac{1}{2} (a_1 - \theta c_{sm} + \tau e). \end{aligned} \quad (E.4)$$

The Hessian matrix of $U(\pi_{m1}^d)$ with respect to p_{d1}^d and ω_1^d is $H = \begin{bmatrix} -((\theta^2 + 4\theta + 2)/\theta + 1) & \theta \\ \theta & -\theta - 1 \end{bmatrix}$. Because $\theta > 0$, $|H| = 4\theta + 2 > 0$; additionally, because $-(\theta^2 + 4\theta + 2/\theta + 1) < 0$, there exist optimal solutions of p_{d1}^d and ω_1^d that maximize $U(\pi_{m1}^d)$.

Let $(\partial U(\pi_{m1}^d)/\partial p_{d1}^d) = 0$ and $(\partial U(\pi_{m1}^d)/\partial \omega_1^d) = 0$; the simultaneous equations are solved to arrive at the optimal solutions of p_{d1}^d and ω_1^d , which are equations (17) and (18). Substitution of the solutions of p_{d1}^d and ω_1^d into p_{r1}^d arrives at equation (19). Theorem 3 is proved.

F. Proof of Theorem 4

The following is calculated based on equation (21):

$$\begin{aligned} \max U(\pi_{m2}^d) &= \frac{1}{2} \omega_2^d [p_{d2}^d \theta - (1 + \theta) \omega_2^d + a_1 + \tau e] - \frac{1}{2} z e^2 - (p_{d2}^d - c_{sm})^2 \eta_m \sigma^2 \\ &+ \frac{(p_{d2}^d - c_{sm}) [2(a_1 + a_2)(1 + \theta) - 2a_1 - 2(1 + 2\theta)p_{d2}^d + (\omega_2^d - p_{d2}^d)\theta^2 + (\omega_2^d - a_1)\theta + (2 + 3\theta)\tau e]}{2(\theta + 1)}. \end{aligned} \quad (F.3)$$

$$\frac{\partial U(\pi_{r2}^d)}{\partial p_{r2}^d} = \theta(p_{d2}^d - p_{r2}^d) - p_{r2}^d + a_1 + \tau e - (p_{r2}^d - \omega_2^d)(\theta + 1). \quad (F.1)$$

The second-order partial derivative of $U(\pi_{r2}^d)$ with respect to p_{r2}^d is $-2\theta - 2 < 0$; therefore, p_{r2}^d has an optimal solution that maximizes $U(\pi_r)$.

Let $(\partial U(\pi_{r2}^d)/\partial p_{r2}^d) = 0$; solving this equation gives

$$p_{r2}^d = \frac{\theta p_{d2}^d + a_1 + \tau e + \omega_2^d(\theta + 1)}{2(\theta + 1)}. \quad (F.2)$$

Substituting the above equation into equation (20), we have

Taking the first-order partial derivative of the above equation with respect to p_{d2}^d and ω_2^d and rearranging the equation, we have

$$\begin{aligned} \frac{\partial U(\pi_{m2}^d)}{\partial p_{d2}^d} &= \frac{2a_2 + 2(a_1 + a_2)\theta + 2(1 + 2\theta)(c_{sm} - 2p_{d2}^d) + (c_{sm} - 2p_{d2}^d + 2\omega_2^d)\theta^2 + (2\omega_2^d - a_1)\theta + (2 + 3\theta)\tau e}{2(\theta + 1)} \\ &\quad + 2(c_{sm} - p_{d2}^d)\eta_m\sigma^2, \\ \frac{\partial(\pi_{m2}^d)}{\partial \omega_2^d} &= \theta p_{d2}^d - (1 + \theta)\omega_2^d + \frac{1}{2}(a_1 - \theta c_{sm} + \tau e). \end{aligned} \quad (F.4)$$

The Hessian matrix of $U(\pi_{m2}^d)$ with respect to p_{d2}^d and ω_2^d is $H = \begin{bmatrix} -(2\theta(\theta + 2)/2\theta + 2) - 2\eta_m\sigma^2 - 2 & \theta \\ \theta & -\theta - 1 \end{bmatrix}$. Because $\theta > 0$, $|H| = 4\theta + 2(1 + \theta)\eta_m\sigma^2 + 2 > 0$; additionally, because $-(2\theta(\theta + 2)/2\theta + 2) - 2\eta_m\sigma^2 - 2 < 0$, p_{d2}^d and ω_2^d have optimal solutions that maximize $U(\pi_{m2}^d)$.

Let $(\partial U(\pi_{m2}^d)/\partial p_{d2}^d) = 0$ and $(\partial(\pi_{m2}^d)/\partial \omega_2^d) = 0$. These simultaneous equations are solved to arrive at equations (23) and (24), which are substituted into p_r to arrive at equation (25). Theorem 4 is proved.

G. Proofs of Propositions 6–9

We can obtain Propositions 6–9 by solving the first partial derivative. So we omit the proofs.

H. Proof of Proposition 10

The following equations are derived based on equations (21) to (23).

$$\begin{aligned} \frac{\partial p_{d2}^d}{\partial \eta_m} &= -\frac{(\theta + 1)\sigma^2[a_2 + (a_1 + a_2)\theta + (1 + 2\theta)(\tau e - c_{sm})]}{2(2\theta + \eta_m\sigma^2 + \theta\eta_m\sigma^2 + 1)^2} < 0, \\ \frac{\partial \omega_2^d}{\partial \eta_m} &= -\frac{\theta\sigma^2[a_2 + (a_1 + a_2)\theta + (1 + 2\theta)(\tau e - c_{sm})]}{2(2\theta + \eta_m\sigma^2 + \theta\eta_m\sigma^2 + 1)^2} < 0, \\ \frac{\partial p_{r2}^d}{\partial \eta_m} &= -\frac{\theta\sigma^2[a_2 + (a_1 + a_2)\theta + (1 + 2\theta)(\tau e - c_{sm})]}{2(2\theta + \eta_m\sigma^2 + \theta\eta_m\sigma^2 + 1)^2} < 0. \end{aligned} \quad (H.1)$$

Therefore, p_{d2}^d , ω_2^d , and p_{r2}^d are decreasing functions of η_m ; that is, as η_m increases p_{d2}^d , ω_2^d and p_{r2}^d decrease. Proposition 10 is proved.

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

Sharing Economy for Cost Reduction and Efficiency Increase: The Case of Sharing E-Commerce Logistics

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In the real business environment, due to unpredictable market demand or high prediction difficulty and low prediction accuracy, there will be inevitably operational loss in the field of e-commerce logistics caused by undersupply or oversupply of express service capabilities. At present, China is deepening the supply-side structural reforms. Confronted with the growing demand for e-commerce logistics express delivery, especially the urgent demand for tackling orders piling up to 1 billion pieces during the recent “Double 11” shopping carnival, it is very important and practical for us to study how to make scientific decisions on the supply side in the field of e-commerce express delivery. Therefore, in this paper, we design a sharing logistics cooperation mechanism considering both the undersupply and oversupply of express delivery service capabilities under stochastic demand. By comparing the earnings data of several listed express companies, we analyze four types of optimization strategies: the order flow proportion revenue sharing strategy (RE-OF), the combined factors revenue sharing strategy (RE-RSF), the order flow proportion risk sharing strategy (RS-OF), and the combined factors risk sharing strategy (RS-RSF). The research results demonstrate that the four optimization strategies of RE-OF, RE-RSF, RS-OF, and RS-RSF could achieve Pareto improvements in the operational performance of e-commerce express service. The performance of four revenue sharing and risk sharing strategies varies with different revenue sharing or risk sharing factors. Under some certain combined factors, the revenue sharing contract could help realize the supply chain coordination of the sharing logistics service. The sharing logistics cooperation mechanism based on equity investment proposed hereafter provides a feasible solution to solve the problems of high empty driving rate and operational cost of e-commerce express delivery service in urban areas.

1. Introduction

The sharing economy has set off a boom in China since 2017, with the emergence of business models such as shared bikes, shared cars, shared umbrellas, shared chargers, shared massages, shared travel platforms, and shared rentals. The logistics industry, especially e-commerce logistics, as a service model with a long industrial chain, multiple resource elements, and many nodes and processes, is trying to use the principles of the sharing economy in various aspects to organize production and reform itself. In recent years, typical business models of sharing logistics such as shared fleets, shared distribution, shared warehousing, shared logistics parks, and shared logistics dedicated lines have been

avored by the capital market, leading to its rapid development. In other words, the sharing economy is leading in reforms and innovations at each link of the logistics chain, such as trunk transportation, urban distribution, warehousing, and logistics. With the rapid development of e-commerce in China, the daily sales volume of major e-commerce brands appears to be in a blowout state. In 2019, the number of orders processed on the “Double 11” day was as high as 1 billion. The way to optimize the supply of e-commerce logistics has practical significance and is worthy of attention. At present, many express delivery companies in China, such as ZTO, STO, YTO, and YUNDA, are coming together to jointly invest in building Cainiao Alliance to solve the problem of supply chain integration and “last mile”

distribution through a sharing model. For example, the Cainiao courier station of the Cainiao Alliance is a network platform of logistics service for the community and campus, providing parcel collection service for users, making it a suitable example of sharing economy.

By improving the interconnectivity of logistics information, urban joint distribution can promote the intensive and large-scale development of the logistics industry, improve the utilization rate of logistics vehicles, and reduce the empty driving rate, which help to realize the goals of reducing costs and carbon emission as well as increasing the efficiency of the logistics industry. At present, China is exploring reforms and innovations in the field of logistics operation to improve the efficiency of logistics operations and reduce energy consumption in the logistics process. For example, Beijing, Chongqing, Chengdu, and Wuhan have launched joint distribution pilot projects, leading to the emergence of much more joint distribution platforms, such as Yimidida.com, Yunniao.cn, and Chengdu Panda Joint Distribution and Sichuan Swap Trailer Transport (special line) Alliance.

With the joint efforts of the government and enterprises in the market, the sharing logistics distribution model has achieved certain development. But we must clearly realize that the current level and depth of development are not enough, and many issues involve refined management of operations, and sustainable development needs to be further resolved. One way forward is collaboration between businesses, logistics service providers, and public. By working together, multiple actors create their efficiency through sharing resources, such as vehicles, cargo consolidation or distribution centers, or last mile delivery services. Collaboration could potentially lead to fewer vehicles in urban areas, less pollution, and lower prices. However, experience from past logistics practice has shown that collaboration in city logistics projects is challenging since additional efforts of planning and control of collaboration are significant. Many operations' research contributions present solution approaches for planning and operating urban transportation systems. However, these approaches often oversimplify practice requirements and ignore challenges of synchronization between different players and modes [1]. For example, why do companies with different logistics services build a sharing logistics distribution platform? Which is feasibility, sharing or nonsharing logistics? Which kind of sharing logistics mechanisms is better than another one? How to encourage the participating parties to actively maintain this kind of sharing logistics platform [2]?

To solve these problems, this paper designs an equity-based sharing logistics distribution cooperation mechanism considering both the shortage and surplus of express delivery service capacity under stochastic demand. We compare and analyze four types of optimization strategies based on the financial data of several logistics companies: revenue sharing strategy based on order flow proportion (RE-OFP), revenue sharing strategy based on combination factors (RE-RSF), risk sharing strategy based on order flow proportion (RS-OFP), and risk sharing strategy based on combination factors (RS-RSF). The results show that all the RE-OFP, RE-

RSF, RS-OFP, and RS-RSF could realize Pareto improvements for the operation performance of logistics service. Under different combination factors, the advantages and disadvantages of the four revenue sharing and risk sharing strategies are different, but both the revenue sharing and risk sharing strategies based on the order flow proportion and the revenue sharing and risk sharing strategies based on the combinatorial sharing factors have feasible domain spaces superior to decentralized logistics service supply chain. Revenue sharing contract could achieve the coordination of sharing logistics distribution service supply chain under specific combinatorial factors. When the combinatorial sharing factor approaches 0.5, that is, the revenue sharing is equal, the revenue sharing and risk sharing mechanisms based on the combinatorial sharing factor are, respectively, superior to the revenue sharing and risk sharing mechanisms based on order flow proportion. This paper puts forward an equity-based sharing logistics distribution cooperation mechanism, which provides a feasible operation scheme to effectively solve the problem of high empty driving rate, high operational cost, as well as carbon emission of logistics service in urban areas.

The contributions of our study are as follows. First, we study the urban distribution problems based on the sharing economy in OM. Second, existing supply chain management research, especially supply chain coordination research, mainly analyzes the design problem of supply chain coordination contracts under specific business operational environments, mainly including buyback contract, wholesale price contract, quantity discount contract, revenue sharing contract, and risk sharing contract. Because of the coordination of various coordination contracts under different business operational background and the causal relationship of key coordination factors as well as the detailed design may change, so the traditional supply chain coordination research mainly focuses on these aspects. However, how to apply such many supply chain coordination contracts to specific business operations and how to implement these operational improvement strategies are seldom considered in previous research literatures. This paper makes interviews and exchanges with many top-class logistics enterprises and e-commerce logistics enterprises, then summarizes and refines the characteristics of business-based equity cooperation projects, which often occur in modern logistics industry, and designs the equity-based sharing logistics distribution cooperation mechanism based on these.

The rest of this paper is organized as follows. Section 2 summarizes the related literatures. Section 3 identifies the problems and hypothesis used in this paper. Section 4 discusses the benchmark model, which is the centralized and decentralized SC. We provide the revenue sharing strategy based on the OFP and RSF, respectively, in Section 5 and the risk sharing strategy based on the OFP and RSF, respectively, in Section 6. Section 7 gives some comparative analysis on the sharing logistics mechanisms. Section 8 proceeds the case study and numerical analysis and compares various optimization methods. Section 9 summarizes the managerial implications. Section 10 concludes the paper by identifying future research directions.

2. Literature Review

This study focuses on logistics service supply chain and sharing mechanisms in the OM, which are mainly related to the following research streamlines: logistics service supply chain, sharing economics in the OM, and supply chain coordination. There is some literature on logistics service supply chain from different directions. The order allocation problem of logistics service supply chain composed of a logistics service integrator, and many functional logistics service providers are studied based on cumulative prospect theory [3]. A new multiobjective program scheduling model for logistics service supply chain is established by Liu et al. [4]. Liu et al. [5] discussed how the parameters inserted into the order affect the location of the customer order decoupling point when the logistics service integrator runs a mass customization logistics service. Bektas et al. [6] highlighted that innovations such as standardized containers and combined passenger and freight transportation may improve future urban delivery. Savelsbergh and Van Woensel [7] gave the most recent overview from an OR perspective, discussing trends that include the increase of e-commerce, need for speed, sustainability, sharing economy, population growth, and technological advancements. In the city logistics, long distance transports are consolidated in Urban Consolidation Centers (UCCs), and the joint operation as well as cost advantages is the crucial aspect when implementing UCCs in practice [8–10].

A key feature of sharing economy providers (SEP) is that they usually charge lower prices for the same service than traditional providers (TP) [11]. The sharing economy is decentralized and could provide new avenues for collaborative freight in urban environments. Apps and business models centered around the sharing economy are turning into an important aspect of collaborative freight [1]. Sharing economy platforms can choose from a variety of demand allocation mechanisms, from full concentration to purely market-based mechanisms. This mechanism affects how much information is displayed by service providers (such as Uber shared trips) and users and how they choose to display them to each other. For example, in the short-term rental sharing market, Airbnb, Xiaozhu, and others adopt a market-based matching mechanism, in which travelers choose potential renters and renters can decide to accept or reject the request. On the contrary, in the travel sharing market, Uber uses a centralized allocation mechanism, where passengers and drivers do not make choices, but are allocated to each other. However, Didi, the market leader in China's travel sharing market, uses a hybrid mechanism, where drivers can choose which customers to serve and passengers cannot choose drivers [12]. At present, the sharing mode of new energy fields, such as small electric fast charging and shared electric vehicles in China, relates to the company's centralized optimization in resource allocation and the consumers' independent choice of products and services in bilateral choice.

Zervas et al. [13] claimed that the core issue surrounding the sharing economy is their impact on existing companies, understanding which will help municipalities and regulators

formulate appropriate laws to better regulate the sharing economy and direct existing companies' focus on marketing strategies being developed by new competitors. Cohen et al. [14] estimated that the consumer surplus created by UberX service in Chicago, Los Angeles, New York, and San Francisco was about \$2.9 billion in 2015 and \$6.8 billion in the United States as a whole. Consumer-to-consumer product sharing tends to benefit the two companies because the production capacity is relatively high compared to the cost, but the manufacturer is benefitted more than the retailer [15]. Guda and Subramanian [16] illustrated the role and effectiveness of two strategies commonly used by on-demand platforms in managing variable demand and supply conditions, namely, sharing market information with suppliers and surge pricing to solve the fundamental problem of dynamically balancing supply and demand. In general, sharing includes participation in the sharing economy driven by a variety of motives, including caring about the natural needs of others, cultural orientation, prosocial behavior, altruism, reciprocity, affiliation, pleasure, achievement, social consistency, collectivism, and the practicality and attachment of objects [17, 18]. As of January, 2018, the number of bicycle users in China has reached 221 million and well-known brands such as Mobike, ofo, and Hello bicycles have become leading companies in this sector. A new logistics service paradigm-joint distribution is proposed [19].

Cachon et al. [20] indicated that, under the revenue sharing contract, the supplier charges the retailer a wholesale price, while obtaining a certain percentage of revenue from terminal sales. Revenue sharing contracts are popular in the cassette tape rental industry, which incentivizes retailers to increase the inventory of cassette tapes, thereby increasing the availability of popular movies. Wang et al. [21] indicated that, in a typical revenue sharing contract, the manufacturer not only charges the wholesale price per unit from the retailer but also requires to share part of the retailer's revenue. Wei et al. [22] revealed a joint optimal decision-making strategy that involves revenue sharing and cooperative investment contracts based on an order flow proportion (OFP) and a revenue sharing factor (RSF) and found that an OFP system offers the best solution in designing revenue sharing contracts based on RSFs.

Zhang et al. [23] studied the two-echelon supply chain of deteriorating items and found that the manufacturer and the retailer make joint investments in preservation technology to prevent product deterioration and design revenue sharing and cooperative investment contract to coordinate the supply chain. Revenue sharing and cost-sharing contracts are widely used in the research on sustainable supply chain and green supply chain [24–32]. Yang and Chen [28] investigated the impact of revenue sharing and cost-sharing provided by retailers on manufacturers' efforts to reduce carbon emissions and the profitability of the two companies. They also analyzed the supply chain performance under revenue sharing and investment cost-sharing independently and both together. Based on Yang and Chen [28], Li et al. [29] also analyzed supply chain performance under revenue sharing and investment cost-sharing independently or both together, but they further discussed the bargaining of supply

chain members on the cost-sharing or revenue sharing rate. Yu et al. [30] discussed whether supply chain members choose revenue sharing or cost-sharing contracts in emission reduction cooperation and gave the optimal decision of supply chain members through numerical examples.

The works that are of particular relevance to our study are Zhang et al. [23], Yang and Chen [28], Wei et al. [22], and Yu et al. [30]. As only the implicit solution of the optimal decision can be obtained, the optimal decision is finally presented through numerical examples. Zhang et al. [23] employed revenue sharing and cost-sharing contracts to coordinate the deteriorating items' supply chain, but the coordination is not included in our study. Similar to Zhang et al. [23], our optimal decision can only be obtained by an implicit solution, and finally, a numerical example is used to choose a cooperative contract. Wei et al. [22] discussed an omni-channel supply chain structure in the joint distribution logistics cooperation model, but we focus on the omni-channel service supply chain structure considering the joint distribution cooperation mechanism under a circumstance with insufficient supply of logistics service capacity and surplus and design a mechanism of revenue sharing and cost-sharing based on equity cooperation. Yang and Chen [28] and Yu et al. [30] both discuss whether supply chain members choose sharing of revenue, cost, or both in emission reduction cooperation. However, we consider whether city joint distribution enterprises and many logistics companies should choose revenue sharing contract or cost-sharing contract to cooperate to improve the performance of logistics service supply chain.

3. Problem Description and Hypothesis

Considering the actual operation process, it is inevitable that there will be some difficulties in practice, such as under-supply or oversupply of express service capacity due to the asymmetry of market information and the inaccuracy of market demand forecast. This article will study the cooperative mechanism of sharing logistics under stochastic demand, with shortage and surplus of express delivery service capacity. It also compares and analyses the advantages and disadvantages of adopting revenue sharing contract and risk sharing contract under the background of equity cooperation. In order to display the results of this study as clearly as possible, we will first consider that the random demand of express service companies is relatively independent. Referring to Yun et al. [33] hypothesis about independent stochastic demand, the same hypothesis is applied to the price elasticity of demand for goods belonging to the same product category in their research literature, and it is pointed out that the price elasticity of demand for many goods is between 1 and 2.

In addition, this paper focuses on how to cope with the risk of insufficient or excessive service caused by uncertain market requirements when express companies cooperate in

equity-based sharing logistics. Therefore, we assume that each express delivery company meets the same and independent random market demand $x \sim U[0, a]$, and the probability density function is $f(x) = 1/a$, and the probability function is $F(x) = \int_0^x f(x)dx$. The price demand function of each express company for customer service is $p_i = a - q_i$. Among them, q_i is the express order quantity and p_i is the express service price. Considering the cooperation and competition relationships among express companies, the model is very complex, which makes it difficult to find a clear explicit expression. Therefore, in order to give a relatively intuitive comparative analysis result as far as possible, we assume that $i = 1$ and 2 , it is to say that it focuses on the analysis of the cooperation and competition between any two express companies in a sharing logistics supply chain. At this time, the differences of the product and service among express delivery companies are mainly reflected in the price of express service p_i and unit operating cost c_i (if a has different meanings, a_i , $i = 1$ and 2 , it means that the influence of brand awareness and service quality of express companies on customer demand is reflected in different a_i , in addition to the influence of express service price on customer demands. Since the focus of this article is not this, we assume that the cross-sectional moments of the price demand function are the same, all of which are a . More general information will be discussed in the following study).

At this time, the revenue of the sharing logistics distribution company based on equity cooperation is

$$\pi_s = w \sum_{i=1}^2 q_i - \left[c \sum_{i=1}^2 q_i + e \left(\sum_{i=1}^2 q_i \right)^2 \right], \quad (1)$$

where w is the unit distribution service price between the sharing logistics distribution company and each express delivery company, c is the unit operational cost of the sharing logistics distribution company, and e is the nonscale economic cost of the sharing logistics distribution company.

For order decision-making, that is, the purchase volume of each express company, when the purchase volume is higher than the final realized customer demand, the benefits it receives in the final are the ultimate benefit of meeting customer needs, and the excess amount of purchasing orders will bear the corresponding loss of service. For the excess of urban logistics distribution service, it is possible to take emergency service measures to provide urban distribution services and obtain certain "residual value gains" (less than the price of the urban distribution service during the same period); when the purchasing quantity is lower than the demand of the express delivery service of the market, the final income obtained is determined by the quantity of the purchasing order, and the unmet market demand will bear the corresponding loss of opportunity cost. Therefore, the revenue of express delivery company i can be expressed as

$$\begin{aligned}
\pi_i &= \int_0^{q_i} (p_i - w - c_i) x f(x) dx + \int_{q_i}^a (p_i - w - c_i) q_i f(x) dx \\
&= (p_i - w - c_i) \times \frac{q_i^2}{2a} + (p_i - w - c_i) \times q_i \times \frac{a - q_i}{a} \\
&= \frac{q_i^3}{2a} - \frac{q_i^2}{2a} (3a - w - c_i) + q_i (a - w - c_i).
\end{aligned} \tag{2}$$

The oversupply cost of express delivery company i is

$$O_i(p_i, q_i) = \int_0^{q_i} (w - v)(q_i - x) f(x) dx = \frac{q_i^2}{2a} (w - v). \tag{3}$$

In the above formula, v is the unit residual value of the urban logistics distribution service. In the real business environment, it is the express delivery company which sells the excess resources of urban logistics distribution capacity to other ones which need logistics on the market and then earns the unit income. Because it is a temporary supply, the unit residual value is lower than the price of the urban logistics distribution service w .

The undersupply cost of express delivery company i is

$$U_i(p_i, q_i) = \int_{q_i}^a k(x - q_i) f(x) dx = \frac{kq_i^2}{2a} - kq_i + \frac{ak}{2}. \tag{4}$$

In the above formula, k is the unit opportunity cost, that is, the market demand which failed to be accurately predicted by the express delivery company. It is accurate to underestimate the market demand and cannot fully meet the service requirements caused by the market terminal demand.

The basic assumptions that need to be preset in the research process are as follows:

- (1) $0 < p_i < a$, $0 < q_i < a$, and $\forall i = 1$ and 2 ; the unit service price of the express delivery company i and the purchasing order quantity are both lower than a
- (2) $k > v \geq 0$; the unit opportunity cost of express delivery company i is higher than the unit residual value

The mathematical symbols shown in following Table 1 are used a lot in the research process of this article:

4. Benchmark Model

This section will separately study the centralized and decentralized supply chain of the sharing logistics based on equity investment. In the decentralized supply chain, we analyze two different situations. In the first situation, the sharing logistics distribution company takes the risks independently while each express delivery company independently bears the risk loss in the second situation. In a real business environment, because of the pursuit of financial performance or better market value performance of listed

companies, there are indeed flexible arrangements between the vertically-holding companies to realize the cost and benefit reallocation between upstream and downstream through transfer payments in some industry chains or supply chains.

4.1. Centralized SC of the Sharing Logistics. The centralized supply chain takes the total revenue of the sharing logistics distribution company and all express delivery companies as its decision-making goal. At the same time, they share the risk loss caused by the oversupply and undersupply of express delivery services. Therefore, the overall benefit of this centralized supply chain can be expressed as

$$\begin{aligned}
\pi_{sc}^c &= \pi_s + \sum_{i=1}^2 \pi_i - \sum_{i=1}^2 O_i(p_i, q_i) - \sum_{i=1}^2 U_i(p_i, q_i) \\
&= w \sum_{i=1}^2 q_i - \left[c \sum_{i=1}^2 q_i + e \left(\sum_{i=1}^2 q_i \right)^2 \right] \\
&\quad + \sum_{i=1}^2 \left[\int_0^{q_i} (p_i - w - c_i) x f(x) dx + \int_{q_i}^a (p_i - w - c_i) q_i f(x) dx \right. \\
&\quad \left. - \int_0^{q_i} (w - v)(q_i - x) f(x) dx - \int_{q_i}^a k(x - q_i) f(x) dx \right] \\
&= w \sum_{i=1}^2 q_i - \left[c \sum_{i=1}^2 q_i + e \left(\sum_{i=1}^2 q_i \right)^2 \right] \\
&\quad + \sum_{i=1}^2 \left[\frac{q_i^3}{2a} - \frac{q_i^2}{2a} (3a - w - c_i) + q_i (a - w - c_i) \right. \\
&\quad \left. - \frac{q_i^2}{2a} (w - v) - \frac{kq_i^2}{2a} + kq_i - \frac{ak}{2} \right] \\
&= -c \sum_{i=1}^2 q_i - e \left(\sum_{i=1}^2 q_i \right)^2 + \sum_{i=1}^2 \left[\frac{q_i^3}{2a} - \frac{q_i^2}{2a} (3a - c_i - v + k) \right. \\
&\quad \left. + q_i (a - c_i + k) - \frac{ak}{2} \right].
\end{aligned} \tag{5}$$

As shown in the above formula, the decision variable of the centralized supply chain at this time is the purchase order quantity (the express delivery service price) of each express delivery company, and it is a binary cubic equation which is difficult to be solved in its explicit expression. Next, Proposition 1 will prove the existence of the optimal solution of the centralized decision and gives its implicit expression.

Proposition 1. *The total revenue of the centralized supply chain of the sharing logistics based on equity investment π_{sc}^c has the optimal solution $(p_1^*, p_2^*; q_1^*, q_2^*)$, and the optimal solution satisfies*

TABLE 1: Symbol description.

| Symbol | Symbol description Meaning |
|------------------|---|
| x | Stochastic market demand |
| $f(x)$ | Probability density function for stochastic market demand |
| $F(x)$ | Probability distribution function for stochastic market demand |
| a | Market size |
| p_i | Unit service price of express delivery companies |
| q_i | The market service requirements for express delivery companies |
| c | Unit transportation cost of sharing logistics distribution service |
| e | Nonscale economic cost of sharing logistics distribution service |
| c_i | Intercity unit transportation cost of express delivery companies |
| w | The unit service price of the sharing logistics distribution company for offering sharing delivery services to the express delivery companies |
| v | The unit residual value of the sharing logistics distribution service (usually the price of temporary provision of social logistics services) |
| k | The unit opportunity cost of the sharing logistics distribution service |
| π_s | The revenue function of the sharing logistics distribution company |
| π_i | The revenue function of the express delivery company |
| $O_i(p_i, q_i)$ | Oversupply loss |
| $U_i(p_i, q_i)$ | Undersupply loss |
| π_{sc}^c | The overall revenue of the centralized sharing logistics supply chain |
| π_{sc}^d | The overall revenue of the decentralized sharing logistics supply chain |
| π_{sc}^{sef} | The overall revenue of the RE-OFP sharing logistics supply chain |
| π_{sc}^{rsf} | The overall revenue of the RS-OFP sharing logistics supply chain |
| π_{sc}^{res} | The overall revenue of the RE-RSF sharing logistics supply chain |
| π_{sc}^{rss} | The overall revenue of the RS-RSF sharing logistics supply chain |

$$\begin{cases} -c - 2eq_2^* + \frac{3q_1^{*2}}{2a} - \frac{q_1^*}{a} (3a - c_1 - v + k + 2ea) + a - c_1 + k = 0, \\ -c - 2eq_1^* + \frac{3q_2^{*2}}{2a} - \frac{q_2^*}{a} (3a - c_2 - v + k + 2ea) + a - c_2 + k = 0, \\ p_i^* = a - q_i^*, \quad 0 < p_i^* < a \text{ and } 0 < q_i^* < a, i = 1 \text{ and } 2. \end{cases} \quad (6)$$

Proof. See the Appendix. \square

4.2. Decentralized SC of the Sharing Logistics. In the decentralized supply chain of the sharing logistics based on equity investment, the sharing logistics distribution companies and express delivery companies, respectively, take their own profit maximization as the decision-making goal. Next, we will study the decentralized supply chain decision-making, while the sharing logistics distribution company takes risk loss independently, and each express delivery company independently undertakes its own risk loss caused by the undersupply and oversupply of express delivery service, which are due to its own decision-making mistakes.

4.2.1. Sharing Logistics Distribution Company Taking Risks. At this time, the sharing logistics distribution company, as the main body of the joint venture, takes the main responsibility of controlling the business risk. Therefore, its business objectives include both the maximization of

expected returns and the effective control of potential risks resulting from the uncertainty of market demands. Its revenue function is

$$\begin{aligned} \pi_s^{d1} &= w \sum_{i=1}^2 q_i - \left[c \sum_{i=1}^2 q_i + e \left(\sum_{i=1}^2 q_i \right)^2 \right] \\ &\quad - \sum_{i=1}^2 \left[\int_0^{q_i} (w - v)(q_i - x) f(x) dx + \int_{q_i}^a k(x - q_i) f(x) dx \right] \\ &= w \sum_{i=1}^2 q_i - \left[c \sum_{i=1}^2 q_i + e \left(\sum_{i=1}^2 q_i \right)^2 \right] \\ &\quad - \sum_{i=1}^2 \left[\frac{q_i^2}{2a} (w - v) + \frac{kq_i^2}{2a} - kq_i + \frac{ak}{2} \right]. \end{aligned} \quad (7)$$

In the above formula, the optimal decision for sharing logistics distribution company is

$$\begin{aligned} \frac{\partial \pi_s^{d1}}{\partial q_i} &= w - \left(c + 2e \sum_{j=1}^2 q_j \right) - \frac{w - v + k}{a} q_i + k = 0, \\ &=> w = \frac{ac + 2ae \sum_{j=1}^2 q_j + (k - v)q_i - ak}{a - q_i}, \quad \forall i = 1 \text{ and } 2. \end{aligned} \quad (8)$$

According to the formula of w , there will be $q_1 = q_2$, which means two express delivery companies have equal opportunities for cooperation.

Thus we have

$$w = \frac{(4ae + k - v)q_i + a(c - k)}{a - q_i}, \quad \forall i = 1 \text{ and } 2. \quad (9)$$

At this point, the revenue function of the express delivery company is

$$\begin{aligned} \pi_i^{d1} &= \int_0^{q_i} (p_i - w - c_i)xf(x)dx + \int_{q_i}^a (p_i - w - c_i)q_i f(x)dx \\ &= \frac{q_i^3}{2a} - \frac{q_i^2}{2a} (3a - w - c_i) + q_i(a - w - c_i). \end{aligned} \quad (10)$$

The optimal decision-making process is as follows:

$$\begin{aligned} \frac{d\pi_i^{d1}}{dq_i} &= \frac{3q_i^2}{2a} - \frac{q_i}{a} (3a - c_i + 4ae + k - v) + (a - c_i + k - c) \\ &\quad - \frac{[2aq_i - q_i^2](4ae + c - v)}{2(a - q_i)^2} = 0, \quad \forall i = 1 \text{ and } 2, \\ &= > q_i^* = q_i(c_i), \quad \forall i = 1 \text{ and } 2. \end{aligned} \quad (11)$$

But because $c_1 \neq c_2$, we got

$$= > q_1 \neq q_2. \quad (12)$$

Obviously, this contradicts with $q_1 = q_2$ which is obtained from the previous analysis. Therefore, at this time, there is no equilibrium solution for the distributed decision-making mechanism for the sharing logistics distribution company taking risks. In the following, we will analyze the situation of express delivery companies taking risks.

4.2.2. Express Delivery Companies Taking Risks. At this time, each express delivery company, as the investment entity of the joint venture of the sharing logistics distribution company, will hand over the respective urban logistics distribution business to the sharing logistics distribution company and be responsible for the controlling of the business risk. At this point, the optimal decision for the sharing logistics distribution company is

$$\begin{aligned} \frac{\partial \pi_s^{d2}}{\partial q_i} &= w - \left(c + 2e \sum_{j=1}^2 q_j \right) = 0 \\ &= > w = c + 2e \sum_{j=1}^2 q_j. \end{aligned} \quad (13)$$

The business objectives of each express delivery company include both the maximization of expected returns and the effective control of operational risks caused by the market uncertainty. At this time, the revenue of each express delivery company is

$$\begin{aligned} \pi_i^{d2} &= \pi_i - O_i(p_i, q_i) - U_i(p_i, q_i), \\ &= \int_0^{q_i} (p_i - w - c_i)xf(x)dx + \int_{q_i}^a (p_i - w - c_i)q_i f(x)dx \\ &\quad - \int_0^{q_i} (w - v)(q_i - x)f(x)dx - \int_{q_i}^a k(x - q_i)f(x)dx, \\ &= \frac{q_i^3}{2a} - \frac{q_i^2}{2a} (3a - w - c_i) + q_i(a - w - c_i) - \frac{q_i^2}{2a} (w - v) \\ &\quad - \frac{kq_i^2}{2a} + kq_i - \frac{ak}{2}. \end{aligned} \quad (14)$$

As shown in the above formula, the decision variable of the decentralized supply chain at this time is the purchase order quantity (express delivery service price) of each express delivery company, and it is a binary cubic equation which is difficult to be solved in its explicit expression. Now we give the proof of the Proposition 2 to prove the existence of the optimal decision solution of the decentralized supply chain and give its implicit expression.

Proposition 2. *In the decentralized supply chain of the sharing logistics in which the express delivery company independently assumes operational risks, there exists an optimal solution (p_i^*, q_i^*) for the revenue function π_i^{d2} of express company i , and the optimal solution satisfies*

$$\begin{cases} -c - 2eq_1^* + \frac{3q_2^{*2}}{2a} - \frac{q_2^*}{a} (3a - c_2 - v + k + 4ea) + a - c_2 + k = 0, \\ -c - 2eq_2^* + \frac{3q_1^{*2}}{2a} - \frac{q_1^*}{a} (3a - c_1 - v + k + 4ea) + a - c_1 + k = 0, \\ p_i^* = a - q_i^*, \quad 0 < p_i^* < a \text{ and } 0 < q_i^* < a, i = 1 \text{ and } 2. \end{cases} \quad (15)$$

Proof. See the Appendix.

It proves that there are both cooperative and competitive relationships among express delivery companies at this time. On the one hand, they cooperate to establish a sharing logistics distribution company, and on the other hand, they compete when deciding their respective express delivery service supply. Therefore, its decision-making thought is similar to the Cournot game. Firstly, we will solve the optimal response of the purchase order decision of each express delivery company to the order decision of other express delivery companies and then solve the equilibrium solutions of these optimal responses. But because the optimal response curve is a quadratic equation, for the dual channel structure composed of two express companies, the final solution equation at this time is a quaternary equation of one variable, and it is difficult to give explicit expressions. However, it is

clear that the optimal decision of purchase order quantity meets the above conditions. \square

5. SC of the Sharing Logistics with Revenue-Sharing

According to the analysis of the decentralized supply chain of sharing logistics, it is feasible for each express delivery company taking risks. On the contrary, there is no possibility of existence of the sharing logistics distribution company bearing the risk together. Therefore, in the process of classification discussion of the sharing logistics supply chain with revenue sharing strategy, it is only necessary to consider the situation in which each express delivery company bears its own business risk. At this point, the optimal decision of the sharing logistics distribution company is always

$$\begin{aligned} \frac{\partial \pi_s^{\text{re}}}{\partial q_i} &= w - \left(c + 2e \sum_{j=1}^2 q_j \right) = 0 \\ &= > w = c + 2e \sum_{j=1}^2 q_j. \end{aligned} \quad (16)$$

5.1. Revenue-Sharing Based on the OFP: RE-OFP. In the order flow proportion revenuesharing supply chain, each express delivery company determines the mutual benefit of each other according to the proportion of their respective order flow contributions. The order flow proportion is

$$\left(\frac{q_1}{\sum_{j=1}^2 q_j}, \frac{q_2}{\sum_{j=1}^2 q_j} \right). \quad (17)$$

At this time, the revenue of each express delivery company includes both the part of the operational risk as well as the OFP share of the revenue of the sharing logistics distribution company. Therefore, the revenue function is

$$\begin{aligned} \pi_i^{\text{ref}} &= \pi_i - O_i(p_i, q_i) - U_i(p_i, q_i) \\ &+ \frac{q_i}{\sum_{j=1}^2 q_j} \left\{ w \sum_{j=1}^2 q_j - \left[c \sum_{j=1}^2 q_j + e \left(\sum_{j=1}^2 q_j \right)^2 \right] \right\}, \\ &= \int_0^{q_i} (p_i - w - c_i) x f(x) dx + \int_{q_i}^a (p_i - w - c_i) q_i f(x) dx \\ &- \int_0^{q_i} (w - v) (q_i - x) f(x) dx - \int_{q_i}^a k(x - q_i) f(x) dx \\ &+ \frac{q_i}{\sum_{j=1}^2 q_j} \left\{ w \sum_{j=1}^2 q_j - \left[c \sum_{j=1}^2 q_j + e \left(\sum_{j=1}^2 q_j \right)^2 \right] \right\}, \\ &= \frac{q_i^3}{2a} - \frac{q_i^2}{2a} (3a - c_i - v + k) + q_i \left(a - c_i + k - c - e \sum_{j=1}^2 q_j \right) - \frac{ak}{2}. \end{aligned} \quad (18)$$

As shown in the above formula, the decision variable of the sharing logistics supply chain with OFP revenue

sharing strategy is the purchase order quantity (express delivery service price) of each express delivery company. And, it is a binary cubic equation, so it is difficult to be solved in its explicit expression. Next, we use Proposition 3 to prove the existence of the optimal decision solution of the revenue sharing supply chain and give its implicit expression.

Proposition 3. *In the OFP revenue sharing supply chain of the sharing logistics, the revenue function π_i^{ref} of the express delivery company i has an optimal solution (p_i^*, q_i^*) , and the optimal solution satisfies*

$$\begin{cases} -c - eq_1^* + \frac{3q_2^{*2}}{2a} - \frac{q_2^*}{a} (3a - c_2 - v + k + 2ea) + a - c_2 + k = 0, \\ -c - eq_2^* + \frac{3q_1^{*2}}{2a} - \frac{q_1^*}{a} (3a - c_1 - v + k + 2ea) + a - c_1 + k = 0, \\ p_i^* = a - q_i^*, \quad 0 < p_i^* < a \text{ and } 0 < q_i^* < a, i = 1 \text{ and } 2. \end{cases} \quad (19)$$

Proof. See the Appendix.

At this time, each express delivery company has a relationship of both cooperation and competition. On the one hand, they will work together to establish a sharing logistics distribution company, and on the other hand, they will simultaneously compete in the decision-making of their respective express service supply. Therefore, the decision-making idea is similar to the Cournot game. Firstly, the optimal response of the purchase order decision of each express delivery company to the purchase order decision of other express delivery companies is solved, and then, the equilibrium solution of these optimal responses is solved. However, because the optimal response curve is a quadratic equation, for the dual channel supply chain structure composed of two express companies, the final solution equation at this time is a quaternary equation of one variable, and it is difficult to give a dominant expression. However, it is clear that the optimal decision of purchase order quantity satisfies the above conditions. \square

5.2. Revenue-Sharing Based on the RSF: RE-RSF. In the combined sharing factor revenue sharing supply chain, each express delivery company determines the mutual benefit of each other according to the combination sharing factor. Among them, it is assumed that this sharing factor combination is

$$(\gamma_1^{\text{res}}, \gamma_2^{\text{res}}) \quad \gamma_i^{\text{res}} \in [0, 1] \text{ and } \sum_{i=1}^2 \gamma_i^{\text{res}} = 1. \quad (20)$$

At this point, the revenue of each express delivery company not only includes the part of business risk but also includes the part of revenue sharing based on the combined sharing factors. Thus, its revenue function is

$$\begin{aligned}
\pi_i^{\text{res}} &= \pi_i - O_i(p_i, q_i) - U_i(p_i, q_i) + \gamma_i^{\text{res}} \left\{ w \sum_{j=1}^2 q_j - \left[c \sum_{j=1}^2 q_j + e \left(\sum_{j=1}^2 q_j \right)^2 \right] \right\}, \\
&= \int_0^{q_i} (p_i - w - c_i) x f(x) dx + \int_{q_i}^a (p_i - w - c_i) q_i f(x) dx \\
&\quad - \int_0^{q_i} (w - v)(q_i - x) f(x) dx - \int_{q_i}^a k(x - q_i) f(x) dx + \gamma_i^{\text{res}} \left\{ w \sum_{j=1}^2 q_j - \left[c \sum_{j=1}^2 q_j + e \left(\sum_{j=1}^2 q_j \right)^2 \right] \right\}, \\
&= \frac{q_i^3}{2a} - \frac{q_i^2}{2a} (3a - c_i - v + k) + q_i \left(a - c_i + k - c - 2e \sum_{j=1}^2 q_j \right) - \frac{ak}{2} + \gamma_i^{\text{res}} e \left(\sum_{j=1}^2 q_j \right)^2.
\end{aligned} \tag{21}$$

As shown in the above formula, at this time, the decision variable of the combination sharing factor revenue sharing supply chain is the purchase order quantity (express delivery service price) of each express delivery company, and it is a binary cubic equation which is difficult to be solved in its explicit expression. Next, we use Proposition 4 to prove the

existence of the optimal decision solution of the revenue sharing supply chain and give its implicit expression.

Proposition 4. *In the RSF revenue sharing supply chain of the sharing logistics, the revenue function π_i^{res} of the express delivery company i has an optimal solution (p_i^*, q_i^*) , and the optimal solution satisfies*

$$\begin{cases} -c - 2(1 - \gamma_2^{\text{res}})eq_1^* + \frac{3q_2^{*2}}{2a} - \frac{q_2^*}{a} (3a - c_2 - v + k + 4ea - 2\gamma_2^{\text{res}}ea) + a - c_2 + k = 0, \\ -c - 2(1 - \gamma_1^{\text{res}})eq_2^* + \frac{3q_1^{*2}}{2a} - \frac{q_1^*}{a} (3a - c_1 - v + k + 4ea - 2\gamma_1^{\text{res}}ea) + a - c_1 + k = 0, \\ p_i^* = a - q_i^*, \quad 0 < p_i^* < a \text{ and } 0 < q_i^* < a, i = 1 \text{ and } 2. \end{cases} \tag{22}$$

Proof. See the Appendix.

At this time, each express delivery company has a relationship of both cooperation and competition. On the one hand, they cooperate to establish a sharing logistics distribution company, and on the other hand, they also have a competitive relationship when deciding its own supply of express delivery services. Therefore, the decision-making idea is similar to the Cournot game. Firstly, we calculate the optimal response based on the impact of the purchase order decision of each express company on the purchase order decision of other express companies, and then, we solve the equilibrium solution of these optimal responses. However, because the optimal response curve is a quadratic equation, for the dual channel supply chain structure composed of two express companies, the final solution equation at this time is a quaternary equation of one variable, and it is difficult to give a dominant expression. However, it is clear that the optimal decision purchase order quantity satisfies the above conditions. \square

6. SC of the Sharing Logistics with Risk Sharing

According to the analysis of the decentralized supply chain of sharing logistics, it is feasible for each express delivery company to take risks. On the contrary, it is not feasible for the sharing logistics distribution company to share the risks. Therefore, in the process of classification discussion of risk sharing supply chain, it is only necessary to consider the situation in which each express delivery company bears its own business risk. Therefore, the optimal decision of the sharing logistics distribution company is always

$$\begin{aligned}
\frac{\partial \pi_s^{\text{re}}}{\partial q_i} &= w - \left(c + 2e \sum_{j=1}^2 q_j \right) = 0, \\
&\Rightarrow w = c + 2e \sum_{j=1}^2 q_j.
\end{aligned} \tag{23}$$

6.1. Risk Sharing Based on the OFP: RS-OFP. In the order flow proportion risk sharing supply chain of sharing logistics, each express delivery company determines the risk sharing of each other according to their respective order flow contribution. Among them, the proportion of their respective order flows is

$$\left(\frac{q_1}{\sum_{j=1}^2 q_j}, \frac{q_2}{\sum_{j=1}^2 q_j} \right). \quad (24)$$

At this point, the revenue of the express delivery company is

$$\begin{aligned} \pi_i^{\text{rsf}} &= \pi_i - \frac{q_i}{\sum_{j=1}^2 q_j} \sum_{j=1}^2 [O_i(p_i, q_j) + U_i(p_i, q_j)], \\ &= \int_0^{q_i} (p_i - w - c_i) x f(x) dx + \int_{q_i}^a (p_i - w - c_i) q_i f(x) dx \\ &\quad - \frac{q_i}{\sum_{j=1}^2 q_j} \sum_{j=1}^2 \left[\int_0^{q_i} (w - v)(q_i - x) f(x) dx + \int_{q_i}^a k(x - q_i) f(x) dx \right], \\ &= \frac{q_i^3}{2a} - \frac{q_i^2}{2a} (3a - c_i - w) + q_i(a - c_i - w) - \frac{q_i}{\sum_{j=1}^2 q_j} \sum_{j=1}^2 \left[\frac{q_j^2}{2a} (w - v) + \frac{kq_j^2}{2a} - kq_i + \frac{ak}{2} \right]. \end{aligned} \quad (25)$$

As shown in the above formula, the decision variable at this time is the purchase order quantity (express delivery service price) of each express delivery company, and it is a binary cubic equation which is difficult to be solved in its explicit expression. Next, we use Proposition 5 to prove the existence of the optimal decision solution of the risk sharing supply chain and give its implicit expression.

Proposition 5. In the OFP risk sharing supply chain of sharing logistics, the revenue function π_i^{rsf} of the express delivery company i has an optimal solution (p_i^*, q_i^*) , and the optimal solution satisfies

$$\left\{ \begin{aligned} &-c - 4eq_1^* + \frac{(3+6e)q_1^{*2}}{2a} - \frac{q_1^*}{a} (3a - c - c_1 - 2eq_2^*) + a - c_1 - 2eq_2^* - \frac{q_2^*}{(q_1^* + q_2^*)^2} \\ &\sum_{j=1}^2 \left[\frac{q_j^{*2}}{2a} \left(c - v + k + 2e \sum_{j=1}^2 q_j^* \right) - kq_j^* + \frac{ak}{2} \right] - \frac{q_1^*}{q_1^* + q_2^*} \left[\frac{q_1^* (c - v + k + 2e \sum_{j=1}^2 q_j^*)}{a} - k + \frac{e(q_1^{*2} + q_2^{*2})}{a} \right] = 0, \\ &-c - 4eq_2^* + \frac{(3+6e)q_2^{*2}}{2a} - \frac{q_2^*}{a} (3a - c - c_2 - 2eq_1^*) + a - c_2 - 2eq_1^* - \frac{q_1^*}{(q_1^* + q_2^*)^2} \\ &\sum_{j=1}^2 \left[\frac{q_j^{*2}}{2a} \left(c - v + k + 2e \sum_{j=1}^2 q_j^* \right) - kq_j^* + \frac{ak}{2} \right] - \frac{q_2^*}{q_1^* + q_2^*} \left[\frac{q_2^* (c - v + k + 2e \sum_{j=1}^2 q_j^*)}{a} - k + \frac{e(q_1^{*2} + q_2^{*2})}{a} \right] = 0, \\ &p_i^* = a - q_i^*, \quad 0 < p_i^* < a \text{ and } 0 < q_i^* < a, i = 1 \text{ and } 2. \end{aligned} \right. \quad (26)$$

Proof. See the Appendix.

At this time, each express delivery company has a relationship of both cooperation and competition. On the one hand, they cooperate to establish a sharing logistics distribution company, and on the other hand, they also have a

competitive relationship when deciding their respective express delivery service supply. Therefore, the idea of decision-making is similar to Cournot game. First, we calculate the optimal response based on the impact of the purchase order decision of each express company on the purchase

order decision of other express companies, and then, we solve the equilibrium solution of these optimal responses. However, because the optimal response curve is a quadratic equation, for the dual channel supply chain structure composed of two express companies, the final solution equation at this time is a quaternary equation of one variable, and it is difficult to give a dominant expression. However, it is clear that the optimal decision purchase order quantity satisfies the above conditions. \square

6.2. Risk Sharing Based on the RSF: RS-RSF. In the combined sharing factor risk sharing supply chain of sharing logistics, each express delivery company determines the risk sharing of each other according to the combination factor. Among them, the risk sharing factor combination is

$$(\gamma_1^{\text{rss}}, \gamma_2^{\text{rss}}) \quad \gamma_i^{\text{rss}} \in [0, 1] \text{ and } \sum_{i=1}^2 \gamma_i^{\text{rss}} = 1. \quad (27)$$

At this point, the revenue of the express delivery company is

$$\begin{aligned} \pi_i^{\text{rss}} &= \pi_i - \gamma_i^{\text{rss}} \sum_{j=1}^2 [O_j(p_j, q_j) + U_j(p_j, q_j)] \\ &= \int_0^{q_i} (p_i - w - c_i) x f(x) dx + \int_{q_i}^a (p_i - w - c_i) q_i f(x) dx \\ &\quad - \gamma_i^{\text{rss}} \sum_{j=1}^2 \left[\int_0^{q_j} (w - v)(q_j - x) f(x) dx \right. \\ &\quad \left. + \int_{q_j}^a k(x - q_j) f(x) dx \right] \\ &= \frac{q_i^3}{2a} - \frac{q_i^2}{2a} (3a - c_i - w) + q_i(a - c_i - w) \\ &\quad - \gamma_i^{\text{rss}} \sum_{j=1}^2 \left[\frac{q_j^2}{2a} (w - v) + \frac{kq_j^2}{2a} - kq_j + \frac{ak}{2} \right]. \end{aligned} \quad (28)$$

As shown in the above formula, the decision variable of the combined sharing factor risk sharing supply chain at this time is the purchase order quantity (express delivery service price) of each express delivery company, and it is a binary cubic equation which is difficult to be solved in its explicit expression. Next, we use Proposition 6 to prove the existence of the optimal decision solution of the risk sharing supply chain and give its implicit expression.

Proposition 6. In the RSF risk sharing supply chain of sharing logistics, the revenue function π_i^{rss} of the express delivery company i has an optimal solution (p_i^*, q_i^*) , and the optimal solution satisfies

$$\begin{cases} -c - 4eq_1^* + \frac{(3+6e)q_1^{*2}}{2a} - \frac{q_1^*}{a} (3a - c_1 - c - 2eq_2^*) + a - c_1 - 2eq_2^* \\ -\gamma_1^{\text{rss}} \left[\frac{q_1^* (c - v + k + 2e \sum_{j=1}^2 q_j^*)}{a} - k + \frac{e(q_1^{*2} + q_2^{*2})}{a} \right] = 0, \\ -c - 4eq_2^* + \frac{(3+6e)q_2^{*2}}{2a} - \frac{q_2^*}{a} (3a - c_2 - c - 2eq_1^*) + a - c_2 - 2eq_1^* \\ -\gamma_2^{\text{rss}} \left[\frac{q_2^* (c - v + k + 2e \sum_{j=1}^2 q_j^*)}{a} - k + \frac{e(q_1^{*2} + q_2^{*2})}{a} \right] = 0, \\ p_i^* = a - q_i^*, \quad 0 < p_i^* < a \text{ and } 0 < q_i^* < a, i = 1 \text{ and } 2. \end{cases} \quad (29)$$

Proof. See the Appendix.

At this time, each express delivery company has both a cooperative relationship and a competitive relationship. On the one hand, they cooperate to establish a sharing logistics distribution company, and on the other hand, they also have a competitive relationship when deciding its own supply of express delivery services. Therefore, the decision-making idea is similar to the Cournot game. First, we calculate the optimal response based on the impact of the purchase order decision of each express company on the purchase order decision of other express companies, and then, we solve the equilibrium solution of these optimal responses. However, because the optimal response curve is a quadratic equation, for the dual channel supply chain structure composed of two express companies, the final solution equation at this time is a quaternary equation of one variable, and it is difficult to give a dominant expression. However, it is clear that the optimal decision purchase order quantity satisfies the above conditions. \square

7. Comparative Analysis

According to Propositions 1–6, we see that all the optimal decision variables p_i and q_i can be solved through a quaternary equation of one variable as following Lemma 1 shows. However, the solution expression of a quartic equation in one variable is very complicated, and it is difficult to give a clear comparative analysis result. We will give some comparative analysis results in this section, while the others will be analyzed through the case study and numerical analysis in following Section 8.

Lemma 1. For a standard unary quartic equation $\hat{a}z^4 + \hat{b}z^3 + \hat{c}z^2 + \hat{d}z + \hat{e} = 0$, we can solve the variable z as follows:

Set $\hat{P} = (\hat{c}^2 + 12\hat{a}\hat{e} - 3\hat{b}\hat{d})/9$, $\hat{Q} = (27\hat{a}\hat{d}^2 + 2\hat{c}^3 + 27\hat{b}^2\hat{e} - 72\hat{a}\hat{c}\hat{e} - 9\hat{b}\hat{c}\hat{d})/54$, and $\hat{D} = \sqrt{\hat{Q}^2 - \hat{P}^3}$. We have

$$\hat{u} = \begin{cases} \sqrt[3]{\hat{Q} + \hat{D}}, & \text{if } |\hat{Q} - \hat{D}| \leq |\hat{Q} + \hat{D}|, \\ \sqrt[3]{\hat{Q} - \hat{D}}, & \text{else } |\hat{Q} - \hat{D}| > |\hat{Q} + \hat{D}|, \end{cases} \quad (30)$$

$$\hat{v} = \begin{cases} 0, & \text{if } \hat{u} = 0, \\ \frac{\hat{p}}{\hat{u}}, & \text{else.} \end{cases}$$

$$\text{Make } \hat{w} = -(1/2) + (\sqrt{3}/2)i \quad \text{and} \quad \hat{m} = \sqrt{\hat{b}^2 - (8\hat{a}\hat{c}/3) + 4\hat{a}(\hat{w}^k\hat{u} + \hat{w}^{3-k}\hat{v})}.$$

For $k = 0, 1$, and 2 , solve the value of \hat{m} . If all the three values of \hat{m} are zero, we have

$$\hat{S} = \hat{b}^2 - \frac{8\hat{a}\hat{c}}{3}, \quad (31)$$

$$\hat{T} = 0.$$

Else if $k = \text{argmax}_k |\hat{m}|$, we have

$$\hat{S} = 2\hat{b}^2 - \frac{16\hat{a}\hat{c}}{3} - 4\hat{a}(\hat{w}^k\hat{u} + \hat{w}^{3-k}\hat{v}), \quad (32)$$

$$\hat{T} = \frac{8\hat{a}\hat{b}\hat{c} - 16\hat{a}^2\hat{d} - 2\hat{b}^3}{\hat{m}}.$$

Therefore, the decision variable will be

$$z_1 = \frac{-\hat{b} - \hat{m} + \sqrt{\hat{S} - \hat{T}}}{4\hat{a}},$$

$$z_2 = \frac{-\hat{b} - \hat{m} - \sqrt{\hat{S} - \hat{T}}}{4\hat{a}}, \quad (33)$$

$$z_3 = \frac{-\hat{b} + \hat{m} + \sqrt{\hat{S} + \hat{T}}}{4\hat{a}},$$

$$z_4 = \frac{-\hat{b} + \hat{m} - \sqrt{\hat{S} + \hat{T}}}{4\hat{a}}.$$

Next, we will give some comparative analysis results according to Propositions 1–6 as the following corollary shows.

Corollary 1. *If $c_1 = c_2$, which means the express companies are completely homogeneous, we have $\max\{q_1^*, q_2^* | \text{ref}\} < \max\{q_1^*, q_2^* | c\} < \max\{q_1^*, q_2^* | d_2\}$.*

Corollary 1 demonstrates that when the two express delivery companies are completely homogeneous, the optimal order quantity in the centralized SC is bigger than that in the SC of sharing logistics with revenue sharing based on the OFP, while not bigger than that in the decentralized SC with express delivery companies taking risks.

Example 1. $a = 10, c = 1, e = 1, v = 2$, and $k = 2.5$.

According to the visualization in Figure 1, $\max\{q_1^*, q_2^* | \text{ref}\} < \max\{q_1^*, q_2^* | c\} < \max\{q_1^*, q_2^* | d_2\}$ satisfies when the variables $a = 10, c = 1, e = 1, v = 2$, and $k = 2.5$.

Corollary 2. *If $\gamma_1^{\text{res}} = \gamma_2^{\text{res}} = 1/2$, which means the express companies distribute income equally from the sharing logistics distribution company, we have $q_i^* | \text{res} = q_i^* | c$, $i = 1$ and 2 ; $\pi_1^{\text{res}*} = \pi_2^{\text{res}*} = (1/2)\pi_{sc}^*$.*

Corollary 2 demonstrates that when the two express delivery companies distribute income equally from the sharing logistics distribution company in the SC of sharing logistics with revenue sharing based on the RSF, the optimal order quantity q_i in the SC of sharing logistics with revenue sharing based on the RSF is equal to that in the centralized SC. It means that the sharing logistics mechanism achieves the optimal supply chain coordination.

Corollary 3. *To compare and analyze the income gap between express delivery companies before and after the implementation of sharing logistics, it should be considered that, before the implementation of sharing logistics, each express delivery company only runs intercity logistics transportation services, and all urban logistics distribution services are outsourced, so the calculation of its income needs to deduct the cost of urban logistics distribution. After the implementation of sharing logistics, the effect of vertical integration has been produced, and the operational boundaries of express delivery companies have increased. In addition to intercity logistics transportation revenues, there are also urban logistics distribution revenues.*

8. Case Study

8.1. Data Source. As a subdivision of the modern logistics industry, e-commerce logistics express delivery has gradually standardized the logistics operation costs between provinces or economic zones and has been well optimized and improved. However, in the wider urban logistics sector, due to the different characteristics of industrial structures in various regions, the flow direction and flow of materials in the logistics industry exhibit a highly nonequilibrium character. Moreover, most e-commerce express delivery companies and even large-scale urban logistics distribution companies still adopt the traditional franchise business model in the city level, and it is difficult to achieve centralized and unified management and control of operating costs; for this reason, the cost of first-line logistics in various regions is often very different. In view of this, in order to study more general issues and explain the general results, the data used in the case study and numerical analysis of this paper mainly comes from the previous years' earnings data of several listed express delivery companies [22, 34]. At the same time, it combines research and interviews on the actual operation of some e-commerce express delivery companies and related cost information. We will mainly use the data listed in Table 2 and 3.

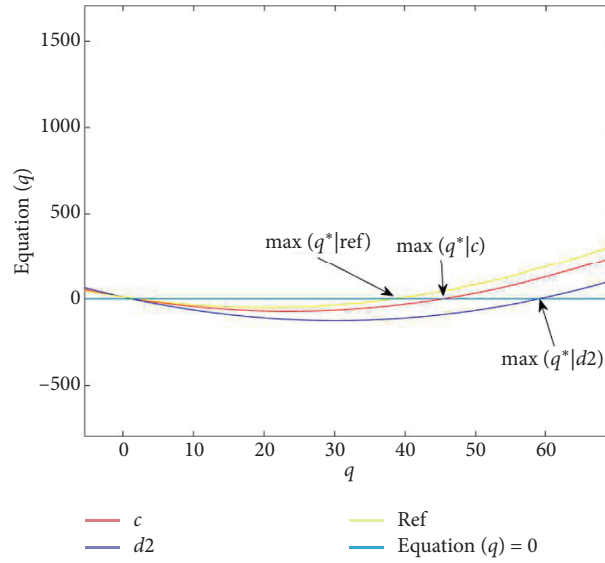


FIGURE 1: Example of Corollary 1.

TABLE 2: Market size and market share data of listed express delivery companies.

| Total market size | Market share | | | |
|-------------------|----------------------------|----------------------------|------------------------------|----------------------------|
| 19894417401 | STO Express 0.196364433 | YTO Express 0.254281639 | YUNDA Express 0.236758698 | ZTO Express 0.312595231 |
| | Market size | | | |
| | STO Express 3906555984 | YTO Express 5058785063 | YUNDA Express 4710176354 | ZTO Express 6218900000 |

TABLE 3: Operating cost data of listed express delivery companies.

| | | | | |
|---|--------------------------------|---------------------|-----------------------|---------------------|
| Unit cost of sharing logistics distribution | c 1.50 | | | |
| Nonscale economic cost | e 0.01 \rightarrow 0.11 | | | |
| Unit transportation cost | STO Express 1.00 | YTO Express 1.13 | YUNDA Express 1.02 | ZTO Express 0.93 |

According to Table 2, the total express delivery market of the four listed express delivery companies is about 19.894 billion. Moreover, the market share of STO Express is about 19.64%, the market share of YTO Express is about 25.43%, the market share of YUNDA Express is about 23.68%, and the market share of ZTO Express is about 31.25%. Therefore, the market service scale of each express delivery company measured according to the market share is as follows: the market service scale of STO Express is about 3.907 billion pieces, the market service scale of YTO Express is about 5.059 billion pieces, the market service scale of YUNDA Express is about 4.71 billion pieces, and the market service scale of ZTO Express is about 6.219 billion pieces.

According to Table 3, the unit cost of the sharing logistics distribution service is 1.50 yuan/piece, and the cost data is very close to the real urban distribution cost of the express delivery industry. The nonscale economic cost of a sharing logistics distribution company ranges from 0.01 yuan to 0.11 yuan. The transportation cost of intercity logistics of each express delivery company is as follows: the unit transportation

cost of STO Express is 1.00 yuan/piece, the unit transportation cost of YTO Express is 1.13 yuan/piece, the unit transportation cost of YUNDA Express is 1.02 yuan/piece, and the unit transportation cost of ZTO Express is 0.93 yuan/piece. These cost data are also very close to the real intercity transportation costs of the express delivery industry.

This paper analyzes the performance optimization strategy of revenue sharing and risk sharing under the circumstances of sharing logistics cooperation between two express delivery companies. Table 1 gives the market size and market share data of each listed express delivery company, and then, we obtain the market demand scale of each express delivery company. According to the model hypothesis and problem setting in this paper, when the two-two cooperation between express delivery companies is solved, the market size will be as shown in Table 4. There are six sets of data, that is, six kinds of cooperation situations.

Table 5 gives the cost data of each listed express delivery company. According to the research ideas in this paper, any two companies cooperate with each other. Therefore, in

TABLE 4: Average market size of listed express delivery companies when cooperating two-two.

| | STO Express | YTO Express | YUNDA Express | ZTO Express |
|---------------|------------------|------------------|------------------|-------------|
| STO Express | — | — | — | — |
| YTO Express | $a = 4482670524$ | — | — | — |
| YUNDA Express | $a = 4308366169$ | $a = 4884480709$ | — | — |
| ZTO Express | $a = 5062727992$ | $a = 5638842532$ | $a = 5464538177$ | — |

order to distinguish the combination of the unit transportation cost when the two-two express delivery companies share the urban logistics distribution service, the cost data combination will be as shown in Table 5. There are six sets of data, that is, six kinds of cooperation situations.

8.2. Numerical Analysis. The numerical analysis will be developed in three sections: firstly, we analyze the performance improvement of the OFP revenue sharing strategy and the OFP risk sharing strategy when all the express delivery companies cooperate in the two-two sharing logistics; secondly, we compare the advantages and disadvantages of RSF revenue sharing strategy and risk sharing strategy with OFP revenue sharing strategy and risk sharing strategy; finally, we give the comparative results of various performance improvement strategies when the two dimensions' data of nonscale economic cost and combination factor changes.

8.2.1. The Performance of the OFP Supply Chain. In this section, we mainly analyze the changing trends of the total performance of the centralized SC, the decentralized SC, the OFP revenue sharing SC, and the OFP risk sharing SC when all the express delivery companies cooperate in the two-two sharing logistics and the nonscale economic cost e changes. At the same time, we quantitatively show the degree of performance improvement of OFP revenue sharing strategy and OFP risk sharing strategy. Although the proportion of performance improvement is relatively low, relative to the overall market size of more than 400 billion yuan in the e-commerce express delivery industry, even a 0.4% performance improvement means a revenue increase of nearly 1.6 billion yuan.

As shown in Table 6, when the nonscale economic costs e change from 0.01 to 0.11, all the four kinds of supply chain decision-making strategies will decrease with the increase of the cost, that is, the optimal decision is about the monotone decreasing function of nonscale economic cost. And, no matter what the nonscale economic cost is, the overall performance of the OFP revenue sharing supply chain is higher than that of the OFP risk sharing supply chain, which is also between that of the centralized supply chain and the decentralized supply chain. At the same time, it could be seen from the performance improvement data of the above six types of two-two cooperation that the performance improvement of the OFP revenue sharing strategy is roughly between 0.007% and 0.4% and that of the OFP risk sharing strategy is roughly between 0 and 0.166%. The change trends are shown in the visual graphs of Figures 2 and 3.

8.2.2. Combined Sharing Factor Supply Chain Performance. In this section, we mainly analyze when the sharing factor combination changes within the range of 0-1 and the overall performance changing trends of the centralized SC, the decentralized SC, the OFP revenue sharing SC, the OFP risk sharing SC, the RSF revenue sharing SC, and the RSF risk sharing SC of the sharing logistics based on the equity investment.

As shown in Figure 4, when the sharing factor combination changes within the value range 0-1, in the above several situations, the comparison of the overall performance of the supply chain has undergone significant changes specifically. For example, when the nonscale economic cost $e = 0.01$, if the sharing factor γ_1 is taken as follows, there are

- (1) When $\gamma_1 \in [0, R_1)$, $\pi_{sc}^c > \pi_{sc}^{\text{ref}} > \pi_{sc}^{\text{rsf}} > \pi_{sc}^{\text{rss}} > \pi_{sc}^d > \pi_{sc}^{\text{res}}$
- (2) When $\gamma_1 \in [R_1, R_2)$, $\pi_{sc}^c > \pi_{sc}^{\text{ref}} > \pi_{sc}^{\text{rsf}} > \pi_{sc}^{\text{rss}} > \pi_{sc}^{\text{res}} > \pi_{sc}^d$
- (3) When $\gamma_1 \in [R_2, R_3)$, $\pi_{sc}^c > \pi_{sc}^{\text{ref}} > \pi_{sc}^{\text{rss}} > \pi_{sc}^{\text{rsf}} > \pi_{sc}^{\text{res}} > \pi_{sc}^d$
- (4) When $\gamma_1 \in [R_3, R_4)$, $\pi_{sc}^c > \pi_{sc}^{\text{ref}} > \pi_{sc}^{\text{rss}} > \pi_{sc}^{\text{res}} > \pi_{sc}^{\text{rsf}} > \pi_{sc}^d$
- (5) When $\gamma_1 \in [R_4, R_5)$, $\pi_{sc}^c > \pi_{sc}^{\text{ref}} > \pi_{sc}^{\text{res}} > \pi_{sc}^{\text{rss}} > \pi_{sc}^{\text{rsf}} > \pi_{sc}^d$
- (6) When $\gamma_1 \in [R_5, R_6)$, $\pi_{sc}^c > \pi_{sc}^{\text{res}} > \pi_{sc}^{\text{ref}} > \pi_{sc}^{\text{rss}} > \pi_{sc}^{\text{rsf}} > \pi_{sc}^d$
- (7) When $\gamma_1 \in [R_6, R_7)$, $\pi_{sc}^c > \pi_{sc}^{\text{ref}} > \pi_{sc}^{\text{res}} > \pi_{sc}^{\text{rss}} > \pi_{sc}^{\text{rsf}} > \pi_{sc}^d$
- (8) When $\gamma_1 \in [R_7, R_8)$, $\pi_{sc}^c > \pi_{sc}^{\text{ref}} > \pi_{sc}^{\text{rss}} > \pi_{sc}^{\text{res}} > \pi_{sc}^{\text{rsf}} > \pi_{sc}^d$
- (9) When $\gamma_1 \in [R_8, R_9)$, $\pi_{sc}^c > \pi_{sc}^{\text{ref}} > \pi_{sc}^{\text{rss}} > \pi_{sc}^{\text{rsf}} > \pi_{sc}^{\text{res}} > \pi_{sc}^d$
- (10) When $\gamma_1 \in [R_9, R_{10})$, $\pi_{sc}^c > \pi_{sc}^{\text{ref}} > \pi_{sc}^{\text{rsf}} > \pi_{sc}^{\text{rss}} > \pi_{sc}^{\text{res}} > \pi_{sc}^d$
- (11) When $\gamma_1 \in [R_{10}, 1)$, $\pi_{sc}^c > \pi_{sc}^{\text{ref}} > \pi_{sc}^{\text{rsf}} > \pi_{sc}^{\text{rss}} > \pi_{sc}^d > \pi_{sc}^{\text{res}}$

According to Figure 4, the four performance optimization strategies RE-OFP, RS-OFP, RE-RSF, and RS-RSF do not have absolute advantages and disadvantages, but change with the value of the combination sharing factor.

8.2.3. Change Trends of Supply Chain Performance. In this section, we mainly analyze the advantages and disadvantages of several supply chain performance optimization strategies when there is change in both the nonscale economic cost and combination sharing factors. According to Figure 5, for a certain combined sharing factor, as the change of nonscale economic cost, the relationship between several performance optimization strategies changes. For a certain nonscale economic cost, the advantages and disadvantages of several performances between the optimization strategies change with the combined sharing factors. At the same time, in the vast majority of cases, the supply chain performance under the combined sharing factor risk sharing strategy is higher than that under the OFP risk sharing strategy, but is lower than that under the OFP

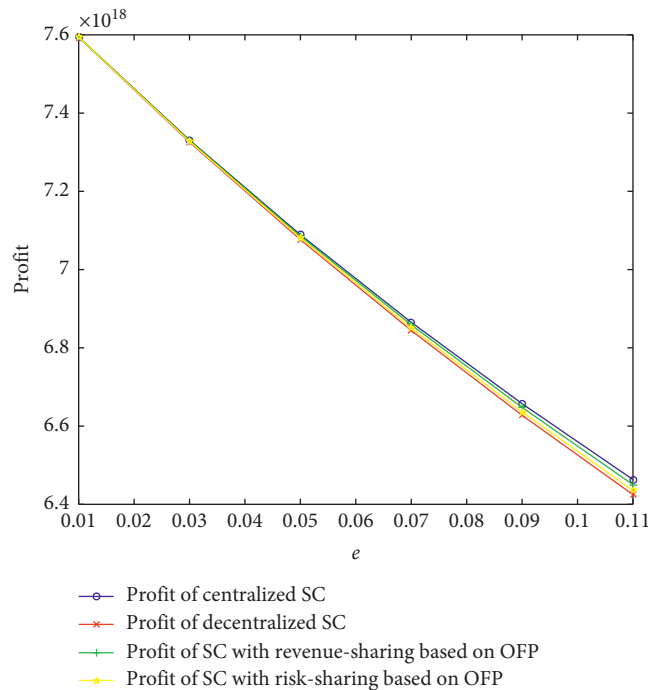
TABLE 5: Unit transportation cost combination of two-two cooperation.

| | STO Express | YTO Express | YUNDA Express |
|---------------|-----------------------------|-----------------------------|-----------------------------|
| STO Express | — | — | — |
| YTO Express | $(c_1, c_2) = (1.00, 1.13)$ | — | — |
| YUNDA Express | $(c_1, c_2) = (1.00, 1.02)$ | $(c_1, c_2) = (1.13, 1.02)$ | — |
| ZTO Express | $(c_1, c_2) = (1.00, 0.93)$ | $(c_1, c_2) = (1.13, 0.93)$ | $(c_1, c_2) = (1.02, 0.93)$ |

TABLE 6: Change trends of SC performance on the nonscale economic cost e (unit: 10^{18}).

| | e | 0.01 | 0.03 | 0.05 | 0.07 | 0.09 | 0.11 | Performance ratio (%) | Performance improvement (%) |
|-------------|------------------|--------|--------|--------|--------|--------|--------|-----------------------|-----------------------------|
| STO + YTO | π_{sc}^c | 7.5940 | 7.3311 | 7.0891 | 6.8653 | 6.6573 | 6.4633 | — | — |
| | π_{sc}^d | 7.5932 | 7.3256 | 7.0765 | 6.8443 | 6.6275 | 6.4246 | 99.401–99.989 | — |
| | π_{sc}^{ref} | 7.5938 | 7.3296 | 7.0854 | 6.8587 | 6.6476 | 6.4502 | 99.797–99.997 | 0.008–0.396 |
| | π_{sc}^{rsf} | 7.5935 | 7.3275 | 7.0805 | 6.8506 | 6.6360 | 6.4351 | 99.564–99.993 | 0.004–0.163 |
| STO + YUNDA | π_{sc}^c | 7.0149 | 6.7720 | 6.5485 | 6.3418 | 6.1496 | 5.9704 | — | — |
| | π_{sc}^d | 7.0142 | 6.7670 | 6.5369 | 6.3224 | 6.1221 | 5.9347 | 99.402–99.990 | — |
| | π_{sc}^{ref} | 7.0147 | 6.7706 | 6.5451 | 6.3357 | 6.1407 | 5.9583 | 99.797–99.997 | 0.007–0.395 |
| | π_{sc}^{rsf} | 7.0144 | 6.7687 | 6.5406 | 6.3282 | 6.1299 | 5.9444 | 99.565–99.993 | 0.003–0.163 |
| STO + ZTO | π_{sc}^c | 9.6864 | 9.3511 | 9.0425 | 8.7570 | 8.4916 | 8.2442 | — | — |
| | π_{sc}^d | 9.6855 | 9.3442 | 9.0264 | 8.7302 | 8.4536 | 8.1948 | 99.401–99.991 | — |
| | π_{sc}^{ref} | 9.6862 | 9.3492 | 9.0377 | 8.7486 | 8.4793 | 8.2275 | 99.797–99.998 | 0.007–0.396 |
| | π_{sc}^{rsf} | 9.6858 | 9.3465 | 9.0315 | 8.7382 | 8.4645 | 8.2082 | 99.563–99.994 | 0.003–0.162 |
| YTO + YUNDA | π_{sc}^c | 9.0164 | 8.7042 | 8.4170 | 8.1512 | 7.9042 | 7.6739 | — | — |
| | π_{sc}^d | 9.0155 | 8.6978 | 8.4020 | 8.1263 | 7.8688 | 7.6280 | 99.402–99.990 | — |
| | π_{sc}^{ref} | 9.0161 | 8.7024 | 8.4125 | 8.1434 | 7.8927 | 7.6583 | 99.797–99.997 | 0.007–0.395 |
| | π_{sc}^{rsf} | 9.0158 | 8.7000 | 8.4068 | 8.1338 | 7.8789 | 7.6404 | 99.563–99.993 | 0.003–0.161 |
| YTO + ZTO | π_{sc}^c | 12.016 | 11.600 | 11.218 | 10.863 | 10.534 | 10.227 | — | — |
| | π_{sc}^d | 12.015 | 11.592 | 11.198 | 10.830 | 10.487 | 10.166 | 99.404–99.992 | — |
| | π_{sc}^{ref} | 12.016 | 11.598 | 11.212 | 10.853 | 10.519 | 10.207 | 99.804–100 | 0.008–0.4 |
| | π_{sc}^{rsf} | 12.016 | 11.595 | 11.204 | 10.840 | 10.501 | 10.183 | 99.570–100 | 0.008–0.166 |
| YUNDA + ZTO | π_{sc}^c | 11.285 | 10.894 | 10.535 | 10.202 | 9.893 | 9.605 | — | — |
| | π_{sc}^d | 11.284 | 10.886 | 10.516 | 10.171 | 9.849 | 9.547 | 99.396–99.991 | — |
| | π_{sc}^{ref} | 11.285 | 10.892 | 10.529 | 10.192 | 9.879 | 9.585 | 99.792–100 | 0.009–0.396 |
| | π_{sc}^{rsf} | 11.284 | 10.889 | 10.522 | 10.180 | 9.861 | 9.563 | 99.563–99.991 | 0–0.167 |

Performance ratio represents the proportion of the supply chain performance in the other situations to that in the centralized situation. Performance improvement represents the improvement ratio of the supply chain performance in the other situations to that in the centralized situation.

FIGURE 2: SC performance under the cooperation of STO and YTO with the change trend of nonscale economic cost e .

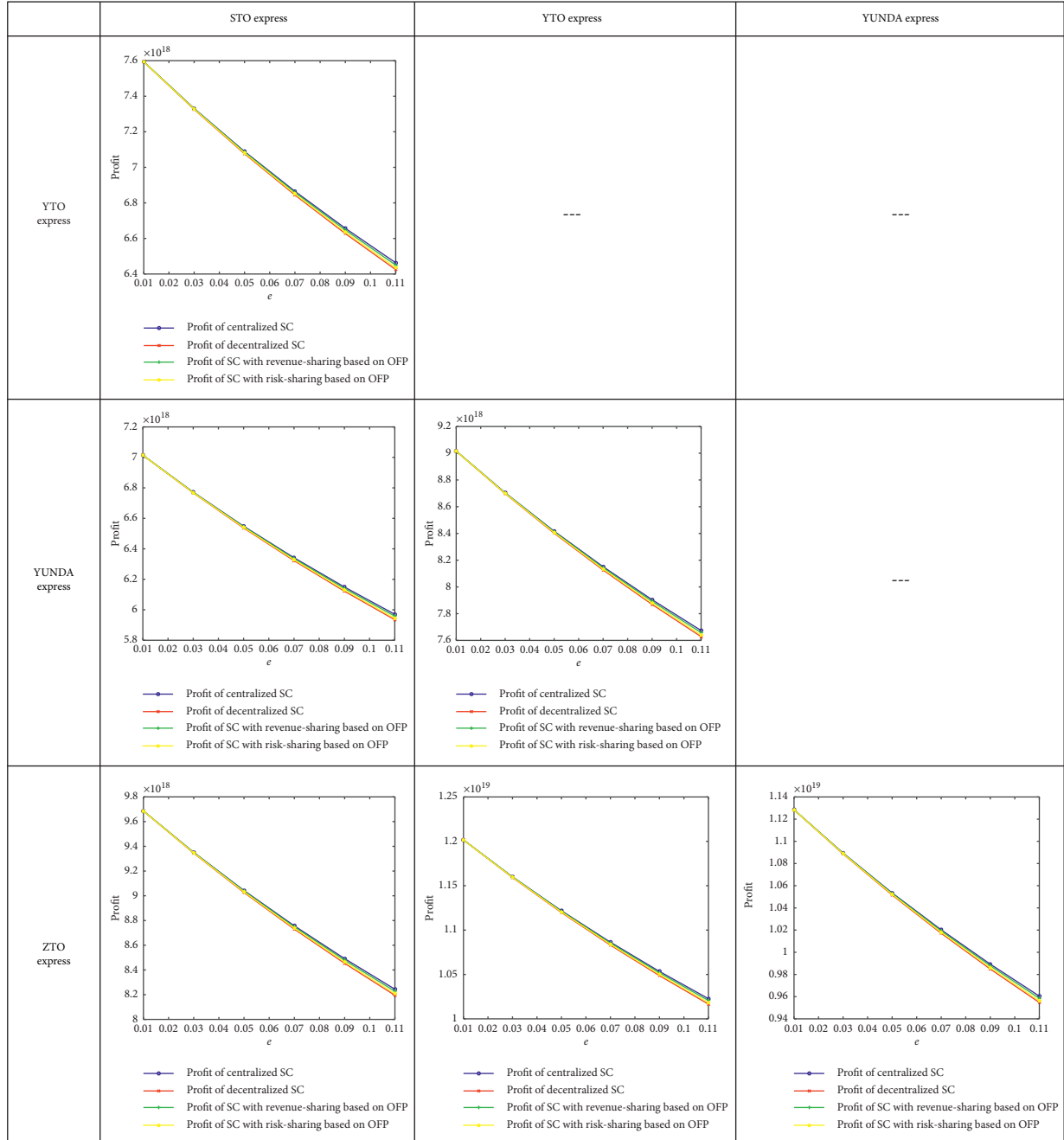


FIGURE 3: SC performance during the two-two cooperation on the change trends of nonscale economic cost e .

revenue sharing strategy. If the value of the combined sharing factor is too high or too low, which means the value is too close to 0 or 1, supply chain performance under a combined sharing factor revenue sharing strategy may be lower than the overall performance under the decentralized supply chain.

9. Theoretical and Managerial Implications

9.1. Theoretical Implications. There are two types of sharing distribution: vertical sharing and horizontal sharing. For vertical sharing, distribution is often organized along

modes and service operators. For instance, the first leg within the city may be carried out by conventional trucks, whereas the last mile to the recipient may be operated by environment-friendly city freighters. In horizontal sharing, multiple providers work together in the same section of the distribution chain, potentially sharing orders and infrastructure [1]. The previous scholars' research on the sharing logistics distribution mainly focuses on the distribution method. In contrast, only fewer scholars consider the serious problems that hinder the promotion of sharing distribution in practice, such as the construction process of the sharing distribution

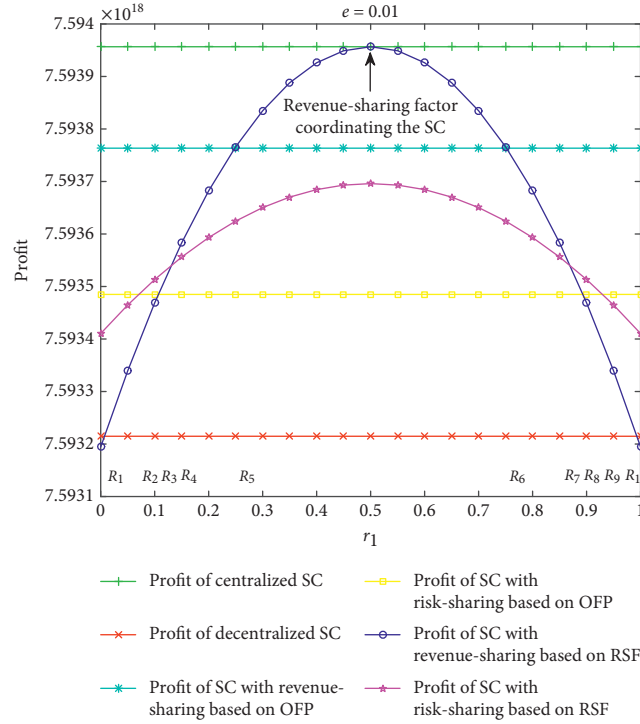


FIGURE 4: Change trends of the SC performance on the combined sharing factors.

cooperative organization, specific operation methods, coordination and supervision, and establishment of incentive mechanisms, as well as establishment of trust mechanisms. Further obstacles include low load factors, empty trips, long dwell times at loading and unloading points, and large numbers of deliveries to individual customers [35]. The horizontal and vertical transportation alliances are too loose and have many of the aforementioned drawbacks. Therefore, the equity investment-based model proposed in this paper further strengthens the cooperation depth of transportation alliances and enhances its operability in commercial practice. We make interviews and exchanges with many top-class logistics enterprises and e-commerce logistics enterprises, then summarize and refine the characteristics of business-based equity cooperation projects, which often occur in modern logistics industry, and design the equity-based sharing logistics distribution cooperation mechanism based on this.

9.2. Managerial Implications

9.2.1. Vertical and Horizontal Integration. Different from the exogenous vertical integration, for example, extending from iron ore smelting to the production of finished steel products, the express delivery companies obtain logistics orders from online e-commerce enterprises that need to be finally delivered to end e-commerce customers, but

only self-operate intercity logistics transportation and outsource the urban logistics distribution business to professional urban distribution companies. In this case, if the express delivery companies extend the development of the urban logistics distribution business based on the vertical integration strategy adopted by the logistics order that one has already mastered, this is an endogenous vertical integration strategy. Compared with exogenous vertical integration, the biggest advantage of endogeneity is that it does not need to redevelop a new customer market, but it can better provide existing e-commerce enterprises and customers with more value-added services. Obviously, the sharing logistics mechanisms that we propose in this paper belong to the endogenous vertical integration.

9.2.2. Income Distribution Mechanism. Due to the imbalance of market power among supply chain members, there are often many obstacles in implementing traditional supply chain coordination mechanisms among supply chain members, and there is also a lack of necessary institutional mechanism guarantees. The combination contract mechanism of supply chain coordination and equity investment proposed in this paper can solve the problem fundamentally from the interests of all parties and greatly improve the feasibility of the implementation of the sharing logistics cooperation mechanism. At the same time, we have also analyzed and compared the equity cooperation

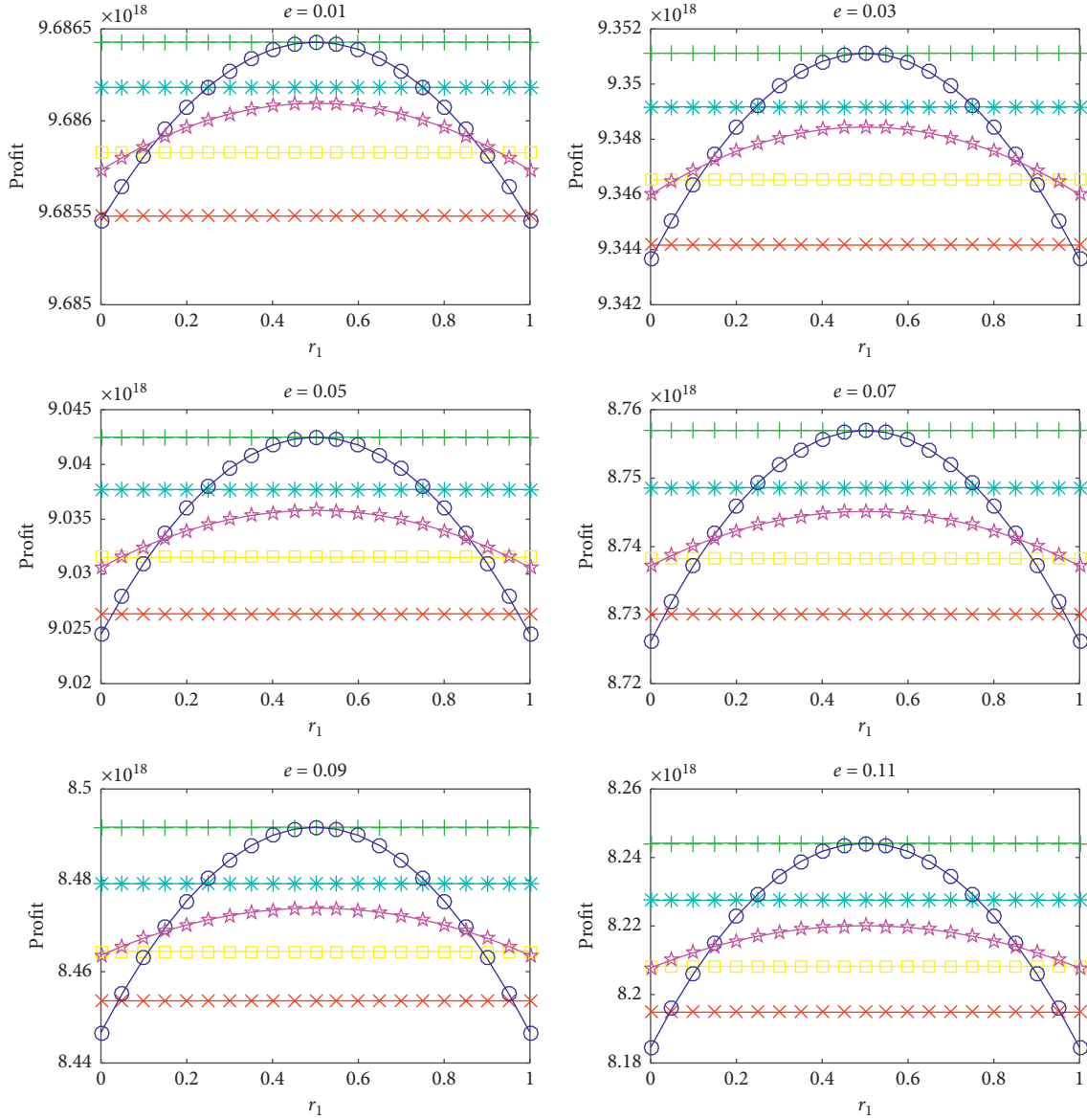


FIGURE 5: Change trends of the SC performance on combined sharing factors and nonscale economic cost. (a) $e = 0.01$. (b) $e = 0.03$. (c) $e = 0.05$. (d) $e = 0.07$. (e) $e = 0.09$. (f) $e = 0.11$.

mechanisms of revenue sharing and risk sharing. The study found that equity cooperation based on the proportion of order flow is more conducive to the achievement and sustainable development of the sharing cooperation mechanism. This also explains theoretically why is the order flow charge gradually becoming a benefit distribution

mechanism often used in the practice of logistics operations, instead of the traditional fixed equity proportional distribution mechanism. This equity cooperation and revenue distribution mechanism based on the proportion of order flow is similar to the TUP mechanism design of Huawei and others.

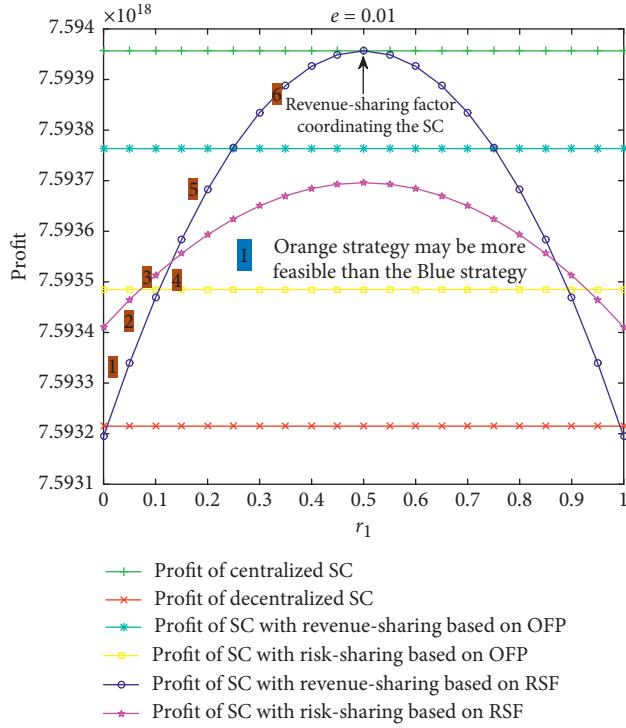


FIGURE 6: The optimization strategy cannot be completed in one step, but step by step

10. Conclusions

In this paper, we study the sharing logistics cooperation mechanism under the condition of random demand considering the undersupply and oversupply of the express delivery service, and we compare and analyze the revenue sharing contract and risk sharing contract based on equity investment cooperation. Moreover, by using the recent financial report data of several listed express delivery companies in China, we carry out the numerical analysis of the main research conclusions and results and give the analysis and comparison results of relevant visualizations. The research results show that when faced with the stochastic market demand, in the case of comprehensive consideration of undersupply and oversupply of express delivery services, revenue sharing and risk sharing strategies based on the OFP and RSF both have better feasible space than decentralized supply chain of the sharing logistics. When the combined sharing factor approaches 0.5, which means the benefit sharing is evenly distributed, the revenue sharing mechanism and the risk sharing mechanism based on the combined sharing factor are better than those based on the OFP.

There are certain revenue sharing factors that make the supply chain performance under the revenue sharing mechanism very close to or even equal to the overall performance under the centralized supply chain.

In the real e-commerce express operation environment, the market demand of each express delivery company is not only related to the price of the express delivery service of the company but also affected by the service price of other express delivery companies, which is a perturbed type of price-dependent demand structure. At the same time, we should also consider the risk of undersupply and oversupply of express delivery services due to unpredictable market demand or high prediction difficulty and low prediction accuracy. Therefore, an optimization model that comprehensively considers the price disturbance-type stochastic demand and the undersupply and oversupply risk loss will be the key content of the next research process. At the same time, under the premise that scientific decision-making has been formulated, how to carry out gradual practice optimization instead of blindly implementing policies and making one step at a time will be another problem in the following research. Looking to the future, we should have a clearer understanding that most optimization decisions of management science only give the good results that we want to achieve in the end. However, we do not give an implementation strategy of how to reach the end point step by step. In reality, there are too many obstacles to solve the problem at once. Therefore, a step-by-step strategy similar to the “gradient descent method” may have a stronger practical guiding significance (Figure 6).

Appendix

A. Proof of Proposition 1

Solving the first and second derivative of the total revenue decision in turn, they are as follows:

$$\frac{\partial \pi_{sc}^c}{\partial q_i} = -c - 2e \sum_{i=1}^2 q_i + \frac{3q_i^2}{2a} - \frac{q_i}{a} (3a - c_i - v + k) + a - c_i + k,$$

$$\frac{\partial^2 \pi_{sc}^c}{\partial q_i^2} = -2e + \frac{-3(a - q_i) + c_i + v - k}{a} < 0,$$

$$\frac{\partial^2 \pi_{sc}^c}{\partial q_i \partial q_j} = \frac{\partial^2 \pi_{sc}^c}{\partial q_j \partial q_i} = -2e < 0.$$

(A.1)

Furthermore, the solution of the Hesse determinant is

$$\begin{aligned}
H_2 &= \begin{vmatrix} \frac{\partial^2 \pi_{sc}^c}{\partial q_1^2} & \frac{\partial^2 \pi_{sc}^c}{\partial q_1 \partial q_2} \\ \frac{\partial^2 \pi_{sc}^c}{\partial q_2 \partial q_1} & \frac{\partial^2 \pi_{sc}^c}{\partial q_2^2} \end{vmatrix} = \begin{vmatrix} -2e + \frac{-3(a - q_1) + c_1 + v - k}{a} & -2e \\ -2e & -2e + \frac{-3(a - q_2) + c_2 + v - k}{a} \end{vmatrix} \\
&= -2e \times \frac{-3(a - q_1) - 3(a - q_2) + c_1 + c_2 + 2v - 2k}{a} + \frac{-3(a - q_1) + c_1 + v - k}{a} \times \frac{-3(a - q_2) + c_2 + v - k}{a} > 0.
\end{aligned} \tag{A.2}$$

Hence, it is known from $(\partial^2 \pi_{sc}^c / \partial q_i^2) < 0, \forall i = 1$ and 2 and $H_2 > 0$, that the centralized decision function has an optimal solution and satisfies the above first-order conditional expression. The proof of the formula is completed.

B. Proof of Proposition 2

Solving the first and second derivatives of the revenue function of the express delivery company i as follows:

$$\begin{aligned}
\frac{d\pi_i^{d2}}{dq_i} &= \frac{3q_i^2}{2a} - \frac{q_i}{a} (3a - c_i - v + k) \\
&\quad + \left(a - c_i + k - c - 2e \sum_{j=1}^2 q_j \right) - 2eq_i, \\
\frac{d^2 \pi_i^{d2}}{dq_i^2} &= \frac{3q_i}{a} - \frac{1}{a} (3a - c_i - v + k) - 4e \\
&= -\frac{3}{a} (a - q_i) + \frac{c_i + v - k}{a} - 4e < 0.
\end{aligned} \tag{B.1}$$

It could be seen from $(d^2 \pi_i^{d2} / dq_i^2) < 0$ that there is an optimal response function of each express delivery company to the purchase order quantity of other express delivery companies. The optimal decision can be obtained by solving the intersection of these optimal response functions, that is, to say the equilibrium point.

C. Proof of Proposition 3

Firstly, we solve the first and second derivatives of the revenue function of the express delivery company i :

$$\begin{aligned}
\frac{d\pi_i^{\text{ref}}}{dq_i} &= \frac{3q_i^2}{2a} - \frac{q_i}{a} (3a - c_i - v + k) \\
&\quad + \left(a - c_i + k - c - e \sum_{j=1}^2 q_j \right) - eq_i, \\
\frac{d^2 \pi_i^{\text{ref}}}{dq_i^2} &= \frac{3q_i}{a} - \frac{1}{a} (3a - c_i - v + k) - 2e \\
&= -\frac{3}{a} (a - q_i) + \frac{c_i + v - k}{a} - 2e < 0.
\end{aligned} \tag{C.1}$$

It could be known from $(d^2 \pi_i^{\text{ref}} / dq_i^2) < 0$ that there is an optimal response function of each express delivery company to the purchase order quantity of other express delivery companies. It is only required to solve the intersection point of these optimal reaction functions, that is, the equilibrium point, and then, the optimal decision could be obtained.

D. Proof of Proposition 4

Firstly, we solve the first and second derivatives of the revenue function of the express delivery company i :

$$\begin{aligned}
\frac{d\pi_i^{\text{res}}}{dq_i} &= \frac{3q_i^2}{2a} - \frac{q_i}{a} (3a - c_i - v + k) + \left(a - c_i + k - c - 2e \sum_{j=1}^2 q_j \right) - 2eq_i + 2\gamma_i^{\text{res}} e \sum_{j=1}^2 q_j, \\
\frac{d^2 \pi_i^{\text{res}}}{dq_i^2} &= \frac{3q_i}{a} - \frac{1}{a} (3a - c_i - v + k) - 4e + 2\gamma_i^{\text{res}} e = -\frac{3}{a} (a - q_i) + \frac{c_i + v - k}{a} - 4e + 2\gamma_i^{\text{res}} e < 0.
\end{aligned} \tag{D.1}$$

It could be known from $(d^2 \pi_i^{\text{res}} / dq_i^2) < 0$ that there is an optimal response function of each express delivery company to the purchase order quantity of other express delivery

companies. It is only required to solve the intersection point of these optimal reaction functions, that is, the equilibrium point, and the optimal decision can be obtained.

E. Proof of Proposition 5

Firstly, we calculate the first derivative and the second derivative of the revenue function of express company i :

$$\begin{aligned}
 \frac{d\pi_i^{\text{rsf}}}{dq_i} &= -c - 4eq_i + \frac{(3+6e)q_i^2}{2a} - \frac{q_i}{a} (3a - c - c_i - 2eq_j) + a - c_i - 2eq_j \\
 &\quad - \frac{q_j}{(q_i + q_j)^2} \sum_{j=1}^2 \left[\frac{q_j^2}{2a} \left(c - v + k + 2e \sum_{j=1}^2 q_j \right) - kq_j + \frac{ak}{2} \right] \\
 \frac{q_i}{q_i + q_j} &\left[\frac{q_i (c - v + k + 2e \sum_{j=1}^2 q_j)}{a} - k + \frac{e(q_i^2 + q_j^2)}{a} \right], \frac{d^2\pi_i^{\text{rsf}}}{dq_i^2} = \frac{3q_i}{a} - \frac{1}{a} \left(3a - c - c_i - 2e \sum_{j=1}^2 q_j \right) + \frac{4eq_i}{a} - 4e \\
 &\quad - \frac{2q_j \sum_{j=1}^2 q_j}{(q_i + q_j)^4} \sum_{j=1}^2 \left[\frac{q_j^2}{2a} \left(c - v + k + 2e \sum_{j=1}^2 q_j \right) - kq_j + \frac{ak}{2} \right] - \frac{2q_j}{(q_i + q_j)^2} \left[\frac{q_i (c - v + k + 2e \sum_{j=1}^2 q_j)}{a} - k + \frac{e(q_i^2 + q_j^2)}{a} \right] \\
 &\quad - \frac{q_i}{q_i + q_j} \left(\frac{c - v + k + 2e \sum_{j=1}^2 q_j + 4eq_i}{a} \right) < 0.
 \end{aligned} \tag{E.1}$$

It could be known from $(d^2\pi_i^{\text{rsf}}/dq_i^2) < 0$ that there is an optimal response function of each express delivery company to the purchase order quantity of other express delivery companies. It is only required to solve the intersection point of these optimal reaction functions, that is, the equilibrium point, and then, the optimal decision can be obtained.

F. Proof of Proposition 6

Firstly, we solve the first and second derivatives of the revenue function of the express delivery company i :

$$\begin{aligned}
 \frac{d\pi_i^{\text{rss}}}{dq_i} &= -c - 4eq_i + \frac{(3+6e)q_i^2}{2a} - \frac{q_i}{a} (3a - c_i - c - 2eq_j) \\
 &\quad + a - c_i - 2eq_j - \gamma_i^{\text{rss}} \left[\frac{q_i (c - v + k + 2e \sum_{j=1}^2 q_j)}{a} - k + \frac{e(q_i^2 + q_j^2)}{a} \right], \\
 \frac{d^2\pi_i^{\text{rss}}}{dq_i^2} &= \frac{3q_i}{a} - \frac{1}{a} \left(3a - c_i - c - 2e \sum_{j=1}^2 q_j \right) \\
 &\quad + \frac{4eq_i}{a} - 4e - \gamma_i^{\text{rss}} \left(\frac{c - v + k + 2e \sum_{j=1}^2 q_j + 4eq_i}{a} \right) < 0.
 \end{aligned} \tag{F.1}$$

It could be known from $(d^2\pi_i^{\text{rss}}/dq_i^2) < 0$ that there is an optimal response function of each express delivery company to the purchase order quantity of other express delivery

companies. It is only required to solve the intersection point of these optimal reaction functions, that is, the equilibrium point, and the optimal decision can be obtained.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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Research Article

SD Simulation Research on the Green Low-Carbon Development of Coal Enterprises

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The green low-carbon development system of enterprises, differing from the traditional linear system, is a nonlinear feedback system with complex causality. Based on self-organization theory, this study clarified the self-organization evolution logic of the green low-carbon development of coal enterprises and constructed a system dynamics model following a system dynamics method. Through a scenario simulation analysis, the impact of the market environment, environmental regulation, and enterprises' innovation level on the green low-carbon development of coal enterprises was revealed. Applicability suggestions based on simulation results were proposed. The results confirmed that the main challenge for coal enterprises is that the coal market environment restricts the promotion of green low-carbon development level of coal enterprises. Improving innovation levels is the most effective way for coal enterprises to address these issues.

1. Introduction

Since 1980, the concept of sustainable development was first put forward in the World Conservation Strategy jointly published by the International Union for Conservation of Nature (IUCN), the United Nations Environment Programme (UNEP), and the World Wide Fund for Nature (WWF). The Our Common Future report published by the World Commission on Environment and Development (WCED) in 1987 defines sustainable development as development that meets the needs of the present without compromising the ability of future generations to meet their own needs [1]. So far, how to balance the relationship between the economy, society, environment, and energy has become the focus of attention of all countries. In recent years, extreme weather events such as hot summers, droughts, and floods have frequently occurred worldwide. There is evidently an urgent need to address global climate change. In November 2016, the Paris Agreement on Climate Change came into force, and this agreement demonstrates the belief and determination of all countries to deal with climate change. To cope with climate change, green low-

carbon development has become the development trend for all countries in the world [2]. According to the International Energy Agency (IEA)'s global coal market report for 2018–2023, coal still constitutes the core source of fuel in the global energy system, and it still remains the main source of energy in many countries. As a large coal-consuming country, the status of coal as the main source of energy in China is not expected to change in the foreseeable future. Hence, the clean and efficient use of green low-carbon coal development is extremely important, since coal enterprises—as the main bodies of the microeconomy—bear an important responsibility in this area. In recent years, how to better achieve green low-carbon development of coal enterprises in the future has been a key focus of research.

With social development and global environmental change, a series of sustainable development paradigms, such as green economy, green development, circular development, low-carbon economy, and low-carbon development, have been proposed as solutions to address such social and environmental changes. Green development focuses on environmental protection, which is a development model that considers economic development and ecological

environment protection, contemporary economic prosperity, and future generations' development, and at the core of low-carbon development are energy issues, that is, the pursuit of high resource productivity with less resource consumption and less pollution. At present, China not only needs to continue to address the problem of regional environmental pollution but also needs to deal with the global problem of climate change. Therefore, it is of great academic value and practical significance to put forward the concept of green low-carbon development and to study how green low-carbon development can be achieved. This study considers green low-carbon development as an organic combination of green development and low-carbon development. We not only pay attention to the protection of the ecological environment but also take into account resource saving, energy efficiency improvement, and emission reduction. At the same time, this study aims to achieve a coordinated development of economic development, environmental protection, and resource utilization. Its essential goal is to provide a means to achieve the coordinated development of economic development, environmental protection, and resource consumption, and green innovation is important in this regard. The system thought of "the whole is greater than the sum of parts" could provide theoretical support and development ideas for research on the green economy [3]. At the same time, the meaning of coupling includes development and coordination, which not only includes the "quantity expansion" part of system evolution development but also the "quality improvement" part of mutual cooperation and harmonious development among systems [4], which provides a way to evaluate green low-carbon development. Thus, this study uses the system analysis method to analyze the green low-carbon development of coal enterprises and introduces the coupling coordination degree to measure the green low-carbon development level of coal enterprises.

The self-organization theory examines how complex systems automatically evolve from disorder to order, from low-level order to high-level order, and provides ideas for clarifying the logic and mechanism of the green low-carbon development of coal enterprises. Meanwhile, the system dynamics model provides a causal description or structure-oriented model that aims to reproduce the historical behavior of a real system and explain the structural determinants of this behavior [5]. It has special advantages in dealing with complex dynamic feedback systems with nonlinear interactions. The tools of system dynamics can provide a more complete picture of the economics of the growth of a firm and stronger and more general conclusions about the evolution of self-organizing market structures [6]. On the one hand, the system dynamics method can better reflect the causality and action mechanism in the process of green low-carbon development of coal enterprises. On the other hand, through simulation, we can better analyze the impact of the market environment, environmental regulation, and enterprises' innovation level on the green and low-carbon development of coal enterprises. The contributions of this study are as follows: (1) the coupling coordination degree model is introduced to measure the green low-carbon

development level of enterprises with the coupling coordination degree among enterprise economic, environmental, and energy systems, which supplements the existing literature on evaluating the green low-carbon development level of enterprises. (2) Based on the self-organization theory, this study clarifies the green low-carbon development mechanism of enterprises and influencing factors from a systematic perspective. (3) The simulation results show that improving the innovation level and promoting the intelligent construction of coal mines are the most effective ways to achieve sustainable green low-carbon development of coal enterprises.

The remainder of this paper is organized as follows. The second section, following the self-organization theory, clarifies the self-organization evolution logic and action mechanism of the green low-carbon development of coal enterprises, as the basis of system modeling. In the third section, we use the system dynamics method to build a simulation model of the green low-carbon development system of coal enterprises. In the fourth section, the system model is simulated with relevant coal industry data. Through a scenario simulation analysis, this study reveals the impact of market environment, environmental regulation, and enterprises' innovation level on the green low-carbon development of coal enterprises. Finally, based on the simulation results, suggestions for the green low-carbon development of coal enterprises are proposed.

2. Theoretical Logic

The German theoretical physicist Haken first put forward the concept of self-organization. He believed that "if a system is not interfered with by the outside world in the process of acquiring space, time, or functional structure, it is said that the system is self-organized." Here, "not interfered by the outside world" means that the structure or function is not imposed on the system by the outside world, and the outside world acts on the system in a nonspecific manner. Luo proposed that "self-organization refers to the process of things moving towards organization or order through spontaneity [7]." The self-organization theory mainly involves complex system problems [8]. This study holds that the green low-carbon development of coal enterprises refers to a sustainable development method to achieve the coordinated development of environmental performance and economic performance of coal enterprises through technological innovation and other means to improve energy efficiency, reduce energy consumption, and reduce emissions. After the early blind pursuit of economic benefits and extensive mining and operation, coal enterprises have had to abandon the original development mode of "high pollution and high energy consumption" and choose the mode of green low-carbon development to pursue the balanced and coordinated development of economic development and ecological environment. The green low-carbon development system of coal enterprises is a complex system for coal enterprises to enhance their adaptive ability and ensure sustainable development in response to market and environmental changes. In addition, the green low-carbon

development process of coal enterprises is a self-organization process of their green low-carbon development system. It is a process in which the subsystems (economy, environment, energy, etc.) of the green low-carbon development system interact with each other and cause the entire system to evolve from disorder to order through feedback, interaction, and promotion.

First, the green low-carbon development system of coal enterprises is open. Dissipative structure theory requires that the system should be open. Through the exchange of material, information, and energy with the environment, the system introduces negative entropy flow from the outside to offset an increase in its positive entropy and promotes the system to evolve from disorder to order [9]. The openness of the green low-carbon development system of coal enterprises is reflected in that, in the process of this development, the three subsystems frequently exchange material, information, and energy with the external environment, obtain market environment, ecological environment, and government policy information, introduce advanced technology and talent, and offset the positive entropy flow generated in the system. The openness of the green low-carbon development system of coal enterprises is the basic premise to ensure its development from disorder to order. Only by fully opening and grasping the market environment dynamics can the green low-carbon development system of coal enterprises adapt to the environment and not be eliminated by the market and society [10]. Simultaneously, the openness of the system also provides a boost to the orderly development of the system.

Second, the green low-carbon development of coal enterprises is far from being at an equilibrium. When coal enterprises encounter market environment changes (such as coal price fluctuations, supply, and demand structure changes) or environmental policy changes, environmental protection requirements increase, which inevitably introduce new challenges to the environmental benefits and economic development of coal enterprises. To adapt to environmental changes, maintain development, and pursue benefits, coal enterprises must respond, distance themselves from the initial equilibrium state and reallocate resources among subsystems, improve their level of technological innovation, and seek new collaborative development among subsystems. The self-organization process of the green low-carbon development system of coal enterprises is a process in which coal enterprises constantly break the existing balance, distance themselves from the balance state, and then seek a new orderly and stable state in response to environmental changes.

Third, there is a nonlinear mechanism between the internal elements of the green low-carbon development system of coal enterprises. The “order parameters” of this development system derive from the three subsystems of economy, environment, and energy, including the economic situation, environmental situation, and energy situation of coal enterprises. These order parameters compete, cooperate, coordinate, and feed back to each other [11], which promotes the internal subsystems of the green low-carbon development system of coal enterprises to connect and

restrict each other and realize the coupling and coordinated development among subsystems through resource allocation and integration. The interaction between order parameters is nonlinear and is represented by nonlinear equations in the process of system evolution.

Finally, fluctuation is the driving force for the evolution of the green low-carbon development of coal enterprises. On the one hand, the fluctuation in the evolution of this development system derives from the influence of external environmental elements, such as changes in the coal market environment, the coal price, the supply and demand structure, the market science and technology level, government policy changes, and ecological environment changes. These factors will continue to affect the interaction between the various systems of coal enterprises, changing the resource allocation among the subsystems of the coal enterprise, which makes the green low-carbon development system of coal enterprises rise and fall; on the other hand, the fluctuation in the evolution of this development system comes from the influence of the internal innovation level. The coupling and coordinative evolution among the economic, environmental, and energy subsystems of the green low-carbon development internal system of coal enterprises is affected by a system’s innovation level. A change in the innovation level affects the fluctuation of elements of each subsystem and constantly affects the interaction among subsystems, which leads to a change in the collaborative feedback among subsystems. This change also leads to the green low-carbon development internal system of coal enterprises fluctuating, continuously coupling and coordinating evolution, and enhancing the degree of order.

In summary, this study proposes a self-organization system model of green low-carbon development of coal enterprises, as shown in Figure 1.

3. Method, Model, and Data

3.1. System Boundary Analysis. The openness of the green low-carbon development system of coal enterprises ensures that coal enterprises are able to exchange different materials, energy, and information with the external environment, interact with the external environment, and form a certain system boundary. In this study, the system is divided into three subsystems: economic, environment, and energy subsystems. The coupling and coordinated development of the three subsystems is the core of green low-carbon development. Among these, the economic subsystem mainly considers the industrial output value and the number of employees of coal enterprises, the environmental subsystem considers SO₂ emissions and CO₂ emissions per unit output value, and the energy subsystem considers the total energy consumption and energy consumption per unit output value. As the main external factors, government environmental regulation and market environment change affect the role of internal systems. The strengthening of government environmental regulation increases the pressure on the internal environment of enterprises, and enterprises increase the allocation of resources in the environment. At the same

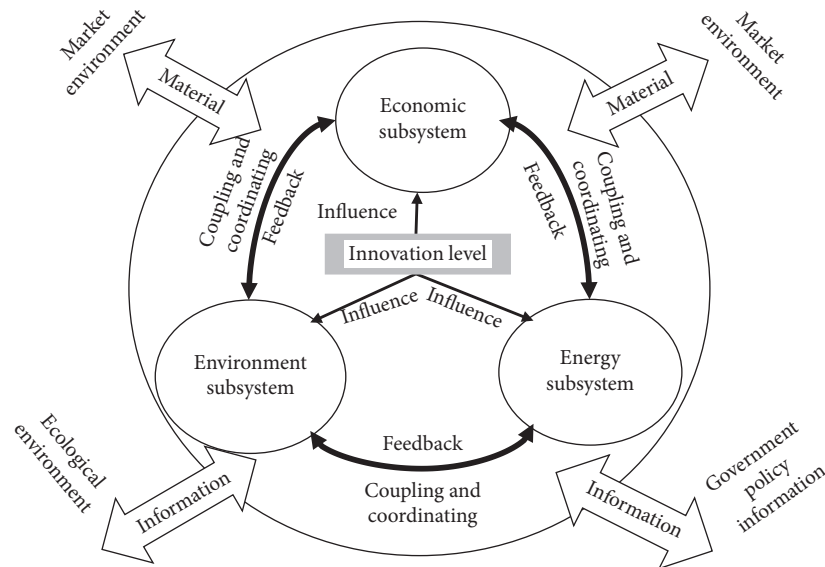


FIGURE 1: Self-organization system model for coal enterprises' green low-carbon development.

time, internal feedback will stimulate enterprises to improve their innovation ability and ensure the coordinated development of the economy and the environment [12]. Changes in the market environment have an impact on the economic development of enterprises. To ensure that enterprises will not be eliminated by the market, improve their core competitiveness, and achieve sustainable development, the internal system must make corresponding responses, the allocation of resource elements among systems should be adjusted, their innovation ability enhanced, and the overall coordination ability of the internal system improved. At the same time, it can be seen that the innovation level within the system is the main influencing factor in this area, which affects the change in the order parameters of the economic, environmental, energy subsystems and, subsequently, the interaction among subsystems.

3.2. Logical Framework of the SD. Model system dynamics (SD) is a methodology and mathematical modeling technique used to frame, understand, and discuss dynamic behaviors and issues of complex systems by setting variables with positive and negative feedback and is integrated by management science and computer simulation technology. Based on the above analysis, the system dynamics causality logical diagram of the green low-carbon development of coal enterprises is constructed, as shown in Figure 2.

3.3. System Stock Flow Chart and Main Equations. According to the causality diagram of the green low-carbon development system of coal enterprises, a stock flow diagram of this system is drawn (as shown in Figure 3). The dynamic stock flow diagram of the system is the basis for the quantitative analysis of dynamic evolution. It is a graphical representation that further distinguishes the properties of variables and uses more intuitive symbols to represent the logical relationship of elements between systems [13]. Considering the quantifiability of variables and the availability and reality of data, this study adjusts and simplifies the causality diagram [14] and generates a stock flow diagram that includes 1 state variable, 1 rate variable, 6 constants, and 27 auxiliary variables. Among these, coupling coordination degree is an important observation variable, which shows the coupling coordination level of the system, that is, the green low-carbon development level of coal enterprises. Market impact factor, enterprise R&D investment intensity, and environmental regulation intensity are the important adjustment parameters of the system. By adjusting these parameters, the scenario observation system is set, and the auxiliary variables of industrial output value, number of employees, CO₂ emissions per unit output value, SO₂ emissions, total energy consumption, and energy consumption per unit output value of coal enterprises are the representative indexes of the economic, environmental, and energy conditions. The main equations in this study are as follows:

Cumulative number of patent applications = INTEG (Annual increase of patent application, 375),

Industrial output value of coal enterprises = Market impact factor * (394226 * Coal price + 11898.5

$$* \text{Cumulative number of patent applications} - 1.115e + 08), \quad R^2 = 0.879,$$

Environmental protection investment = Investment intensity of environmental protection

$$* (1.75e - 05 * \text{Industrial output value of coal enterprises} - 0.038 * \text{Gap delay} + 7883.38),$$

R&D investment = (0.005 * Industrial output value of coal enterprises + 33.233)

$$* \text{Enterprise R\&D investment intensity} \quad R^2 = 0.9239,$$

SO₂ emissions = -11.293 * Environmental protection investment - 0.461

$$* \text{Cumulative number of patent applications} + 243769,$$

SO₂ emissions gap = -11.293 * Environmental protection investment - 0.461

$$* \text{Cumulative number of patent applications} + 243769,$$

Gap delay = DELAY FIXED (SO₂ emissions gap, 1, 25000),

CO₂ emissions = Coal consumption * CO₂ emission coefficient of coal + Electricity consumption

$$* \text{CO}_2 \text{ emission coefficient of electricity},$$

$$\text{CO}_2 \text{ emissions per unit output value} = \frac{\text{CO}_2 \text{ emissions}}{\text{Industrial output value of coal enterprises}},$$

Total energy consumption = Coal consumption + Electricity consumption,

$$\text{Energy consumption per unit output value} = \frac{\text{Total energy consumption}}{\text{Industrial output value of coal enterprises}},$$

Coal price = with lookup ([(2006, 400) - (2020, 900)], (2006, 426.73), (2007, 465.59), (2008, 729),

(2009, 600.2) (2010, 745.2), (2011, 822), (2012, 706.3), (2013, 591),

((2014, 516.7) (2015, 516.73), (2016, 473.9), (2017, 639.5), (2018, 639.53), (2019, 593), (2020, 570),

$$\text{Coupling degree} = \frac{27 * \text{Energy situation} * \text{Economic situation} * \text{Environmental situation}}{(\text{Environmental situation} + \text{Economic situation} + \text{Energy situation})^3},$$

$$\text{Coordination degree} = \frac{(\text{Environmental situation} + \text{Economic situation} + \text{Energy situation})}{3},$$

$$\text{Coupling coordination degree} = (\text{Coordination degree} * \text{Coupling degree})^{1/2},$$

$$\text{Standardization of variable } x_i: x'_i = \begin{cases} \frac{\max(x_i) - x_i}{\max(x_i) - \min(x_i)}, & x_i \text{ has negative effect,} \\ \frac{x_i - \min(x_i)}{\max(x_i) - \min(x_i)}, & x_i \text{ has positive effect,} \end{cases}$$

Economic situation = 0.5 * Standardization of the number of employees + 0.5

$$* \text{Standardization of industry output value of coal},$$

Environmental situation = 0.5 * Standardization SO₂ emission + 0.5

$$* \text{Standardization of CO}_2 \text{ emissions per unit output value},$$

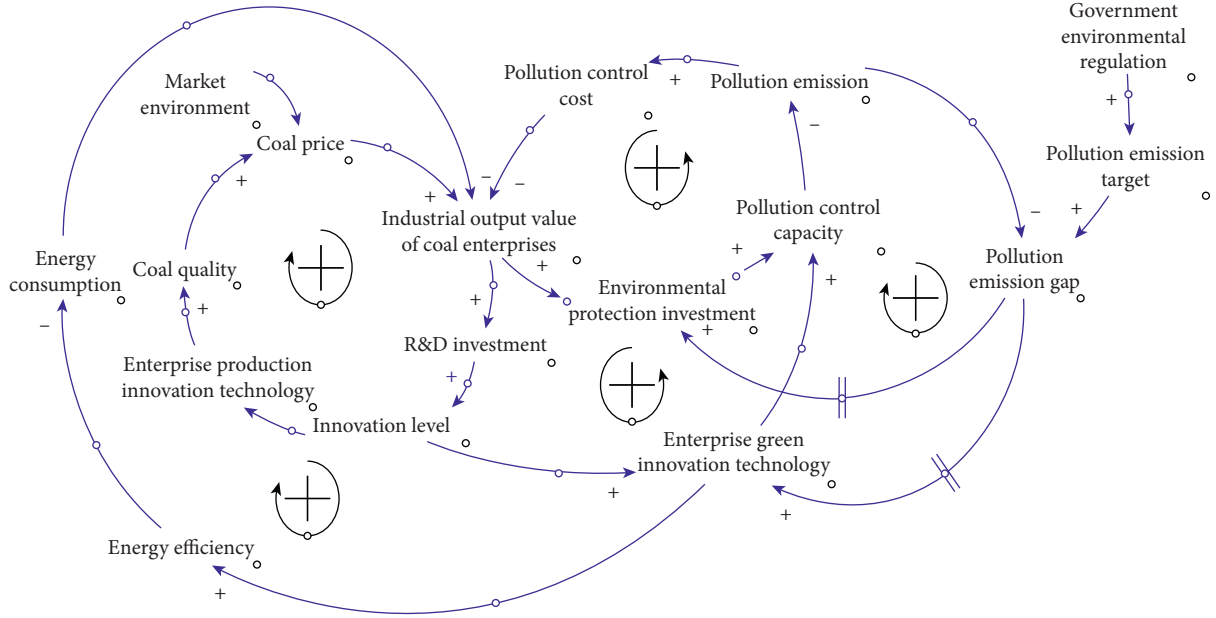


FIGURE 2: Logical framework of the SD model.

$$\text{Energy situation} = 0.5 * \text{Standardization of total energy consumption} + 0.5$$

$$* \text{Standardization of energy consumption per unit output value,}$$

$$\text{CO}_2 \text{ emission coefficient of electricity} = 1.3203,$$

$$\text{CO}_2 \text{ emission coefficient of coal} = 1.9003.$$

(1)

3.4. Data Sources. The data used in this study has been sourced principally from statistical yearbooks such as the China Statistical Yearbook, the China Industrial Statistical Yearbook, the China Environmental Statistical Yearbook, the China Science and Technology Statistical Yearbook, and the China Energy Statistical Yearbook, among others. This study also refers to a number of government planning documents and reports. For example, the emission targets of SO₂ in our study are sourced from the “11th Five-Year Plan,” the “12th Five-Year Plan,” and the “13th Five-Year Plan.” Meanwhile, the CO₂ emission coefficients of coal and electricity are sourced from the guidelines of the Intergovernmental Panel on Climate Change. The relationship and equation of the variables in our model have been mainly determined using a regression analysis and table function. The trend extrapolation method has been used to supplement the missing values. The application of the table function effectively deals with nonlinear relationships. The parameters in the model are set according to the principle of real data and reasonable inference. The initial value is set based on actual data from 2006. To simplify the model parameters, the model takes the variables that are used to adjust and control the scenario setting as constants, such as market influence factor, enterprise R&D investment intensity, and environmental regulation intensity. At the same time, to reduce the error between the simulation results and

historical data as much as possible, some parameters are adjusted in the process of model calibration.

4. Model Checking

System dynamics modeling seeks to solve problems in analyses through a system analysis and scenario simulation. The effectiveness of a system determines the applicability of a model [15]. Therefore, to ensure the correctness, rationality, and effectiveness of the model, it is necessary to verify the validity of the model before it is applied in a simulation. The commonly used methods of system dynamics model testing include applicability tests, consistency analyses, historical value tests [16], function tests, structural tests [17], extreme value tests [18], and sensitivity tests [19]. Historical value and sensitivity tests are commonly used test methods. In this study, the validity of the model is tested using a historical value test and a sensitivity test.

4.1. Historical Value Testing. SO₂ emission is an important indicator of the environmental status of coal enterprises. In this study, comparing the real value with the simulated value from 2006 to 2015, SO₂ emission can be used to test the robustness of the model. The results from our related analysis are shown in Table 1, which shows that the error rate

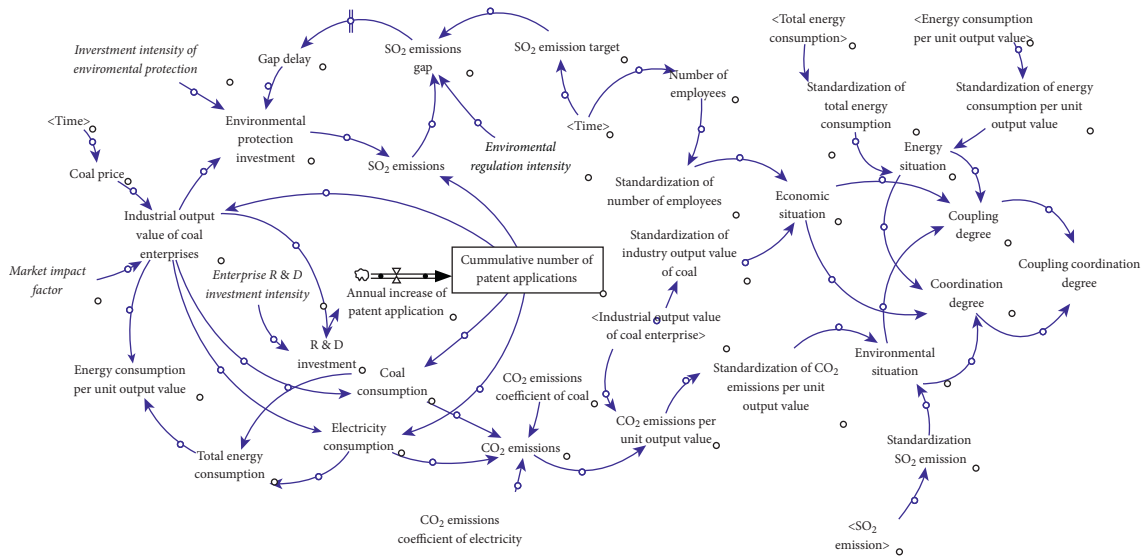


FIGURE 3: Stock flow chart of the green low-carbon development system of coal enterprises.

between the simulation value and the real value is within 10%, and the average error is 1.98%, which is within the acceptable error range. Therefore, the model established in this study has passed the test of the historical value and can reflect the real situation of the green low-carbon development system of coal enterprises.

4.2. Sensitivity Testing. Sensitivity testing is used to test the sensitivity of a system to parameter adjustment by changing the values of some parameters in the model to observe the changes in the operation results of the model. According to the green low-carbon development system model of coal enterprises constructed in this study, combined with the model construction logic mentioned above, enterprises' innovation level (cumulative number of patent applications) has an important impact on the economy, environment, and energy system, and the enterprise R&D (research and development) investment intensity has a direct impact on the innovation level. Therefore, this study selects enterprise R&D investment intensity as a test variable to evaluate the sensitivity of SO₂ emission, industrial output value of coal enterprises, CO₂ emission per unit output value, and energy consumption per unit output value on the change in the R&D investment intensity of enterprises. The R&D investment intensity parameter is adjusted from 1 to 1.2 and then reduced to 0.8. The simulation results are shown in Figure 4. It can be seen that when the R&D investment intensity increases (reduces), the innovation level improves (reduced), and the trend of SO₂ emission, industrial output value of coal enterprises, energy consumption per unit output value, and CO₂ emission per unit output value over time is consistent with that under the original scenario, but the range of decrease of SO₂ emission, energy consumption per unit output value, and CO₂ emission per unit output value becomes larger (smaller), and the range of increase of the industrial output value of coal enterprises also becomes larger (smaller). Therefore, the model conforms to reality

and theoretical logic and has no strict requirements for parameters. It has passed the sensitivity test and is suitable for application as our actual model.

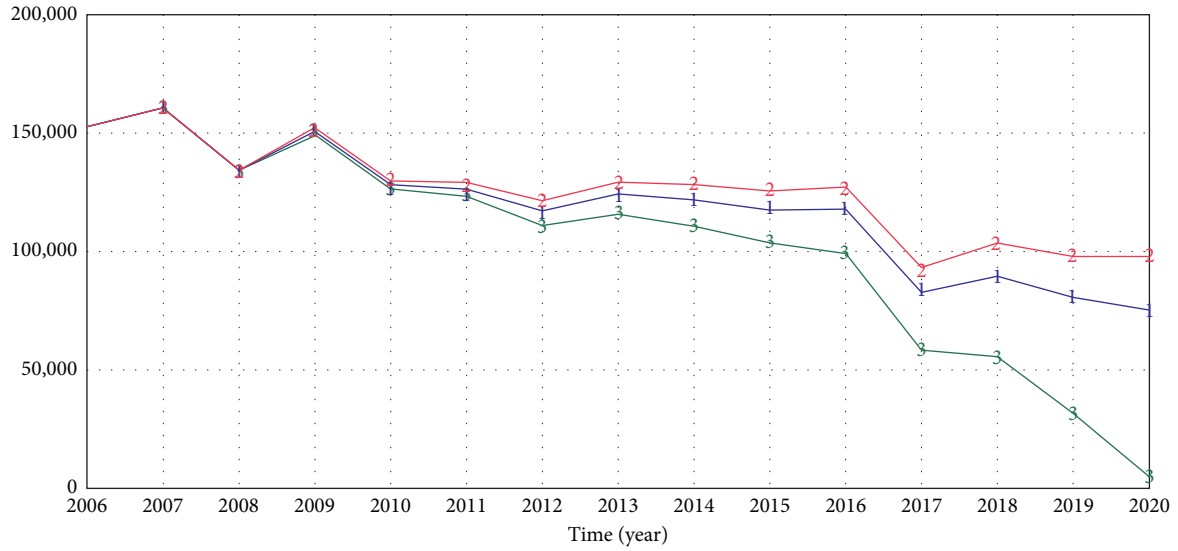
5. Results and Analysis

5.1. Scenario Design. A scenario analysis can describe the development direction of research objects through different scenarios [20], which has become a common method for providing evidence and analyzing development planning investment, especially with regards to low-carbon development and different green economy strategies [21]. The purpose of this study is to analyze the impact of internal and external factors on the green low-carbon development of coal enterprises and the path of green low-carbon development of these enterprises by building a system model of this development. Based on the theoretical analysis of the previous model, mainly considering the impact of the market environment, government environmental regulation, and enterprise innovation level, six scenarios (as shown in Table 2) are formed by adjusting the setting of the three parameters of market influence factor, environmental regulation intensity, and enterprise R&D investment intensity. By observing the corresponding changes in an enterprise's economic situation, environmental situation, energy situation, and coupling coordination degree under different situations, the influence of different influencing factors can be analyzed to provide a decision-making reference for the future green and low-carbon development path of coal enterprises.

In our analysis, the “original scenario” refers to a parameter setting based on the actual real-world situation, which reflects the trend of the green low-carbon development of coal enterprises based on historical situations. Scenarios 1 to 3 adjust a single parameter to reflect the impact of the market environment, government environmental regulation, and enterprise innovation level on the green low-carbon development of coal enterprises.

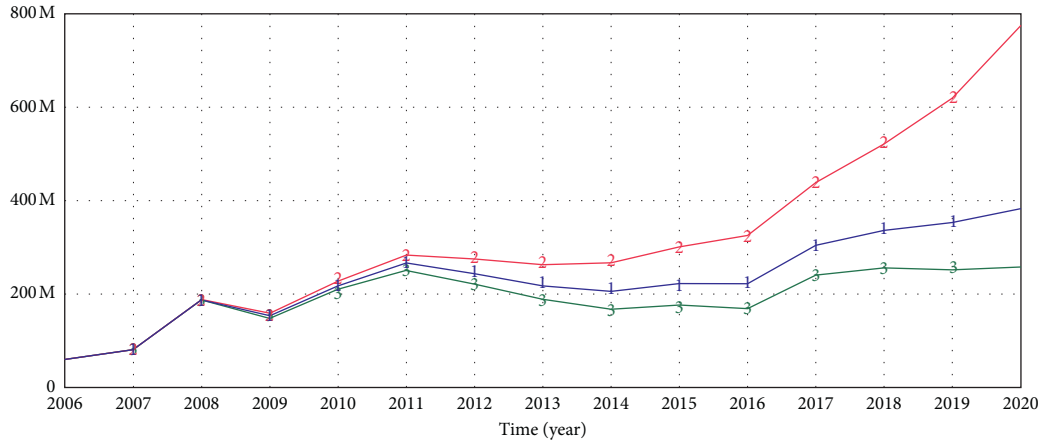
TABLE 1: Historical value testing.

| Year | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 |
|-----------------|---------|--------|--------|---------|--------|--------|--------|--------|---------|---------|
| Real value | 145000 | 175300 | 148700 | 149861 | 160255 | 129254 | 124866 | 126231 | 114320 | 105000 |
| Simulated value | 153205 | 161213 | 134311 | 150901 | 148430 | 126336 | 117049 | 124041 | 121678 | 107923 |
| Error rate | -0.0566 | 0.0804 | 0.0968 | -0.0069 | 0.0739 | 0.0226 | 0.0626 | 0.0173 | -0.0644 | -0.0278 |
| Average error | 0.0198 | | | | | | | | | |



— SO₂ emissions: sensitivity test-original
— SO₂ emissions: sensitivity test-reduced R & D investment intensity
— SO₂ emissions: sensitivity test-increased R & D investment intensity

(a)



— Industrial output value of coal enterprises: sensitivity test-original
— Industrial output value of coal enterprises: sensitivity test-increased R & D investment intensity
— Industrial output value of coal enterprises: sensitivity test-reduced R & D investment intensity

(b)

FIGURE 4: Continued.

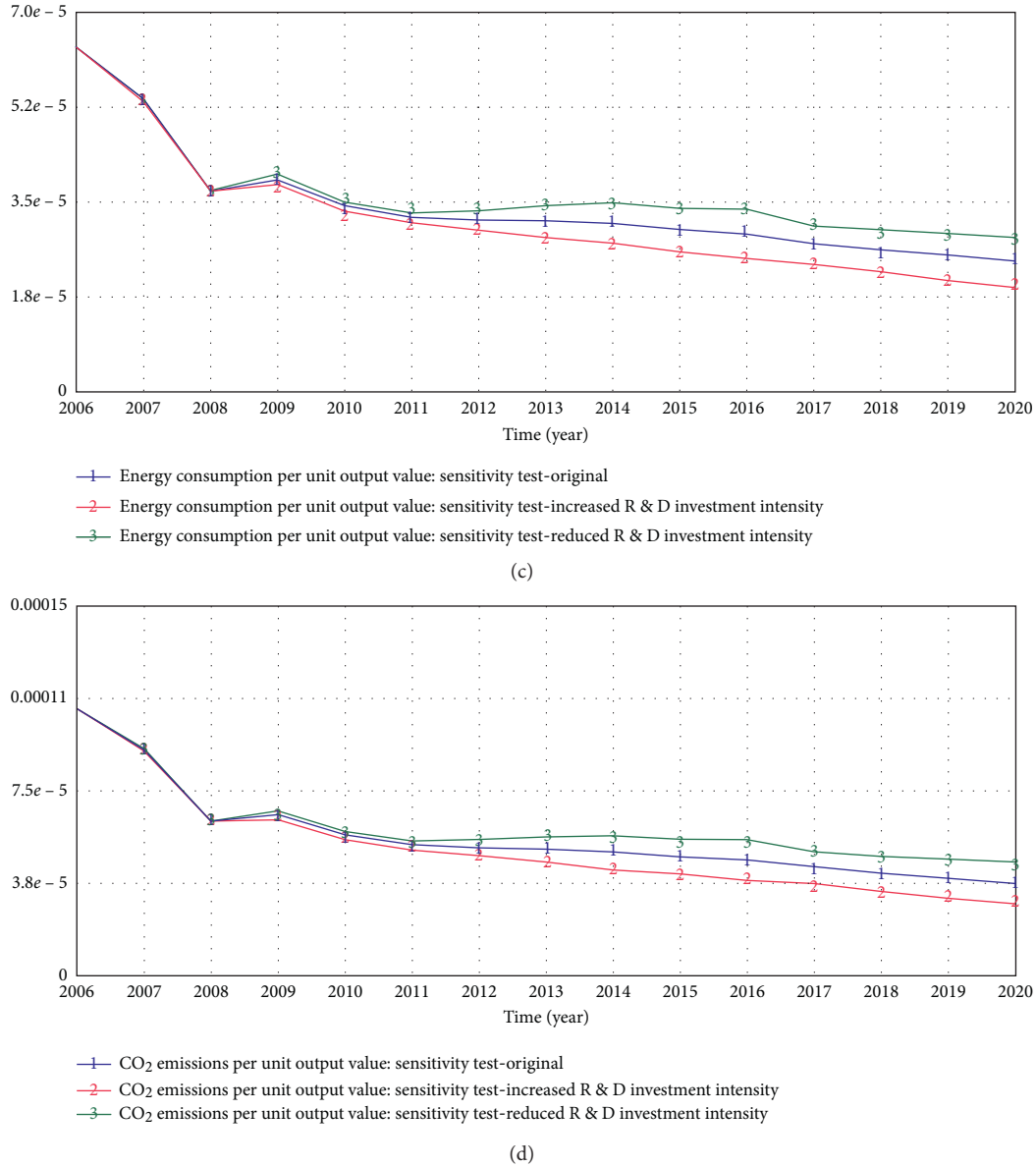


FIGURE 4: Parameter sensitivity test results. (a) CO₂ emission. (b) Industrial output value of coal enterprises. (c) Energy consumption per unit output value. (d) CO₂ emission per unit output value.

TABLE 2: Scenario analysis parameter setting table.

| Parameter | Original scenario | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 | Scenario 6 |
|-------------------------------------|-------------------|------------|------------|------------|------------|------------|------------|
| Market influence factor | 1 | 1.1 | 1 | 1 | 1.1 | 1 | 0.9 |
| Environmental regulation intensity | 1 | 1 | 1.2 | 1 | 1.2 | 1.2 | 1 |
| Enterprise R&D investment intensity | 1 | 1 | 1 | 1.2 | 1 | 1.2 | 1.4 |

Scenarios 4 to 6 adjust multiple parameters simultaneously to reflect the comprehensive impact of the market environment, government environmental regulation, and enterprise innovation level on the green low-carbon development of coal enterprises. Scenario 4 discusses whether strengthening environmental regulations would benefit the green low-carbon development of coal enterprises if the market environment is slightly warmer.

Scenario 5 discusses whether the market environment remaining unchanged as well as environmental regulations being strengthened and the level of enterprises' innovation being improved will produce better results. Scenario 6 discusses whether adjusting the intensity of R&D investment can improve the green low-carbon development of coal enterprises if the market environment further deteriorates.

5.2. Scenario Simulation Results and Analysis

5.2.1. Original Scenario Analysis. Figure 5 shows the trend in changes regarding the green low-carbon development of coal enterprises under the original scenario, that is, the trend in changes of the coupling coordination degree, economic situation, energy situation, and environmental situation. The economic situation of coal enterprises shows a trend of growth first and then decline. Before 2012, it grew each year and then declined rapidly from 2012 to 2016. After 2016, it still showed a downward trend, but the speed of decline slowed down. The environmental situation of coal enterprises is improving and essentially shows a trend of increasing each year. The energy situation experienced a short-term rapid growth from 2006 to 2008, reached a good level, and then showed a steady development trend. The green low-carbon development level of coal enterprises (coupling coordination degree) experienced a rapid improvement stage before 2013, and then began to decline after 2013. This is mainly affected by the environment of China's coal industry. Before 2013, China's coal industry experienced a "golden decade" in which the demand for coal surged, coal prices soared, and coal enterprises made huge profits. However, due to the slowdown in the demand for coal and the impact of imported coal, China's coal market stagnated overall after 2013, and the economy of coal enterprises has been seriously damaged. After the 18th National Congress of the Communist Party of China, the coal industry carried out structural reforms on the supply side, solved the excess capacity, and merged and reorganized large coal enterprises. As a result, the coal market gradually changed from oversupply to a supply-demand balance. The coal market gradually recovered, and the economic benefits of enterprises improved. On the contrary, environmental constraints have been strengthened further, the environmental situation of coal enterprises is steadily improving, and energy consumption is stable. Hence, while the green low-carbon development level of coal enterprises has entered a declining stage since 2013, it has not decreased significantly. The change in the economic benefits of coal enterprises caused by the change of the market environment and the intensity of government environmental regulations will have an impact on the green low-carbon development level of coal enterprises. At present, how to further activate the coal industry and promote its high-quality development as well as how to seek a self-development mode in a dynamic environment remain as top priorities.

5.2.2. Scenario Analysis under Single Factor Influence. Figure 6 shows a comparison of the green low-carbon development levels of coal enterprises under the original scenario and Scenarios 1, 2, and 3. At the beginning of 2016, the Chinese State Council issued the "Opinions on Resolving Overcapacity and Realizing the Development of the Coal Industry," which clarified the direction of reform for the coal industry. Following the implementation of coal capacity reduction reforms, the coal market slowly warmed up. Scenario 1 raised the market impact factor to 1.1, aiming to

simulate change in the green low-carbon development level of coal enterprises under the situation that the coal market turned better, coal prices rose, and the economic benefits of coal enterprises improved; to cope with climate change, environmental pollution and greenhouse gas emissions are still long-term tasks for China. In the second scenario, the intensity of environmental regulation increased to 1.2, which is intended to simulate change in the green low-carbon development level of coal enterprises under the situation of further strengthening environmental regulation, and as an important factor in the system, the change in enterprises' innovation level will have an important impact on the three subsystems. Scenario 3 increases the enterprise R&D investment intensity to 1.2, which aims to simulate the impact of further increasing R&D investment and improving innovation levels on the green low-carbon development of coal enterprises. The three scenarios have a positive effect on the green low-carbon development level of coal enterprises. Under Scenario 3, the green low-carbon development level of coal enterprises is the highest, that is, to strengthen the R&D investment of coal enterprises and improve their innovation level, which is the most effective path for the green low-carbon development of coal enterprises. The level of green low-carbon development of coal enterprises takes second place under Scenario 1. The economic benefit of coal enterprises is an important factor that affects this development, and the sustainable profit of coal enterprises is a necessary condition for the sustainable development of coal enterprises. Scenario 2 improves the intensity of environmental regulation. Although it can promote the level of green low-carbon development of coal enterprises, the effect is very small. This is mainly because environmental regulations have not been relaxed in recent years, and the environmental conditions of enterprises are improving. Excessive environmental regulation would increase the costs of enterprises. The development level of green low-carbon coal enterprises is mainly affected by the economic situation. This is also illustrated by the trend of the economic situation and environmental situation in Figure 5.

5.2.3. Scenario Analysis under Mixed Factor Influence. Figure 7 shows the changes in the coupling coordination degree under the original scenario and Scenarios 4 to 6. It can be seen from Figure 7 that Scenarios 4 to 6 all improve the green low-carbon development level of coal enterprises. From the overall changes in the past 15 years, the effect of Scenario 4 is not good in the late stage; however, on the contrary, the effect of Scenario 6 is more sustainable. This shows that appropriate environmental regulations would be conducive to the green low-carbon development of coal enterprises, but are not the most stable way in the long-term. Development that is innovation driven is the most effective way to promote the sustainable development of enterprises. Compared with the original scenario, Scenarios 4 to 6 have a positive effect, but what combination would be more conducive to the green low-carbon development of coal enterprises is a question. To answer this, we need to further compare the results of single-factor and mixed-factor

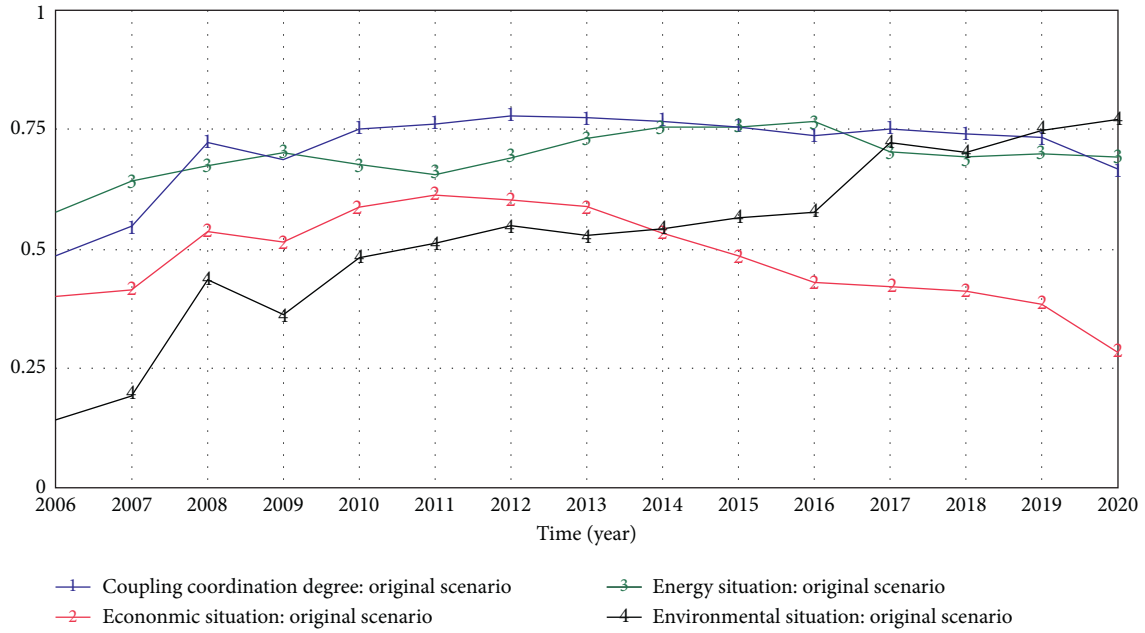


FIGURE 5: Green low-carbon development of coal enterprises under the original scenario.

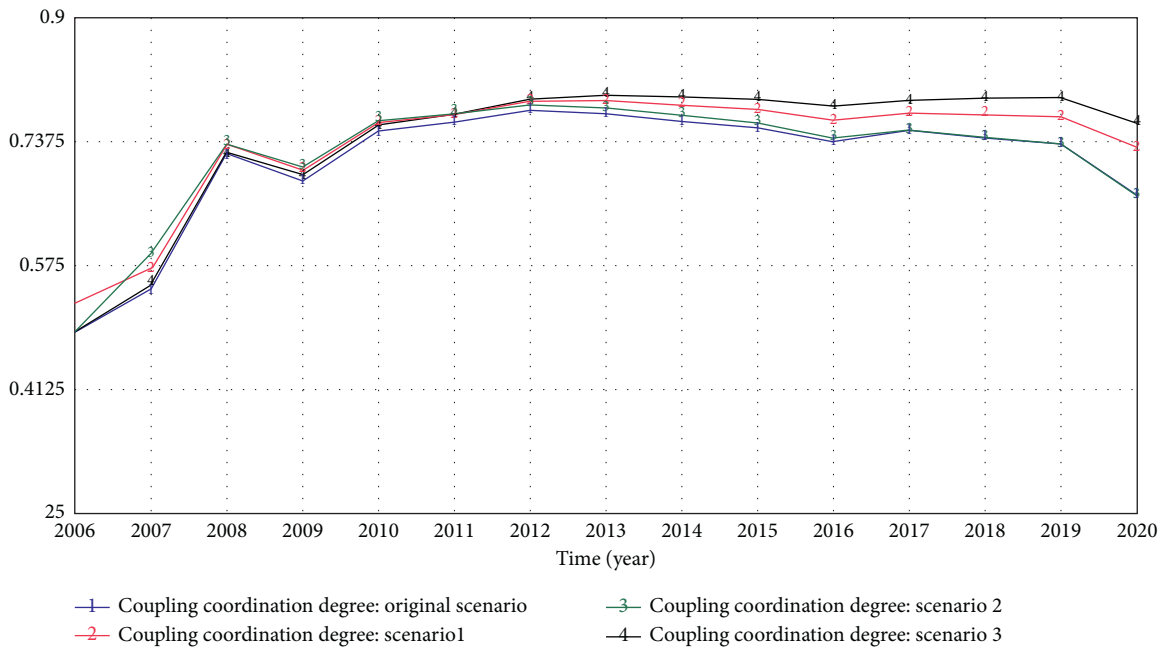


FIGURE 6: Influence of single factor change on the green low-carbon development level of coal enterprises.

impacts. Figure 8 shows the operation results for Scenarios 1 to 6. Comparing Scenario 1 with Scenario 4, the latter enhances environmental regulation intensity based on the former. By comparing the two scenarios, we explore whether strengthening environmental regulations would benefit the green low-carbon development of coal enterprises if the economic benefits of coal enterprises improve. The results we obtained show that Scenario 4 results in a better effect than Scenario 1 before 2015. However, after 2015, strengthening environmental regulations had little effect. Properly strengthening the intensity of environmental

regulations would be conducive to the green low-carbon development of coal enterprises. Excessive intensity of environmental regulations cannot produce positive effects. Comparing Scenario 5 with Scenarios 2 and 3, Scenario 5 evidently leads to the greatest improvement in the green low-carbon development level of coal enterprises, followed by Scenario 3 and Scenario 2. Organic combination of appropriate environmental regulation and innovation drive can better promote the green low-carbon development level of coal enterprises. Comparing Scenario 6 with other scenarios, although affected by the bad market environment at

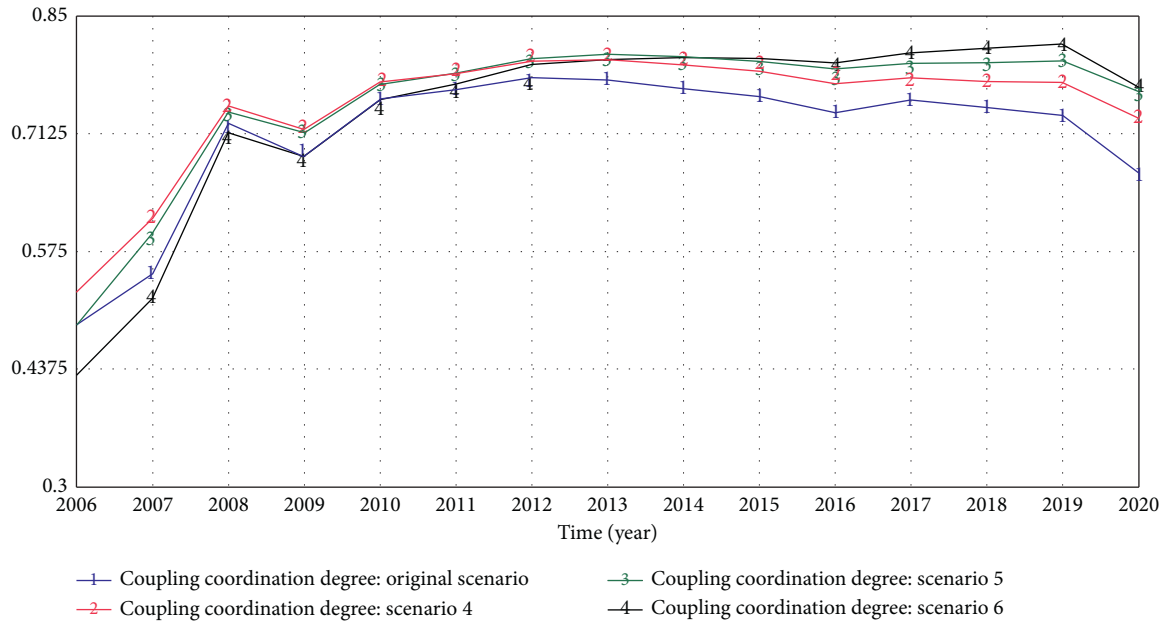


FIGURE 7: Influence of mixed factor change on the green low-carbon development level of coal enterprises.

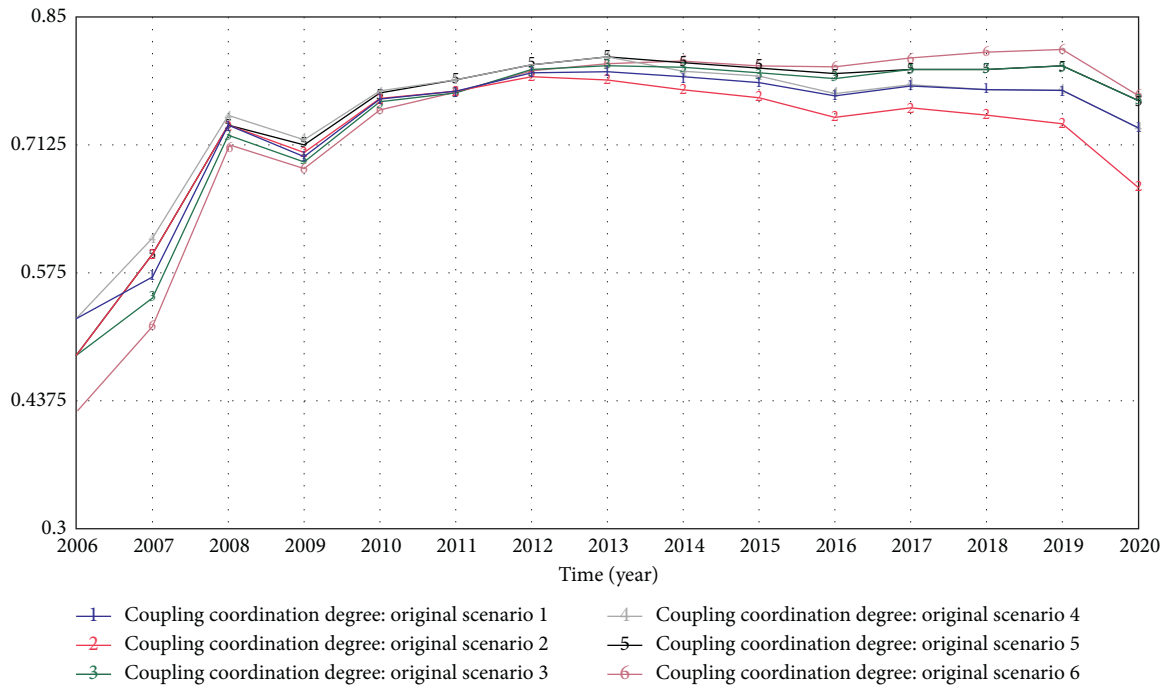


FIGURE 8: Green low-carbon development level of coal enterprises under Scenarios 1 to 6.

the beginning, the green low-carbon development level of coal enterprises under Scenario 6 had been at the lowest level before 2012; however, its development trend was essentially on the increasing trend. Since 2012, the trend under this scenario gradually surpassed other scenarios, and after 2015, the green low-carbon development level has been higher than the other scenarios, which shows that even when the coal market environment is depressed and the economy of coal enterprises is damaged, coal enterprises can drive the development of enterprises with

innovation, and by vigorously improving the level of innovation, the enterprise can reverse the scenario and realize sustainable development.

In summary, the market environment, appropriate government regulation, and enterprises' innovation level have a positive impact on the level of green low-carbon development of enterprises. The effect intensity of the enterprise innovation level is higher than that of market factors and higher than that of government environmental regulation. The organic combination of appropriate government

environmental regulation and development that is innovation-driven would better promote the green low-carbon development of coal enterprises, which is an effective way for the sustainable development of coal enterprises.

6. Conclusions and Suggestions

Based on the self-organization theory, this study clarifies the self-organization evolution logic of green low-carbon development of coal enterprises and proposes that this development is affected by the external market environment, environmental regulations, and the enterprises' internal innovation level. The system simulation model of green low-carbon development of coal enterprises is constructed using the system dynamics method, which is simulated using the relevant data of the coal industry from 2006 to 2015. This study reveals the influence of the market environment, environmental regulation, and enterprises' innovation level on the green low-carbon development of coal enterprises through a scenario simulation analysis and attempts to put forward applicable suggestions for the green low-carbon development of coal enterprises based on the simulation results. Based on the scenario simulation results regarding system dynamics, the following conclusions and suggestions are drawn.

- (1) The coal market environment restricts the level of green low-carbon development of coal enterprises and is still the main challenge faced by coal enterprises.

After experiencing its "golden decade," China's coal market entered a historic turning point in 2013. Affected by the slowdown of economic growth, energy reforms, and impact of imported coal, the demand for coal dropped sharply, a surplus in the supply capacity occurred, the relationship between supply and demand became unbalanced, and coal prices fell, reaching a significantly low level in 2015. A large number of coal enterprises were deeply mired in difficult situations, and the economic benefits of coal enterprises were seriously damaged. In 2016, the State Council issued the "Opinions on Resolving Excess Capacity in the Coal Industry and Realizing the Development Out of Poverty," which combined actively and steadily resolving excess capacity with structural adjustment, transformation, and upgrading, and helped the coal industry reverse the deficit, eliminate difficulties, upgrade, and engage in healthy development. These actions achieved good results. The business landscape is gradually recovering, and the economic benefits of coal enterprises are gradually improving; nevertheless, the landscape has still not fully recovered, which is consistent with the simulation results of the original scenario in this study. At the same time, we found that China's coal enterprises are greatly affected by fluctuations in the coal market. When the coal market declines, the economic benefits of coal enterprises decline or they

even lose money. The core competitiveness and sustainable development mechanism needed to counter market turbulence has yet to be formed. Hence, coal enterprises should further explore the mechanism of sustainable development, and the formation of core competitiveness should be the focus of future development.

- (2) Appropriate environmental regulations can promote the green low-carbon development of coal enterprises.

The results of our scenario simulation show that appropriate environmental regulations may further improve the environmental conditions of coal enterprises and, subsequently, the level of their green low-carbon development. However, if the economic situation of coal enterprises is poor, excessive environmental regulations may burden enterprises, which would curb their green low-carbon development. However, in the current and foreseeable future, the dominant position and ballast role of coal in China's energy system is not expected to change significantly, and the pressure of ecological environmental protection is expected to increase further. Strengthening environmental regulations is inevitable. Hence, coal enterprises should further explore ways to balance the environment and economy to realize green mining and clean, efficient, and intensive utilization.

- (3) Improving the level of innovation is the most effective way for coal enterprises to improve the level of green and low-carbon development.

Innovation has always been the most effective way for enterprises to enhance their core competitiveness. For coal enterprises, green innovation may effectively promote these enterprises' green low-carbon development. As the results of our scenario simulation show, even if the market environment further deteriorates, coal enterprises can reverse this trend through innovation. Hence, coal enterprises should put green innovation in the core position of green low-carbon development, increase R&D investment, increase the introduction of talent, improve the level of scientific and technological innovation, improve production efficiency through science and technology, produce high-quality coal, eliminate backward production capacity, develop advanced production capacity, promote the high-quality development of coal enterprises, and replace the development mode of high yield and low efficiency with high quality and high efficiency. As information technology has evolved, digital media have become increasingly fragmented and have started to proliferate multiple information channels [22]. Through breakthrough innovation, it will promote the intelligent and information construction of coal mines, form a safe green and efficient intelligent mine technology system, and realize the

safe and efficient intelligent production of coal. At the same time, through the innovation of system and mechanism, the transformation and upgrading of enterprises should be accelerated, the efficiency of resource allocation improved, and the green low-carbon sustainable development of coal enterprises promoted.

Data Availability

The data that support the findings of this study are openly available in China Industrial Statistical Yearbook, China Environmental Statistical Yearbook, China Science and Technology Statistical Yearbook, and China Energy Statistical Yearbook (<https://data.cnki.net/Yearbook/>).

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

China's New Environmental Protection Law and Green Innovation: Evidence from Prefecture-Level Cities

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This paper examines the impact of China's new environmental protection law on green innovation. Using a large sample of Chinese prefecture-level cities for the 2010–2016 period and the difference-in-differences (DID) methodology, we provide strong evidence that the new environmental protection law promotes green innovation. This finding is robust to a battery of sensitivity tests. The micromechanism analysis shows that the new environmental protection law can promote green innovation by imposing stricter financial constraints on enterprises in high-pollution industries and increasing their incentives for green innovation to meet green credit requirements. Further, we find that the impact of the new environmental protection law on green innovation is more prominent in prefecture-level cities with a lower level of banking competition and for prefecture-level cities with stronger intellectual property protection. Overall, these findings suggest that the new environmental protection law has played an important role in promoting green innovation in China. To improve the effect of the new environmental protection law on green innovation, the government can consider lowering banking competition and strengthening intellectual property protection.

1. Introduction

Although China has embraced rapid economic development in the past 40 years, the country also faces serious environmental issues, causing great losses in resident health and economic benefits [1, 2]. For example, according to the State of Global Air Report 2019, 425 million people were exposed to household air pollution, and 1.2 million Chinese people lost their lives due to air pollution in 2017 (<https://www.stateofglobalair.org/>). Reducing environmental pollution is receiving increasing attention from policymakers and the academic community [3–9].

Recently, various studies have focused on agricultural and industrial sectors for the estimation of resources and environmental protection [10–15]. Similarly, some studies have determined the environmental performance of the industrial sector [16–21]. In addition, scholars have examined the effect of environmental regulations on environmental protection [6–9]. However, green innovation is regarded as the key to resolving environmental issues

[22, 23]. Green innovation refers to hardware or software innovations related to green products or processes, including technological innovations involved in energy conservation, waste recycling, pollution prevention, green product design, and environmental management, leading to the coordination of economic development and environmental protection [24].

Previous studies have found that environmental regulations play an important role in green innovation [25–29]. For example, using data on five manufacturing sectors in the European Union from 1996 to 2007, Costantini and Mazzanti tested the Porter hypothesis and found that environmental policies can promote environmental innovation efforts and foster green exports [26]. Shen et al. tested the impact of different environmental policies on regional green innovation and found that pollution charges can promote green innovation and that, in general, carbon emissions trading has an insignificant effect on green innovation in provinces [27]. Calel and Antoine examined the impact of the European Union Emissions Trade Scheme on

technological change and noted that environmental policy has a limited impact on low-carbon patents [28]. Using publicly listed firms in China from 2003 to 2015, Cui et al. investigated whether carbon emissions trading in China had affected low-carbon innovation and found that the policy had a significant and positive impact on low-carbon innovation [29]. Although these studies examined the effects of different government regulations on green innovation, we know little about whether the environmental protection law, the most critical environmental regulation, has a positive impact on green innovation. The new environmental protection law in China provides a chance to investigate this issue.

China enacted its environmental protection law, which contains 6 chapters and 47 articles, in 1989. Although the environmental protection law was issued, environmental protection was weak in China because China's top priority was economic development [30]. The government, without prioritizing environmental protection, allowed extensive economic growth to dominate China's economy. Consequently, China now faces more serious environmental pollution issues, thus causing considerable losses to human health. Environmental protection became increasingly important to Chinese economic development, causing the government to revise its environmental protection law.

Revisions to the environmental protection law were proposed from 1995 to 2011. The Chinese government decided to revise the environmental protection law in 2011. The first draft issued by China's National People's Congress (NPC) Standing Committee encountered resistance and was not passed because it only included minor amendments (the draft followed a "limited revision" principle, and many internationally established practices and concepts, such as sustainable development, strategic environmental impact assessment, market-based instruments, environmental rights and interests, and public litigation, were not included). The 18th CPC National Congress in 2012 emphasized ecological civilization as the basic direction of national construction, which promoted the revision of the environmental law. The second draft and third draft were submitted after consulting from experts, scholars, local environmental protection departments, entrepreneurs, and other environmental interest groups in 2013. Finally, the NPC Standing Committee passed the revised law in 2014, and the new environmental protection law went into effect on January 1, 2015. The new environmental protection law includes 7 chapters and 70 articles, which represent major revisions of those in the previous environmental protection law [30, 31] and have had a substantial effect on Chinese environmental protection.

The effect of the new environmental protection law on economic society has attracted attention from scholars [30, 32–34]. For example, Zhang et al. reviewed the enactment of the new environmental protection law and pointed out some problems with it [30]. Liu et al. showed that the new environmental protection law makes Chinese firms face more public pressure and higher operating costs, resulting in a significant drop in the financing capacity of heavily pollution firms [32]. Applying the theory of planned

behavior, Chen et al. showed that the new environmental protection law has a positive effect on the relationship between environmental intentions and the public's environmental behaviors [33]. Cai and Ye found that the new environmental protection law has a negative effect on enterprises' total factor productivity [34]. To our limited knowledge, however, no existing studies have systematically explored the new environmental protection law on green innovation in Chinese prefecture-level cities. Our paper helps fill this gap by examining the impact of the new environmental protection law on green innovation in Chinese prefecture-level cities.

We use the enactment of the new environmental protection law as an exogenous shock to examine the impact of government environmental regulation on green innovation. More specifically, we test whether the new environmental protection law provides a positive incentive for green innovation, how the new environmental protection law impacts green innovation, and whether the relationship between the new environmental protection law and green innovation can be affected by other factors.

Using unbalanced panel data on Chinese prefecture-level cities from 2010 to 2016 and a difference-in-differences (DID) methodology, we investigate the causal effect of China's new environmental protection law on green innovation. We use prefecture-level cities as research objects and measure green innovation by green patents. The law was enacted by the central government and affects all prefecture-level cities in China; therefore, our research is unaffected by sample selection bias. Although all prefecture-level cities are affected by the law, the exogenous shock to green innovation varies according to the environmental quality of the different prefecture-level cities. The lower the environmental quality is in a prefecture-level city, the greater the influence of the new environmental law is. We document evidence that the new environmental protection law has stimulated green innovation in prefecture-level cities.

To investigate the microchannel through which the new environmental protection law affects green innovation, we use data on listed firms to study the value of green innovation for firms from the financial constraint perspective. The new environmental protection law is found to aggregate the financial constraints on firms that belong to high-pollution industries. However, firms' financial constraints can be effectively alleviated by participating in green innovation. This finding shows that the new environmental protection law can enhance firms' green innovation incentives by affecting firms' financial constraints. In addition, we discuss how to enhance the positive impact of the new environmental law on green innovation.

Banking competition affects innovation [35, 36]. Because a firm's incentive to engage in green innovation is to offset the negative effect of the financial constraints caused by the introduction of the new environmental law, a lower level of banking competition improves the market power of banks, thus strengthening the negative effects of the new environmental protection law on the financial constraints of firms in high-pollution industries and increasing their incentives to invest in green innovations. Our empirical results

support the view that the positive association between the new environmental protection law and green innovation is more prominent in regions with lower levels of banking competition. Moreover, prior studies have argued that intellectual property protection is conducive to innovation [37]. Better intellectual property protection can improve the marginal benefits of engaging in innovation, thus encouraging innovation. We find that intellectual property protection strengthens the effect of the new environmental protection law on green innovation.

By investigating the micromechanism underlying the effect of the new environmental protection law on green innovation and the moderating effects of the banking structure and intellectual property protection on the relationship between the new environmental protection law and green innovation, this paper contributes to the current literature in three dimensions.

First, this paper expands the research on the impact of environmental regulation on green innovation. Prior literature mainly focused on the government regulation of green innovation in developed countries [26, 28] and provided less evidence about whether the changing law could impact green innovation. Our research examines the impact of the Chinese new environmental protection law on green innovation and finds that the stringency of environmental protection can promote green innovation, which can help policymakers and scholars to better understand the role of government regulation in green innovation.

Second, this paper enriches the research on green innovation. The literature on green innovation concentrates on the impacts of green innovation, such as energy efficiency [38], environmental quality [39], employment [40], firm competence [41], and firm performance [42]. Scholars also have examined which factors affect green innovation, such as customer demand [43], political capital [44], loans [22], corporate governance [45], and environmental regulation [26]. This paper finds that green innovation can be stimulated by the implementation of new environmental laws, enriching research in the field of green innovation. In addition, we find that intellectual property protection strengthens the effect of the new environmental protection law on stimulating green innovation.

Finally, our paper enriches the literature on the effect of the banking structure on technological change. As the source of most external financial resources for enterprises worldwide [46], the banking sector plays an important role in innovation [35, 36]. More competition in the banking sector can reduce the market power of banks, increase firms' access to finance [47, 48], and alleviate firms' financial constraints [48]. As some scholars have pointed out, more competition in the banking sector can promote innovation [49]. However, this paper finds that fiercer competition among banks may harm the new environmental law's effect on promoting green innovation, as the environmental requirement for green credits can be relaxed when banks compete seriously for borrowers. Given enterprises' investments in green innovation to offset the negative effect of the financial constraints caused by the introduction of the new environmental law, it is believed that limiting banking

competition may be crucial for realizing the positive effect of the new environmental law on green innovation.

The rest of this paper is organized as follows. We develop our hypothesis in Section 2; describe the sample selection procedure, variables, and empirical methodology in Section 3; present the empirical results and robustness tests in Section 4; discuss the micromechanisms in Section 5; provide further discussion in Section 6; and conclude this paper in Section 7.

2. Hypothesis Development

The new environmental protection law promotes green innovation in the following ways. First, the law changed the focus of economic development in China and strengthened environmental protection as a basic national policy. If an enterprise does not engage in green innovation, it will be difficult for it to survive in the future. Article 1 of the law mandates that the purposes of the law are to protect public health, promote ecological civilization, and promote the sustainable development of the economy and of society. Article 4 states that environmental protection is a basic national policy for the first time. This means that the Chinese government has given up the model of economic development at the cost of environmental pollution, and China's economy has embarked on a path of sustainable development. In this context, enterprises with higher energy consumption and higher pollution must face the fact that they might not survive. For example, according to the Environmental Status Bulletin of Henan Province in 2017, the province shut down 83000 enterprises with high levels of pollution to improve air quality. Therefore, enterprises with higher energy consumption and higher pollution must develop green innovations for survival.

Second, the government has expanded its penalties for enterprises that generate environmental pollution and its support for the environmentally friendly development of enterprises. In terms of environmental punishments, article 53 states that the environmental protection department shall record information on the environmental violations of enterprises in social credit files and promptly announce the list of violators to society. This article affects enterprise development because banks, the most important source of external capital to firms around the world [46], consider environmental credit information (the Ministry of Environmental Protection, together with the National Development and Reform Commission, the People's Bank of China, and the China Banking Regulatory Commission, issued the "enterprise environmental credit evaluation measures (for trial implementation)" in 2013; this means that the environmental credits of enterprises are considered when enterprises apply for bank loans). Polluting enterprises face higher financing costs and have a lower ability to receive financing after the enactment of the new environmental protection law [32]. In contrast, if an enterprise develops a green innovation to protect the environment, it can obtain green credits at a low cost. In addition, article 3 of the law mandates that if enterprises without a discharge permit refuse to execute environmental protection measures, the

judicial authority can detain the management in charge, meaning that the price of environmental pollution is higher when enterprises violate environmental protection rules. This might give management an incentive to develop green innovations to avoid possible criminal penalties. Moreover, the Chinese government has also provided incentives for enterprises. Article 22 of the law states that if enterprises further reduce their pollution emissions and their discharge of pollutants meets statutory rules, the Chinese government will use policies and measures, including finance, taxation, price adjustments, and government procurement, to support them. Huang et al. found that government support is conducive to green innovation [22].

Finally, the new environmental protection law also improved people's demand for environmentally friendly products. Article 9 of the law mandates that administrative education departments and schools incorporate environmental protection knowledge into school educational content and cultivate students' awareness of environmental issues to improve people's concern for the environment and increase preferences for environmentally friendly products. The demands of environmentally friendly people are an important factor that motivates firms to engage in green innovation [50]. Therefore, to acquire a more positive ecological reputation and satisfy the increasing demand for environmentally friendly products, enterprises have greater incentives to conduct green innovation.

In summary, the new environmental protection law can promote green innovation by changing the old economic development model, expanding the penalties and support for enterprises' different environmental behaviors, and increasing people's demand for environmentally friendly products. Thus, we propose the following hypothesis.

Hypothesis. The new environmental protection law has a positive effect on green innovation.

3. Sample and Empirical Methodology

3.1. Sample. Although many studies focus on the green innovation of listed firms, green innovation data from prefecture-level cities can comprehensively reflect the impact of the new environmental protection law on green innovation because the IPO market in China is strictly regulated, allowing only a small proportion of firms to list successfully [51]. Many firms are private enterprises. The data on green innovation in prefecture-level cities contain the green innovation outputs of all innovation parties. Therefore, using prefecture-level cities as research objects can better represent the impact of the new environmental protection law on green innovation.

To construct our sample, we start with all Chinese prefecture-level cities during 2010–2016. The macrodata are collected from the China Research Data Service (CNRDS) database, which provides detailed economic statistics on prefecture-level cities. Green patent data are collected from the Chinese National Intellectual Property Administration. Because there is no specific definition of green innovation, following Li et al. [52], we regard a patent as being for a green

innovation when the introduction of the patent includes the following Chinese keywords: green, environmental, ecology, sustainable, low carbon, clean, cycling, energy-saving, and emission reduction. Environmental quality data are collected from the Columbia University Social and Economic Data Center, which provides environmental data for China from 1998 to 2016. Then, we exclude city-year observations with missing information for any variable. Our final sample includes 1798 city-year observations representing 266 prefecture-level cities (according to Chinese Nation Bureau of Statistics, there are 293 prefecture-level cities in 2019). We winsorize all continuous variables at the 1% and 99% levels to mitigate the effects of outliers.

3.2. Measuring Green Innovation. Following Sun et al. [38], Zhang et al. [42], Amore and Bennesen [45], and Li et al. [52], we use patent data as a measure of green innovation. There are three types of patents in China: invention patents, utility model patents, and external design patents. Invention patents have three characteristics: inventiveness, novelty, and practical applicability. Thus, innovations under invention patents are the most novel. Utility model patents require innovation in the application of a product. External design patents are only for external innovations. Therefore, external design patents are not issued for green innovations, and green innovations are patented under invention patents and utility model patents only [42]. Additionally, owing to the lag between a patent being applied for and being granted, the timing of the patent application better captures the actual timing of the innovation [53]. Therefore, we use the application date of green patents to measure green innovation. Specifically, we use the number of green patents divided by the number of total patents in prefecture-level cities to measure green innovation (*Ginnovation*).

3.3. Methodology. The enactment of the new environmental protection law was an exogenous shock to green innovation in prefecture-level cities; thus, we use the difference-in-differences methodology to test whether this new environmental law has promoted green innovation. Specifically, we investigate the differences in green innovation in prefecture-level cities that are more greatly affected by the new environmental protection law before and after the law ("Treatment" group) compared to the same differences in prefecture-level cities that are less affected ("Control" group).

Due to the new environmental protection law being enforced in all Chinese prefecture-level cities, we need to divide the prefecture-level cities into two groups: "Treatment" and "Control". Because air pollution is the main environmental issue, we use the $PM_{2.5}$ concentration to measure environmental quality. We define a prefecture-level city as being in the "Treatment" group when its mean value of $PM_{2.5}$ is higher than the mean value of environmental quality across all prefecture-level cities before 2015. This approach is taken because a prefecture-level city with heavier environmental issues should be more greatly affected after the enactment of the new environmental protection law.

Simultaneously, a prefecture-level city is defined as being in the “Control” group when its mean value of $PM_{2.5}$ is lower than the mean value of environmental quality across all

prefecture-level cities before 2015. Then, we use the following model to examine the impact of the new environmental protection law on air pollution:

$$\begin{aligned} Ginnovation_{i,t} = & \beta_0 + \beta_1 Treat_i \times Post_t + \beta_2 AGDP_{i,t} + \beta_3 \times Struct_{i,t} + \beta_4 \times FDI_{i,t} + \beta_5 Science_{i,t} \\ & + \beta_6 \times Industry_{i,t} + \beta_7 \times POP_{i,t} + \beta_8 PM25_{i,t} + \mu_i + \nu_t + \varepsilon_{i,t}. \end{aligned} \quad (1)$$

where i and t represent prefecture-level cities and years, respectively. *Ginnovation* denotes green innovation in a prefecture-level city. *Treat* is an indicator variable that equals 1 when a prefecture-level city belongs to the “Treatment” group and 0 otherwise. *Post* is also an indicator variable. *Post* is set to 1 after 2014 and 0 otherwise, because the new environmental protection law came into effect on January 1, 2015. We also control for other factors that affect air pollution in prefecture-level cities. Specifically, we include the natural logarithm of GDP per capita (*AGDP*), tertiary sector output divided by secondary sector output (*Struct*), foreign direct investment divided by GDP (*FDI*) (foreign direct investment is measured in dollars in the database; we convert dollars into RMB by using the annual average exchange rate), the natural logarithm of government subsidies on science and technology (*Science*), the natural logarithm of the number of industrial enterprises (*Industry*), the natural logarithm of the population (*POP*), and the natural logarithm of the $PM_{2.5}$ concentration (*PM25*). We also include prefecture-level city fixed effects (μ_i) to control for unobservable time-invariant prefecture-level city characteristics and year fixed effects (ν_t) to control for common time trends. We do not include *Post_t* and *Treat_i* in our model individually because these variables are absorbed by the year fixed effects and prefecture-level city effects. The coefficient of interest is β_1 . According to our hypothesis, we expect β_1 to be positive. All variables are defined in Table 1.

4. Empirical Tests and Results

4.1. Descriptive Statistics. Panel A of Table 2 reports the summary statistics for the variables used in our analysis. As shown in Panel A, green innovation’s mean and median values are 0.0278 and 0.0240, respectively. The mean value of *Treat* is 0.4667, suggesting that 46.67% of samples belong to the “Treatment” group. Panel B reports the correlation coefficient between variables. The correlation between green innovation and the other variables is not high, indicating that multicollinearity is not a serious problem.

4.2. Main Results. Table 3 reports the results from estimating model (1). In column 1, we regress the dependent variable on the interaction term *Treat* × *Post* only. The coefficient on *Treat* × *Post* is positive and statistically significant at the 1% level, which preliminarily shows that the new environmental protection law promotes green innovation. In column 2, we control for economic development (*AGDP*), foreign direct investment (*FDI*), and government expenditure on science

and technology subsidies (*Science*); the coefficient on *Treat* × *Post* is significant and positive. In column 3, we control for all variables, and the coefficient on *Treat* × *Post* is positive and statistically significant at the 1% level, supporting our hypothesis that the new environmental protection law has a positive effect on green innovation.

In terms of control variables, we find that the coefficient of *Science* is significant and positive in column 3, consistent with the fact that the government provides funds for enterprises to implement research and development, reducing the financial stress on enterprises. In addition, the regression result for *PM25* is positive and statistically significant at the 10% level, suggesting that environmental issues force prefecture-level cities to engage in green innovation.

4.3. Robustness Tests. In this subsection, we run several robustness tests. First, the DID methodology is based on the parallel trend assumption, suggesting that the trends in green innovation in the “Treatment” group and the “Control” group have no significant differences before the enactment of the new environmental protection law. Following Xu et al. [54], we test the parallel trends assumption by replacing the *Post* indicator with several cohort-year dummy variables in model (1): *Year2011*, *Year2012*, *Year2013*, *Year2014*, *Year2015*, and *Year2016*. If the parallel trends assumption is satisfied, the interaction terms between *Treat* and *Year2011*, *Year2012*, *Year2013*, and *Year2014* should not be significant. As shown in column 1 of Table 4, we find that the parallel trends assumption is satisfied. In addition, the interaction terms between *Treat* and *Year2015* and *Year2016* are significant and positive, indicating an overall persistent increase in green innovation after the enactment of the new environmental protection law.

In addition, to ensure that the “Treatment” group and the “Control” group are comparable, we employ propensity score matching (PSM) to match the groups. The matching procedure relies on the one-to-one nearest neighbor matching of cities by propensity score without replacement; the propensity scores are estimated by a logit regression of *Treat* on a set of control variables that include economic development (*AGDP*), foreign direct investment (*FDI*), and government expenditure on science and technology subsidies (*Science*). Then, we use model (1) to investigate the impact of the new environmental protection law on green innovation. As shown in column 2 of Table 4, the coefficient on *Treat* × *Post* is positive and statistically significant, which is consistent with our hypothesis.

TABLE 1: Variables and definitions.

| Variable | Definition |
|--------------|---|
| Ginnovation | The share of green patents in total patents within a prefecture-level city |
| Treat | A dummy variable that equals 1 if the mean value of PM2.5 in the prefecture-level city is greater than the mean value of environmental quality across all prefecture-level cities before 2015 and 0 otherwise |
| Post | A dummy variable that is 1 after 2014 and 0 otherwise |
| AGDP | The natural logarithm of GDP per capita |
| FDI | Foreign direct investment divided by GDP |
| Struct | Tertiary sector output divided by secondary sector output |
| Science | The natural logarithm of government subsidies for science and technology |
| Industry | The natural logarithm of the number of industrial enterprises |
| POP | The natural logarithm of the population |
| PM25 | The natural logarithm of the PM _{2.5} concentration |
| Ginnovation1 | The number of green patents granted divided by the number of all patents granted |
| Town | Area of urban construction land divided by the area of the prefecture-level city |
| HHI | The definition is shown in model 2 |
| IPP | The natural logarithm of the number of first instances of intellectual property infringement in a province |
| SA | $-0.737 \times \ln(\text{Assets}) + 0.043 \times \ln(\text{Asset})^2 - 0.04 \times \text{Firm age}$ |
| Treatt | A dummy variable that is 1 when an enterprise belongs to a heavily polluting industry and 0 otherwise |
| Size | The natural logarithm of total assets |
| Lev | Total debt divided by total assets |
| Tangi | Tangible assets divided by total asset |
| ROA | Net profit divided by total assets |
| Age | The natural logarithm of firm's age |
| SOE | A dummy variable that is 1 when an enterprises is controlled by government and 0 otherwise |
| TOP1 | The number of shares held by the controlling shareholder divided by the number of all shares |
| Duality | A dummy variable that is 1 if the CEO and chair of the board are not separate and 0 otherwise |

TABLE 2: Summary statistics.

| Panel A | | | | | | | | |
|-------------|-------------|-----------|----------|-----------|----------|----------|----------|-------|
| Variable | N | Mean | Std | Min | Median | Max | | |
| Ginnovation | 1798 | 0.0278 | 0.0183 | 0.0018 | 0.0240 | 0.1051 | | |
| Treat | 1798 | 0.4667 | 0.0000 | 1.0000 | 1.0000 | 1.0000 | | |
| AGDP | 1798 | 10.5683 | 0.5652 | 9.3238 | 10.5298 | 12.0075 | | |
| FDI | 1798 | 0.0182 | 0.0161 | 0.0002 | 0.0135 | 0.0721 | | |
| Struct | 1798 | 37.7214 | 8.9673 | 11.4700 | 36.7750 | 76.3500 | | |
| Science | 1798 | 10.1692 | 1.1721 | 7.7102 | 10.0353 | 13.4326 | | |
| Industry | 1798 | 6.6649 | 0.9782 | 4.3577 | 6.6425 | 8.8969 | | |
| POP | 1798 | 5.904 | 0.616 | 4.304 | 5.945 | 7.063 | | |
| PM25 | 1798 | 3.5046 | 0.4818 | 1.9671 | 3.5327 | 4.3081 | | |
| Panel B | | | | | | | | |
| | Ginnovation | AGDP | FDI | Struct | Science | Industry | POP | PM2.5 |
| Ginnovation | 1 | | | | | | | |
| AGDP | 0.135* * | 1 | | | | | | |
| FDI | 0.021 | 0.322* * | 1 | | | | | |
| Struct | 0.184* * | 0.346* * | 0.181* * | 1 | | | | |
| Science | 0.084* * | 0.642* * | 0.393* * | 0.431* * | 1 | | | |
| Industry | -0.092* * | 0.431* * | 0.334* * | 0.195* * | 0.748* * | 1 | | |
| POP | 0.023 | -0.180* * | 0.002 | 0.074* * | 0.390* * | 0.598* * | 1 | |
| PM25 | -0.021 | 0.032 | 0.260* * | -0.095* * | 0.265* * | 0.502* * | 0.425* * | 1 |

*, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively. All variables are defined in Table 1.

The number of patents granted is also used to measure innovation [55]. Therefore, we replace the original measure of green innovation with this measure. Specifically, we use the number of green patents granted divided by the number of all patents granted in a prefecture-level city to measure green innovation (*Ginnovation1*). In column 3 of Table 4, the coefficient on $Treat \times Post$ is positive and statistically

significant at the 5% level, suggesting that the new environmental protection law is conducive to green innovation.

Bian et al. [56] found that urbanization is an important factor that affects regional innovation. Thus, we further control for the effect of urbanization on green innovation [56]. Following Bian et al. [56], we use the area of urban construction land divided by the area of the prefecture-level

TABLE 3: The impact of the new environmental protection law on green innovation.

| | (1) Ginnovation | (2) Ginnovation | (3) Ginnovation |
|----------------|-----------------------|-----------------------|---------------------|
| Treat × Post | 0.0044*** (0.0014) | 0.0046*** (0.0014) | 0.0049*** 0.0014 |
| AGDP | | −0.0052 (0.0034) | −0.0032 0.0035 |
| FDI | | 0.0111 (0.0411) | 0.0316 0.0425 |
| Struct | | 0.0002 (0.0002) | 0.0001 0.0002 |
| Science | | 0.0011 (0.0009) | 0.0017* 0.001 |
| Industry | | | −0.0038* 0.0022 |
| POP | | | −0.0039 0.0068 |
| PM25 | | | 0.0054* 0.003 |
| Constant | 0.0259*** (0.0008) | 0.0630* (0.0365) | 0.0673 0.0579 |
| City FE | Yes | Yes | Yes |
| Year FE | Yes | Yes | Yes |
| N | 1798 | 1798 | 1798 |
| R ² | 0.0235 | 0.0270 | 0.0318 |

Robust standard errors are presented in parentheses. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

city to measure urbanization (*Town*). As shown in column 4 of Table 4, the coefficient on *Treat* × *Post* is positive and statistically significant, which is consistent with the finding in column 3 of Table 3.

Finally, we adjust the time frame of our analysis. We exclude observations from before 2013 to maintain balance in the number of years before and after the enactment of the law because the new environmental protection law came into effect in 2015. The results are presented in column 5 of Table 4, and the coefficient on *Treat* × *Post* is positive and significant, which is consistent with our hypothesis.

5. Mechanism Tests

In Section 2 of this paper, we pointed out that the new environmental protection law promotes green innovation by changing the old economic development model, expanding the penalties and support for enterprises' environmental behavior, and increasing people's demand for environmentally friendly products. However, the data from prefecture-level cities do not include the indicators needed to measure these possible mechanisms. Therefore, we use data from the Chinese listed firms to test the possible economic mechanisms through which the new environmental protection law affects green innovation.

The new environmental protection law mandates that the environmental protection department record the environmental violation information of enterprises in social credit files and promptly announce the list of violators to society (article 53 of the law). Moreover, the Chinese government requests banks to consider the environmental information of enterprises. If an enterprise belongs to a heavily polluting industry, that enterprise faces larger financial constraints. Furthermore, an enterprise in a heavily polluting industry can alleviate its financial constraints by developing green innovations to meet the green credit requirements of banks. Thus, we examine the economic mechanism through which the new environmental protection law affects green innovation by investigating the changes in listed firms' financial constraints.

We collect financial data on Chinese A share firms during 2010–2018 from the China Securities Market and Accounting Research (CSMAR) database. In addition, we collect information on the green innovations of listed firms from the Chinese National Intellectual Property Administration. Then, we exclude financial service firms. To mitigate the effects of outliers, we also winsorize all continuous variables at the 1% and 99% levels.

We use the DID methodology to measure the impact of the new environmental protection law on listed firms' financial constraints. The model is set as follows:

$$SA_{i,t} = \gamma_0 + \gamma_1 Treat_i \times Post_t + \gamma_2 Treat_i + \gamma_3 Post_t + \gamma_4 Size_{i,t} + \gamma_5 Lev_{i,t} + \gamma_6 Tangi_{i,t} + \gamma_7 Roa_{i,t} + \gamma_8 Age_{i,t} + \gamma_9 SOE_{i,t} + \gamma_{10} Top1_{i,t} + \gamma_{11} Dualit_{i,t} + \delta_i + \nu_t + \epsilon_{i,t}, \quad (2)$$

$$SA_{i,t} = \gamma_0 + \gamma_1 Treat_i \times Post_t \times Ginnovation_{i,t} + \gamma_2 Treat_i \times Ginnovation_t + \gamma_3 Post_t \times Ginnovation_{i,t} + \gamma_4 Ginnovation_{i,t} + \gamma_5 Size_{i,t} + \gamma_6 Lev_{i,t} + \gamma_7 Tangi_{i,t} + \gamma_8 Roa_{i,t} + \gamma_9 Age_{i,t} + \gamma_{10} SOE_{i,t} + \gamma_{11} Top1_{i,t} + \delta_i + \nu_t + \epsilon_{i,t}, \quad (3)$$

where *i* and *t* represent the firm and year, respectively. SA denotes financial constraints. We calculate the SA index values proposed by Hadlock and Pierce [57] to measure financial constraints (the index is defined as $-0.737 \times \ln(\text{Assets}) + 0.043 \times \ln(\text{Asset})^2 - 0.04 \times \text{Firm age}$). The larger the value of SA is, the more serious the financial

constraints firms face. *Treat* is an indicator variable that equals 1 when an enterprise belongs to a heavily polluting industry and 0 otherwise (the guidelines for the disclosure of environmental information for listed companies issued by the Ministry of Environmental Protection point out that the iron and steel, coal, metallurgy, chemical, petrochemical,

TABLE 4: Robustness tests.

| | (1) Ginnovation | (2) Ginnovation | (3) Ginnovation1 | (4) Ginnovation | (5) Ginnovation |
|-------------------------|-----------------------|-----------------------|-----------------------|-----------------------|------------------------|
| Treat \times Year2011 | 0.0011 (0.0023) | | | | |
| Treat \times Year2012 | 0.0012 (0.0023) | | | | |
| Treat \times Year2013 | 0.0031 (0.0023) | | | | |
| Treat \times Year2014 | 0.0034 (0.0023) | | | | |
| Treat \times Year2015 | 0.0044* (0.0023) | | | | |
| Treat \times Year2016 | 0.0091*** (0.0023) | | | | |
| Treat \times Post | | 0.0048** (0.0019) | 0.0026** (0.0010) | 0.0048*** (0.0014) | 0.0028** (0.0014) |
| AGDP | -0.0032 (0.0035) | 0.0004 (0.0050) | -0.0032 (0.0026) | -0.0031 (0.0036) | 0.0036 (0.0039) |
| FDI | 0.0292 (0.0425) | 0.0946 (0.0679) | 0.0180 (0.0315) | 0.0276 (0.0433) | 0.0369 (0.0593) |
| Struct | 0.0001 (0.0002) | 0.0001 (0.0002) | 0.0000 (0.0001) | 0.0001 (0.0002) | -0.0001 (0.0002) |
| Science | 0.0016* (0.0010) | 0.0002 (0.0012) | 0.0017** (0.0007) | 0.0018* (0.0010) | 0.0033*** (0.0012) |
| Industry | -0.0038* (0.0022) | -0.0065** (0.0032) | -0.0014 (0.0017) | -0.0037 (0.0023) | -0.0125*** (0.0035) |
| POP | -0.0045 (0.0068) | 0.0021 (0.0105) | -0.0085* (0.0051) | -0.0042 (0.0069) | 0.0126 (0.0093) |
| PM25 | 0.0061** (0.0031) | 0.0075* (0.0044) | 0.0064*** (0.0023) | 0.0057* (0.0031) | 0.0023 (0.0035) |
| Town | | | | 0.0000 (0.0001) | |
| Constant | 0.0708 (0.0581) | 0.0212 (0.0785) | 0.0643 (0.0430) | 0.0654 (0.0590) | -0.0410 (0.0736) |
| City FE | Yes | Yes | Yes | Yes | Yes |
| Year FE | Yes | Yes | Yes | Yes | Yes |
| N | 1798 | 1152 | 1798 | 1773 | 1021 |
| R ² | 0.0364 | 0.0231 | 0.0824 | 0.0307 | 0.0481 |

Robust standard errors are presented in parentheses. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

building material, paper making, brewing, textile, tanning, and mining industries are heavily polluting industries, so the CSRC industry codes B06, B07, B08, B09, B11, C17, C18, C19, C22, C25, C26, C28, C29, C31, and C32 are the codes for heavily polluting enterprises). Post is also an indicator variable. Post is 1 after 2014 and 0 otherwise. In addition, we control for factors that affect enterprises' financial constraints [58], including the natural logarithm of total assets (*Size*), financial leverage (*Lev*), tangible assets divided by total assets (*Tangi*), the return on assets (*ROA*), and the natural logarithm of firm age. We also include a dummy variable that indicates whether a firm belongs to the government (*SOE*). Because ownership concentrations tend to be high and the controlling shareholder plays an important role in corporate governance [59], we control for the controlling shareholder's shareholding ratio (*TOP1*). Finally, we also consider CEO duality (*Duality*). We also include industry fixed effects (δ_i) to control for unobservable time-invariant industry-specific characteristics and year fixed

effects (v_t) to control for common time trends. All variables are defined in Table 1.

First, we use model (2) to investigate the impact of the new environmental protection law on financial constraints. As shown in column 1 of Table 5, the coefficient on *Treat* \times *Post* is positive and significant, suggesting that the new environmental protection law increases the financial constraints on firms in heavily polluting industries, which is consistent with the findings of Liu et al. [32], who noted that the new environmental protection law reduces the financing capacity of heavily polluting enterprises.

Then, we use model (3) to test whether enterprises' investments in green innovation can alleviate financial constraints. As shown in column 2 of Table 5, the coefficient on *Treat* \times *Post* \times *Ginnovation* is negative and significant, indicating that enterprises in high-pollution industries can alleviate their financial constraints by developing green innovation in the context of the new environmental protection law.

TABLE 5: Economic mechanism tests.

| | (1) SA | (2) SA |
|--|--------------------------|--------------------------|
| Treat \times Post | 0.0111* * (2.4287) | 0.0139*** (2.6866) |
| Treat | 0.00450 (0.6760) | -0.0107 (-1.6419) |
| Post | -0.0268*** (-5.1176) | -0.0289*** (-5.4169) |
| Size | -0.00540 (-1.4843) | -0.0079* * (-2.2319) |
| Lev | 0.0382*** (2.7750) | 0.0373*** (2.7273) |
| Tangi | 0.0378* * (2.4520) | 0.0340* * (2.2324) |
| ROA | -0.0803*** (-3.0255) | -0.0888*** (-3.3643) |
| Age | -0.6071*** (-70.7974) | -0.6072*** (-70.4597) |
| SOE | -0.0063* * (-2.2639) | -0.0063* * (-2.2682) |
| TOP1 | 0.0000 (0.3619) | 0.0000 (0.2161) |
| Duality | 0.0102*** (3.0259) | 0.0099*** (2.9506) |
| Treat \times Post \times Ginnovation | | -0.0131* (-1.6726) |
| Treat \times Ginnovation | | 0.0488*** (3.7273) |
| Post \times Ginnovation | | 0.0099*** (2.9239) |
| Ginnovation | | 0.0021 (0.4313) |
| Constant | -1.9688*** (-24.2725) | -1.9114*** (-24.2617) |
| Industry FE | Yes | Yes |
| Year FE | Yes | Yes |
| N | 23186 | 23062 |
| R ² | 0.766 | 0.771 |

Robust standard errors are presented in parentheses. *, * *, and * * * indicate statistical significance at the 10%, 5%, and 1% levels, respectively. All variables are defined in Table 1.

In summary, the analysis suggests that the new environmental protection law can affect green innovation by changing the financial constraints that enterprises face.

6. Further Analyses

6.1. The Effect of Banking Competition. In the micro-mechanism tests, we found that the new environmental protection law affects green innovation by changing enterprises' financial constraints. Fierce banking competition reduces the market power of banks, which increases the bargaining power of enterprises and reduces the impact of the new environmental protection law on green innovation, which comes through the imposition of stronger

financial constraints on enterprises in heavily polluting industries. Therefore, a lower level of banking competition can positively affect the relationship between the new environmental protection law and green innovation by increasing the market power of banks. As a result, we expect the effect of the new environmental protection law on the stimulation of green innovation to be more prominent in prefecture-level cities with lower levels of banking competition.

Data on the loan market and on deposits are not available for prefecture-level cities. Following Degryse and Ongena [60] and Chong et al. [61], we use the number of bank branches in each prefecture-level city to develop a Herfindahl–Hirschman index (HHI) to measure banking

competition. The HHI for a city's banking sector is calculated as follows:

$$HHI_{i,t} = \sum_{k=1}^N \left(\frac{Branch_{k,t}}{TotalBranches_{i,t}} \right)^2, \quad (4)$$

where $Branch_{k,t}$ is the number of branches of bank k in prefecture-level city i in year t . $TotalBranches_{i,t}$ is the total

number of different banks in city i in year t . The value of the HHI ranges from 0 to 1. A higher value of the HHI means a lower level of banking competition.

Then, we use the following model to test the impact of banking competition on the relationship between the new environmental protection law and green innovation:

$$\begin{aligned} Ginnovation_{i,t} = & \beta_0 + \beta_1 HHI_{i,t} \times Treat_i \times Post_t + \beta_2 Treat_i \times Post_t + \beta_3 Treat_i \times HHI_{i,t} + \beta_4 Post_t \times HHI_{i,t} \\ & + \beta_5 HHI_{i,t} + \beta_6 AGDP_{i,t} + \beta_7 \times Struct_{i,t} + \beta_8 \times FDI_{i,t} + \beta_9 Science_{i,t} + \beta_{10} \times Industry_{i,t} + \beta_{11} \times POP_{i,t} \\ & + \beta_{12} PM25_{i,t} + \mu_i + \nu_t + \varepsilon_{i,t}, \end{aligned} \quad (5)$$

where i and t represent prefecture-level cities and years, respectively. The coefficient of interest is β_1 . We expect β_1 to be positive because the larger the value of the HHI is, the lower the banking sector's competition is.

As shown in column 1 of Table 6, the coefficient on $Treat \times Post \times HHI$ is positive and statistically significant at the 5% level, suggesting that the relationship between the new environmental protection law and green innovation is more prominent in prefecture-level cities with lower levels of banking competition.

6.2. The Effect of Intellectual Property Protection.

Intellectual property protection is regarded as an effective incentive for innovation [37, 62]. Innovations are nonrival goods, suggesting that inventors cannot prevent others from using their inventions [37]. This means that other inventors can copy innovations and appropriate at least a portion of the profits from those innovations without R&D investments [63]. Intellectual protection provides inventors with the right to obtain monopoly profits over a certain period of time to offset the cost of R&D investments, which can encourage innovation. Although the legal system is underdeveloped in China [64], some regions, such as Beijing,

Shanghai, and Guangdong, have better intellectual property protection. Thus, in terms of intellectual property protection, there is extensive heterogeneity. Better intellectual property protection promotes innovation, including green innovation. Therefore, we expect that the relationship between the new environmental protection law and green innovation is more prominent in prefecture-level cities with stronger intellectual property protection.

We use the natural logarithm of the number of first instances of intellectual property infringement in a province to measure intellectual property protection (IPP). This approach is taken because the legal system is underdeveloped, and the number of first instances of intellectual property infringement can reflect the level of intellectual property protection. In addition, prefecture-level cities in the same province have a similar level of intellectual property protection. Specifically, a larger number of first instances of intellectual property infringement indicate better intellectual property protection.

To examine the impact of intellectual property protection on the association between the new environmental protection law and green innovation, we use the following model:

$$\begin{aligned} Ginnovation_{i,t} = & \beta_0 + \beta_1 IPP_{i,t} \times Treat_i \times Post_t + \beta_2 Treat_i \times Post_t + \beta_3 Treat_i \times IPP_{i,t} \\ & + \beta_4 Post_t \times IPP_{i,t} + \beta_5 IPP_{i,t} + \beta_6 AGDP_{i,t} + \beta_7 \times Struct_{i,t} + \beta_8 \times FDI_{i,t} \\ & + \beta_9 Science_{i,t} + \beta_{10} \times Industry_{i,t} + \beta_{11} \times POP_{i,t} + \beta_{12} PM25_{i,t} + \mu_i + \nu_t + \varepsilon_{i,t}, \end{aligned} \quad (6)$$

where i and t represent prefecture-level cities and years, respectively. The coefficient of interest is β_1 . We expect β_1 to be positive.

In column 2 of Table 6, we find that the coefficient on $Treat \times Post \times IPP$ is positive and significant, indicating that the relationship between the new environmental property

TABLE 6: Further analyses.

| | (1) Ginnovation | (2) Ginnovation |
|--------------------|-----------------------|-----------------------|
| Treat × Post × HHI | 0.0125* * (0.0063) | |
| Treat × HHI | 0.0087* * (0.0042) | |
| Post × HHI | 0.0004 (0.0029) | |
| Treat × Post × IPP | 0.0019* | (0.0010) |
| Treat × IPP | | 0.0007 (0.0007) |
| Post × IPP | | 0.0005 (0.0007) |
| IPP | | −0.0002 (0.0006) |
| HHI | −0.0046 (0.0035) | |
| Treat × Post | 0.0029 (0.0020) | −0.0105 (0.0068) |
| AGDP | −0.0041 (0.0035) | −0.0044 (0.0035) |
| FDI | 0.0319 (0.0421) | 0.0356 (0.0435) |
| Struct | 0.0002 (0.0002) | 0.0001 (0.0002) |
| Science | 0.0020* * (0.0010) | 0.0011 (0.0010) |
| Industry | −0.0040* (0.0022) | −0.0033 (0.0022) |
| POP | −0.0029 (0.0068) | −0.0057 (0.0067) |
| PM25 | 0.0056* (0.0030) | 0.0071* * (0.0031) |
| Constant | 0.0670 (0.0575) | 0.0864 (0.0574) |
| City FE | Yes | Yes |
| Year FE | Yes | Yes |
| N | 1795 | 1775 |
| R ² | 0.0390 | 0.0429 |

Robust standard errors are presented in parentheses. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

protection law and green innovation is more prominent in prefecture-level cities with stronger intellectual property protection.

7. Conclusion

Law is one of the most formal institutions in a country and affects the development of the economy and society. This paper investigates the impact of China's new environmental protection law on green innovation. Using a large sample of prefecture-level cities in China over the 2010–2016 period and the difference-in-differences (DID) methodology, we provide strong evidence that the new environmental protection law can promote green innovation. In addition, the positive association remains stable after testing the parallel trend assumption, changing the identification method, using an alternative measure of

green innovation, controlling for the effect of urbanization, and adjusting the time window. The micromechanism analysis shows that enterprises in high-pollution industries can relieve the financial constraints aggravated by the introduction of the new environmental protection law by increasing green innovation. Further, we find that the association between the new environmental protection law and green innovation is more prominent in prefecture-level cities with a lower level of banking competition and in prefecture-level cities with stronger intellectual property protection.

The evidence provided in this paper should be of interest not only to scholars but also to policymakers. Many developing countries have achieved higher levels of economic development at the cost of air pollution, which has caused a great loss of human health. China, the largest developing country, has proven that improving legal protection of the environment is conducive to green innovation. Therefore, other developing countries seeking to coordinate economic development and environmental protection can enact stricter environmental protection laws that are in line with their own national conditions to promote green innovation and achieve sustainable development.

In addition, the government can consider limiting fierce banking competition. The new environmental protection law imposes more financial constraints on firms in heavily polluting industries, providing an impetus for these firms to engage in green innovation. Firms can alleviate financial constraints by engaging in green innovation. Therefore, banks play a crucial role in the association between the new environmental protection law and green innovation. However, stronger banking competition has a negative effect on the market power of banks, which gives firms greater access to external financing, reducing the impact of the new environmental protection law on firms' financial constraints. Thus, the government can limit the number of bank branches to lower banking competition to strengthen the effect of the new environmental protection law on green innovation.

Finally, intellectual property rights protection can provide a positive incentive for innovators to invest more resources in green innovation. Therefore, to improve the level of green innovation, the government should strengthen laws and regulations on intellectual property rights protection. Moreover, the government should invest more resources in intellectual property protection, such as employing more law enforcers and reducing the cost of intellectual property suits.

Data Availability

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

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

Two-Stage Robust Optimization Model for Fresh Cold Chain considering Carbon Emissions and Uncertainty

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Sustainable development is an everlasting theme and lasting strategy in today's era. Low-carbon economy is an inevitable approach to the implementation of sustainable development. Cold chain logistics has become one of the main sources of carbon emissions. However, in the research on location planning of cold chain logistics, the costs of carbon emissions have not been taken into consideration in previous studies. The two-stage stochastic optimization (TSSO) model was established based on the comprehensive consideration of transportation costs, time penalty costs, and carbon emission costs. In this case, it is extremely difficult to deal with uncertainty in TSSO model. Therefore, this paper constructs a two-stage robust optimization (TSRO) model using data-driven method and robust optimization theory and verifies the validity of this model through an actual case. The application of this method to a cold chain logistics enterprise showed that the service level of logistics cannot be guaranteed by stochastic optimization model. In the TSRO model, the costs increase by 2.18% at the price of robustness, whereas logistics service level shows an upward trend (from 85.83% to 92.75%). In the TSRO model, enterprises are forced to choose a better distribution path when carbon tax increases, which not only helps enterprises save costs but also achieves low-carbon environmental benefits.

1. Introduction

Sustainable development is a long-standing concept of human society. The deteriorating environment is constantly challenging national sustainable development strategies. Statistics show that a significant increase in greenhouse gas emissions is the primary cause of deterioration in the ecological environment. In consequence, how to reduce carbon emissions has become an extremely urgent global issue. Governments around the world are increasingly concentrating on reducing carbon emissions in their economic activities. Under the background of advocating sustainable environmental development, it is imperative to take action on energy saving and emission reduction. Cities such as Beijing, Tokyo, and California have issued policies to promote sustainable development strategies [1, 2]. China has discharged the largest amount of carbon dioxide since 2009 [3, 4]. In pursuit of sustainable development, government will set caps on carbon emissions on the basis of actual

capacity, while related enterprises will then make production plans. These policies and deteriorating environment make people aware of the fact that it is necessary to develop low-carbon economy [5, 6].

With the rapid growth of industrial economy, the focus of decision-makers has gradually shifted from economic benefits to coordinated development of economic and environmental benefits. Previous research has focused on manufacturing, while it has been rarely concerned about transportation. In fact, the carbon emissions of transportation are enormous, especially in the cold chain logistics industry [7]. Statistics show that carbon emissions from vehicles in logistics transportation are one of the major sources of greenhouse gases worldwide. Greenhouse gases generated during logistics transport, among which large quantities of greenhouse gases come from cold chain logistics, account for 14% of those around the world [8, 9]. Low-carbon vehicle routing problem is the research basis of traditional vehicle routing problem, which adds carbon

emission constraints. Besides economic benefits, environmental factors should also be considered to effectively reduce carbon emissions during transportation [10].

Many literatures have studied the influence of carbon emission on logistics and transportation industry. When carbon trading mechanism exists in the market, the costs need to be considered in the logistics distribution routing problem. Hoen et al. carried out research on emission control management mechanism and suggested that policymakers should adopt carbon emission limit management mechanism [11]. The government is tightening carbon emission control to enterprises, which will inevitably result in certain economic costs. It is obviously more realistic to add carbon emission constraints when figuring out the vehicle optimal path problem. If the carbon emission in transportation can be effectively controlled, it is of great significance to promote development of low-carbon logistics. Therefore, vehicle routing optimization with carbon emission constraints is gradually becoming an important research field.

With the increase of CO₂ emission and pressure of environmental pollution, many scholars pay attention to the research on carbon emission reduction of cold chain logistics enterprises. However, most of the research methods are single-stage models, and few scholars use two-stage models. Zhou et al. proposed a low carbon supply chain framework based on supply chain process criteria [12]. Others have made quantitative research on the implementation of cold chain logistics. Tang et al. proposed a benchmark model for carbon reduction [13]. Hariga et al. proposed activity-based cost minimization models and carbon footprint minimization models [14]. Elhedhli et al. proposed an optimization model for constructing food cold chain inventory and transportation network and studied the cold chain logistics transportation [15]. The carbon emission studied in this paper is an extension of traditional vehicle routing problem, and the low carbon cold chain logistics transportation planning problem in two stages is studied.

Two-stage optimization model is widely utilized in supply chain management, emergency dispatching, industrial production, energy grid, and other fields [16, 17]. In the two-stage optimization problem, previous researchers often started with deterministic model, while few scholars studied its uncertainty. Dillon et al. studied the optimization of medical supply chain network using a two-stage optimization model [18]. Weskamp et al. studied two-stage optimization of supply chain network with delayed payment strategy under uncertain demand [19]. Chen et al. studied the two-stage stochastic distribution robust linear complementarity problem [20, 21]. Lin et al. established a two-stage model considering late payment and analyzed the integrated production inventory strategy [22]. Sainathuni et al. studied the inventory-transportation problem to determine the optimal distribution plan from the supplier to the customer to minimize total costs [23]. Scenario-based stochastic optimization can work out supply chain management and system optimization problems [24, 25]. Rezaee et al. put forward the design of a green supply chain network with stochastic demand and carbon price [26]. However, the

solution of scenario-based stochastic optimization model depends to a large extent on the defined scenario and its probability of occurrence, and the solution of such model will dramatically increase the amount of calculation and increase the difficulty or even no solution as the number of scenarios increases [27]. The above optimization models usually assume that the probability distribution of stochastic demand is known beforehand, which is inconsistent with the actual situation. In addition, it is difficult to deal with uncertain parameters and solve unexpected situations in production through these models.

In recent years, many scholars and experts have introduced robust optimization methods to the solution of various problems of supply chain management to improve the robustness of the model. Robust optimization model methods have been extensively studied to reduce the chance of stochastic problems. Gulpinar and Pachamanova proposed a robust optimization model for equipment location under worst-case scenarios by assuming that stochastic demand belongs to an uncertain set [28]. Zokaee et al. studied the optimization of robust supply chain networks by assuming that demand, inventory capacity, and cost parameters belong to box set [29]. This model considers that uncertain parameters belong to a set and studies the decision-making problem with minimum total costs in the worst case. In addition, robust optimization as optimization theory is widely used in many practical scenarios, such as large-scale group decision-making [30], consensus decision-making [31], multicriteria decision-making [32], and energy forecasting [33]. The extensive application of robust optimization model in different fields makes scholars pay more attention to its expansibility. However, it is rarely found in the previous literature that robust optimization is used to study the sustainable development of cold chain. Therefore, it is more attractive to further expand the research of robust optimization.

As an effective tool for uncertain optimization, robustness optimization does not rely on the probability distribution of events but represents unknown parameters with specific sets of uncertainties. As a result, considering the uncertainty of cold chain logistics research, there are many potential benefits of extending robust optimization theory to solve the transportation problems of fresh cold chain logistics [34, 35]. They are independent of the probability distribution of the needs of the target audience; and they maintain robustness even in the worst case. Robust optimization is introduced into cold chain logistics. However, in the research of fresh product cold chain logistics, only a few scholars use stochastic probability model, and no other scholars use two-stage robust optimization theory to study. Robust optimization can consider the risk preference and conservativeness of decision-makers to some extent, and it has important research value in the research of fresh cold chain logistics.

In conclusion, although scholars have carried out extensive research on the impact of carbon emission factors and policy factors on cold chain logistics, there are still some problems in the existing research. Firstly, the qualitative type of overview paper covers a comprehensive range of fields but

lacks comparative analysis of data. Secondly, most of the mathematical model papers of quantitative type study low-carbon cold chain logistics from a single angle or aspect, and the factors involved in the research are not comprehensive enough. In addition, most of the studies do not consider the impact of uncertainty parameters on logistics transportation services, which is difficult to reflect the real market operation. Few researchers use quantitative methods to study low-carbon cold chain logistics under uncertain demand. What is more, there are few papers on the research of cold chain logistics in low-carbon economy mode using robust optimization theory in methodology. Therefore, how to apply robust optimization theory to low-carbon cold chain is particularly novel.

The contributions and innovations of this research are as follows:

- (i) Carbon emission factors are introduced into the study of cold chain logistics, taking into account fixed costs, time window costs, transportation costs, and carbon emission costs. A two-stage stochastic optimization model is built according to the actual situation.
- (ii) Robust optimization theory is applied to fresh cold chain logistics, and stochastic optimization model is converted into robust optimization model considering uncertainty.
- (iii) Data-driven method is used to preprocess model parameters, which is more universal than stochastic optimization method and can describe the real scene more accurately.
- (iv) The data from real market operation is used for simulation calculation to provide decision support for fresh cold chain transportation enterprises.
- (v) It provides important theoretical support and design scheme for the green and efficient development of cold chain logistics industry distribution.

This paper studies how to construct TSRO models to discuss warehousing-transportation joint optimization under uncertain demand. The first-stage decision is node selection, and the second-stage decision is transportation route planning. First, in order to improve customer satisfaction with commodity demand, TSRO models with carbon emission constraints are considered. Unlike the classical two-stage stochastic facility location problem, the model in this chapter does not assume a preknown probability distribution of stochastic demand but obtains a feasible range by means of data-driven methods. Through such a method, the research of this paper will be more valuable and meaningful.

The rest of this paper is organized as follows. Section 2 covers description of the problem and model building. Section 3 builds TSSO model and TSRO model. Section 4 verifies the validity of the model with the aid of an example. Section 5 makes detailed analysis and comparison on the performance of the model. Section 6 summarizes the conclusions of this study and future research directions.

2. Problem Description

2.1. Problem Description. This paper studies the two-stage location and path planning problem of cold chain considering carbon emission (Figure 1). In this problem, fresh products are transported from the place of origin to the demand stores through the intermediate warehouses. Two types of sites are considered: candidate intermediate warehouses and demand stores. Considering cost minimization and demand responsiveness, transfer cold storage has binary functions. On the one hand, in order to meet the demand, the intermediate warehouse should consider the prestorage quantity of products; on the other hand, the goal is to minimize the total cost after meeting the demand.

In the two-stage location path planning problem, the cost types considered include the construction cost of refrigerated warehouse, vehicle operation cost, time window cost, carbon emission cost, and transportation cost. In the distribution of products, the fairness of material distribution should be ensured as far as possible, and the delay loss caused by insufficient material supply and the cost consumed in the process of storage and distribution should be minimized. Enterprises can optimize the distribution of goods from warehouse to retail store [36, 37]. This paper merely considers the selection of warehouse and the distribution from warehouse to retail store and does not consider the upstream procurement and the sales process from retail store to customer. Under the uncertain demand environment, the first stage decision is to choose the warehouse. In the second stage, the basic inventory of the selected warehouse and the distribution proportion of goods from the warehouse to the demand site are determined. The goal of the problem is to minimize the total cost under the constraint of satisfying the demand.

2.2. Basic Assumptions. Considering the actual situation of cold chain, the following assumptions are proposed for the material scheduling problem:

- (i) Path optimization problem provides distribution services from multiple distribution centers to multiple demand sites
- (ii) All demand sites must obtain cold chain distribution service, and each demand site has a refrigerator car to provide delivery service
- (iii) Refrigerated vehicle is the same model, with the same fuel consumption and load capacity
- (iv) The geographical location and time window of the demand stores are known
- (v) The vehicle runs at a constant speed, directly transports, and returns to the distribution center immediately after completing the distribution

For the convenience of introduction, the symbols of relevant parameters and decision variables are summarized as shown in Table 1.

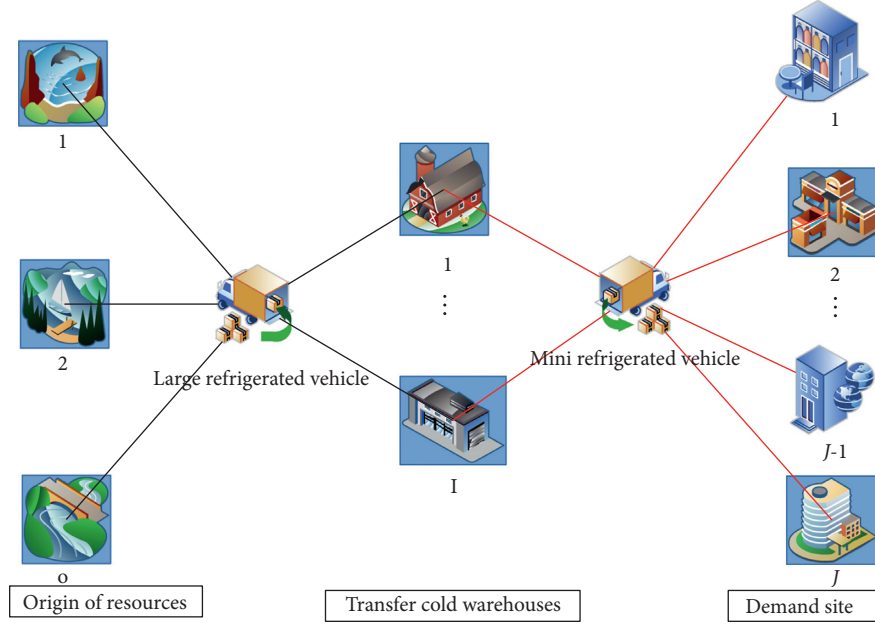


FIGURE 1: Schematic diagram of fresh cold chain path planning.

TABLE 1: Description of relevant parameters and variables of the model.

| Sign | Description |
|--------------------|---|
| x_i | $x_j \in \{0, 1\}$, 0-1 variable, if $x_i \neq 0$, select i as the storage site; else, do not select; |
| y_{ij} | $y_{ij} \in [0, 1]$, continuous variable, if $y_{ij} \neq 0$, select the path ij ; |
| D_j | Demand |
| c_f | Fixed cost |
| λ | Corruption rate of fresh products |
| H_j^{Max} | Maximum inventory of transfer cold storage |
| H_v | Maximum load capacity of large refrigerated vehicle |
| h_v | Maximum load capacity of minirefrigerated vehicle |
| h_k | Fuel consumption cost of unit vehicle transportation |
| c_v | Unit consumption cost of fuel |
| E_c | Unit fuel consumption of vehicle |
| c_t | Unit delay penalty cost |
| c_e | Unit carbon tax |
| d_{oi} | Distance between place of origin and transfer cold storage |
| d_{ij} | Distance from temporary cold storage to demand site |
| \bar{v}_i | Average vehicle speed |
| t_j | Base time of arrival |
| T_j^{Max} | Maximum arrival time |
| I | The set of transfer cold storages consists of i |
| J | The set of demand sites consists of j |

2.3. Cost Analysis. The objective of this study is to minimize the comprehensive cost of cold chain to reflect the actual situation of cold chain transportation process. It not only considers the minimum carbon emissions but also weighs the cost of distribution under the condition of low-carbon economy. Comprehensive cost includes fixed cost, transportation cost, time cost, and carbon emission cost. The cost is explained in detail as follows.

2.3.1. Fixed Cost. Fixed costs are investment costs for infrastructure, including operating costs for cold storages, vehicle maintenance costs, and driver wages. Fixed costs are

independent of inventory management and total mileage of the vehicle. The fixed costs of cold chain are calculated as follows:

$$C_f = \sum_i f_i[x_i], \quad \forall i \in \mathcal{I}. \quad (1)$$

2.3.2. First-Stage Transportation Cost. The first stage is when the product is transported from its origin to a cold storage warehouse with a large capacity and a single fixed vehicle type. Therefore, the transportation costs of fresh products during this stage are as follows:

$$C_{t1} = \frac{c_{t1}}{(1-\lambda)H_v} \sum_i \sum_j D_j d_{oi}, \quad \forall i \in \mathcal{I}, \forall j \in \mathcal{J}, \quad (2)$$

where c_{t1} represents the unit fuel consumption cost. H_v represents the carrying capacity of a large transport vehicle. λ represents the corruption rate of fresh products and $1-\lambda$ represents the product survival rate [38, 39].

2.3.3. First-Stage Carbon Emission Cost. The first phase is when products are shipped from their origin to cold storage warehouse, where the carbon cost of cold chain is as follows:

$$C_{e1} = \frac{c_{e1}}{(1-\lambda)H_v} \sum_i \sum_j e E_1 D_j d_{oi}, \quad \forall i \in \mathcal{I}, \forall j \in \mathcal{J}. \quad (3)$$

In the previous equation, c_{ce} is the carbon tax amount. E_1 is the unit energy consumption. e is the carbon dioxide factor.

2.3.4. Second-Stage Transportation Cost. The second stage is the transportation of fresh products from transfer cold storages to demand stores. Fresh products are precisely distributed with the following transportation costs:

$$C_{t2} = \frac{c_{t2}}{h_v} \sum_i \sum_j D_j y_{ij} d_{ij}, \quad \forall i \in \mathcal{I}, \forall j \in \mathcal{J}. \quad (4)$$

In the previous equation, c_t represents the unit fuel consumption cost of mini vehicles.

2.3.5. Cost of Time Window. Time costs are penalties for time delays in the following form:

$$C_p = c_p \sum_i \sum_j x_i \left(\frac{d_{ij}}{\bar{v}_i} - t \right), \quad \forall i \in \mathcal{I}, \forall j \in \mathcal{J}, \quad (5)$$

where c_p represents the time-related unit penalty cost [40].

2.3.6. Second-Stage Carbon Emission Cost. Due to the environmental requirements of the government, a certain amount of carbon tax will be levied on the vehicle at the following cost:

$$C_{e2} = c_{e2} \sum_i \sum_j \left[e d_{ij} E_{21} (D_j y_{ij}) + e E_{22} y_{ij} D_j \frac{d_{ij}}{\bar{v}_j} \right], \quad (6)$$

$$\forall i \in \mathcal{I}, \forall j \in \mathcal{J}.$$

In the previous equation, c_e is the unit carbon tax amount, E_{21} is the unit oil consumption, expressed as $E_{21} = D_j y_{ij} (\eta_{\max} - \eta_0) / h_v + \eta_0$, η_{\max} is the full load oil consumption, η_0 is the no-load oil consumption, and E_{22} represents the unit oil consumption of the refrigeration equipment [41].

3. Model Establishment

3.1. TSSO Model. In this section, we build a two-stage stochastic optimization (TSSO) model, which aims to

minimize the total cost on the basis of maximizing customer demand. The specific model is as follows:

$$\min \{C_f + C_2(\tilde{D}_j | x, y)\}, \quad (7)$$

$$\text{s.t. } x_i \in \{0, 1\}, \quad \forall i \in \mathcal{I}. \quad (8)$$

Depending on the actual scenario, the first stage of a TSSO model aims to minimize the total cost. The first item of objective function (7) is fixed cost, which includes infrastructure investment costs, including equipment loss costs and basic hydropower costs. Fixed cost is independent of vehicle routing planning. The second cost is affected by the uncertain parameters of the second stage. Constraint (8) represents 0-1 variable that participates in the corresponding logistics operation if and only if $x_i = 1$. The random variable ε is defined in the probability space P, Ξ and assumes that the first and second moment are precisely known beforehand; that is, $E_P[\varepsilon] = \mu_0$, $E_P[(\varepsilon - \mu_0)(\varepsilon - \mu_0)^T] = \Sigma_0 > 0$. The second stage of the TSSO model is shown as follows:

$$\begin{aligned} & C_p + \max_P [C_{t1}(\tilde{D}_j) + C_{t2}(\tilde{D}_j) + C_{e1}(\tilde{D}_j) + C_{e2}(\tilde{D}_j)] \\ & \leq C_2(\tilde{D}_j | x, y), \end{aligned} \quad (9)$$

$$\text{s.t. } \sum_i \sum_j y_{ij} \leq 1, \quad \forall i \in \mathcal{I}, \forall j \in \mathcal{J}, \quad (10)$$

$$y_{ij} \leq x_j, \quad \forall i \in \mathcal{I}, \forall j \in \mathcal{J}, \quad (11)$$

$$\sum_i \sum_j y_{ij} \tilde{D}_j \leq H_j^{\text{Max}}, \quad \forall i \in \mathcal{I}, \forall j \in \mathcal{J}, \quad (12)$$

$$\lceil y_{ij} \rceil \left(\frac{d_{ij}}{\bar{v}_j} \right) \leq T_{ij}^{\text{Max}}, \quad \forall j \in \mathcal{J}, \quad (13)$$

$$\max_P [C_{e1}(\tilde{D}_j) + C_{e2}(\tilde{D}_j)] \leq C_E^{\text{Max}}, \quad \forall j \in \mathcal{J}, \quad (14)$$

$$P\{\varepsilon \notin \Xi_j\} \leq 1 - \alpha_j, \tilde{D}_j = D_j^0 + \varepsilon D_j^0, \quad \forall j \in \mathcal{J}, \quad (15)$$

$$0 \leq y_{ij}, x_i \in \{0, 1\}, \quad \forall i \in \mathcal{I}, \forall j \in \mathcal{J}. \quad (16)$$

In the process of solving optimization problem (7)–(16), the following difficulties will be faced. On the one hand, in practical applications, the probability distribution of random parameters is unknown. Even if it is assumed to follow a known probability distribution, the calculation of the objective function of the problem is extremely difficult for continuous random variables. There is no ideal model in real life. It is often difficult to obtain the development law of key parameters, especially the probability distribution of demand parameters. On the other hand, the model contains multiple opportunity constraints because the probability distribution of random demand is unknown. Therefore, this constraint problem is nonconvex, which is also very difficult to deal with in calculation. Based on the above two

difficulties, the concept of robust optimization is introduced, and robust model can effectively provide an effective measure of uncertainty. Robust optimization research has higher applicability and stability than others. In this section, the above deterministic TSSO model is transformed into TSRO models by applying the relevant theory of robust optimization, so that the uncertain parameters change within the uncertain set, so that the probability distribution independent of the model can also be used to study the inventory routing problem. Based on stochastic model, initial site demand is defined as stochastic demand parameter $\tilde{D}_j = D_j^0 + \hat{D}_j$, D_j^0 is nominal demand, $\hat{D}_j = \varepsilon D_j^0$ is fluctuation demand, and ε is disturbance proportion. Then, the TSRO models are established, respectively [42–44].

3.2. Box Set Two-Stage Robust Optimization (BTSRO) Model. In the BTSRO model, the uncertain demand is \tilde{D}_j . According to the robust optimization theory, the TSSO model is further transformed into a BTSRO model, and the definition domain of uncertain parameters is $\cup_B = \{\varepsilon: \|\varepsilon\|_\infty \leq \Psi_j\} \Leftrightarrow \{\varepsilon_j: \varepsilon_j \leq \Psi_j\}$, and Ψ_j represents uncertain level parameters (i.e., safety parameters), indicating that at most Ψ_j parameters deviate from nominal values [45].

Theorem 1. *With the box set uncertain parameters, when the uncertain parameter is not 0, the BTSRO model $\inf x, y \{t: \cup_B(C, A, B) \{ \sup C_1^T(\varepsilon)x \leq t \& \sup C_2^T(\varepsilon)y \leq t \& A^T x \leq B \} \}$ is equivalent to them in the TSSO model $\min x, y \{t: P(C, A, B) \{ C_1^T x \leq t \& C_2^T y \leq t \& A^T x \leq B \} \geq 1 - \alpha_j \}$. When the uncertain parameter is 0, the BTSRO model degenerates into a two-stage linear optimization model.*

The first stage of the BTSRO model is (17)–(19), the goal of which is how to pursue the minimization of the total cost under uncertain conditions.

$$\inf Z_B, \quad (17)$$

$$\text{s.t. } \sup_{\cup_B} (C_f + C_2(\tilde{D}_j|x, y)) \leq Z_B, \quad (18)$$

$$x_i \in \{0, 1\}, \quad \forall i \in \mathcal{I}. \quad (19)$$

The second stage of the BTSRO model is (20)–(27) with the goal of pursuing a minimized distribution cost on the basis of maximizing the met customer demand.

$$\inf_{\cup_B} C_2(\tilde{D}_j|x, y), \quad (20)$$

$$\text{s.t. } C_p + \left\{ C_{t1,t2}(D_j^0) + C_{e1,e2}(D_j^0) + \sup_{\cup_B} \Psi_j \cdot [C_{t1,t2}(\hat{D}_j) + C_{e1,e2}(\hat{D}_j)] \right\} \leq C_2, \quad (21)$$

$$\sum_i \sum_j y_{ij} \leq 1, \quad i \in I, \forall j \in \mathcal{J}, \quad (22)$$

$$\sum_i \sum_j y_{ij} D_j^0 + \Psi_j' \sum_i \sum_j y_{ij} \hat{D}_j \leq H_j^{\text{Max}}, \quad \forall i \in \mathcal{I}, j \in \mathcal{J}, \quad (23)$$

$$\lceil y_{ij} \rceil \cdot \left(\frac{d_{ij}}{\bar{v}_j} \right) \leq T_{ij}^{\text{Max}}, \quad \forall j \in \mathcal{J}, \quad (24)$$

$$\sup_{\cup_B} [C_{e1}(\tilde{D}_j) + C_{e2}(\tilde{D}_j)] \leq C_E^{\text{Max}}, \quad \forall j \in \mathcal{J}, \quad (25)$$

$$\mathcal{P}\{\varepsilon | \varepsilon \notin \cup_B\} \leq 1 - \alpha_j, \quad \forall j \in \mathcal{J}, \quad (26)$$

$$0 \leq y_{ij} \leq x_i, x_i \in \{0, 1\}, \quad \forall i \in \mathcal{I}, \forall j \in \mathcal{J}. \quad (27)$$

Proof. In stochastic optimization (SO), the uncertain numerical data are assumed to be random. In the simplest case, these random data obey the probability distribution that is known in advance, while, in more advanced settings, this distribution is only partially known. Here again an uncertain problem is associated with a deterministic counterpart, most notably with the chance constrained problem $\min x, y \{t: P(C, A, B) \{ C_1^T x \leq t \& C_2^T y \leq t \& A^T x \leq B \} \geq 1 - \alpha_j\}$, where $\alpha_j \ll 1$ is a given tolerance and P is the distribution of the data (C, A, B) . When this distribution is only partially known, all we know is that P belongs to a given family \mathbb{P} of probability distributions on the space of the data. The above setting is replaced with the constrained setting. The stochastic optimization approach seems to be more conservative than the worst-case-oriented robust optimization approach. In the stochastic optimization model, the probability distribution of parameters in the model is required to be high, and a large amount of historical data is frequently needed for reasoning and analysis. Therefore, the feasibility of stochastic optimization is not high. We transform it into a robust optimization model. Set $\mathbb{P}_\infty = [\mathcal{F}_{L \times L}; \mathbb{O}_{1 \times L}]$, $\mathcal{P}_\infty = [\mathcal{O}_{L \times 1}; \Psi] \dots \infty = \{[\theta_{L \times 1}; t]: \|\theta\|_\infty = t\}$, where L is the number of uncertain parameters. The parameters of the model change from uncertain distribution probability \mathbb{P} to uncertain set \cup_B . The original probability distribution constraint form, $P(C, A, B) \{ C_1^T x \leq t \& C_2^T y \leq t \& A^T x \leq B \} \geq 1 - \alpha_j$ (i.e., $\mathbb{P}(\cdot) \geq 1 - \varepsilon$) for all $P \in \mathbb{P}$, is transformed into robust optimization form $\cup_B(C, A, B) \{ \sup C_1^T(\varepsilon)x \leq t \& \sup C_2^T(\varepsilon)y \leq t \& A^T x \leq B \}$ (i.e., $\sup C_n^T(\varepsilon)x \leq t$) for all $n \in \{1, 2, \dots, n-1, n\}$, where t is the corresponding right-hand constraint. So, Theorem 1 is proved. \square

3.3. Ellipsoid Set Two-Stage Robust Optimization (ETSRO) Model. In the ETSRO model, the uncertain demand is \tilde{D}_j and the uncertain parameters belong to the set of ellipsoids [46]. $\{\{\cup_E\} \|\varepsilon\|_2 \leq \Omega_j \Leftrightarrow \varepsilon \sqrt{\sum_j \varepsilon_j^2} \leq \Omega_j\} \Rightarrow \{\tilde{D}_j \in \mathbb{R}, \sum_j [(\tilde{D}_j - D_j^0)/\hat{D}_j]^2 \leq \Omega_j^2\}$ is defined according to l_2 norm, of which Ω_j is an adjustable security parameter. This is a nonlinear constraint problem, $\{\cup_E\} \Leftrightarrow \{\tilde{D} \in \mathbb{R}, (\tilde{D}_j - D_j)^T$

$C^{-1}(\tilde{D}_j - D_j) \leq \Omega_j^2$, where C is an n -order diagonal matrix with elements; then $C(D_j^0) + \Omega_j \sqrt{\sum_j (\hat{D}_j^2) [\sum_{l,j} (y_{lj}) c_t]^2} \leq Z_E$.

Theorem 2. *With the ellipsoid set uncertain parameters, when the uncertain parameter is not 0, the ETSRO model $\inf x, y \{t: \cup_E (C, A, B) \{ \sup C_1^T(\varepsilon) x \leq t \& \sup C_2^T(\varepsilon) y \leq t \& A^T x \leq B \} \}$ is equivalent to them in the TSSO model $\min x, y \{t: P(C, A, B) \{ C_1^T x \leq t \& C_2^T y \leq t \& A^T x \leq B \} \geq 1 - \alpha_j \}$. When the uncertain parameter is 0, the ETSRO model degenerates into a two-stage linear optimization model.*

The first stage of ETSRO model is (28)–(30), and the goal is how to pursue the minimization of the total cost under the condition that the uncertain parameters obey the ellipsoid set.

$$\inf_{\cup_E} Z_E, \quad (28)$$

$$\text{s.t. } C_f + \sup_{\cup_E} [C_2(\tilde{D}_j | x, y)] \leq Z_E, \quad (29)$$

$$x_i \in \{0, 1\}, \quad \forall i \in \mathcal{I}. \quad (30)$$

The second stage of the ETSRO model is (31)–(41), which aims to pursue a minimized path transportation cost on the basis of maximizing the met demand.

$$\inf_{\cup_E} Z_E C_2(\tilde{D}_j | x, y), \quad (31)$$

$$\text{s.t. } C_2(D_j^0) + \Omega_j Y_j + \sup_{\cup_E} [C_3(\tilde{D}_i)] \leq C_2, \quad (32)$$

$$C_p + C_{t1,e2}(D_j^0) + C_{e1,e2}(D_j^0) \leq C_2(D_j^0), \quad (33)$$

$$Y_j \geq \sqrt{\sum_{j \in \mathcal{I}} \hat{D}_j^2 r_i'^2}, \quad \forall i \in \mathcal{I}, \forall j \in \mathcal{J}, \quad (34)$$

$$r_j' \geq \sum_i \sum_j \left(x_j c_h^2 y_{ij} + \frac{c_v^2 y_{ij} d_{ij}}{h_j} \right), \quad \forall i \in \mathcal{I}, \forall j \in \mathcal{J}, \quad (35)$$

$$\sum_i \sum_j y_{ij} D_j^0 + \Omega_j Y_j \leq H_j^{\text{Max}}, \quad \forall i \in \mathcal{I}, \quad (36)$$

$$\sum_i \sum_j y_{ij} \leq 1, \quad \forall j \in \mathcal{J}, \quad (37)$$

$$\lceil y_{ij} \rceil \cdot \left(\frac{d_{ij}}{\bar{v}_j} \right) \leq T_{ij}^{\text{Max}}, \quad \forall j \in \mathcal{J}, \quad (38)$$

$$\sup_{\cup_E} [C_{e1}(\tilde{D}_j) + C_{e2}(\tilde{D}_j)] \leq C_E^{\text{Max}}, \quad \forall j \in \mathcal{J}, \quad (39)$$

$$\mathcal{P}\{\varepsilon \notin \cup_E\} \leq \alpha_j, \quad \forall j \in \mathcal{J}, \quad (40)$$

$$0 \leq y_{ij} \leq x_i, x_i \in \{0, 1\}, \quad \forall i \in \mathcal{I}, \forall j \in \mathcal{J}. \quad (41)$$

Proof. It is similar to the BTSRO model proof method. In the ETSRO model, the uncertain set is transformed from probability distribution constraint $\mathbb{P}(\cdot) \geq 1 - \varepsilon$ to uncertain robust constraint $\sup C_n^T(\varepsilon) x \leq t$. In addition, the constraints of the model are scaled down appropriately, $Y_j \geq \sqrt{\sum_{j \in \mathcal{I}} \hat{D}_j^2 r_i'^2}$, and $r_j' \geq \sum_{i,j} (C_n^T x \leq B), A^T x \leq B, C, A, B \in \cup_E$. For general constraints of the model, define $\cup_E = \{a_i \in R^n: a_i = \bar{a}_i + \Delta \xi, \xi \leq \Omega\}$, where $\Delta = \sum^{1/2}$, and the constraints $\max a_i^T X \leq B$ of it can be translated as $\max \{a_i^T X: (a_i - \bar{a}_i)^T \Sigma^{-1} (a_i - \bar{a}_i) \in \Omega^2\}$. As for Σ is positive, so it is a convex problem. Set $\mathbb{P}_2 = [\mathcal{I}_{L \times L}; \mathbb{O}_{1 \times L}], \mathcal{P}_2 = [\mathcal{O}_{L \times 1}; \Omega_j], \dots, 2 = \{[\theta_{L \times 1}; t]: \|\theta\|_2 = t\}$, where L is the number of uncertain parameters. The parameters of the model change from uncertain distribution probability \mathbb{P} to uncertain set \cup_E . The original probability distribution constraint form, $P(C, A, B) \{C_1^T x \leq t \& C_2^T y \leq t \& A^T x \leq B\} \geq 1 - \alpha_j$, is transformed into robust counterpart form $\cup_E (C, A, B) \{ \sup C_1^T(\varepsilon) x \leq t \& \dots, \sup C_n^T(\varepsilon) y \leq t \& A^T x \leq B \}$, where t is the corresponding right-hand constraint. The latter is called the robust counterpart of the original uncertain problem.

So, Theorem 2 is proved. \square

4. Simulation Experiment

This section verifies the effectiveness of the proposed model in solving cold chain management problems through simulation. This paper selects a cold chain company in Zhejiang Province (coastal eastern China). The company is engaged in cold chain transportation and distribution services. Products are transported from Zhoushan aquatic products trading center to inland demand sites through transit warehouse, as shown in Figure 2. In the process of production and operation, the transportation department is faced with vehicle location and path planning problem. Due to the perishability of products, strict cold chain technology must be adopted for storage and transportation. On the basis of comprehensive consideration of related costs, the following numerical case simulation is carried out.

The first stage is the location problem of transfer of cold storage sites. Due to the perishability of fresh products, it strongly depends on cold fresh technology for storage and transportation. In the process of transportation, fresh products require the whole cold chain, once exposed to normal-temperature or high-temperature environment, it is easy to rot. In site selection, the feasibility of transportation cost and the convenience of transportation distance should be considered. Therefore, the location problem is very important. In this section, through screening, we selected Jifeng cold storage, Michaelis cold storage, Liheng cold storage, Fenghua Xiwu cold storage, and friendship cold storage factory as alternative sites. They are represented by



FIGURE 2: Logistics transportation scenario.

C1, C2, C3, C4, and C5. The goal of the first stage is to determine the location site and calculate the total cost.

The second stage is path planning. There are 5 alternative transfer cold storages and 8 demand sites. The demand sites are Walmart (plant doctor store), Walmart Shopping Plaza (Ningbo Siming Middle Road store), Metro RT Mart, Carrefour (Beilun store), RT Mart (Nanshan Road store), RT Mart (Xiangshan store), RT Mart (Cixi store), and Carrefour (Jiangdong store), which are expressed by $D_1, D_2, D_3, D_4, D_5, D_6, D_7$, and D_8 . The goal of the second stage is to minimize the initial distribution cost, including material handling cost, transportation cost, and time cost. In the process of calculation, the setting of transportation cost is based on the comprehensive calculation of real-time oil price and actual distance and even involves factors such as traffic congestion and time limit. On the basis of comprehensive consideration of related costs, the following numerical case simulation is carried out in this section.

4.1. Relevant Data Acquisition. The basic data information includes the fixed operating cost, demand, average vehicle speed of shelter hospital, demand of designated hospital, and vehicle speed (Table 2).

This section directly obtains the actual distance between sites through Google Maps, as shown in Table 3. The vehicle-related parameters are listed (Table 4).

Other parameters of the model are as follows. In addition, the energy consumption of refrigeration equipment is 0.25 L/h * t, and the emission coefficient of CO₂ is 2.61 kg/L [41, 47, 48].

TABLE 2: Basic parameters.

| Transfer cold storages | C_1 | C_2 | C_3 | C_4 | C_5 |
|------------------------|--------|--------|--------|--------|--------|
| Distance | 110.6 | 127.8 | 88.5 | 134.1 | 153.9 |
| Maximum inventory | 160 | 170 | 140 | 135 | 140 |
| Average speed | 56 | 47 | 48 | 62 | 50 |
| Fixed cost | 17,500 | 16,500 | 15,500 | 14,500 | 13,200 |
| Demand site | D_1 | D_2 | D_3 | D_4 | D_5 |
| Nominal demand | 55 | 45 | 40 | 35 | 60 |
| Demand site | D_6 | D_7 | D_8 | — | — |
| Nominal demand | 50 | 75 | 68 | — | — |

TABLE 3: Distance between sites.

| Distance | D_1 | D_2 | D_3 | D_4 | D_5 | D_6 | D_7 | D_8 |
|----------|-------|-------|-------|-------|-------|-------|-------|-------|
| C_1 | 24.6 | 26.3 | 26.4 | 53.2 | 41.3 | 92.8 | 48.7 | 32.9 |
| C_2 | 26.9 | 19.2 | 30.4 | 54.2 | 20.9 | 80.9 | 77.2 | 34.9 |
| C_3 | 15.3 | 16.4 | 22.4 | 30.2 | 39.8 | 76.5 | 63.6 | 8.7 |
| C_4 | 27.3 | 21.4 | 44.3 | 53.1 | 11.1 | 67.5 | 89.4 | 28.9 |
| C_5 | 45.3 | 37.8 | 58.7 | 67.5 | 25.4 | 64.3 | 107.5 | 45.7 |

4.2. Results of Two-Stage Stochastic Optimization Model. In this section, we use MATLAB as the programming platform and use the solvers Gurobi (G) and CPLEX (C), respectively, to solve the above models. The results of the two-stage stochastic optimization model are shown in Table 5.

In the TSSO model, the operation results of the model are affected by the probability distribution of random parameters. In this section, the common probability distribution is selected for simulation experiment. With the increase of the mean value of random parameters

TABLE 4: Vehicle related parameters.

| Types | Length | Max-loading | Transportation cost | Fuel | Corruption rate |
|-------|--------|-------------|---------------------|--------|-----------------|
| Large | 5.6 m | 5–8 t | 20 CNY/km | 25.5 L | 0.03 |
| Small | 3.6 m | 3–5 t | 12 CNY/km | 14.4 L | 0.04 |

TABLE 5: Calculation results of TSSO model.

| Type | Mean | Cost (G) | Cost (C) | Sites | Time (G) | Time (C) | Gap % |
|-------------|------|----------|----------|---------------|----------|----------|-------|
| Uniform | 0.10 | 9.13E+04 | 9.13E+04 | 1, 2, 3, 4, 5 | 366.9 ms | 642.1 ms | <0.01 |
| Weibull | 0.10 | 9.11E+04 | 9.12E+04 | 1, 2, 3, 4, 5 | 396.8 ms | 635.3 ms | <0.01 |
| Normal | 0.10 | 9.17E+04 | 9.17E+04 | 1, 2, 3, 4, 5 | 320.5 ms | 631.3 ms | <0.01 |
| Bernoulli | 0.10 | 9.15E+04 | 9.14E+04 | 1, 2, 3, 4, 5 | 366.8 ms | 639.6 ms | <0.01 |
| Exponential | 0.10 | 9.58E+04 | 9.58E+04 | 1, 2, 3, 4, 5 | 370.0 ms | 633.2 ms | <0.01 |
| Gamma | 0.10 | 9.16E+04 | 9.17E+04 | 1, 2, 3, 4, 5 | 381.5 ms | 636.1 ms | <0.01 |
| Poisson | 0.10 | 9.17E+04 | 9.17E+04 | 1, 2, 3, 4, 5 | 336.3 ms | 646.9 ms | <0.01 |

(0.02 \rightarrow 0.20), the total cost shows an upward trend (9.13E+04 \rightarrow 9.58E+04). There are five level-1 rescue sites opened. Acting on the different distribution, the total cost of emergency management is also quite different. This implies that, in the stochastic model, the change of parameters directly affects the total cost. However, under the circumstances of actual emergency, the development of the situation has great uncertainty frequently. It is difficult to obtain sufficient historical data to calculate the specific distribution function of parameters or even to accurately estimate the mean and variance of parameters, so the feasibility of stochastic optimization model in emergency management is low. It can be seen from the comparison of computational efficiency and performance of the model that two kinds of solvers are used to solve the model. The speed of Gurobi is at least 1.5 times faster than that of CPLEX. Obviously, Gurobi is better than CPLEX. It is found that there is a relationship Gap < 0.01 in the error comparison, which shows that the two algorithms are effective.

4.3. Results of Data-Driven Two-Stage Robust Optimization Model. The existence of big data service platform provides a strong guarantee for the specific demand value of samples collected before the route planning, so that the two-stage stochastic programming problem in this paper can be transformed into a more practical decision-making problem.

As shown in Figure 3, with the big data service platform as the core, a complete process from data input, data collection to data analysis, and processing is constructed. Among them, the data processing end plays a dual role in the collection of demand data: on the one hand, the data processing end connects with the big data service platform, within the feasible authority, directly obtains the user's personal data from the platform, plays the role of text mining, and obtains the original data. On the other hand, the collected data are cleaned to obtain the key parameters.

The specific data processing steps are shown in Table 6.

Through the above steps, this paper obtains the basic sample data set of the region. The fitting interval shown in Table 7 can be obtained by normalizing the sample data. The validity of the interval is represented by the coverage of

sample requirements. The range of fluctuation parameters of the sampled data is used as the classification basis, and the coverage rate is used to measure the advantages and disadvantages. Through MATLAB programming, the following results are obtained.

It can be seen that, with the increase of safety parameters, the two total costs show a gradual upward trend. When the safety parameter is 0, the two-stage robust optimization model is equivalent to the two-stage stochastic chance constrained model. In the two-stage box set robust optimization model, when the safety parameter increases from 1 to 8, the total cost increases from 9.23E+04 to 9.48E+04 CNY, with an increase of 2.71%. In the ellipsoid set two-stage robust optimization model, when the safety parameter increases from 1 to 8, the total cost increases from 9.23E+04 to 9.47E+04 CNY, with an increase of 2.54%. These rising costs are the cost of robustness. It is found that the ETSRO model is more robust. In terms of demand coverage, the larger the upper and lower bounds of demand fluctuation are, the wider the coverage is. When the upper and lower bounds of demand fluctuation change from ± 0.05 to ± 0.10 , the coverage increases from 95.90% to 99.00%.

4.4. Path Planning Scheme Based on Model. From Table 8, it can be seen that, under the TSSO model, the first stage is about the location of the cold storages, and C1, C2, C4, C5 are chosen. The second stage is the path planning. The proportion of transportation is mainly C1, C2, 37.34% and 26.07% of total demand, respectively. It is responsible for the supply of main materials to meet the needs of demand site.

From Table 9, it can be seen that, under the BTSRO model, the first stage is to choose the location of the cold storage, and C1, C2, C3, C4, C5 are chosen. Compared with the TSSO model, the number of the sites increases by C3. The second stage is path planning, with C1, C5 as the main transshipment proportion, accounting for 36.31% and 23.30% of the total demand, respectively, to meet the needs of all required sites.

From Table 10, it can be seen that, under the TSRO model of the oval collection, the first stage is about the location of the cold storage, and C1, C2, C3, C4, C5 are chosen. Compared with the TSSO model, the new station C3

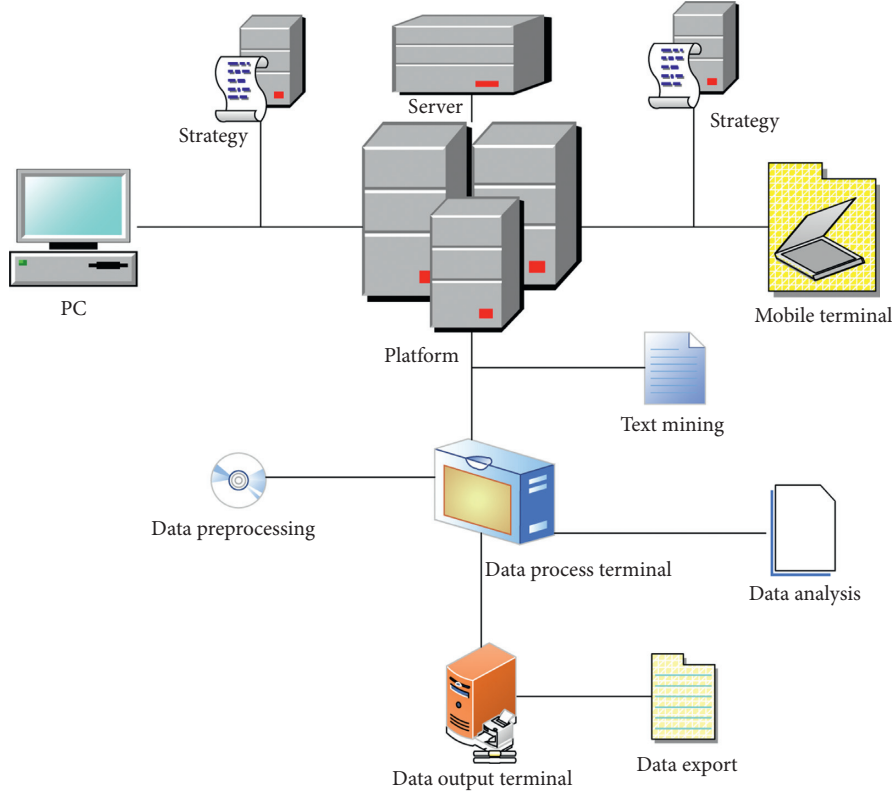


FIGURE 3: Data acquisition and processing based on platform.

TABLE 6: Detailed explanation of data processing steps.

| Step | Specific description |
|--------|--|
| Step 1 | Original data collection: with the help of big data service platform, mining the sample set of demand through text; |
| Step 2 | Data cleaning: eliminate incomplete data; set filtering range to eliminate data group with abnormal value; |
| Step 3 | Data processing: fitting regression analysis of sample set data; |
| Step 4 | Demand estimation: with the help of the parameter index of the sample data set, the overall demand parameters are estimated; |
| Step 5 | Input the initial value, input the constraint variables, and set the parameters to obey the probability distribution; |
| Step 6 | Input parameter variable constraints, storage capacity constraints and time window constraints, etc.; |
| Step 7 | The solution environment is set and solved by the solver Gurobi; |
| Step 8 | If step 2 is satisfied, terminate; if not, reexecute step 1; |
| Step 9 | If the model converges or iterates to a certain number of times, the optimal solution is output. |

TABLE 7: Results of a two-stage robust optimization model.

| SP | ϵ | BTSRO model | | | ETSRO model | | |
|----|------------|-------------|-----------|--------------|-------------|-----------|--------------|
| | | Cost | Time | Coverage (%) | Cost | Time | Coverage (%) |
| 1 | ± 0.05 | $9.23E+04$ | 411.60 ms | 95.50 | $9.23E+04$ | 399.25 ms | 95.90 |
| 2 | ± 0.05 | $9.25E+04$ | 405.52 ms | 95.50 | $9.23E+04$ | 393.36 ms | 95.90 |
| 3 | ± 0.05 | $9.27E+04$ | 401.02 ms | 95.50 | $9.25E+04$ | 388.99 ms | 95.90 |
| 4 | ± 0.05 | $9.30E+04$ | 409.74 ms | 95.50 | $9.28E+04$ | 397.45 ms | 95.90 |
| 5 | ± 0.05 | $9.31E+04$ | 411.21 ms | 95.50 | $9.29E+04$ | 398.87 ms | 95.90 |
| 6 | ± 0.05 | $9.33E+04$ | 416.11 ms | 95.50 | $9.32E+04$ | 403.62 ms | 95.90 |
| 7 | ± 0.05 | $9.35E+05$ | 417.68 ms | 95.50 | $9.35E+05$ | 405.15 ms | 95.90 |
| 8 | ± 0.05 | $9.39E+04$ | 408.27 ms | 95.50 | $9.38E+04$ | 396.02 ms | 95.90 |
| 1 | ± 0.10 | $9.24E+04$ | 423.85 ms | 98.50 | $9.23E+04$ | 411.13 ms | 99.00 |
| 2 | ± 0.10 | $9.27E+04$ | 412.09 ms | 98.50 | $9.26E+04$ | 399.73 ms | 99.00 |
| 3 | ± 0.10 | $9.31E+05$ | 415.13 ms | 98.50 | $9.31E+05$ | 402.67 ms | 99.00 |
| 4 | ± 0.10 | $9.35E+04$ | 413.66 ms | 98.50 | $9.34E+04$ | 401.25 ms | 99.00 |
| 5 | ± 0.10 | $9.39E+04$ | 414.93 ms | 98.50 | $9.38E+04$ | 402.48 ms | 99.00 |
| 6 | ± 0.10 | $9.41E+04$ | 418.07 ms | 98.50 | $9.40E+04$ | 405.53 ms | 99.00 |
| 7 | ± 0.10 | $9.45E+05$ | 420.32 ms | 98.50 | $9.45E+05$ | 407.71 ms | 99.00 |
| 8 | ± 0.10 | $9.48E+04$ | 421.40 ms | 98.50 | $9.47E+04$ | 408.76 ms | 99.00 |

TABLE 8: Path planning of TSSO model.

| | D_1 | D_2 | D_3 | D_4 | D_5 | D_6 | D_7 | D_8 |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| C_1 | | 1 | | | 0.987 | 1 | | |
| C_2 | 0.085 | | | 1 | | | | 1 |
| C_3 | | | | | | | | |
| C_4 | | | 1 | | 0.013 | | 1 | |
| C_5 | 0.915 | | | | | | | |

TABLE 9: Path planning of BTSRO model.

| | D_1 | D_2 | D_3 | D_4 | D_5 | D_6 | D_7 | D_8 |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| C_1 | 0.905 | | 1 | | | | 1 | |
| C_2 | | 0.753 | | 0.549 | 0.213 | | | |
| C_3 | 0.095 | | | 0.451 | | | | 0.136 |
| C_4 | | 0.247 | | | 0.787 | | | |
| C_5 | | | | | | 1 | | 0.864 |

TABLE 10: Path planning of ETSRO model.

| | D_1 | D_2 | D_3 | D_4 | D_5 | D_6 | D_7 | D_8 |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| C_1 | 0.925 | | 1 | | | | 1 | |
| C_2 | | 0.453 | | | 0.713 | | | |
| C_3 | 0.075 | | | 1 | | | | 1 |
| C_4 | | 0.547 | | | 0.287 | | | |
| C_5 | | | | | | 1 | | |

is chosen. The second stage is the path planning problem. The center of gravity of transportation is different from the two stages of the oval collection. The TSRO model consisted of C_1 , C_3 , 36.56% and 25.94%, respectively. Compared with the first two models, the load on some of the sites of the TSSO model is too heavy. The load proportion of the TSRO models is more reasonable and balanced.

After careful analysis, it can be found that the distribution route cost is a large part of the total cost under the TSSO model. Although this planning method can guarantee the stable supply of materials and meet the rescue needs, there would still be some problems in the specific service path planning. For example, the cost of long-distance transportation will be increased; the roundabout transportation will be caused by the crossed distribution paths, which will increase the cost; the main disaster relief spots are not used properly, which will cause the subsequent transportation costs to increase; once there is uncertainty in the actual rescue process, it will be more uncertain than the fluctuation of demand, and the stability and perseverance of the model will be randomly improved in two stages. In this way, the logistics of the rescue materials will face some challenges and difficulties. Therefore, in the process of production operation, we must make a reasonable plan and find out a better improvement strategy.

As can be seen in Figure 4, the two largest increasing transfer cold storages increase by 25.9% and 12.0%, respectively, and the two largest decreasing sites are C_2 , C_4 , respectively, -11.5% and -14.7%. The change of site inventory directly affects the change of total cost. In the sites with increasing transshipment proportion, the BTSRO model takes on more distribution tasks than the TSSO

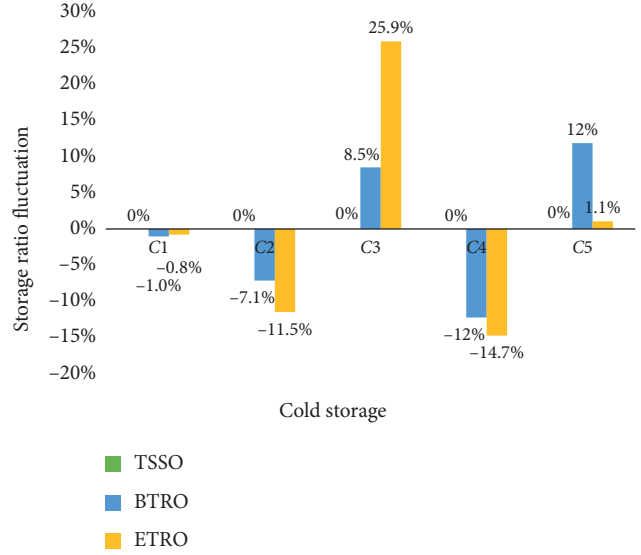


FIGURE 4: Change range of inventory proportion of cold storages.

model. In the path planning of the second stage, C_3 takes on more distribution tasks and the transshipment proportion increases by 8.5%. The ETSRO model is compared with the TSSO model. In the second stage of path planning, the proportion of transit increases by 25.9%.

In the sites with reduced transshipment proportion, in the stage of path planning, the BTSRO model is compared with the TSSO model, and the transshipment proportion of the cold storage C_2 is reduced by 7.1%. Compared with the TSSO model, the transit proportion of the ETSRO model decreases by 11.5%. In the second stage of path planning, the BTSRO model is compared with the TSSO model, and the cold storage transfer proportion decreased by 12.0%. Compared with the TSSO model, the transit ratio of the TSRO model in ellipsoid set decreases by 14.7%. In the second stage of path planning, the BTSRO model is compared with the TSSO optimization model, and the transfer proportion of C_4 decreases by 12.0%. Compared with the TSSO model, the transit ratio of the TSRO model in ellipsoid set decreases by 14.7%.

In the second stage of path planning, the proportion of transit is relatively balanced in each major transfer center, and the transit capacity and load pressure of each designated hospital are relatively balanced. As can be clearly seen in Figure 5, site C_3 goes deeper into the hinterland and is closer to the demand site, which makes path planning more reasonable. Compared with BTSRO, the ETSRO model further reduces the proportion of long-distance line transportation and increases the proportion of short-distance transportation, especially after fully utilizing C_3 . Comparatively speaking, the service proportion in each path tends to be short-haul route, which bears less cost and therefore increases the proportion of material supply. As a result, on-board mileage is more efficient, and delivery routes are more accurate and fast, showing better optimization performance. For warehousing-transportation optimization with uncertain demand, a TSRO model is



FIGURE 5: Optimal path planning scheme.

constructed by data-driven method. The uncertain set contains probability distribution functions with equal first and second moment. Compared with traditional stochastic optimization model, the established model is more robust in numerical simulation.

5. Parameter Sensitivity Analysis

This section provides a comparative analysis of the performance of each model, including the impact of carbon tax costs and safety parameters on total costs and service levels. The model performance is analyzed by Level of Service (SL). Due to the high requirement for timeliness of material dispatch in logistics management, this section compares SL of different models through time differences and analyzes the advantages and disadvantages. The SL is calculated as follows:

$$SL = \left[1 - \frac{\sum_I (y_{ij}) \tilde{D}_j d_{ij} / \bar{v} - t_j \sum_I \tilde{D}_j}{t_j \sum_I \tilde{D}_j} \right] \times 100\%, \quad (42)$$

where I, J is the indicator parameter in the model. The simulation results under different parameters are as follows.

From Figure 6, it can be seen that, as a whole, the TSRO model has better robustness than the TSSO model. When the cost of carbon tax per unit increases from 0.0 to 4.0, the cost of TSSO model increases the most, much higher than that of TSRO model. From the details, the ETSRO model is better optimized than the BTSRO model. The cost of the

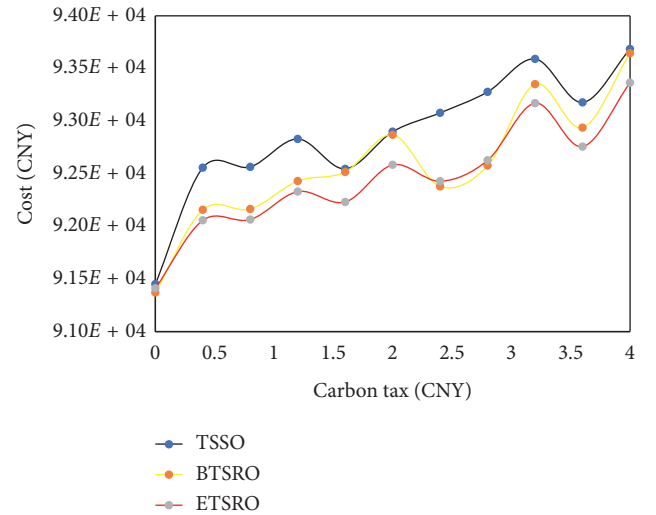


FIGURE 6: The impact of carbon emission cost on total cost.

ETSRO model grew slowly and increased slightly (+2.18%). The rising cost of carbon emissions will lead to the rise of total costs. Therefore, policymakers can implement certain restriction strategies to achieve environmental benefits in the implementation of sustainable development strategies.

Figure 7 analyzes the impact of carbon tax on SL. On the whole, with the increase of carbon tax cost, the SL of the

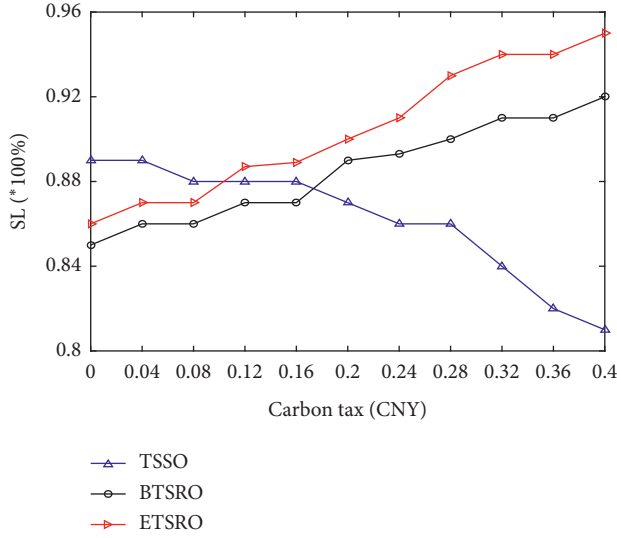


FIGURE 7: The impact of carbon tax on logistics service level.

TSSO model shows a downward trend, while the SL of the TSRO model shows an upward trend. Details show that there are differences in the rising cost trends of the TSRO model. Comparatively, the BTSRO shows more obvious trend of increasing SL and better optimization performance than the ETSRO model.

5.1. Influence of Safety Parameters and Their Responsiveness.

Figure 8 analyzes the effect of safety parameters on total cost (fixed volatility is 0.15). It can be seen that, with the increase of safety parameters, the total cost of logistics distribution is on the rise as a whole. Different two-stage robust optimization models have different rate of cost increase, while the two-stage stochastic optimization model is not affected by safety parameters and can be used as a reference standard. The box set two-stage robust optimization model increases the cost at the highest rate and pays the greatest robustness cost for improving the safety level. The ETSRO model is the most stable and pays the lowest price due to the increase of safety parameters.

Figure 9 illustrates the impact of safety parameters on the service level of the model with a fixed level of stochastic volatility ($\varepsilon = 0.10$). Overall, with the increase of security level, logistics service level shows an increasing trend. This variable compensates for the increased total cost due to uncertainty and mitigates the loss of reduced service levels due to random volatility. Careful comparison shows that the ETSRO model has strong robustness. When the safety parameters increase from 1 to 8, the logistics service level increases from 85.83% to 92.97% during the path planning phase. The performance improvement of the BTSRO model is relatively low, and the logistics service level increases from 85.67% to 90.16%. In the process of logistics transportation, managers must pay attention to fast responsiveness. Considering uncertainties, although the TSRO model can give path planning plans, the performance and application range of each scheme are also different. Therefore, decision-makers

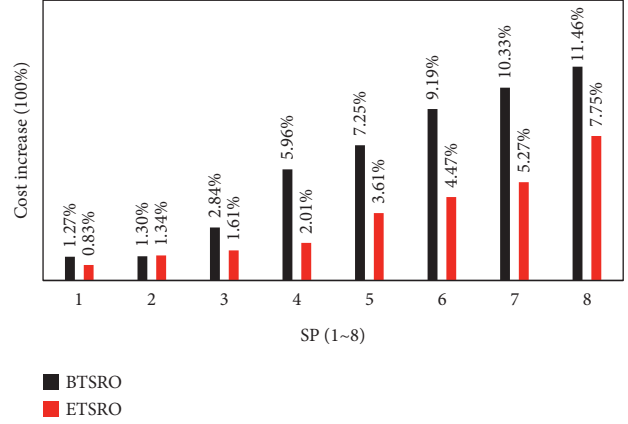


FIGURE 8: Impact of total cost with safety parameter.

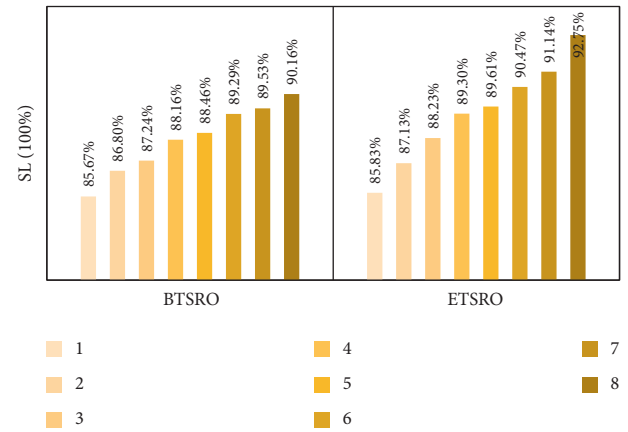


FIGURE 9: Impact of safety parameters on logistics service level.

must review the situation and make the most reasonable path planning plan according to local conditions. Decision-makers need to weigh the various objectives against the actual situation and trends of the epidemic and choose the ideal alternative for decision-making. Ideally, limited resources should be fully utilized while minimizing all costs to achieve cost savings and environmental protection.

6. Conclusion

With the continuous improvement of people's living standards, the demand for cold chain logistics is also increasing. Low carbon economy has also become the key word of logistics development.

In this paper, from the perspective of low-carbon economy, considering fixed costs comprehensively, the cold chain logistics distribution routing optimization is analyzed. A low carbon two-stage stochastic optimization model is established to solve the problem. The two-stage robust optimization model is further constructed to resist uncertain disturbances. The practicability, reliability, and stability of the two-stage model are verified by taking a fresh and cold

chain logistics transportation enterprise in the eastern coastal area of China as an example.

The simulation results show that the model proposed in this paper can solve the inventory routing optimization problem of cold chain low carbon logistics distribution in a short time.

This hybrid approach enables rational route planning, reduces overall costs and carbon emissions, and ensures the quality of logistics services. When carbon tax increases, forcing enterprises to choose a better distribution route will not only save costs but also obtain certain environmental benefits. This finding can provide some enlightenment for low-carbon transformation and development of cold chain logistics enterprises. For complex network distribution models with numerous demand stations, this paper constructs a target model and algorithm, which takes equity and efficiency into account.

This model can obtain route planning plans under different conditions in effective time, more closely match the actual situation of capital distribution, and provide more decision-making options for decision-makers. This study has the following limitations: The premise of this study is the supply chain, without considering the situation of insufficient supply. In addition, there are a lot of direct sales and direct transportation in real life, which may be the focus of future research. Low-carbon economy is widely promoted in China. The model provides theoretical support for the transformation and sustainable development of cold chain logistics enterprises. Cold chain logistics is a complex system that is affected by various attributes. In addition, this parameter configuration has not been fully verified in previous studies.

Future research may improve the proposed model and parameter configuration. The development of cold chain logistics informatization is the latest trend of logistics industry development.

Data Availability

No data were used in this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.


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Research Article

Coordination Mechanisms for the Two-Echelon Newsvendor Model with Rapidly Responsive and Strategic Consumers

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Aiming at the two-echelon newsvendor problem in which the market demand of commodities is random both in normal sales period and in liquidation period, this paper studies the pricing and ordering decision of retailers by using rational expectation equilibrium under the condition of considering consumers' strategic behavior and rapid response mechanism. Then, the decision-making problem under retailers' initial order quantity commitment is discussed, as well as the effect of commitment mechanism on supply chain performance. On this basis, both the two-part pricing contract and revenue-sharing contract are introduced to achieve supply chain coordination aiming at the profit maximization under the initial order quantity commitment mechanism. The results show that the rapid response mechanism can reduce the negative impact of consumers' strategic behavior, and the initial order quantity commitment can further reduce the impact and improve the retailers' profit. Both the two-part pricing contract and revenue-sharing contract can coordinate the whole supply chain in which the two-part pricing contract can distribute profit arbitrarily between manufacturers and retailers while the revenue-sharing contract can share risks among members of the supply chain.

1. Introduction

Newsvendor model is the basic model of stochastic storage theory, and it mainly discusses the retailers' decision-making problem under uncertain demand. The newsvendor model has always been a hotspot in operations management research. A large number of researchers have made in-depth discussions on pricing and ordering under uncertain conditions and expanded the classical newsvendor model from many aspects. At present, most of the studies on newsvendor problem are single-echelon; that is, the market demand of commodities in normal sales stage is random. After the end of the sales stage, all the remaining commodities (if any) can be sold in full clearance with residual value. It is more reasonable to assume that the decision-making procedure is a two-echelon newsvendor model with random market demand of commodities both in normal sales period and in liquidation period. Since the classical newsvendor model can

be regarded as a special case of the two-echelon newsvendor model, it is more general to study the two-echelon stochastic demand.

In traditional supply chain management research, consumers' behavioral characteristics are often ignored. These documents assume that customers are passive participants who do not participate in supply chain decisions, as long as the consumer's reserved value of the product is not lower than the current retail price of the product, consumers will immediately buy goods. However, due to fierce market competition, discounted sales have become a commonly used promotional method. Faced with wave after wave of price reductions, consumers gradually learned to wait for the best buying opportunity. This rational behavior of consumers is called strategic customer in marketing. In this case, consumers are no longer passive recipients of prices, and strategic consumers will compare the consumer surpluses that they can obtain when manufacturers implement

different price stages, thereby deciding when to buy. Current research has found that consumer's strategic behavior will have a great impact on supply chain members' decisions and supply chain performance. Ignoring consumer's strategic behavior may cause huge losses to decision makers. For example, Coase, the Nobel Prize winner in economics, found in his classic 1972 literature that in the face of consumers' waiting behavior, monopolistic retailers only set their retail prices as marginal production costs so that retailers can only obtain Zero profit; Anthes [1] research shows that if 10% of passengers believe that future ticket sales will reduce prices and choose to postpone the purchase, then airlines will lose at least 1% of their profits. Therefore, it is necessary to incorporate consumer's strategic behavior into our research.

Since the production of goods requires a certain lead time, retailers basically need to order in advance. In this case, it is often difficult to accurately match the order quantity and the demand quantity, which can easily cause insufficient supply or waste. Make-to-order is the most effective way to solve the above problems. Companies such as Toyota use order-oriented inventory strategies to significantly increase their own profits and reduce their risks. However, for seasonal commodities such as clothing and food, due to the low value of these commodities and the short sales cycle, the average consumer will not book such commodities. In this case, a quick response strategy will be an effective response. The rapid response system of the famous Spanish clothing brand ZARA should be a classic case in operation management. The company has an efficient supply chain system to ensure that it is the only fashion company in the world that can distribute the produced clothing to more than 850 specialty stores worldwide in 15 days. The rapid response mechanism effectively solves the balance between inventory and demand and is a green and sustainable operation improvement strategy [2, 3]. At the same time, because the retailer has maintained a low inventory level, it also gives consumers the expectation that it is difficult to reduce prices in the future, so it is a common mean to respond to the strategic consumers.

In the decentralized supply chain, "double marginalization" is universal. In order to avoid its adverse effects, it is an important part of the research in the supply chain management to increase the overall profit of the supply chain and realize the Pareto improvement of the profit of each member. Constraining the decision of each member in the supply chain and realizing supply chain coordination through the supply chain contract is an effective method. Under the traditional supply chain, the centralized supply chain is usually the most profitable situation, and this profit level is the goal of supply chain coordination. However, due to the influence of consumers' strategic behaviors, the profit level under centralized conditions is not necessarily the most profitable. Therefore, it is necessary to find a higher level of overall supply chain profit as the goal of supply chain coordination and to introduce a reasonable coordination contract to realize supply chain coordination, and at the same time, according to the needs of practical applications, rationally profits are distributed and risks are shared among supply chain members.

Based on the above reasons, this paper studies a two-stage supply chain system consisting of a manufacturer and a retailer. When the retailer is faced with two-echelon uncertain demand, considering the strategic behavior of consumers, the rapid response mechanism is introduced. The following three issues are discussed:

- (1) In a centralized supply chain system, when consumers have strategic behavior, the equilibrium initial output of the supply chain and the retail price of goods in the first echelon are determined.
- (2) How to cope with consumers' strategic behavior and improve the overall performance of supply chain through rapid response and initial order commitment mechanism of retailers.
- (3) Because the retailer's one-sided initial order commitment is not credible, how to solve the problem of unreliable commitment, then achieve the maximum performance of the supply chain as a whole, and allocate profits and risk among the members of the supply chain.

The remaining parts of this paper are organized as follows. Section 2 gives a literature review; Section 3 is the basic setting of the model; Section 4 discusses the pricing and ordering decision-making of supply chain under centralized circumstances; Section 5 studies the role of retailer's initial order commitment; Section 6 introduces two-part pricing contracts and revenue-sharing contracts to coordinate the supply chain; Section 7 is the numerical experiment; and Section 8 gives the conclusion. The prospects of research are discussed.

2. Literature Review

The newsvendor model is the basic model of stochastic storage theory. It mainly discusses the decision-making problem of retailers under uncertain demand. Under the assumption that the market demand of commodities is random and the retail price is exogenous, the classical newsvendor model studies the retailer's decision-making method to maximize the expected profit. The newsvendor model has been the focus of operation management research since it has been put forward. A large number of researchers have conducted in-depth discussions on newsvendor and expanded the newsvendor model from many directions. For example, Petruzzi and Dada [4], Agrawal and Seshadri [5], and Dana and Petruzzi [6] have studied the joint decision-making problem of inventory and retail price under the condition of random market demand and price sensitivity. Kyparisis and Koulamas [7] discussed the optimal decision-making of retailers under the condition of nonlinear price sensitivity plus a stochastic variable demand function. Khouja [8] introduced multiple discount strategy to improve the sales volume and optimize the profit of retailers by continuously reducing the retail price of goods in the sales echelon. Ma et al. [9] extended the demand distribution from uniform distribution and normal distribution to arbitrary distribution on the basis of Khouja and studied the

situation of reducing discount price according to nonlinearity. Cachon and Kok [10] regarded the residual value of goods after the normal selling period as the decision variable of the retailer and discussed the joint decision of the retailer's inventory and residual value under the setting of the newsvendor model. Based on the classical newsvendor model, the uncertainty of commodity supply is considered by Tang et al. [11]. Alfares and Elmorra [12] and Raza [13] analyzed the expectation and variance of commodity demand, while the distribution function was unknown. As a generalization, Adhikary et al. [14] studied the free distribution newsvendor model when the demand was a fuzzy random variable.

At present, most of the studies assume that the market demand of commodities in the normal sales stage is random. After the end of the sales echelon, all the remaining commodities (if any) can be sold in full clearance with residual value. The residual value set in the model is often less than the production cost, and the promotion is very strong, so this assumption has certain rationality. A more reasonable assumption is that the demand for goods is a random variable in multiple sales stages. Lee et al. [15] assumed that the market demand of commodities is divided into two stages [16] and that the market demand of each stage is a random variable, and the optimal ordering strategies of retailers are studied for retailers with only one order opportunity and two orders opportunity. Linh and Hong [17] and Hematyar and Chaharsooghi [18] aimed at a two-echelon supply chain system consisting of a single manufacturer and a single retailer. When retailers are faced with stochastic demand in both sales stages, the pricing and ordering of supply chain members and channel coordination are studied. Our model follows the assumption of two-echelon uncertain demand. The biggest difference from the above research is that we consider the strategic behavior of consumers.

The research on consumer strategic behavior is also closely related to this paper. Coase's [19] classical literature first focuses on the impact of consumer strategic behavior on retailer's pricing and performance. It is found that in the face of consumers' waiting behavior, monopoly retailers only set their retail price as marginal production cost so that retailers can only get zero profit. On the basis of Coase [19], a large number of subsequent literatures have studied the optimal decision-making problem based on consumer strategic behavior under different conditions. Mersereau and Zhang [20], Liu and Cooper [21], and Yan and Ke [22] have studied dynamic pricing strategies based on strategic consumers. Cachon and Swinney [23], Yin et al. [24], and so on took inventory as decision variable and discussed the ordering strategy based on strategic consumers. There are also some studies that regard retail price and order volume as decision variables, such as Lai et al. [25] assuming that both strategic and myopic consumers exist in the market, focusing on the pricing and inventory strategy formulation of retailers after introducing the final price matching strategy (PM). Dong and Wu [26] expanded to two stages of joint inventory and retail price decision-making. Su and Zhang [27] firstly considered the strategic behavior of consumers in the two-echelon supply chain system, which was composed by

introducing manufacturers. The subsequent literature has been expanded on the basis of Su and Zhang's research. Yang [28] studied the two-stage pricing and ordering problem in a supply chain system consisting of a manufacturer and competing retailers, taking into account the strategic behavior of consumers. Li and Wang introduced repurchase contracts to discuss supply chain coordination for different types of strategic consumers. Ahmadi et al. [29] studied the decision-making of supply chain members in the face of grey market and strategic consumers and introduced wholesale price contracts and quantities to coordinate the supply chain. Hu et al. [30] analyzed the optimal prices and trade-in rebates for successive-generation products with strategic consumers and limited trade-in duration. Che et al. [31] studied the pricing decisions of retailers facing strategic consumers with low-carbon preferences in two situations based on a two-stage pricing model.

Related to this study is the literature on rapid response and supply chain coordination. Fisher and Raman [32] studied the role of rapid response mechanism in responding to demand uncertainty. Iyer and Bergen [33] introduced rapid response mechanism in supply chain channel selection and coordination. After introducing rapid response mechanism, the decision-making of manufacturers and retailers was analyzed by model analysis. Choi et al. [34] studied the effect of rapid response on supply chain when retailers' risk preferences were random. In the study by Chan et al. [35], considering the reduction of production lead time, greenhouse gas emissions and energy waste may become more serious, and a two-stage rapid response supply chain system with clean technology was proposed. Xu et al. [36] explored the effect of consumer disappointment aversion on the online seller's decisions about pricing, ordering, and quick response. In addition, some studies combine the quick response mechanism with the consumer's strategic behavior. Cachon and Swinney [23] studied the two-stage pricing and inventory strategy formulation of retailers under the assumption that there are both myopic customers, discount-only customers, and strategic customers in the market. Swinney [37] studied retailers' decision-making when facing both strategic and myopic consumers under the condition of second order and analyzed the effect of rapid response mechanism. Dong and Wu [26] studied two-echelon dynamic pricing and ordering strategies with strategic consumers and rapid response mechanism. Similar to our study are the studies of Yang et al. [22] and Wang et al. [2]. Yang et al. [22] analyzed the role of rapid response systems in responding to consumer strategic behaviors in four different supply chain structures, and Wang et al. [2] introduced rapid response mechanisms to study pricing and ordering issues under coexistence conditions of both the strategic and myopic consumers. However, they are all carried out under the framework of the classic newsvendor model. Yang et al. [22] did not realize the distribution of profits and risks when discussing supply chain coordination, while Wang et al. [2] did not involve supply chain coordination.

Two-part pricing is a common way of charging in economics. Similar to fixed cost and variable cost in cost theory, the seller divides the cost into two parts when selling

goods: the first part is a fixed cost and the second part is the unit price of goods, through which complete price discrimination can be realized. Io [38] first proposed two-part pricing theory, and subsequent researchers introduced the theory into supply chain management, forming two-part pricing contract. Under the condition that retailers are dominant, the market demand of goods is sensitive to retail price, and the retail price is random, and the coordination of supply chain with two-part pricing contracts is studied by Lau et al. [39]. Wang et al. [40] extended the basis of Lau et al. [39]. Based on discussion of two-part pricing contract, a new batch discount contract was established to achieve supply chain coordination. The research and application of revenue-sharing contract are very extensive. The most classical literature is Cachon and Lariviere [41]. This paper introduces the theory of revenue-sharing contract in detail, compares it with other supply chain coordination contracts, and discusses the advantages and limitations of revenue-sharing contract. Some scholars study supply chain coordination based on multiple contracts. For example, Saha [42] considered the impact of manufacturers' efforts on commodity demand, combined revenue sharing and rebates as tools for supply chain coordination, and proposed three different types of rebate inducement contract. Saha and Goyal [43] studied the ordering and pricing decision-making problems in a two-echelon supply chain in which the demand depends on the inventory level and sales price of the product. They realize supply chain coordination through a combination contract of the rebate contracts, wholesale price discount contracts, and cost sharing contracts; different coordination contracts have their own advantages and disadvantages, which is convenient for managers to make reasonable choices according to actual needs. Based on this, this article will also introduce different contracts to the supply chain coordination.

At present, most of the literatures that have been studied under framework of the newsvendor model are based on the single-period newsvendor model, and only a few literatures involved the two-stage newsvendor model. As far as the author knows, there is no research on the decision-making and coordination of the supply chain based on the two-stage newsvendor problem taking into account both the consumers' strategic behaviors and a quick response mechanism. Compared with the current literatures, our research has three main differences: firstly, under the basic setting of two-stage uncertain demand for the two-echelon supply chain system for the first time, the strategic behavior and rapid response mechanism of consumers are comprehensively considered (from the current literatures). Secondly, because of the existence of strategic consumers, the profit of supply chain under centralized conditions is not necessarily the same. We introduce the retail price commitment mechanism to improve the overall performance of the supply chain and find the goal of supply chain coordination. Thirdly, we use different coordination mechanisms to achieve the supply chain coordination so that profits and risks could be allocated in different ways among the supply chain members.

3. The Basic Model

This paper considers a two-echelon supply chain system consisting of a single manufacturer and retailer and a large number of consumers with strategic behaviors. The supply chain structure is shown in Figure 1. The notations used in this paper are shown in Table 1, and any other additional notations and assumptions will be listed where they are needed.

Similar to the sales process set by Lee et al. [15], the sales process of goods is divided into two stages. The first stage is the normal sales period, and the retailer will sell the goods at the retail price p . The second stage is the discount sales period. In this stage, the retailer will sell the goods at the retail price h ($h < p$) and h is an exogenous variable. At the end of the second stage, the retailer no longer clears the goods but returns the surplus goods to the manufacturer or sells them to the scrap collector. Each unit of the goods receives the residual value s .

It is assumed that the market demand faced by retailers in each stage is random variable X_i , $i = 1, 2$ where X_i is independent of each other. $F_i(x)$ and $f_i(x)$ represent the distribution function and distribution density function of the random variable, respectively. Assume that X_i is a continuous random variable and satisfies $X_i > 0$. Then, $X = X_1 + X_2$ denotes the total market demand of two echelons, and $F(x)$ and $f(x)$ denote the distribution function and density function of X , respectively. In addition, the requirements of the first stage are required to meet the increasing failure rate (IFR), i.e., $f_1(x)/(1 - F_1(x))$ on the monotonic increment of x . Petruzzi and Dada [4], Su and Zhang [27], and Yang et al. [22] have used this hypothesis for many commonly used distributions, such as uniform distribution and normal distribution.

Assuming that the retailer has two order opportunities before the beginning of the first phase of the sales period, the first order is placed with the manufacturer at the wholesale price c_1 . Then, the actual demand information in the first phase is learned (that is, as the sales season approaching, obtaining an accurate estimate for the actual value of the random variable X_1), and the retailer can place an order from the manufacturer again at the wholesale price c_2 . The retailer needs to decide the initial order quantity Q and the retail price p during the first period of sale to maximize its own profit. For the manufacturer's second production, since the production preparation period is short and the output is generally small, it is reasonable to set the unit production cost to rise, so $c_1 < c_2$. In order to ensure that the retailer does not only place a second order and that the second order can only be used to satisfy the first order is insufficient in the first stage of sales, assume $s < h < c_1 < c_2$. As a result, the whole sales operation process is shown in Figure 2.

Assuming that in the first stage there are many homogeneous consumers in the market, their evaluation of the goods is v . And they all have strategic behavior; that is, consumers know that after the end of the first stage of sales period, if there are still goods not sold out, retailers will discount sales in the second stage. Consumers will maximize their expected utility as the goal to make the optimal

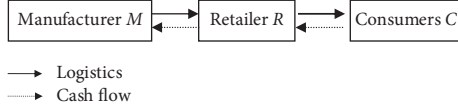


FIGURE 1: Supply chain structure.

TABLE 1: Notations.

| Notation | Description |
|---------------------------|---|
| Parameters | |
| h | Retail price in the second stage |
| X_i | The demand for product in the i stage, $i = 1, 2$ |
| $F_i(x)$ | Distribution function of random variable X_i |
| $f_i(x)$ | Distribution density function of random variable X_i |
| c_1 | Unit production cost of the product when the first order is placed |
| c_2 | Unit production cost of the product when the second order is placed |
| s | Unit residual value of remaining product after the sales period |
| v | Consumers' valuation of product during normal sales period |
| r | Consumers' reservation price for product during normal sales period |
| Decision variables | |
| p | Retail price in the first stage |
| Q | Retailer's initial order quantity |

purchase timing. In the second stage, consumers have no more choices, which is consistent with the classical news-vendor model. Under the exogenous retail price h , they decide whether to buy goods or not.

Assuming that the manufacturer's production capacity is infinite, it can fully satisfy the retailer's initial and second orders; the members of the supply chain are risk-neutral, and the consumer's valuation of the goods in the first stage does not change with time, that is, the same in both sales stages, and the time value of the funds is not taken into account. Events occur in the following order.

Firstly, retailers estimate the retail price r of consumers in the first stage ξ_r , and then determine the optimal retail price p and the initial order quantity Q . At the same time, consumers estimate Q and obtain the probability ξ_{prob} that they can buy goods in the discount sales period so as to determine the retail price r .

Next, the actual selection of the random variable X_1 is worth it. If $Q < X_1$, the retailer will place a second order at the price of c_2 to meet the market demand in the first stage and then sell all the goods at the retail price p in the first stage of the sales period; otherwise, without a second order, the retailer will continue to sell the goods at the retail price h after the first stage of the sales period, and if there are surplus goods after the second stage of the sales period, all remaining goods will be disposed of with residual s .

4. Centralized Supply Chain

Firstly, the pricing and ordering decisions of retailers in centralized supply chain are discussed. In the setting of centralized supply chain, manufacturers and retailers as a

whole are collectively referred to as retailers in order to express conveniently.

According to the sequence of events mentioned above, the consumer's decision-making in the first stage is analyzed. Before the first stage of sales, the retailer will announce the retail price p of the first stage, and the initial order quantity is the retailer's private information. Therefore, consumers need to estimate Q , which is to estimate the probability ξ_{prob} that the goods can be bought at the price h after the end of the first stage of sales. Then, with the goal of maximizing utility, the purchase timing is decided, namely:

$$\max\{v - p, (v - h)\xi_{\text{prob}}\}. \quad (1)$$

The first term $v - p$ in the above expression represents the consumer surplus obtained by purchasing goods in the first stage, and the second term $(v - h)\xi_{\text{prob}}$ represents the expected surplus obtained by purchasing goods at the end of the season. So, if and only if $v - p \geq (v - h)\xi_{\text{prob}}$, the retail price of the commodity is $p \leq v - (v - h)\xi_{\text{prob}}$, and the strategic consumer will choose to buy the commodity in the first stage. Therefore, in the first stage, consumers retain the price of goods as $r = v - (v - h)\xi_{\text{prob}}$.

The retailer's decision-making is analyzed below. Because the retailer's reserved price is also the consumer's private information, the retailer needs to estimate it, assuming that ξ_r represents the estimation of the consumer's reserved price. Obviously, in order to maximize profits, the retailer's retail price in the first stage should be fixed $p = \xi_r$. Initial order quantity $Q = \arg \max \pi(p, Q)$, in which

$$\begin{aligned} \pi(p, Q) = & pE(X_1 \wedge Q) + (p - c_2)E(X_1 - Q)^+ + hE \\ & \cdot [(Q - X_1)^+ \wedge X_2] + sE[(Q - X_1)^+ - X_2]^+ - c_1Q. \end{aligned} \quad (2)$$

In this paper, we use " \wedge " to denote the small between them and " \vee " to denote the large, for example $(X - Q)^+ = (X - Q) \vee 0$. In formula (2), $pE(X_1 \wedge Q)$ is the profit obtained by selling goods at retail price p in the first stage, $(p - c_2)E(X_1 - Q)^+$ is the expected profit from the second order when the initial order quantity is insufficient, $hE[(Q - X_1)^+ \wedge X_2]$ expresses the profit obtained by selling goods at retail price h in the second stage, the residual value $sE[(Q - X_1)^+ - X_2]^+$ denotes the income of goods obtained by the retailer after the second stage of sale, and c_1Q expresses the initial order cost.

In determining the value of ξ_{prob} and ξ_r , this paper uses the rational expectation hypothesis. Rational expectation is put forward by Muth [44]. The so-called rational expectation is that every economic actor's expectation of future events is rational; that is, consumers use their own maximum effectiveness as the criterion of action, producers take profit maximization as the criterion of action, and any economic actor's anticipated future situation when making current decisions is always completely accurate. It is in line with the actual situation in the future. Thus, the following definitions can be obtained.

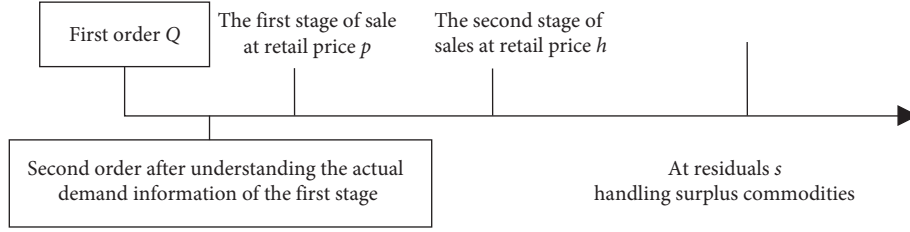


FIGURE 2: Diagram of operation process.

Definition 1. In the two-echelon newsvendor model based on consumer strategic behavior under the rapid response mechanism, a rational expectation equilibrium $(p, Q, \xi_{\text{prob}}, \xi_r)$ should satisfy the following five conditions:

- (i) $r = v - (v - h)\xi_{\text{prob}}$
- (ii) $p = \xi_r$
- (iii) $Q = \arg \max \pi(p, Q)$
- (iv) $\xi_{\text{prob}} = F_1(Q)$
- (v) $\xi_r = r$

Conditions (i), (ii), and (iii) indicate that retailers and consumers should make rational decisions; that is, consumers should maximize consumer surplus and retailers should maximize expected profits; conditions (iv) and (v) indicate that consumers and retailers' estimates of private information are consistent with the actual situation, which is the core of rational expectations.

According to Definition 1, we can get two conditions that the retailer's decision variables should satisfy under the condition of rational expectation equilibrium (introducing subscript c to represent rational expectation equilibrium state, that is, the case of centralized supply chain):

$$p_c = v - (v - h)F_1(Q), Q_c = \arg \max \pi(p, Q). \quad (3)$$

Proposition 1. In the equilibrium of rational expectations, consumers in the first stage will buy goods in the first stage, and there exists only p_c and Q_c to maximize the profit of retailers.

Proof. The expected profit of the retailer obtained by formula (2) is as follows:

$$\pi(p, Q) = (p - c_2)E(X_1) + (c_2 - c_1)Q - (c_2 - h) \cdot \int_0^Q F_1(x)dx - (h - s) \int_0^Q F(x)dx. \quad (4)$$

Therefore, the first-order condition is as follows:

$$\frac{\partial \pi}{\partial Q} = (c_2 - c_1) - (c_2 - h)F_1(Q) - (h - s)F(Q) = 0. \quad (5)$$

Let $g(Q) = (c_2 - c_1) - (c_2 - h)F_1(Q) - (h - s)F(Q)$, then the function $g(Q)$ monotonously decreases on Q in the interval $[0, +\infty)$, and because $g(0) = (c_2 - c_1) > 0$, $g(\infty) = (s - c_1) < 0$; therefore, the profit function has a unique stationary point Q_c . According to the second-order condition $\partial^2 \pi / \partial Q^2 = -(c_2 - h)f_1(Q) - (h - s)f(Q) < 0$, the only

stationary point is the maximum point. From formula (3), we can see that the retail prices p_c and Q_c are one-to-one correspondence under the equilibrium condition, so p_c is the only one that exists. Proof is completed.

Proposition 2. This guarantees the unique existence of equilibrium solution under the assumption of rational expectation. Q_c is the solution of equation $g(Q) = 0$. However, when the random variable X_i is normal or Poisson's distribution, it will be very difficult to solve the analytical expression of Q_c from the equation because of the complexity of the distribution function. Therefore, the numerical solution of Q_c can be calculated by the method of fixed step search in practical application. Property 1 discusses the relationship between retailer's initial order quantity, retail price in the first stage, and profit and parameters c_2 and h :

Property 1. With other parameters unchanged, when the unit cost c_2 of the second order increases, the retailer's initial order quantity Q_c increases, and the retail price p_c and profit π_c of the first stage decrease monotonously. When the retail price h of the second stage increases, the initial order quantity Q_c and profit π_c increase accordingly.

Proof. If Q is regarded as a function of c_2 , we solve the derivative of both sides of formula (5) on c_2 and it can be obtained as follows:

$$\frac{dQ}{dc_2} = \frac{1 - F_1(Q)}{(c_2 - h)f_1(Q) + (h - s)f(Q)} > 0. \quad (6)$$

Therefore, the initial order volume of retailers increases monotonously with the value of c_2 . From formula (3), the retail price p_c will decrease accordingly.

The same is true as follows:

$$\frac{dQ}{dh} = \frac{F_1(Q) - F(Q)}{(c_2 - h)f_1(Q) + (h - s)f(Q)} > 0. \quad (7)$$

Therefore, the initial order volume of retailers increases monotonously with the value of h . Substitute (3) into (4) to obtain the following:

$$\begin{aligned} \pi_c(p, Q) = & [v - (v - h)F_1(Q) - c_2]E(X_1) + (c_2 - c_1)Q \\ & - (c_2 - h) \int_0^Q F_1(x)dx - (h - s) \int_0^Q F(x)dx. \end{aligned} \quad (8)$$

Then, we solve the derivative of formula (8) on c_2 based on the envelope theorem as follows:

$$\frac{d\pi_c}{dc_2} = -E(X_1) + Q - \int_0^Q F_1(x)dx = E(Q \wedge X_1) - E(X_1) \leq 0. \quad (9)$$

Therefore, profits π_c are decreasing monotonously with respect to c_2 . The same is true as follows:

$$\begin{aligned} \frac{d\pi_c}{dh} &= F_1(Q)E(X_1) + \int_0^Q F_1(x)dx - \int_0^Q F(x)dx, \\ &= F_1(Q)E(X_1) + \int_0^Q [F_1(x)F(x)]dx. \end{aligned} \quad (10)$$

Because $F(x)$ and $F_1(x)$ are the distribution functions of $X = X_1 + X_2$ and X_1 , respectively, we have $F(x) < F_1(x)$ for $\forall x \in [0, Q]$. Therefore, $F_1(x) - F(x) \geq 0$. Therefore, from the sign-preserving property of definite integrals, we can see that $d\pi_c/dh \geq 0$ and the profit π_c increases monotonously with respect to h . Proof is completed.

The conclusion of Property 1 is easy to understand. With the increase in c_2 , retailers have more profit margin in the first order, so they will increase the initial order quantity. The probability that consumers can buy goods in the second stage will also increase with the increase in initial order quantity, which causes retailers to have to reduce retail prices in the first stage. Therefore, under the condition that other parameters remain unchanged, the retailer's profit will decrease; the increase in h means that the same number of goods will get more profit in the second stage, so the retailer's profit will increase. Because $p_c = v - (\nu - h)F_1(Q)$, it should be pointed out that the relationship between p_c and h is difficult to determine because $\nu - h$ will decrease with the increase in h and $F_1(Q)$ will increase with the increase in order quantity.

In the absence of a second-order opportunity, the retailer's profit function is as follows:

$$\begin{aligned} \pi_1(p, Q) &= pE(X_1 \wedge Q) + hE[(Q - X_1)^+ \wedge X_2] \\ &\quad + \nu E[(Q - X_1)^+ - X_2]^+ - c_1 Q. \end{aligned} \quad (11)$$

Subscript 1 indicates that there is only one order opportunity. From formulas (2) and (11),

$$\pi_c(p, Q) - \pi_1(p, Q) = (p - c_2)E(X_1 - Q)^+ \geq 0. \quad (12)$$

Therefore, we could get the following property.

Property 2. For fixed parameters c_1, s, h, ν , and c_2 , the retailer's profit satisfies $\pi_c(p, Q) \geq \pi_1(p, Q)$.

According to the conclusion of Property 2, the introduction of rapid response mechanism can effectively reduce the negative impact of consumer strategic behavior and improve the profit level of retailers. There are two reasons for the increase in the retailers' profits. First, the initial order quantity will be reduced in the case of two ordering opportunities; that is, the probability that consumers will be able to buy goods during the end-of-season processing

period will be correspondingly reduced, which can be effective to reduce the impact of strategic consumers' waiting behaviors on the retailers' profits. Second, because retailers have a second-order opportunity, they can effectively avoid loss of profits caused by insufficient order quantities. Based on this, in the supply chain operations practice of enterprises, if the conditions permit the introduction of a rapid response mechanism, it can improve the efficiency of the supply chain, increase the profit level of the supply chain, and have practical application value.

5. Initial Order Quantity Commitment

In the rational expectation equilibrium hypothesis, the retailer's initial order quantity is the retailer's private information, which cannot be directly observed by consumers but is estimated according to the principle of rational expectation equilibrium.

If the retailer discloses the first-order quantity Q to the consumer before the first stage of sales, which is different from the previous rational expectation equilibrium, then the consumers in the first stage do not need to estimate the probability of the goods they can buy after the first stage, and the probability of the goods they can buy is $F_1(Q)$. According to the principle of maximizing consumer surplus, consumers make their own purchase timing decision, that is, $\max\{\nu - p, (\nu - h)F_1(Q)\}$. While $\nu - p \geq (\nu - h)F_1(Q)$, they will choose to buy in the first stage, and otherwise, they will wait. Therefore, when the retail price of the first stage satisfies $p \leq \nu - (\nu - h)F_1(Q)$, consumers will buy goods ahead of time, so in order to maximize profits, the retail price of the first stage should be set as follows: $p_q = \nu - (\nu - h)F_1(Q)$, in which the subscript q denotes the quantity commitment mechanism. Then, the optimal initial order quantity of the retailer should be $Q_q^* = \arg\pi_q(p(Q), Q)$, in which

$$\begin{aligned} \pi_q(p(Q), Q) &= [\nu - (\nu - h)F_1(Q) - c_2]E(X_1) \\ &\quad + (c_2 - c_1)Q - (c_2 - h) \int_0^Q F_1(x)dx \\ &\quad - (h - s) \int_0^Q F(x)dx. \end{aligned} \quad (13)$$

Proposition 3. Retailers have a unique initial order quantity commitment, which maximizes the profits $\pi_q(Q)$.

Proof. The derivation of equation (13) on Q can be obtained as follows:

$$\begin{aligned} \frac{d\pi_q}{dQ} &= -(\nu - h)E(X_1)f_1(Q) - (c_1 - h) + (c_2 - h)\bar{F}_1(Q) \\ &\quad - (h - s)F(Q). \end{aligned} \quad (14)$$

So, the first-order condition is as follows:

$$\bar{F}_1(Q) \left[\frac{-(v-h)E(X_1)f_1(Q)}{\bar{F}_1(Q)} - \frac{(c_1-h)}{\bar{F}_1(Q)} + (c_2-h) - (h-s)\frac{F(Q)}{\bar{F}_1(Q)} \right] = 0. \quad (15)$$

Set $G(Q) = -(v-h)E(X_1)f_1(Q)/\bar{F}_1(Q) - (c_1-h)/\bar{F}_1(Q) + (c_2-h) - (h-s)F(Q)/\bar{F}_1(Q)$.

Because the distribution function of X_1 satisfies the monotonic incremental failure rate, that is, $f_1(Q)/\bar{F}_1(Q)$ increase with respect to Q and $\bar{F}_1(Q)$ decreases with respect to Q , $F(Q)$ increases with respect to Q . Therefore, $G(Q)$ decreases monotonously in $(0, +\infty)$. Because $G(0) = c_2 - c_1 > 0$, $G(\infty) = -\infty$, the equation $G(Q) = 0$ has a unique root. Moreover, $\bar{F}_1(Q)$ is greater than zero in $(0, +\infty)$, equation (14) has a unique root; that is, there is a unique stationary point Q_q^* for $\pi_q(Q)$.

Then, $\pi_q'(0) = c_2 - c_1 > 0$ and $\pi_q'(\infty) = s - c_1 < 0$. Therefore, $\pi_q(Q)$ is a quasi-concave function, and Q_q^* is the maximum point of $\pi_q(Q)$. The proof is completed.

This paper compares the relationship between retailer decision variables and profit level under rational expectation equilibrium and initial order commitment mechanism. The conclusions are given by the following property.

Property 3. $Q_q^* < Q_c$, $p_q > p_c$ and $\pi_q(Q_q^*) > \pi_c(Q_c)$.

Proof. As can be seen from (14),

$$\begin{aligned} \pi_q'(Q) = & -(v-h)E(X_1)f_1(Q) + (c_2 - c_1) \\ & - (c_2 - h)F_1(Q) - (h-s)F(Q). \end{aligned} \quad (16)$$

Under the assumption of rational expectation, the retailer's order quantity Q_c should satisfy formula (5):

$$(c_2 - c_1) - (c_2 - h)F_1(Q) - (h-s)F(Q) = 0. \quad (17)$$

Therefore, $\pi_q'(Q_c) = -(v-h)E(X_1)f_1(Q_c) < 0$.

According to the nature of the function of $\pi_q(Q)$ and $\pi_q'(Q)$, we get that the profit functions $\pi_q(Q)$ and $\pi_c(Q)$ have the same function expression under the initial order quantity commitment mechanism and rational expectation equilibrium. So, it can be obtained as shown in Figure 3 that $Q_q^* < Q_c$ and $\pi_q(Q_q^*) > \pi_c(Q_c)$. From the relationship between the initial order quantity and the retail price $p = v - (v-h)F_1(Q)$, it can be concluded that $p_q > p_c$. The proof is completed.

It can be known from Property 3 that the retailer reduces the initial order quantity by committing to the initial order quantity, thereby changing the consumer's expectation; that is, the probability that the product can be purchased at the end of the season clearing period will decrease. At the same time, the retailer increases the retail prices in normal sales period, hedging the loss of the reduction in the number of product sold, which effectively reduces the adverse effects of consumers' strategic behavior. Therefore, retailers can increase their own profit levels by committing to the initial order quantity. In the practice of operations management, many manufacturers have adopted similar marketing methods. For example, manufacturers promise the production quantity of products by launching limited edition

products, conveying to consumers that the supply of products exceeds demand, and the expectation that they will not sell at a price reduction in the future prompts consumers competing to buy in the normal sales period. Therefore, it will effectively improve their own profit levels.

However, such a commitment alone is not credible. Because if this commitment is credible, under the initial order quantity commitment mechanism, the retailer can sell product at a relatively high retail price. Then, the retailer "behind the promise" to increase the initial order quantity can increase its own profits. This means that retailers have the urge to deviate from the equilibrium order quantity. The essential reason for the unreliable commitment is that the order quantity and retail price under the initial order quantity commitment mechanism are not the Nash equilibrium solution of the game between the retailer and the consumer. In order to solve the credibility problem of promises, the coordination problem of the supply chain will be studied in the next section.

6. Supply Chain Coordination

Under the condition that consumers have strategic behavior, the retailer's profit level in the initial order quantity commitment mechanism is higher than that in the centralized situation, so the goal of supply chain coordination should be defined as the profit level in the initial order quantity commitment mechanism. Next, we discuss the use of two-part pricing contract and revenue-sharing contract to achieve supply chain coordination.

6.1. Two-Part Pricing Contract. Suppose that a two-part pricing contract (L, w) is signed between the manufacturer and the retailer, where L is the fixed fee part, w is the wholesale price of the retailer's first order, and the unit price of the second order is the manufacturer's production cost c_2 (the reason why the wholesale price of the second order is set as the marginal production cost is that supply chain coordination can be achieved through parameters L and w , and the system can be established). Part of the profits lost by the manufacturer can be compensated by a fixed fee. Under this contract, the retailer's profit is as follows (subscript L denotes the value of decision variables and profits under two-part pricing contract, subscript R denotes the retailer, and subscript M denotes the manufacturer):

$$\begin{aligned} \pi_L^R = & pE(X_1 \wedge Q) + (p - c_2)E(X_1 - Q)^+ \\ & + hE[(Q - X_1)^+ \wedge X_2] + sE[(Q - X_1)^+ - X_2]^+ \\ & - wQ - L. \end{aligned} \quad (18)$$

The profit of the corresponding manufacturer is as follows:

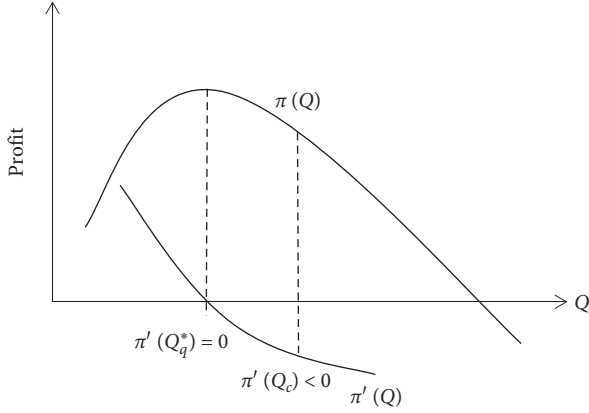


FIGURE 3: Comparisons of centralized SC and initial order quantity under order quantity commitment mechanism.

$$\pi_L^M = (w - c_1)Q + L. \quad (19)$$

Proposition 4. When $w = c_1 + (v - h)E(X_1)f_1(Q_q^*)$ under the conditions of two-part pricing contract (L, w) , it can be concluded that $p_L = p_q$, $Q_L = Q_q^*$ and $\pi_L = \pi_L^M + \pi_L^R = \pi_q(Q_q^*)$.

Proof. According to equation (18), it can be proved that the retailer's profit under two-part pricing contract is as follows:

$$\begin{aligned} \pi_L^R &= (p - c_2)E(X_1) + (c_2 - w)Q - (c_2 - h) \int_0^Q F_1(x)dx \\ &\quad - (h - s) \int_0^Q F(x)dx - L. \end{aligned} \quad (20)$$

From formula (20), we have the following:

$$\frac{\partial \pi_L^R}{\partial Q} = c_2 - w - (c_2 - h)F_1(Q) - (h - s)F(Q) = 0. \quad (21)$$

Similar to the proof method in Proposition 1, it is easy to prove that equation (21) has a unique root Q_L , which is the equilibrium order quantity in the game between retailers and consumers under the assumption of rational expectation equilibrium. Substituting $w = c_1 + (v - h)E(X_1)f_1(Q_q^*)$ into formula (21), we obtain the following:

$$\begin{aligned} c_2 - c_1 - (v - h)E(X_1)f_1(Q_q^*) - (c_2 - h)F_1(Q_L) \\ - (h - s)F(Q_L) = 0. \end{aligned} \quad (22)$$

As can be seen from Proposition 2, Q_q^* is the only root of equation (14), so there is

$$\begin{aligned} c_2 - c_1 - (v - h)E(X_1)f_1(Q_q^*) - (c_2 - h)F_1(Q_q^*) \\ - (h - s)F(Q_q^*) = 0. \end{aligned} \quad (23)$$

According to formulas (22) and (23), we get $(c_2 - h)[F_1(Q_L) - F_1(Q_q^*)] + (h - s)[F(Q_L) - F(Q_q^*)] = 0$. Because both $F_1(Q)$ and $F(Q)$ are strictly monotonic function of Q , $(c_2 - h) > 0$, $(h - s) > 0$, $Q_L = Q_q^*$ must be

valid. Moreover, since the retail price of the first stage corresponds to the initial order quantity one by one, it is established that $p_L = p_q$. Finally, the expression of π_L obtained by adding formulas (18) and (19) is exactly the same to that of π_q , so it holds that $\pi_L = \pi_q(Q_q^*)$ when the order quantity and retail price are equal. Proof is completed.

In traditional supply chain management, the two-part pricing contract generally requires manufacturers to set the wholesale price of a unit product as their unit production cost so as to encourage retailers to order more and make their orders reach the order level of the supply chain under centralized conditions. However, according to the results of Proposition 3, the wholesale price of retailers in two-part pricing contract (L, w) should be fixed $w = c_1 + (v - h)E(X_1)f_1(Q_q^*) > c_1$, which means that the wholesale price should be higher than the marginal cost of products, which is inconsistent with the conclusion of traditional supply chain management. The reason lies in the influence of consumer's strategic behavior. After considering the consumer's strategic behavior, the profit level of the initial order commitment mechanism is higher than that of the centralized supply chain. Therefore, the manufacturers increase the wholesale price to "force" the retailers to reduce the order quantity, which will improve the performance level of the whole supply chain. Of course, the manufacturers are "willing" to do so.

In traditional supply chain management, the fixed fee part L in the two-part pricing contract is the compensation for the manufacturer's profit and L is always greater than 0. However, after considering the strategic behavior of consumers, since $w > c_1$ is established, manufacturers can profit by selling goods themselves, so L may also play a role of compensation for retailers' profits, that is to say, $L < 0$ is also possible. In short, by adjusting the value of L , the profit can be arbitrarily distributed among the supply chain members.

Finally, it should be pointed out that in the two-part pricing contract, the profit of the manufacturer is fixed, so it does not need to bear any risks and all risks are borne by the retailer. In the next section, the revenue-sharing contract will be introduced to coordinate the supply chain. The advantage of the revenue-sharing contract is that the risk is also allocated while the revenue is shared.

6.2. Revenue-Sharing Contract. Suppose the manufacturer and the retailer sign a revenue-sharing contract (w, λ) , where w is the wholesale price of the unit commodity when the retailer first orders to the manufacturer and the manufacturer will share $1 - \lambda$ parts of the retailer's total revenue. Under the above revenue-sharing contract, the retailer's profit is (subscript s means revenue-sharing contract) as follows:

$$\begin{aligned} \pi_s^R &= \lambda \{ pE(X_1 \wedge Q) + pE(X_1 - Q)^+ + hE[(Q - X_1)^+ \wedge X_2] \\ &\quad + sE[(Q - X_1)^+ - X_2]^+ \} - wQ - c_2E(X_1 - Q)^+. \end{aligned} \quad (24)$$

The first bracketed part of the above expression represents the total revenue of the retailer during the whole sales

process, including the revenue from the sale of the goods in the first stage (including the first order and the second replenishment), the revenue from the sale of the goods in the second stage, and the income from the disposal of the residual value of the goods at the end of the two sales stages. The last two items are the first- and second-order costs, respectively.

The profit of the corresponding manufacturer is as follows:

$$\begin{aligned}\pi_s^M = & (1 - \lambda)\{pE(X_1 \wedge Q) + pE(X_1 - Q)^+ \\ & + hE[(Q - X_1)^+ \wedge X_2] + sE[(Q - X_1)^+ - X_2]^+\} \\ & + (w - c_1)Q.\end{aligned}\quad (25)$$

Proposition 5. For any revenue-sharing ratio $0 \leq \lambda < 1$, there exists a unique wholesale price w_s for the first-order unit. When w_s satisfies $w_s = c_2 - (c_2 - \lambda h)F_1(Q_q^*) - \lambda(h - s)F(Q_q^*)$, there exists $p_s = p_q$, $Q_s = Q_q^*$, and the total profit π_s of the supply chain at this time is $\pi_s = \pi_s^R + \pi_s^M = \pi_q$.

Proof. According to (24), under the revenue-sharing contract, the retailer's profit function is as follows:

$$\begin{aligned}\pi_s^R = & (\lambda p - c_2)E(X_1) + (c_2 - w)Q - (c_2 - \lambda h) \\ & \cdot \int_0^Q F_1(x)dx - \lambda(h - s) \int_0^Q F(x)dx.\end{aligned}\quad (26)$$

Therefore, the first-order condition obtained from formula (26) is as follows:

$$\frac{\partial \pi_s^R}{\partial Q} = c_2 - w - (c_2 - \lambda h)F_1(Q) - \lambda(h - s)F(Q) = 0.\quad (27)$$

Substituting $w_s = c_2 - (c_2 - \lambda h)F_1(Q_q^*) - \lambda(h - s)F(Q_q^*)$ into equation (27), we have the following equation:

$$(c_2 - \lambda h)[F_1(Q) - F_1(Q_q^*)] + \lambda(h - s)[F(Q) - F(Q_q^*)] = 0.\quad (28)$$

Since both $F_1(Q)$ and $F(Q)$ are strictly monotonic function of Q and $(c_2 - \lambda h) > 0, \lambda(h - s) > 0$, equation (28) has a unique root Q_q^* , that is, $Q_s = Q_q^*$. Similar to the proof process in Proposition 3, it is easy to prove that there is $p_s = p_q$ and $\pi_s = \pi_s^R + \pi_s^M = \pi_q$. Proof is completed.

According to formula (14), the optimal initial commitment order quantity Q_q^* of the retailer should satisfy the following equation:

$$\begin{aligned}c_2 - c_1 - (v - h)E(X_1)f_1(Q_q^*) - (c_2 - h)F_1(Q_q^*) \\ - (h - s)F(Q_q^*) = 0.\end{aligned}\quad (29)$$

Therefore, for any proportion of revenue sharing λ , it holds the following:

$$\begin{aligned}w_s = & c_1 + (v - h)E(X_1)f_1(Q_q^*) - (h - \lambda h)F_1(Q_q^*) \\ & + (1 - \lambda)(h - s)F(Q_q^*).\end{aligned}\quad (30)$$

It could be seen that the wholesale price w_s may be greater than c_1 , for example, when $\lambda = 1$. This is different from the setting of parameters of revenue-sharing contract in traditional supply chain coordination theory. In traditional supply chain management, w_s is usually set equal to or less than the unit marginal cost of production in order to encourage the retailers to order much more. In return, manufacturers will share part of the profits from retailers' sales. In the case that consumers have strategic behavior, manufacturers tend to set the price w_s to be greater than c_1 , for the same reason as the two-part pricing contract discussed earlier.

By reasonably setting the parameters of revenue-sharing contract, the coordination of supply chain is also realized, and the profit of manufacturer is closely related to the stochastic demand, so the manufacturer also shares part of the risk of supply chain and makes up for the shortcomings of the two-part pricing contract. The disadvantage of the revenue-sharing contract is that when $\lambda = 1$, the manufacturer could still get profits $(w - c_1)Q$, which were monopolized by the manufacturer and could not be distributed among the supply chain members.

7. Numerical Examples

Assume that $c_1 = 5$, $v = 15$, and $s = 2$. At the same time, it is assumed that the market demand X_1 of the product in the first stage obeys a normal distribution with mean value $\mu = 75$ and standard deviation $\sigma = 20$ and the market demand X_2 in the second stage obeys a normal distribution with mean value $\mu = 25$ and standard deviation $\sigma = 15$. Since X_1 and X_2 are independent, $X = X_1 + X_2 \sim N(100, 252)$. When the second unit order price c_2 increases from 5.5 to 6.5, the retailer's corresponding equilibrium retail price, initial order quantity, and profit are shown in Figure 4.

It can be seen from Figure 4 that with the increase in the second-order price c_2 , the retail price and profit level of the retailer in the first stage decrease monotonously, and the initial order quantity increases monotonously, which is consistent with the conclusion of Property 1. With the increase in the second-order cost, the retailer's profit decreased very quickly. When c_2 increased from 5.5 to 6.5, it increased by 18.18%, while the profit decreased from 499.9 to 309.9, a decrease in 38%, which shows that c_2 has a great impact on retailers' profits. Therefore, in practice, taking effective measures to reduce the cost of rapid response is of great significance for reducing the adverse effects of consumer strategic behavior and improving the performance level of the supply chain.

When the second unit order price c_2 increases from 5.5 to 6.5, if the initial order quantity remains unchanged, after the introduction of the quick response mechanism, compared with only one order opportunity, the profit difference is shown in Figure 5.

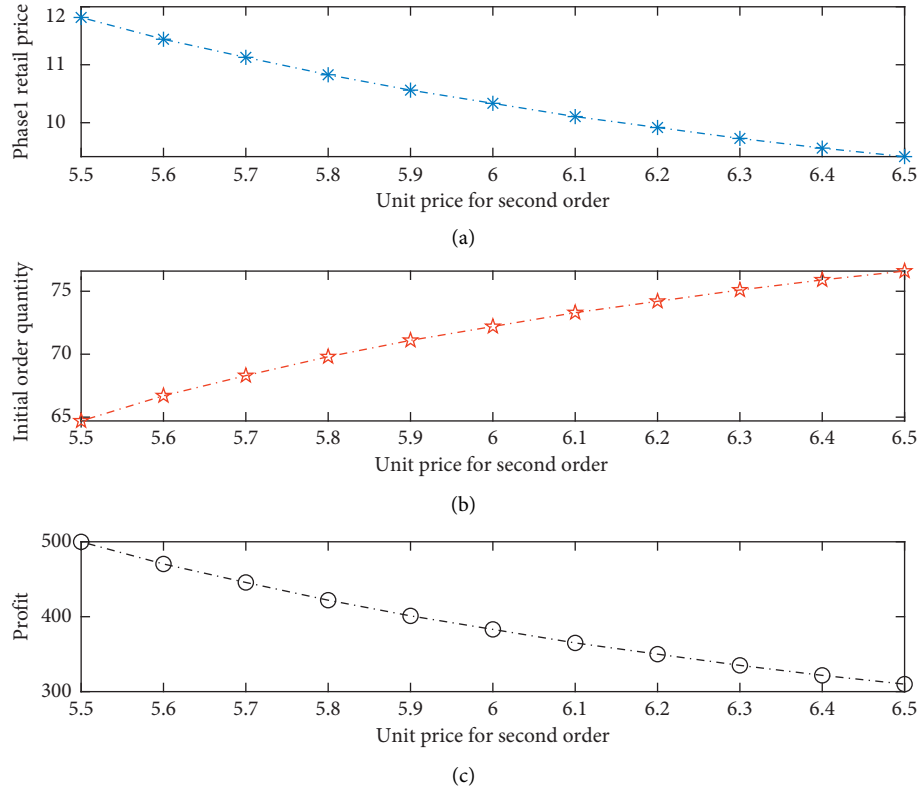


FIGURE 4: The relationship between the second-order price and the first retail price, order volume, and profit.

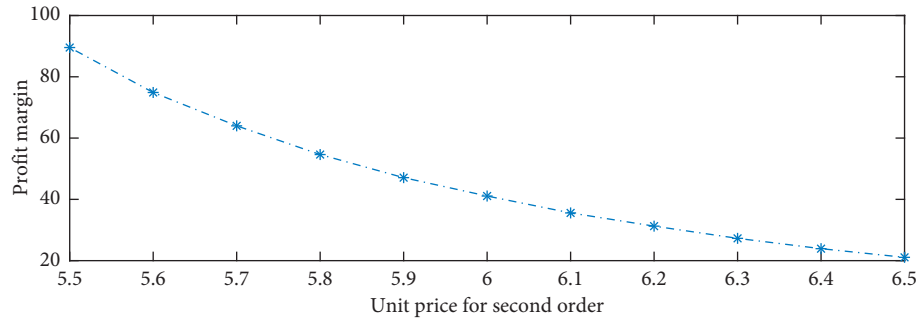


FIGURE 5: Profit difference between quick response mechanism and single order situation.

It can be seen from Figure 5 that the introduction of a rapid response mechanism can always increase the retailer's profit level, which is consistent with the conclusion proved by Property 2, and fully reflect the value of rapid response. We also found that as the unit cost of the second order increases, the profit increase brought about by the rapid response is getting smaller and smaller, because as the cost of the second order increases, the effect that can be obtained through the rapid response decreases.

Suppose $v = 15$, $h = 4.5$, $s = 2$, $X_1 \sim N(75, 202)$, and $X_2 \sim N(25, 152)$, Figure 6 shows when the second unit order price c_2 increases from 5.5 to 6.5, the comparison of the rational expectation equilibrium and the initial order quantity commitment mechanism.

It can be seen from Figure 6 that the initial order quantity commitment mechanism has a relatively large

decline in the initial order quantity relative to the rational expected equilibrium situation. This is also the most effective means to deal with strategic consumers. It can also be seen that the profit level has been greatly increased after committing to the initial order quantity. For example, when $c_1 = 5$, $c_2 = 6$, $v = 15$, $h = 4.5$, $s = 2$, $X_1 \sim N(75, 400)$, and $X_2 \sim N(25, 225)$, under the assumption of rational expectation equilibrium, initial order quantity $Q_c = 72.2$, retail price of the first stage $p_c = 10.3345$, and the retailer's profit $\pi_c^R = 383.0678$. Under the initial order quantity commitment mechanism, the initial order quantity $Q_q^* = 27.9$, the retail price of the first stage $p_c = 14.9027$, and the retailer's profit $\pi_c^R = 695.4776$. The profit has nearly doubled. The result of this example is consistent with Property 3. At the same time, it can be seen that after introducing the initial order commitment, the probability of consumers being

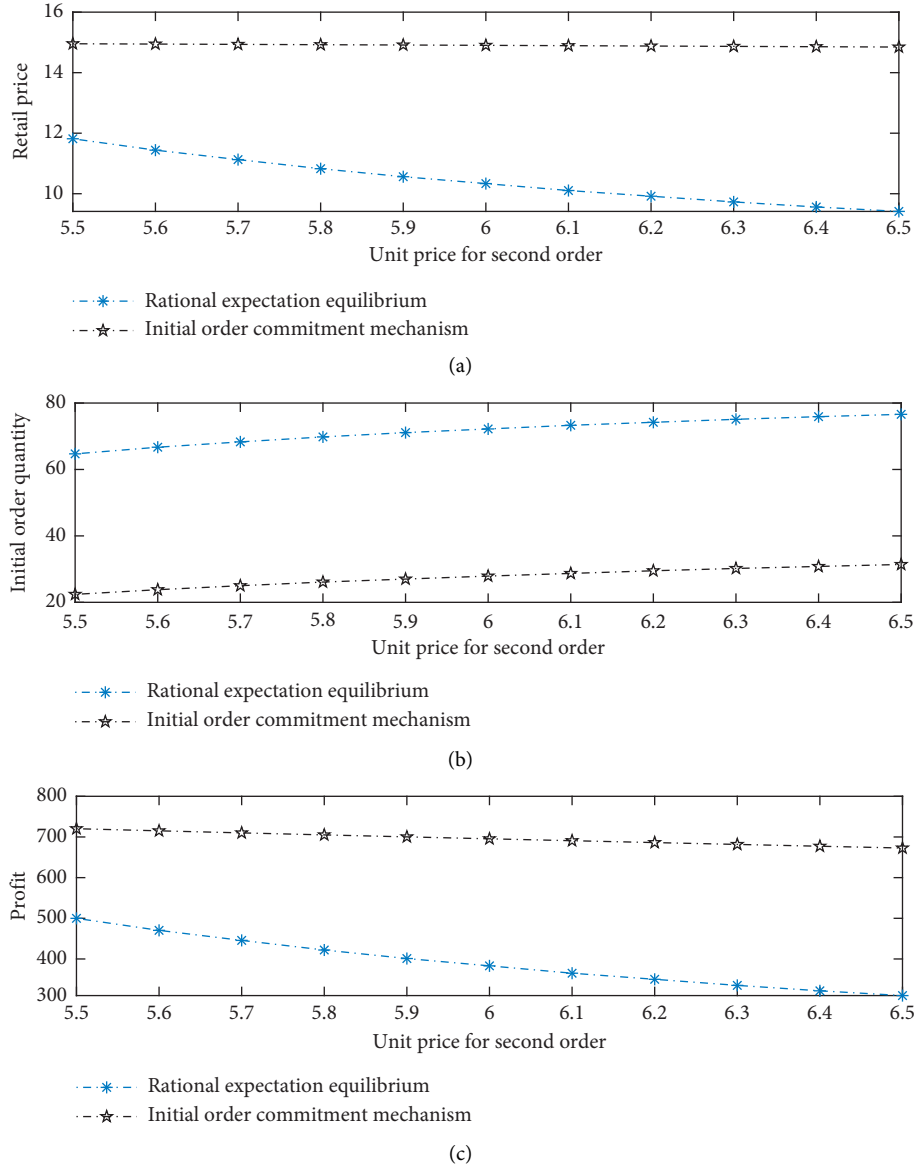


FIGURE 6: Comparison of rational expectation equilibrium and initial order quantity commitment mechanism.

able to buy product in the second stage is greatly reduced by reducing the initial order volume, thus “forcing” consumers to buy product in the first stage and greatly increasing the retail price in the first stage. The profit of retailers has been greatly improved, which shows that the effect of the initial order commitment mechanism is obvious.

In two-part pricing contract, if the parameter is set to $w = 5.9814$ and $L = 0$, then the retailer's profit $\pi_L^R = 668.0978$, the manufacturer's profit $\pi_L^M = 27.3798$, and the total profit of the supply chain $\pi_L = 695.4776$. The calculation results are consistent with the conclusion given in Proposition 3. The total profit of the supply chain is the same as that of the retailer under the initial order commitment mechanism, which shows that the two-part pricing contract achieves the coordination of the supply chain. If the value of

L is reset, the profit can be distributed arbitrarily between manufacturer and retailer.

Under the revenue-sharing contract, when the revenue-sharing ratio λ increases from 0 to 1, the corresponding wholesale price, retailer's profit, and manufacturer's profit change as shown in Figure 7.

As can be seen from Figure 7, with the increase in revenue-sharing ratio λ , the wholesale price has been rising and is greater than the manufacturer's production cost c_1 ; retailer's profits are increasing and manufacturer's profits are decreasing, which is consistent with the theory of revenue-sharing contract. It should be pointed out that no matter what value the λ takes, the profit of the manufacturer is greater than 0. At the end when $\lambda = 1$, when the retailer monopolizes all its profits, the manufacturer still gets 27.37 profit, that is to say, the other profit 668.1 except 27.37 can be

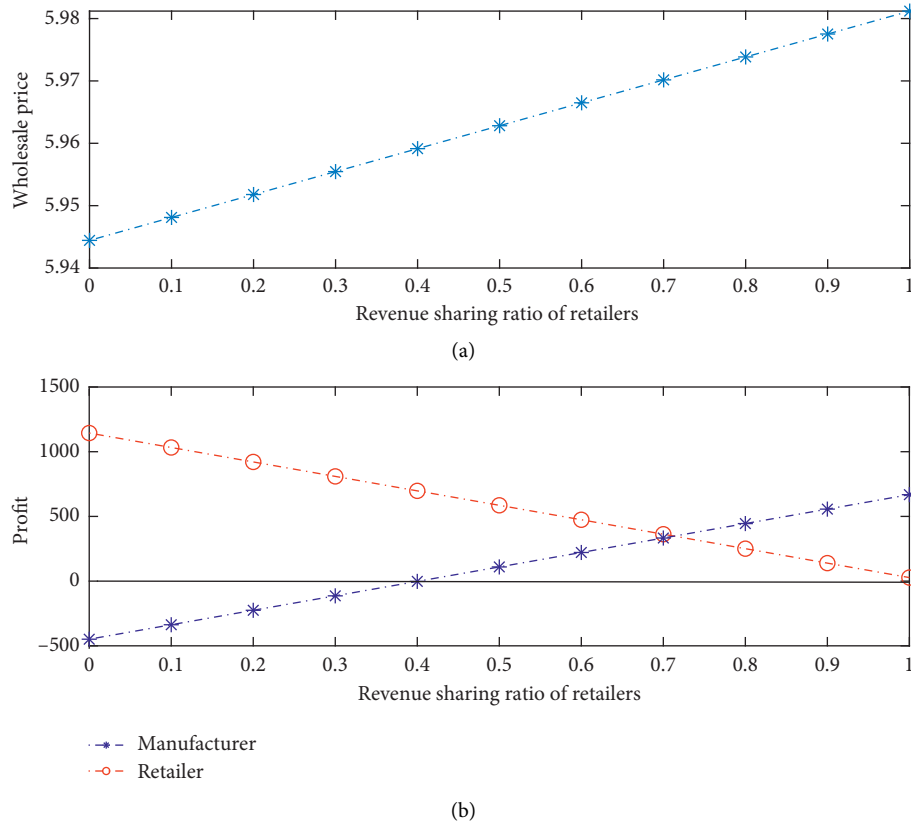


FIGURE 7: Wholesale price and profit under different revenue-sharing proportions.

arbitrarily allocated among the supply chain members by adjusting the value of the λ .

8. Conclusion

In this paper, the optimal decision-making of supply chain members and the coordination of supply chain in the two-echelon newsvendor model are studied based on consumers' strategic behavior and rapid response mechanism under the condition that retailers are faced with two-stage stochastic demand. Based on the assumption of rational expectation, the equilibrium retail price and initial order quantity of retailers in a centralized supply chain are given, and the influence of the change of relevant parameters on retailers' decision-making is analyzed. The retailer's decision-making under the initial order commitment mechanism and its impact on supply chain profit are discussed. On this basis, aiming at the profit level under the initial order quantity commitment mechanism, two-part pricing contract and revenue-sharing contract are introduced to coordinate the two-echelon supply chain system composed of a single manufacturer and a single retailer. It is proved that both coordination mechanisms can achieve supply chain coordination under reasonable contract parameters. At the same time, the two-part pricing contract can distribute profits arbitrarily among the supply chain members by adjusting the value of the fixed fee. The advantage of the revenue-sharing contract is that the manufacturers and retailers share

profits while sharing risks. In practical application, enterprise managers can reasonably choose different supply chain coordination mechanisms according to their own needs.

This paper studies the supply chain system of a single manufacturer and a single retailer. It will be a future research direction to analyze the pricing and coordination of supply chain under the competition of multiple manufacturers and retailers. This paper assumes that the retail price of goods in the second stage is an exogenous variable, which can be considered as an endogenous variable in the follow-up study. This paper assumes that all consumers are homogeneous, and the evaluation of goods is the same. When consumers are of different quality, the decision-making problem needs further study [45–48].

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

Optimal Strategy of Supply Chain considering Interruption Insurance

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The interruption of supply chain caused by unexpected events results in great economic losses. In this paper, we consider that the supply chain risk management consists of a manufacturer and a retailer faced with demand and supply uncertainties caused by the interruption of supply chain. We consider that the manufacturer transfers the disruption risk by purchasing BI (business interruption) insurance. Three models are established to illustrate the impact of insurance on supply chain decision-making under risk. It is observed that business interruption insurance can increase the retailer's order quantity and supply chain profit. The higher the interrupt probability is, the more obvious the value of the business interruption insurance is. Furthermore, the retailer helps the manufacturer to share the premium, and the manufacturer shares the proceeds of insurance with the retailer, which can stimulate retailer to order more and increase the profit of manufacturer and retailer.

1. Introduction

In recent years, various emergencies and disasters (such as fire, earthquake, and flood) are impacting the supply chain more and more frequently, and the globalization of the supply chain further aggravates the risk of the supply chain, especially the supply risk. Procurement is at the source of the whole supply chain, which plays a vital role in the survival and development of enterprises. The operation process of supply chain will be affected by various factors, and there are also various forms of risks. Supply interruption is one of the many risks, which makes the downstream enterprises of the supply chain suffer from excessive downtime due to the lack of production resources and even disconnects the upstream and downstream supply chains and finally brings about huge economic losses to enterprises. BI insurance, as an important tool for enterprises to cope with risk management, has been effectively applied in practice. For example, Ericsson mobile division lost \$1.68 billion as a result of a fire at the Philips plant in 2000; it received \$200 million from the insurance company. After the Wenchuan earthquake, Lafarge company also received \$720 million by purchasing BI insurance. BI insurance provides a strong guarantee for companies

when they face interruption risks, reduces their risk coefficients, and improves their antirisk capabilities. Therefore, it is of great significance to introduce BI insurance into the supply chain. This paper will discuss the impact of the purchase BI insurance by manufacturers on the decision of supply chain members under the risk of disruption.

However, there are few studies on BI insurance, and most of the literatures focus on insurance regulations. Furman and Zitikis [1] considered a prominent problem in actuarial science, defining or describing premium calculation principles that meet certain characteristics, and they derived explicit formulas for weighted premium distribution of loss in several important categories, thus facilitating parameter statistical inference. Dong and Tomlin [2] discussed the relationship between commercial insurance and operation measures and proved that insurance and operation measures are not always substitutes for each other. Under certain conditions, insurance can increase the marginal value of inventory and the overall value of emergency procurement. Later, Dong and Tang [3] considered that a company can purchase BI insurance, implement storage inventory, or take preparatory actions to reduce the expected interruption time and analyzed how the insurance affects the

optimal deployment and preference of these two operational measures. Zhen et al. [4] studied the effect of ex ante BI insurance on ex post transportation recovery and compared ex ante BI insurance with ex post action backup transportation. Stecké and Kumar [5] considered through buying BI insurance to address supply chain risk. Their research shows that when the premium is high and the purchase of BI insurance cannot make up for the decline of the market share of the insured enterprise, the risk transfer through this insurance is not suitable for the small and relatively weak enterprises. Lodree and Taskin [6] studied the optimal inventory level under the uncertainty of demand and extreme event and combines insurance policy with active disaster relief planning, which provides a practical method for decision-makers to quantify the inventory level, premium and income under interruption. Tierney [7] analyzed the value of BI insurance in dealing with risks according to actual cases and discussed the role of BI insurance in the Northridge earthquake. Lin et al. [8] proposed an insurance contract under which suppliers and retailers share the risk of overstock and understock. It proved for the first time that the insurance contract can coordinate the supply chain. On this basis, it compares the insurance contract with the income-sharing contract and focused on the analysis of the differences between the insurance contract and the income-sharing contract. Commercial insurance is traditionally based on a single enterprise as the research background. However, Serpa and Krishnan [9] studied commercial insurance in the context of several companies and believe that insurance can be strategically used as a commitment mechanism to improve the efficiency of risk management by reducing free-rider problems. Alex and Birge [10] studied how commercial credit plays a risk-sharing role in supply chain. When retailers are well funded, interest-free credit is appropriate, and when funding is constrained, suppliers offer two-phase contracts. Most of the above articles mainly study the complementary relationship between insurance and multisource procurement, inventory, as well as some study on insurance clauses. The difference between our paper and the previous literature is that we introduce BI insurance into the supply interruption model and discuss the changes of the optimal wholesale price and optimal order quantity under the three cases of the manufacturer not purchasing insurance, separately purchasing insurance, and the retailer helping the manufacturer to share the premium.

Recently, there are many measures to deal with the risk of interruption, which are mainly divided into the three following categories: inventory management, multisource purchasing, and business interruption insurance. Yang et al. [11], Hu et al. [12], Tomlin [13], and Tang et al. [14] mainly studied the supply chain disruption under the strategies of inventory holding, multisupplier procurement, and alternative supply/backup production from the perspective of retailers. The literature on multiple sources is very rich. Babich et al. [15] considered a retailer facing random market demand and random supply who adopts two competitive suppliers to supply in order to increase the stability of supply; they studied how a retailer chooses suppliers and formulates pricing and purchasing strategies. Aissaoui et al.

[16] pointed out that multisource procurement can prevent the shortage of purchaser resources and make the competition between suppliers firm. Sarkar and Mohapatra [17] divided the emergencies into system emergencies, local emergencies, and individual emergencies and used the method of decision tree to determine the optimal number of suppliers. Meena and Sarmah [18] studied the problem of supplier selection under different interruption risks and established an optimal supplier selection model with different failure probability, capacity, and compensation. The numerical study and sensitivity analysis provide useful guidance for managers to select the optimal supplier number under supply interruption risks. Xanthopoulos et al. [19] proposed a single-cycle inventory model for decision-makers of risk neutrality and risk aversion, and the advantages of contingency strategy in managing uncertainty and risk in dual supply chain are discussed. Lu et al. [20] considered a supply chain with two replaceable products and two suppliers, and products can be ordered from an unreliable supplier or a reliable but more expensive supplier. It is found that, in the optimal procurement strategy, the high-grade products should be superior to the low-end products, and the demand variability and correlation have an impact on the substitution effect of products and the corresponding optimal procurement strategy. Li et al. [21] focused on the impact of the use of dual-source procurement strategies on inventory status, recovery of production capacity, and varying degrees of supply disruption. They analyzed the profit function of manufacturers under different degrees of supply interruption and provided theoretical basis for whether and how to use dual-source procurement strategy under different degrees of supply interruption risk. When facing supply disruptions, the emergency procurement strategy and the optimal allocation procurement strategy are widely used strategies to manage supply risks. Yin and Wang [22] considered the three common purchasing methods between the retailer and the main supplier and the standby supplier: prepurchase, reservation, and emergency purchase; they gave the optimal ordering mode of the retailer under different interruption probability. After that, Wang and Yin [23] considered the procurement problem of a risk-averse retailer with two suppliers, and, in order to reduce the risk of interruption, the retailer adopted a joint backup supply and responsive pricing strategy. Three common backup strategies between the retailer and the backup provider are studied: prepurchase, reservation, and emergency purchase; they deduced the conditions under which each strategy is optimal and the impact of different risk attitudes on the retailer's ordering strategy. He et al. [24] considered that the retailer adopts emergency procurement and optimal allocation strategies under the threat of supply disruption and price competition; they analyzed the effects of reliability level and cost on equilibrium price, expected profit, and equilibrium strategy allocation.

In the strategy of supply chain risk management, inventory can make enterprises maintain continuous and stable production and supply as far as possible in case of interruption, reduce the contradiction between supply and demand to a certain extent, and reduce the negative effect

brought about by supply chain risk. Making appropriate inventory strategy is a common way for enterprises to deal with supply chain risks under multicycle model or continuous model [25]. Parlar and Berkin [26] assumed that both supply normal time and supply interruption time follow exponential distribution and are independent random variables and studied the EOQ problem of a secondary supply chain. In view of the uncertainty of upstream enterprises' supply capacity, Khang and Fujiwara [27] studied the downstream enterprises' strategies based on the market demand, initial inventory, and upstream enterprises' supply capacity. Zhou et al. [28] explored the optimal ordering strategy in a secondary supply chain composed of a risk-averse manufacturer and a risk-averse retailer. Yan et al. [29] studied the effects of channel structure, risk-averse attitude, and scale of the demand disruption on a dual-channel supply chain. Zhao and Zhu [30] explored the risk-averse marking strategy in a remanufacturing supply chain.

This paper mainly studies the value of insurance coping with supply chain interruption risk by establishing three models: manufacturer does not buy BI insurance, purchases insurance separately, and retailer shares the premium. We explored the impact of outage probability on the optimal decision-making of a company. The main contributions of this paper can be summarized as follows: Firstly, in the background of uncertain market demand, we study the impact of introducing BI insurance on the decision-making of retailers in the face of uncertain demand and supply. Secondly, most of the studies on insurance focus on the formulation of insurance policies and clauses, while the research in this paper mainly combines insurance and interruption risk management to study the impact of interruption probability on enterprise decision-making. Finally, we study the effect of business interruption insurance on wholesale price of manufacturers and order quantity of retailers under the shortage of punishment mechanism.

2. The Model

2.1. Notations and Assumptions. A secondary supply chain consisting of manufacturers and retailers is considered. Without loss of generality, we assume that the manufacturer delivers the goods to its retailer, and the retailer purchases only a single product from the manufacturer. The retailer's decision problem is to decide the optimal quantity to order, and the retailer faces random market demand D (probability density function is $f(x)$ and cumulative distribution function is $F(x)$). Due to various natural disasters or equipment failure and other uncertainties of external environment, manufacturer are faced with the risk of supply interruption with a probability α . Once the interruption occurs, the manufacturer can only supply part of the goods to the retailer, and the supply factor is k ($0 < k < 1$). When the manufacturer fails to meet the retailer's order demand, he will face punishment, the punishment for unit product out of stock is h , and the production cost is c . Firstly, the manufacturer sets the wholesale price w , and then the retailer considers the uncertainty on both sides of supply and demand to order. Finally, the manufacturer produces and

supplies to the retailer, and the retailer decides the sales price p according to the market.

The notations used in the paper are provided in Table 1. Consider the following assumptions:

- (1) Manufacturer and retailer are risk neutral, and both aim to maximize their profits
- (2) Supply risks aim at manufacturers' finished goods (e.g., transportation damage, finished goods warehouse fire, etc.), resulting in random delivery by manufacturers, but production costs have occurred
- (3) The premium rate is exogenous, and the indemnity period is within the maximum indemnity period of the insurance contract
- (4) The information among the members of the supply chain is symmetrical

2.2. Uninsured Model without Disruption. Considering a secondary supply chain composed of a manufacturer and a retailer, the retailer faces random market demand D ($f(x)$ is the probability density function and $F(x)$ is the cumulative distribution function). In this section, the model does not consider the interruption of the manufacturer. The unit production cost of the manufacturer is c . Both parties enter into a wholesale price contract, and the manufacturer sets the wholesale price; according to the market demand, the retailer determines the order quantity and sells the products. The retailer's profit function is

$$\begin{aligned}\pi_r &= p \min(q, D) - wq, \\ E(\pi_r) &= p \left(q - \int_0^q F(x) dx \right) - wq,\end{aligned}\quad (1)$$

and when the random market demand obeys uniform distribution $[a, b]$, the retailer's profit can be rewritten as

$$E(\pi_r) = (p - w)q + \frac{apq}{b - a} - \frac{pq^2}{2(b - a)}. \quad (2)$$

The profit function of manufacturer is

$$E(\pi_m) = (w - c)q. \quad (3)$$

Theorem 1. *There is a unique optimal order quantity and wholesale price that maximizes the retailer's and manufacturer's profit. The optimal solutions are as follows:*

$$\begin{aligned}w^* &= \frac{pb + cb - ca}{2(b - a)}, \\ q^* &= \frac{pb - cb + ca}{2p}, \\ E(\pi_r^*) &= \frac{(pb - cb + ca)^2}{8p(b - a)}, \\ E(\pi_m^*) &= \frac{(pb - cb + ca)^2}{4p(b - a)}.\end{aligned}\quad (4)$$

TABLE 1: Symbols and related descriptions.

| Notations | Description |
|------------|--|
| w | Wholesale price of manufacturer |
| p | Retail price |
| c | Production cost of manufacturer |
| q | Retailer's order quantity |
| D | Random market demand |
| $f(x)$ | Probability density function of demand |
| $F(x)$ | Cumulative distribution function of demand |
| α | Probability of interruption |
| k | Random supply factor |
| h | Penalty cost per unit product |
| r | Premium rate |
| β | Premium sharing coefficient |
| γ | Insurance proceeds sharing coefficient |
| $E(\pi_r)$ | The expected profit function of retailer |
| $E(\pi_m)$ | The expected profit function of manufacturer |

Proof. The first and second derivatives of the profit function (2) are

$$\begin{aligned}\frac{d\pi_r}{dq} &= p - w + \frac{ap}{b-a} - \frac{pq}{b-a}, \\ \frac{d^2\pi_r}{dq^2} &= -\frac{p}{b-a} < 0,\end{aligned}\quad (5)$$

and, according to the last inequality, we know that retailer's profit is a concave function of order quantity. Let the first-order derivative be equal to 0, we get

$$q = \frac{ap + (b-a)(p-w)}{p}, \quad (6)$$

substituting (6) into equation (3), and the first and second derivatives of (3) are

$$\begin{aligned}\frac{d\pi_m}{dw} &= b + \frac{(b-a)(2w-c)}{p}, \\ \frac{d^2\pi_m}{dw^2} &= -\frac{2(b-a)}{p} < 0.\end{aligned}\quad (7)$$

The manufacturer's profit is a concave function of wholesale price. Let the first-order derivative be equal to 0, we get

$$w^* = \frac{cb + pb - ca}{2(b-a)}. \quad (8)$$

Substituting (8) into (6), we have

$$q^* = \frac{pb - cb + ca}{2p}. \quad (9)$$

Put (8) and (9) into the profit formula of retailer and manufacturer, we can get that

$$E(\pi_r^*) = \frac{(pb - cb + ca)^2}{8p(b-a)}, \quad (10)$$

$$E(\pi_m^*) = \frac{(pb - cb + ca)^2}{4p(b-a)}.$$

This completes the proof. \square

2.3. Uninsured Model with Disruption. In this section, we study the case where the manufacturer does not purchase BI insurance; due to the occurrence of various emergencies, the manufacturer is faced with the risk of interruption, the probability of interruption is α , and the supply factor is k ($0 < k < 1$). When the supply quantity of the manufacturer is less than the order quantity of the retailer, the manufacturer will face the penalty of out of stock, and the penalty cost of unit product is h . The two sides enter into a wholesale price contract, the manufacturer first determines the wholesale price, and the retailer makes a purchase decision considering the uncertainty of supply and demand.

The retailer's profit function is

$$\begin{aligned}\pi_r &= (1-\alpha)[p \min(q, D) - wq] + \alpha[p \min(kq, D) \\ &\quad - wkq + h(1-k)q], \\ E(\pi_r) &= v_1(p-w)q - (1-\alpha)p \int_0^q F(x)dx \\ &\quad - \alpha p \int_0^{kq} F(x)dx + \alpha h(1-k)q,\end{aligned}\quad (11)$$

where $v_1 = 1 - \alpha + \alpha k$; when the random market demand obeys uniform distribution $[a, b]$, the retailer's profit can be rewritten as

$$E(\pi_r) = v_1(p-w)q - \frac{v_2 p q^2}{2(b-a)} + \frac{v_1 a p q}{b-a} + \alpha h(1-k)q, \quad (12)$$

where $v_2 = 1 - \alpha + \alpha k^2$.

The expected profit function of manufacturer is

$$\pi_m = (1-\alpha)(w-c)q + \alpha[(w-c)kq - h(1-k)q]. \quad (13)$$

Theorem 2. *There is a unique optimal order quantity and wholesale price that maximizes the expected profit function. The optimal policies are as follows:*

$$\begin{aligned}
q^* &= \frac{v_1(pb - cb + ca)}{2pv_2}, \\
w^* &= \frac{cb + pb - ca}{2(b-a)} + \frac{\alpha h(1-k)}{v_1}, \\
E(\pi_r^*) &= \frac{[v_1(pb - cb + ca)]^2}{8pv_2(b-a)}, \\
E(\pi_m^*) &= \frac{[v_1(pb - cb + ca)]^2}{4pv_2(b-a)}.
\end{aligned} \tag{14}$$

Proof. The first and second derivatives of the profit function (12) are

$$\begin{aligned}
\frac{d\pi_r}{dq} &= v_1(p - w) + \alpha h(1 - k) - \frac{v_2 pq}{b - a} + \frac{v_1 ap}{b - a}, \\
\frac{d^2\pi_r}{dq^2} &= -\frac{v_2 p}{b - a} < 0.
\end{aligned} \tag{15}$$

Let the first-order derivative of (12) be equal to 0, we have

$$q = \frac{v_1 bp + \alpha h(1 - k)(b - a) - v_1(b - a)w}{v_2 p}. \tag{16}$$

Similarly, we obtain the optimal wholesale price:

$$w^* = \frac{cb + pb - ca}{2(b-a)} + \frac{\alpha h(1-k)}{v_1}. \tag{17}$$

Substituting (17) into equation (16), we get

$$q^* = \frac{v_1(pb - cb + ca)}{2pv_2}. \tag{18}$$

Put equations (17) and (18) into formulas (12) and (13) to get the optimal profit for the manufacturer and retailer.

This completes the proof. \square

Proposition 1. *The wholesale price of the manufacturer and the order quantity of retailer in case of interruption are greater than those without interruption.*

Proposition 1 indicates that when the manufacturer is at risk of interruption, both the order quantity of the retailer and the wholesale price of the manufacturer will increase. The manufacturer has to bear the cost of interruption penalty in the event of interruption, and the manufacturer is bound to raise the wholesale price to offset the impact of the penalty.

2.4. Manufacturer's Individual Insurance. As an effective tool for risk management, BI insurance is widely used in real life, and many companies deal with the risk of disruption by buying insurance. We consider that the manufacturer buys BI insurance when he is at risk of interruption, and when the interruption occurs, the manufacturer can only supply the quantity of kq to the retailer, and $k(0 < k < 1)$ is the supply factor. The manufacturer and retailer enter into a wholesale price contract, which contains a penalty clause for interruption. The manufacturer first determines the wholesale price, and the retailer decides the order quantity according to the uncertainty of supply and demand.

Here, we assume that BI insurance only considers purchase for the manufacturer's profit under normal production conditions, and the premium rate is r . Under normal production conditions, the manufacturer's profit is $(w - c)q$. When the disruption occurs, the manufacturer's profit is $(w - c)kq$, so the insured amount is $r(w - c)q$. In the event of interruption, the insurance company will compensate the manufacturer for the loss of profits, and the compensation amount is $(1 - k)(w - c)q$. In addition, the precondition for manufacturer to buy insurance is that the compensation amount of the insurance company must be greater than the manufacturer's insurance amount; that is, $\alpha(w - c)(1 - k)q > r(w - c)q$; namely, $\alpha(1 - k) > r$; otherwise, the manufacturer does not buy insurance.

The retailer's profit is

$$\begin{aligned}
\pi_r &= (1 - \alpha)[p \min(q, D) - wq] + \alpha[p \min(kq, D) \\
&\quad - wkq + h(1 - k)q], \\
E(\pi_r) &= v_1(p - w)q - (1 - \alpha)p \int_0^q F(x)dx \\
&\quad - \alpha p \int_0^{kq} F(x)dx + \alpha h(1 - k)q.
\end{aligned} \tag{19}$$

When the random market demand obeys uniform distribution $[a, b]$, the retailer's profit can be rewritten as

$$E(\pi_r) = v_1(p - w)q - \frac{v_2 pq^2}{2(b-a)} + \frac{v_1 mpq}{b-a} + \alpha h(1 - k)q. \tag{20}$$

The manufacturer's profit is

$$\begin{aligned}
E(\pi_m) &= (1 - \alpha)(w - c)q + \alpha[(w - c)kq - h(1 - k)q \\
&\quad + (w - c)(1 - k)q] - r(w - c)q.
\end{aligned} \tag{21}$$

Theorem 3. *There is a unique optimal order quantity and wholesale price maximizing the expected profit function. The optimal policies are as follows:*

$$\begin{aligned} q^* &= \frac{v_1(pb - cb + ca)}{2pv_2} + \frac{\alpha h(1-k)(b-a)(v_4 - v_1)}{2pv_2v_4}; \\ w^* &= \frac{cb + pb - ca}{2(b-a)} + \frac{\alpha h(1-k)(v_1 + v_4)}{2v_1v_4}; \\ E(\pi_r) &= \left[\frac{v_1(pb - cb + ca)}{4(b-a)} + \frac{\alpha h(1-k)(v_4 - v_1)}{4v_4} \right] q^*; \\ E(\pi_m) &= \left[\frac{v_4(pb - cb + ca)}{2(b-a)} + \frac{\alpha h(1-k)(v_4 - v_1)}{2v_1} \right] q^*. \end{aligned} \quad (22)$$

Proof. Let $v_4 = 1 - r$; through $\alpha(1-k) > r$, we can derive $1 - \alpha + \alpha k < 1 - r$; that is, $v_4 > v_1 > v_2$. It is easy to verify that

$$\begin{aligned} \frac{d\pi_r}{dq} &= v_1(p - w) - \frac{v_2pq}{b-a} + \frac{v_1ap}{b-a} + \alpha h(1-k), \\ \frac{d^2\pi_r}{dq^2} &= -\frac{v_2p}{b-a} < 0. \end{aligned} \quad (23)$$

The optimal order quantity must satisfy the first-order condition ($d\pi_r/dq = 0$); then we have

$$q = \frac{v_1bp + \alpha h(1-k)(b-a) - v_1(b-a)w}{v_2p}. \quad (24)$$

Similarly,

$$\frac{d^2\pi_m}{dw^2} = -\frac{2(b-a)(1-r)}{pv_2} < 0. \quad (25)$$

Let ($d\pi_m/dw = 0$), we have

$$w^* = \frac{cb + pb - ca}{2(b-a)} + \frac{\alpha h(1-k)(v_1 + v_4)}{2v_1v_4}. \quad (26)$$

Take w^* into q , we get

$$q^* = \frac{v_1(pb - cb + ca)}{2pv_2} + \frac{\alpha h(b-a)(1-k)(v_4 - v_1)}{2pv_2v_4}. \quad (27)$$

In addition, we can derive that

$$\begin{aligned} E(\pi_r) &= \left[\frac{v_1(pb - cb + ca)}{4(b-a)} + \frac{\alpha h(1-k)(v_4 - v_1)}{4v_4} \right] q^*, \\ E(\pi_m) &= \left[\frac{v_4(pb - cb + ca)}{2(b-a)} + \frac{\alpha h(1-k)(v_4 - v_1)}{2v_1} \right] q^*. \end{aligned} \quad (28)$$

This completes the proof. \square

Proposition 2. *When the manufacturer buys BI insurance, the wholesale price is less than that in the case where the manufacturer does not buy the insurance, and the order quantity of the retailer and the profit of both the manufacturer and the retailer are also greater than those in the case where the manufacturer does not buy the insurance.*

Proposition 2 indicates that, compared with no insurance, the wholesale price is lower and the order quantity is increased, and the profit of both the manufacturer and the retailer is greater than the profit without insurance, which indicates that the BI insurance effectively transfers the impact of interruption risk. With the interruption penalty, the manufacturer will always raise the wholesale price, but when the manufacturer buys the insurance, the manufacturer will get the insurance compensation in case of the interruption, which can be used for the penalty expenditure. Therefore, the manufacturer will reduce the increase of the wholesale price to stimulate the retailer to order more goods.

2.5. Premium Sharing Model for Manufacturers and Retailers. Since the amount of BI insurance is relatively large and the manufacturer wants to involve the retailer, the manufacturer will determine a premium apportionment ratio β and enables the retailer to obtain the insurance income with coefficient γ . At the same time, the insurance income obtained by the retailer from the manufacturer must be greater than its own apportioned premium; that is, $\alpha\gamma(1-k)(w-c)q > \beta r(w-c)q$, so from this we can know that $\alpha\gamma(1-k) > \beta r$. In addition, for the manufacturer, the benefit from the insurance is greater than the amount of insurance he buys; that is, $(1-\beta)r(w-c)q < \alpha(1-\gamma)(1-k)(w-c)q$, which is equivalent to $(1-\beta)r < \alpha(1-\gamma)(1-k)$. Let $v_3 = \alpha\gamma(1-k) - \beta r$, we can derive $v_4 > v_3$.

The retailer's profit is

$$\begin{aligned} E(\pi_r) &= v_1(p-w)q - (1-\alpha)p \int_0^q F(x)dx \\ &\quad - \alpha p \int_0^{kq} F(x)dx + \alpha h(1-k)q \\ &\quad + [\alpha\gamma(1-k) - \beta r](w-c)q, \end{aligned} \quad (29)$$

and when the random market demand obeys uniform distribution $[a, b]$, the retailer's profit can be rewritten as

$$\begin{aligned} E(\pi_r) &= v_1(p-w)q - \frac{v_2pq^2}{2(b-a)} + \frac{v_1mpq}{b-a} \\ &\quad + \alpha h(1-k)q + v_3(w-c)q. \end{aligned} \quad (30)$$

The manufacturer's profit is

$$E(\pi_m) = (v_4 - v_3)(w-c)q - \alpha h(1-k)q. \quad (31)$$

Theorem 4. *There is a unique optimal order quantity and wholesale price maximizing the expected profit function. The optimal policies are as follows:*

$$\begin{aligned}
 q^* &= \frac{v_1(pb - cb + ca)}{2pv_2} + \frac{\alpha h(1-k)(b-a)(v_4 - v_1)}{2pv_2(v_4 - v_3)}, \\
 w_* &= \frac{(2v_3 - v_1)c}{2(v_3 - v_1)} + \frac{v_1bp}{2(v_1 - v_3)(b-a)} \\
 &\quad + \frac{\alpha h(1-k)(v_4 + v_1 - 2v_3)}{2(v_4 - v_3)(v_1 - v_3)}, \\
 E(\pi_r) &= \left[\frac{v_1(pb - cb + ca)}{4(b-a)} + \frac{\alpha h(1-k)(v_4 - v_1)}{4(v_4 - v_3)} \right] q^*, \\
 E(\pi_m) &= \left[\frac{v_1(v_4 - v_3)(pb - cb + ca)}{2(b-a)(v_1 - v_3)} \right. \\
 &\quad \left. + \frac{\alpha h(1-k)(v_4 - v_1)}{2(v_1 - v_3)} \right] q^*.
 \end{aligned} \tag{32}$$

Proof. Refer to the proof of Theorem 1. \square

Proposition 3. *Compared with the manufacturer's individual insurance, the order quantity of the retailer increased when sharing the premium, and the profit of both the manufacturer and the retailer was higher than that of the manufacturer's individual insurance.*

3. Numerical Examples

In this section, we present numerical examples to illustrate how managers apply our models to the risks of disruption in practice; the example problems are accompanied by sensitivity analysis and derive some managerial insights that can guide managers to make decisions. We use MATLAB to carry out numerical simulation; when the market demand for the retailer obeys uniformly distribution $[0, 1000]$, $p = 100$, $c = 10$, $h = 50$, $r = 0.02$, $k = 0.5$, $\beta = 0.2$, and $\gamma = 0.5$. The optimal wholesale price of manufacturer is shown in Table 2 and Figure 1.

As can be seen from Table 2 and Figure 1, as the probability of interruption increases, manufacturers will increase the wholesale price to reduce the risk loss caused by interruption. In addition, we find that the wholesale price of manufacturer under separate insurance is lower than that under no insurance. This is because the manufacturer has transferred part of the interruption risk to the insurance company by purchasing insurance. The manufacturer stimulates the retailer to increase orders by lowering wholesale price. When the probability of interruption is quite low, the wholesale price of the manufacturer in the case of sharing insurance premium is lower than the wholesale price in no insurance, which indicates that when the probability of interruption is very low, the utility of the

TABLE 2: Optimal wholesale price of manufacturer.

| α | No insurance | Separate insurance | Sharing insurance |
|----------|--------------|--------------------|-------------------|
| 0.11 | 44.07 | 44.00 | 65.12 |
| 0.13 | 44.87 | 44.75 | 66.16 |
| 0.15 | 45.68 | 45.52 | 67.22 |
| 0.17 | 46.50 | 46.29 | 68.31 |
| 0.19 | 47.35 | 47.07 | 69.43 |
| 0.21 | 48.21 | 47.86 | 70.58 |
| 0.23 | 49.10 | 48.66 | 71.76 |
| 0.25 | 50.00 | 49.46 | 72.97 |
| 0.27 | 50.92 | 50.28 | 74.22 |
| 0.29 | 51.87 | 51.11 | 75.50 |
| 0.31 | 52.84 | 51.96 | 76.83 |
| 0.33 | 53.83 | 52.81 | 78.19 |
| 0.35 | 54.85 | 53.67 | 79.60 |

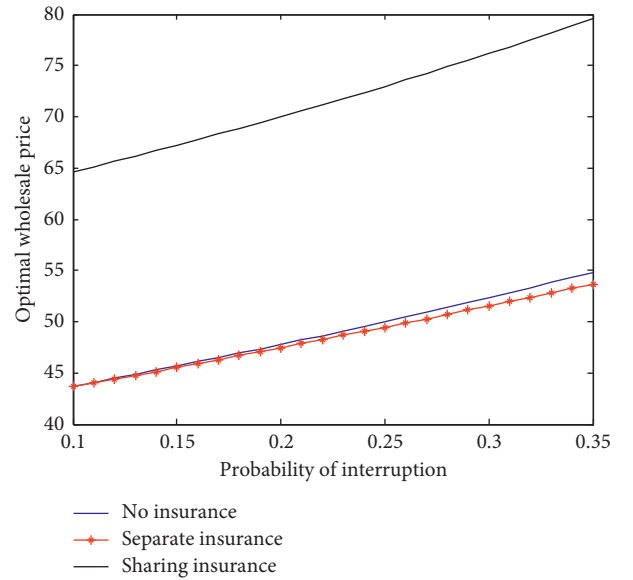


FIGURE 1: Impact of disruption probability on optimal wholesale price.

insurance company is not obvious. In this case, the manufacturer is bound to reduce the wholesale price to encourage the retailer to share the premium. When the probability of interruption is high, the retailer will share the premium and get the compensation from the insurance company, and the manufacturer will raise the wholesale price to make up for the loss.

Table 3 and Figure 2 indicate the relationship between manufacturer's profit and the change of interruption probability. From Table 3, we can know the following: (1) When the manufacturer does not buy insurance, his profit is a decreasing function of interruption probability, which is an intuitive observation. (2) The profit of the manufacturer increases with the interruption probability when the manufacturer purchases business interruption insurance. At this time, the role of BI insurance becomes prominent when the manufacturer's production equipment and other production equipment have a high probability of interruption; the risk can be transferred by purchasing BI insurance to make up for the loss caused by the interruption. (3) The

TABLE 3: Profit of manufacturer.

| α | No insurance | Separate insurance | Sharing insurance |
|----------|--------------|--------------------|-------------------|
| 0.11 | 15573.19 | 16208.77 | 16224.98 |
| 0.13 | 15498.73 | 16335.53 | 16361.84 |
| 0.15 | 15425.35 | 16472.94 | 16512.31 |
| 0.17 | 15353.12 | 16621.57 | 16677.30 |
| 0.19 | 15282.10 | 16782.04 | 16857.82 |
| 0.21 | 15212.34 | 16955.03 | 17054.95 |
| 0.23 | 15143.93 | 17141.25 | 17269.89 |
| 0.25 | 15076.92 | 17341.49 | 17503.95 |
| 0.27 | 15011.41 | 17556.59 | 17758.57 |
| 0.29 | 14947.48 | 17787.48 | 18035.33 |
| 0.31 | 14885.21 | 18035.15 | 18335.99 |
| 0.33 | 14824.72 | 18300.69 | 18662.48 |
| 0.35 | 14766.10 | 18585.29 | 19016.93 |

TABLE 4: Order quantity of retailer.

| α | No insurance | Separate insurance | Sharing insurance |
|----------|--------------|--------------------|-------------------|
| 0.11 | 44.07 | 44.00 | 65.12 |
| 0.13 | 44.87 | 44.75 | 66.16 |
| 0.15 | 45.68 | 45.52 | 67.22 |
| 0.17 | 46.50 | 46.29 | 68.31 |
| 0.19 | 47.35 | 47.07 | 69.43 |
| 0.21 | 48.21 | 47.86 | 70.58 |
| 0.23 | 49.10 | 48.66 | 71.76 |
| 0.25 | 50.00 | 49.46 | 72.97 |
| 0.27 | 50.92 | 50.28 | 74.22 |
| 0.29 | 51.87 | 51.11 | 75.50 |
| 0.31 | 52.84 | 51.96 | 76.83 |
| 0.33 | 53.83 | 52.81 | 78.19 |
| 0.35 | 54.85 | 53.67 | 79.60 |

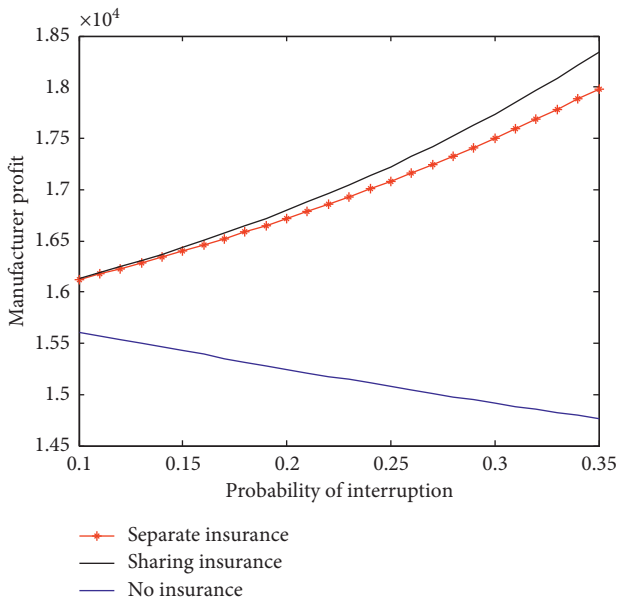


FIGURE 2: Impact of disruption probability on manufacturer's profit.

manufacturer's profit of buying insurance is always greater than that in the case of not buying insurance, and the greater the probability of interruption, the more obvious the effect of buying insurance. (4) As can be seen from Figure 2, with the increase of interruption probability, the manufacturer's profit in the case of sharing insurance premium is greater than that in the case of independent insurance, because coinsurance helps the manufacturer transfer part of the loss of interruption risk.

The following can be seen from Table 4 and Figure 3: (1) the order quantity of retailer is increasing in interruption probability, and when the probability of interruption is higher, the retailer needs to order more products to resist the risk of interruption. (2) The purchase quantity of the individual insurance is larger than that of the uninsured; after buying insurance, the manufacturer transfers part of the interruption risk to the insurance company, so the corresponding wholesale price is lower than that of the interruption without insurance, which will stimulate the retailer

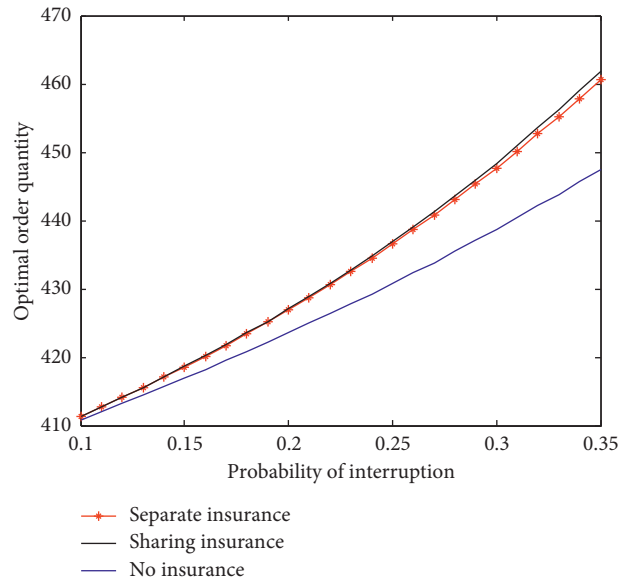


FIGURE 3: Impact of disruption probability on optimal order quantity.

to increase the order quantity. (3) We find that the optimal order quantity of the retailer in the case of sharing the premium is greater than the optimal order quantity of the retailer in the case of the manufacturer's individual insurance. Sharing premiums and insurance premiums can encourage retailers to order more quantity.

Table 5 and Figure 4 demonstrate the relative change in the retailer's profit with disruption probability. When the manufacturer is insured, regardless of the value of the interruption probability, the profit of the retailer will increase, and, with the increase of the interruption probability, the profit of the retailer is increasing. After buying BI insurance, the manufacturer will get some compensation for the loss, and he will reduce the wholesale price to stimulate the retailer to increase the order quantity. Through the transmission of the supply chain, the value of insurance is extended from the insured to the downstream uninsured enterprises, one enterprise insured, and two enterprises benefit, which achieve the effect of twice the result with half the effort. In addition, the insurance cost of retailers' optimal

TABLE 5: Profit of retailer.

| α | No insurance | Separate insurance | Sharing insurance |
|----------|--------------|--------------------|-------------------|
| 0.11 | 7797.72 | 7798.00 | 7786.59 |
| 0.13 | 7766.37 | 7766.88 | 7749.36 |
| 0.15 | 7736.81 | 7737.67 | 7712.68 |
| 0.17 | 7709.09 | 7710.42 | 7676.56 |
| 0.19 | 7683.27 | 7685.23 | 7641.05 |
| 0.21 | 7659.41 | 7662.19 | 7606.17 |
| 0.23 | 7637.58 | 7641.38 | 7571.96 |
| 0.25 | 7617.86 | 7622.90 | 7538.46 |
| 0.27 | 7600.31 | 7606.87 | 7505.71 |
| 0.29 | 7585.02 | 7593.40 | 7473.74 |
| 0.31 | 7572.09 | 7582.60 | 7442.61 |
| 0.33 | 7561.60 | 7574.62 | 7412.36 |
| 0.35 | 7553.67 | 7569.59 | 7383.05 |

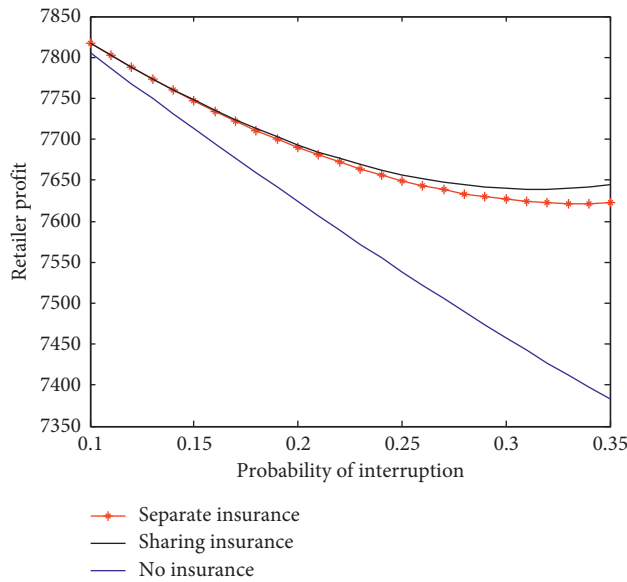


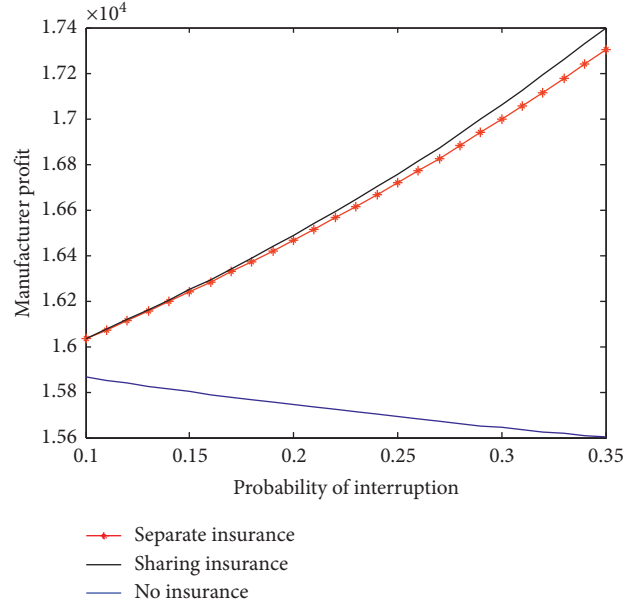
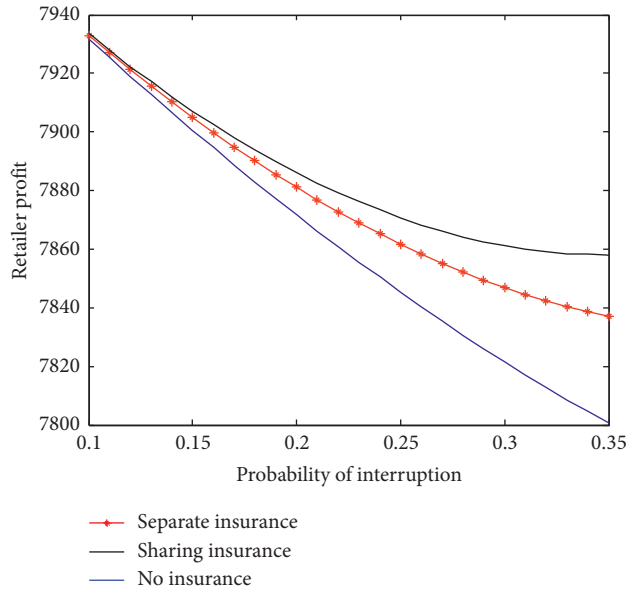
FIGURE 4: Impact of disruption probability on retailer's profit.

profits is greater than the individual insurance profits of retailers, and, with the increase of the interruption probability, the effectiveness of the BI insurance also enhanced, and retailer shares premium, not only helping manufacturers to transfer the risk but also obtaining insurance compensation by share premium.

The profits of manufacturer and retailer when $k = 0.7$ and $k = 0.2$ are shown in Figures 5–8.

From Figures 6–8, we can know that, regardless of the value of the supply factor, the profit of the manufacturer and the retailer after insurance is greater than the profit without insurance. The size of the supply factor does not affect the utility of insurance.

Through the above analysis, we can see that the manufacturer's profit increases with the probability of interruption no matter which way of insurance is adopted. In other words, when the probability of interruption is high, the manufacturer is better to choose to purchase BI insurance to transfer risks and make up for losses. However, no matter which kind of insurance is selected, the profit of the retailer

FIGURE 5: Impact of disruption probability on manufacturer's profit when $k = 0.7$.FIGURE 6: Impact of disruption probability on retailer's profit when $k = 0.7$.

decreases with the increase of interruption probability. However, when the retailer is willing to share the insurance cost with the manufacturer, the profit of the retailer is still greater than that of the manufacturer alone. Secondly, for both manufacturer and retailer, the choice of sharing the premium is always better than the manufacturer of separate insurance. For retailer, the choice is to help manufacturer share part of the premium, and the manufacturer will share part of the premium income to retailers when interrupt occurs, equivalent to retailer passing on the risk of shortages to insurance companies to cover losses; the profit of both

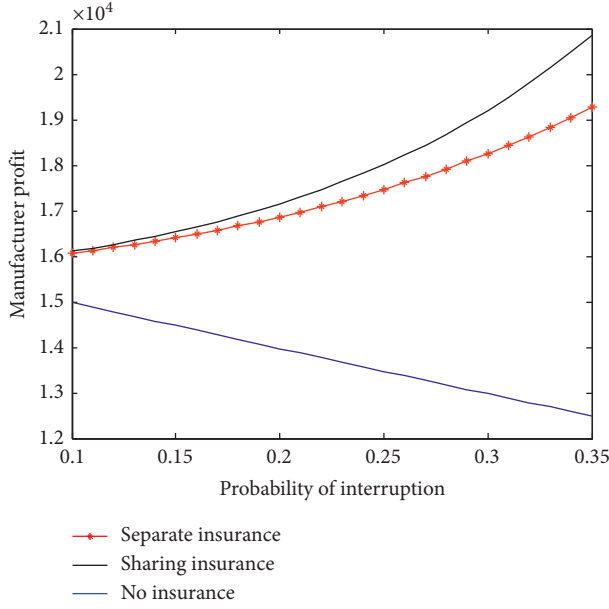


FIGURE 7: Impact of disruption probability on manufacturer's profit when $k = 0.2$.

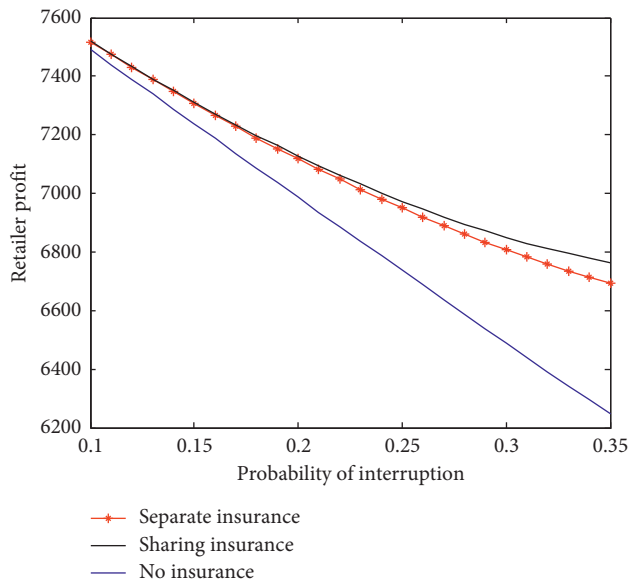


FIGURE 8: Impact of disruption probability on manufacturer's profit when $k = 0.2$.

manufacturer and retailer can be increased by sharing premium and insurance compensation.

4. Conclusion

In this paper, we introduce BI insurance into the disruption model as a tool to manage interruption risk. We established four models, benchmark model, no insurance, manufacturer's individual insurance, and retailer's shared premium, to compare the optimal strategies of manufacturer and retailer under different probability of interruption risk. It is found that when the manufacturer is faced with interruption

risk, it is better to choose buy insurance, and when the probability of interruption is higher, the effect of insurance is more obvious, and the manufacturer transfers part of the interruption risk to the insurance company through the purchase of insurance. Moreover, when the manufacturer purchased the insurance separately, the order quantity and profit of the retailer increased, and the utility of the insurance was transmitted from the upstream enterprise to the downstream retailer through the conduction effect of the supply chain. By sharing premiums and insurance payments with manufacturer, we find that the profits of manufacturer and retailer are increased, and this mechanism can also motivate retailers to order more goods. There are still many deficiencies in our research; for example, we consider that the demand is subject to specific uniform distribution and the risk attitude of the enterprise is not taken into account. Future work will explore the normal distribution of demand and the decision of manufacturers under different risk attitudes.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

A Building-Material Supply Chain Sustainable Operations under Fairness Concerns and Reference Price Benefits

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This paper incorporates fairness concerns and consumer reference price effects into a two-echelon building-material closed-loop supply chain consisting of a manufacturer and a retailer. By establishing four differential game models, we investigate the sustainable operations and cooperation of this supply chain. The four game models are a Nash noncooperative game, Stackelberg game with cost sharing, Stackelberg game with fairness concerns and cost sharing, and centralized decision model. By using dynamic models and optimal control theory, we obtain the two members' optimal equilibrium strategies in the supply chain. Analytical results show that the consumer reference price effect has a positive impact on the manufacturer's effort level, retailer's publicity level, and product brand goodwill, which can improve the supply chain performance. The retailer's partial commitment to cost sharing can enhance the production enthusiasm of the manufacturer, improve the brand reputation of the product, and enhance the two members' individual profitability. The distributional fairness concerns of the manufacturer not only prevent the manufacturer and retailer from achieving Pareto improvement but also lead to the decline of the manufacturer's effort level and profitability. The research conclusions of this paper can provide some insights into the cooperation and sustainable development of the supply chain.

1. Introduction

With the rapid development and promotion of e-commerce, enterprises have gradually entered the era of network economy, the uncertainty of the market environment has further increased, and the competition between enterprises has transformed into competition between the supply chains where the enterprises are located. As a result, the cooperation between supply chain companies has become particularly important. The supply chain contains various important elements, such as suppliers, manufacturers, distributors, and consumers. Among them, consumers are the most important sales targets of commodities, and their behavior characteristics directly affect the overall benefits of the enterprise and the supply chain. In the relevant literature, many scholars regard consumers as the most important influencing factor when studying the sustainable operation process of the supply chain, but they often ignore the cooperation among the companies in the supply chain. Some

scholars regard consumers and enterprises as research objects at the same time. However, in their research, companies are completely rational with the goal of maximizing their own profits. However, in their research, enterprises are fully rational people who pursue their own profit maximization as the goal.

However, due to the influence of the environment and individual perceptions, the enterprise does not appear as a completely rational image. Therefore, when studying the sustainable operation of supply chain, this paper takes into account the behavior characteristics of consumers and the irrational behaviors among enterprises, such as the fairness of interest distribution, trying to analyze the following questions: (1) How does the manufacturer's fair concern behavior affect the supply chain effect? (2) Under the four different operating models, which mode can produce higher effects? (3) How does the importance of consumer reference price effects affect decision-making? From the perspective of cooperation in a supply chain consisting of only one

manufacturer and one retailer, this paper takes fairness concerns and reference effects into consideration and provides some decision-making reference for promoting the long-term dynamic cooperation of supply chain members and improving overall performance.

2. Literature Review

In supply chain decision-making, fully considering the behavior characteristics of consumers is conducive to optimize the decision-making results of enterprises and help enterprises gain more market share.

In the study of consumer behavior, many scholars have found that consumer's reference price effect has a crucial influence on corporate decision-making. Winer [1] constructed an empirical model of brand selection on the effect of reference price, and the results showed that, when predicting the purchase rate of consumers, the model that considers the effect of reference price is better than the model that simply uses sales prices. Lin et al. [2] discussed the significant impact of reference price effects on supply chain cooperation and price promotion by establishing a differential game model. Research by Amit Mehra et al. [3] proved that consumer's reference price effect not only affects product differentiation and company profits but also affects product positioning. Chenavaz [4] found that consumer decision-making is affected by the reference price effect with the help of the Pontryagin principle of maximum value to prove the member's optimal quality strategy. Gavious [5] found that the supply chain effect with consumer's reference price effect is higher than the supply chain effect without reference price effect. Malekian [6] studied the effect of reference price effect on price promotion and national advertisers. The study found that consumer's reference price effect has an important impact on the promotion of advertising level and the increase of supply chain profits. Xu [7] discussed the impact of reference prices on the performance of three decentralized reverse channels and examined the impact of reference price effects on optimal strategies. Hsieh et al. [8] incorporated the reference price effect into the deteriorating inventory problem and established the best dynamic pricing model. The research by Zhang et al. [9] found that the reference price plays an important role in the customer's purchase decision and has an impact on the company's strategy and the most important pricing. The research by He et al. [10] demonstrated that the degree of green innovation in the supply chain will increase with the enhancement of consumer's reference price effect. It can be seen that the consumer's reference price effect directly or indirectly affects the final decision-making and economic effect of enterprises. When enterprises make strategic decisions, they will use the consumer's reference price effect as an influencing factor. However, in addition to consumers, the factors that affect corporate decision-making and profitability include partners or competing companies in the production supply chain, especially partners in the same supply chain.

At present, there are relatively few studies on introducing fairness concerns into corporate decision-making.

Fairness concerns mean that decision-makers compare their own profits and gains with a reference object and show aversion to the unfairness of income distribution, which directly affects the cooperation between enterprises. Economists represented by Kahneman [11] found that, in reality, high-level decision-makers are extremely concerned about the fairness of profit distribution. Povlov and Katok [12] also show through empirical research that fairness concerns can better explain retailer's pricing issues. Cui [13] and others introduced fairness concern behavior in the newsboy model, and the research proved that retailer's aversion to unfairness would have a negative impact on supply chain coordination. Ma et al. [14] found that fairness concerns will lead to a reduction in marketing efforts and costs, but, under certain conditions, they will narrow the profit gap between the two supply chain members. Zhang et al. [15] found that retailer's concerns about fairness affect wholesale prices and retail prices, and retailer's concerns about power and fairness jointly determine whether retailers benefit from fairness concerns. The research results of Li [16] found that the fair concern behavior of retailers can reduce the stability of the supply chain system more than the fair concern behavior of manufacturers. Zheng et al. [17] believe that in a fairer environment, the fair concern behavior of partners can bring about higher profits. It can be seen that companies as rational people are not only concerned about their own profits but also extremely concerned about the fairness of profit distribution. The degree of fairness concerns can directly affect the decision-making and benefits of each company in the supply chain. If the profit distribution is more even, it will stimulate the enthusiasm of the company to innovate and produce. On the contrary, it will make the company passive and slow down, resulting in a decline in the overall benefits of the production supply chain.

In view of this, this article considers the two factors of the reference price effect and fairness concern behavior of consumers that have an important impact in the supply chain and incorporates them into the unified dynamic differential game model. We try to analyze the following questions: (1) How does the manufacturer's fair concern behavior affect the supply chain effect? (2) Under the four different operating models, which mode can produce higher effects? (3) How does the importance of consumer reference price effects affect decision-making? From the perspective of cooperation in a supply chain consisting of only one manufacturer and one retailer, this paper takes fairness concerns and reference effects into consideration and provides some decision-making reference for promoting the long-term dynamic cooperation of supply chain members and improving overall performance.

3. Model Construction and Solution

3.1. Model Construction and Symbol Description

3.1.1. Model Description. This article assumes that the supply chain of building materials products consists of a retailer as a leader and a producer as a follower. Manufacturers can purchase professional equipment or research new

technologies to improve the quality of building materials products and increase the degree of greenness of products. The efforts of building materials manufacturers directly affect the quality, degree of greenness, and brand reputation of products, which can further act on product sales. Building materials retailers can increase the brand reputation of products through certain publicity so that consumers have a deep impression of the products and thus increase product sales. Therefore, the publicity of building materials retailers directly affects product sales and brand reputation. This article chooses retailer as the leading party in the differential game and forms Stackelberg differential game with the manufacturer. The model is divided into four types, namely, the NASH noncooperative game; that is, building materials manufacturers and retailers strive to maximize their profits, and there is no cooperation or mutual assistance. However, in order to encourage manufacturers to improve product quality and greenness, thereby increasing product awareness and product sales, retailers actively bear part of the costs for manufacturers, forming a Stackelberg differential game with retailers as the leader and manufacturers as followers. However, when making strategic decisions for companies, building materials manufacturers will not only consider their own interests but also pay great attention to the fairness of the distribution of interests with partners in the same supply chain. If the manufacturers' interest distribution is on the weak side, they will feel unfair and go slow passively. On the contrary, it will encourage producers to work harder and form a third model with fairness concerns. In centralized decision-making, the goal of decision-making is to maximize the benefits of the supply chain system, while fairness concerns the distribution of benefits within the supply chain, and the goal of each member is to maximize their own profits. Therefore, there is no fairness concern under centralized decision-making.

3.1.2. Model Construction and Symbol Description

Assumption 1. Because the effort cost of building materials manufacturers and the publicity cost of building materials retailers have the same convexity, referring to the setting of cost by Zhang [18], it is assumed that the effort cost of building materials manufacturers and the publicity cost of building materials retailers are quadratic functions of effort level and publicity level. Then the manufacturer's effort cost at time t is $C_n(t) = (1/2)k_1E_n(t)^2$. The publicity cost of building materials retailers is $C_m(t) = (1/2)k_2E_m(t)^2$. Among them, $k_1 > 0$ and $k_2 > 0$ are the manufacturer's effort cost coefficient and the retailer's promotional cost coefficient, $E_n(t)$ represents the level of effort that manufacturers have made to improve product quality and greenness, and $E_m(t)$ represents the level of publicity made by retailers to enhance product branding.

Assumption 2. The effort level of building materials manufacturers and the publicity cost of retailers will not only improve the quality and green degree of products but also

enhance the brand goodwill of products in the market, and the brand goodwill will continue to decline over time; that is, there is a certain natural decay rate. Refer to the dynamic model construction of brand goodwill by Ouardighi [19]. The dynamic model of brand goodwill can be established as follows:

$$\dot{G}(t) = r_n E_n(t) + r_m E_m(t) - \delta G(t). \quad (1)$$

Among them, $G(0) = G_0$ is the initial brand goodwill. r_n and r_m are the influence coefficients of manufacturer's effort level and retailer's publicity level on brand goodwill, respectively, and δ is the natural decay rate of brand goodwill over time.

Assumption 3. Assuming that the reference effect of consumers is affected by the combination of consumer memory price and external stimulus and referring to the treatment of reference price effect by scholars such as Zhang [18] and Fibich [20], we can assume that the reference price of consumers in the supply chain of building materials production is dynamic, and its change rate is affected by the combination of price memory and brand goodwill as follows:

$$\dot{R}(t) = \theta(P(t) - R(t)) + \lambda G(t). \quad (2)$$

In the above equation, θ represents the consumer's "memory parameter." The larger the value of θ is, the lower the consumer's loyalty to the product is, because the consumer's memory of the product's past prices and purchase experience is very short.

$P(t)$ represents the market price of the product at time t , $R(t)$ represents the consumer's reference price at time t , and λ is the influence coefficient of the product's brand goodwill on the consumer's reference price. If the brand goodwill is higher, the consumer's reference price will also increase. The improvement is consistent with the actual market. Among them, $R(0) = R_0$ is the initial reference price.

Assumption 4. The market sales of products are affected by the product price, brand goodwill, and consumer's reference price effect. Referring to the market demand set by Zhang [21], it can be assumed that the market demand function of the product is as follows:

$$Q(t) = a - bp(t) + \alpha G(t) + \beta(R(t) - P(t)). \quad (3)$$

From the above equation, $a > 0$ represents the inherent demand for the product in the market itself and is not affected by other factors. $b > 0$ represents the influence coefficient of product price on demand. The higher the product price is, the less the market demand is, which is consistent with the market law. $\alpha > 0$ represents the influence coefficient of product brand goodwill on market demand. $\beta > 0$ represents the sensitivity coefficient of consumers to the difference between the reference price and the actual price. When $R(t) > P(t)$, consumers will feel that they are taking advantage of it, thereby increasing demand to obtain greater satisfaction.

Assumption 5. In order to encourage manufacturers to make efforts to improve product quality and greenness, increase product awareness and brand reputation, and thereby increase sales, retailers take the initiative to bear a certain effort cost for manufacturers, and the cost coefficient is $\phi(t)$, $0 < \phi(t) < 1$.

Assumption 6. Assuming that both the manufacturer and the retailer of building materials have the same positive discount rate ρ , they pursue the maximization of their own effects in an infinite time range. In order to simplify the model, the inventory cost and shortage cost of retailers and manufacturers are set to zero.

In order to simplify the writing, the time t is omitted when writing this article. The symbols and meanings of other parameters in the model are as follows.

W , manufacturer's wholesale price

P , Retailer's selling price

$\pi_n = W - C$, the marginal profit of the producer

$\pi_m = P - W$, retailer's profit margin

$\pi_s = P - C$, the marginal profit of the product

ε , the intensity of the manufacturer's concern for fairness

3.2. NASH Noncooperative Game. In the NASH noncooperative game, building materials manufacturers and retailers seek to maximize their own interests, and, when making decisions, they only consider how to increase their own profits. If the optimal level of the cooperative game in the supply chain is the upper limit of contract coordination, then the benefits of the NASH noncooperative game with no cost bearing and fairness concerns are the lower limit of

contract coordination. Use superscript D to represent the NASH noncooperative game model. At this time, the objective functions of the manufacturer and retailer are as follows:

$$\begin{aligned} \max_{E_n > 0} J_N^D &= \int_0^\infty e^{-\rho t} \left[\pi_n (a - bp + \alpha G + \beta (R - P)) - \frac{1}{2} k_1 E_n^2 \right] dt, \\ \max_{E_m > 0} J_N^D &= \int_0^\infty e^{-\rho t} \left[\pi_m (a - bp + \alpha G + \beta (R - P)) - \frac{1}{2} k_2 E_m^2 \right] dt. \end{aligned} \quad (4)$$

Theorem 1. The equilibrium result of the Nash noncooperative game is as follows.

(1) The best effort level and publicity level of building materials manufacturers and retailers are as follows:

$$\begin{aligned} E_n^{D*} &= \frac{r_n \pi_n}{k_1 (\rho + \delta)} \left(\alpha + \frac{\lambda \beta}{\rho + \theta} \right), \\ E_m^{D*} &= \frac{r_m \pi_m}{k_2 (\rho + \delta)} \left(\alpha + \frac{\lambda \beta}{\rho + \theta} \right). \end{aligned} \quad (5)$$

(2) The optimal trajectory of brand goodwill is as follows:

$$G^{D*}(t) = H^D - (H^D - G_0) e^{-\delta t}. \quad (6)$$

From the above equation,

$$H^D = \left(\alpha + \frac{\lambda \beta}{\rho + \theta} \right) \left(\frac{r_n^2 \pi_n}{\delta k_1 (\rho + \delta)} + \frac{r_m^2 \pi_m}{\delta k_2 (\rho + \delta)} \right). \quad (7)$$

(3) The optimal effect functions of building materials manufacturers and retailers are as follows:

$$\begin{aligned} V_N^D &= \frac{\pi_n}{\rho + \delta} \left(\alpha + \frac{\lambda \beta}{\rho + \theta} \right) G + \frac{\pi_n \beta}{\rho + \theta} R + \frac{\pi_n (a - bp - \beta p)}{\rho} + \frac{\theta p \pi_n \beta}{\rho (\rho + \theta)} + \frac{r_n^2 \pi_n^2}{2 k_1 \rho (\rho + \delta)^2} \left(\alpha + \frac{\lambda \beta}{\rho + \theta} \right)^2 \\ &\quad + \frac{r_n^2 \pi_n \pi_m}{2 k_2 \rho (\rho + \delta)^2} \left(\alpha + \frac{\lambda \beta}{\rho + \theta} \right)^2, \\ V_M^D &= \frac{\pi_m}{\rho + \delta} \left(\alpha + \frac{\lambda \beta}{\rho + \theta} \right) G + \frac{\pi_m \beta}{\rho + \theta} R + \frac{\pi_m (a - bp - \beta p)}{\rho} + \frac{\theta p \pi_m \beta}{\rho (\rho + \theta)} \\ &\quad + \frac{r_m^2 \pi_m^2}{2 k_2 \rho (\rho + \delta)^2} \left(\alpha + \frac{\lambda \beta}{\rho + \theta} \right)^2 + \frac{r_n^2 \pi_n \pi_m}{2 k_2 \rho (\rho + \delta)^2} \left(\alpha + \frac{\lambda \beta}{\rho + \theta} \right)^2. \end{aligned} \quad (8)$$

Proof. See Appendix A. \square

Corollary 1. In the NASH noncooperative game, because $(\partial E_n^{D*} / \partial \theta) < 0$, that is, the consumer's sensitivity to past prices and purchase experience, will affect the producer's effort level, and this effect is negatively correlated, the higher the consumer sensitivity coefficient, the lower the producer's level of effort;

and, by $(\partial E_n^{D*} / \partial k_1) < 0$, $(\partial E_n^{D*} / \partial \rho) < 0$, $(\partial E_n^{D*} / \partial \delta) < 0$, it can be concluded that the manufacturer's effort level will decrease with the increase of the manufacturer's effort cost coefficient, discount rate, and natural decay rate of brand goodwill. Because of $(\partial E_n^{D*} / \partial \pi_n) > 0$, $(\partial E_n^{D*} / \partial r_n) > 0$, $(\partial E_n^{D*} / \partial \alpha) > 0$, $(\partial E_n^{D*} / \partial \beta) > 0$, the level of effort of building materials manufacturers is positively correlated with factors such as

π_n , r_n , α , and λ . Moreover, the impact coefficient β of consumer's reference price effect on demand is also positively correlated with manufacturer's effort level. This is because manufacturer's effort level can improve product quality and green degree and further improve brand reputation and consumer's reference price. The higher the consumer's reference price effect is, the greater satisfaction can be obtained, thus increasing demand. This has stimulated manufacturers to improve their efforts.

Corollary 2. Similarly, the following results can be obtained:

$$\begin{aligned}
 \frac{\partial E_m^{D^*}}{\partial \pi_m} &> 0, \\
 \frac{\partial E_m^{D^*}}{\partial r_m} &> 0, \\
 \frac{\partial E_m^{D^*}}{\partial \alpha} &> 0, \\
 \frac{\partial E_m^{D^*}}{\partial \lambda} &> 0, \\
 \frac{\partial E_m^{D^*}}{\partial \beta} &> 0, \\
 \frac{\partial E_m^{D^*}}{\partial k_2} &< 0 < \frac{\partial E_m^{D^*}}{\partial \rho} < 0, \\
 \frac{\partial E_m^{D^*}}{\partial \delta} &< 0, \\
 \frac{\partial E_m^{D^*}}{\partial \theta} &< 0.
 \end{aligned} \tag{9}$$

Because retailers and manufacturers have different cost coefficients and profit margins, there are only differences between these two positive and negative correlation factors, and the other positive and negative correlation factors are the same.

Corollary 3. In NASH noncooperative game, the stable value of product brand goodwill dynamic model is positively correlated with one of the following factors. They are the influence coefficients r_n and r_m of effort level of building materials manufacturers and publicity level of retailers on goodwill, the influence coefficient β of consumer reference price effect on demand, the influence coefficient α of product goodwill on demand, the influence coefficient λ of brand goodwill on consumer reference price, and the marginal profits π_n and π_m of manufacturers and retailers. It is negatively correlated with the natural decay rate of brand goodwill δ , discount factor ρ , cost coefficients k_1 and k_2 of manufacturers and retailers, and sensitivity coefficient θ of consumers to product price and purchase experience. Moreover, the optimal trajectory model of product brand goodwill is monotonic transformation. When $H^u > G$, brand goodwill will increase with the increase of time. When $H^u < G$, brand goodwill will decrease monotonously with the increase of time. When $H^u = G$, brand goodwill will be a constant.

3.3. Stackelberg Game with Cost Sharing. When considering the issue of cost sharing, building materials retailers in order to encourage manufacturers to do their best to improve the quality and greenness of their products, building materials retailers take the initiative to provide a certain percentage of subsidies to manufacturer's efforts. From the perspective of long-term dynamics, the decision-making of supply chain investment between building materials retailers and manufacturers constitutes a Stackelberg game model, and this game model is dominated by retailers, and the superscript A is used to represent the case considering cost sharing.

Building materials retailers and manufacturers aim to maximize their own effects when making decisions. The decision-making process is divided into two stages. In the first stage, building materials retailers determine their own publicity level and cost sharing proportion for manufacturers. In the second stage, according to the retailer's publicity level and cost sharing ratio, the building material manufacturer determines the best level of its own effort. Therefore, the objective functions of manufacturer and retailer are as follows:

$$\begin{aligned}
 \max_{E_n > 0} J_N^A &= \int_0^\infty e^{-\rho t} \left[\pi_n (a - bp + \alpha G + \beta (R - P)) - \frac{(1 - \phi)}{2} k_1 E_n^2 \right] dt, \\
 \max_{E_m > 0} J_M^A &= \int_0^\infty e^{-\rho t} \left[\pi_m (a - bp + \alpha G + \beta (R - P)) - \frac{1}{2} k_2 E_m^2 - \frac{\phi}{2} k_1 E_n^2 \right] dt.
 \end{aligned} \tag{10}$$

Theorem 2. In a Stackelberg game with cost bearing, the equilibrium result is as follows.

- (1) The optimal effort cost, publicity cost, and share ratio of building materials manufacturers and retailers are as follows:

$$\begin{cases} E_n^{A^*} = \frac{r_n(2\pi_m + \pi_n)}{2k_1(\rho + \delta)} \left(\alpha + \frac{\lambda\beta}{\rho + \theta} \right), \\ E_m^{A^*} = \frac{r_m\pi_m}{2k_2(\rho + \delta)} \left(\alpha + \frac{\lambda\beta}{\rho + \theta} \right), \\ \phi = \frac{2\pi_m - \pi_n}{\pi_m + \pi_n}. \end{cases} \quad (11)$$

- (2) The optimal trajectory function of the dynamic model of product brand goodwill is as follows:

$$G^{A^*}(t) = H^A - (H^A - G_0)e^{-\delta t}. \quad (12)$$

From the above equation,

$$H^A = \left(\alpha + \frac{\lambda\beta}{\rho + \theta} \right) \left(\frac{r_n(2\pi_m + \pi_n)}{2k_1\delta(\rho + \delta)} + \frac{r_m^2\pi_m}{k_2\delta(\rho + \delta)} \right). \quad (13)$$

- (3) The optimal effect functions of building materials manufacturers and retailers are as follows:

$$\begin{aligned} V_N^{A^*} &= \frac{\pi_n}{\rho + \delta} \left(\alpha + \frac{\lambda\beta}{\rho + \theta} \right) G + \frac{\pi_n\beta}{\rho + \theta} R + \frac{\pi_n(a - bp - \beta p)}{\rho} + \frac{\theta p\pi_n\beta}{\rho(\rho + \theta)} \\ &\quad + \frac{r_n^2\pi(2\pi_m + \pi_n)}{4k_1\rho(\rho + \delta)^2} \left(\alpha + \frac{\lambda\beta}{\rho + \theta} \right)^2 + \frac{r_m^2\pi_n\pi_m}{k_2\rho(\rho + \delta)^2} \left(\alpha + \frac{\lambda\beta}{\rho + \theta} \right)^2, \\ V_N^{A^*} &= \frac{\pi_m}{\rho + \delta} \left(\alpha + \frac{\lambda\beta}{\rho + \theta} \right) G + \frac{\pi_m\beta}{\rho + \theta} R + \frac{\pi_m(a - bp - \beta p)}{\rho} + \frac{\theta p\pi_m\beta}{\rho(\rho + \theta)} \\ &\quad + \frac{r_m^2\pi_m^2}{4k_2\rho(\rho + \delta)^2} \left(\alpha + \frac{\lambda\beta}{\rho + \theta} \right)^2 + \frac{r_n^2(2\pi_m + \pi_n)^2}{2k_1\rho(\rho + \delta)^2} \left(\alpha + \frac{\lambda\beta}{\rho + \theta} \right)^2. \end{aligned} \quad (14)$$

The proof of Theorem 2 is similar to the proof of Theorem 1, so we will not repeat it here.

From Theorem 2, the following inferences can be obtained.

Corollary 4. Building materials retailers are willing to bear part of the cost in order to encourage manufacturers to improve and upgrade their products, but there are implicit conditions. Only when the marginal profits of retailers and manufacturers meet the condition of $2\pi_m > \pi_n$ are building materials retailers willing to bear part of the cost for manufacturers. Moreover, the retailer's cost share is positively correlated with the retailer's marginal profit π_m and negatively correlated with the manufacturer's marginal profit π_n .

3.4. The Stackelberg Game Where Manufacturers Have Fair Concerns about Profit Distribution. As a rational person, a

building material manufacturer not only pays attention to its own interests but also pays attention to the fairness of profit distribution with retailers in the same supply chain. However, this fairness concern is the subjective thinking of the manufacturer, and the building material retailer cannot know whether the manufacturer has fair concern for profit distribution. Therefore, in the minds of retailers, the objective function of manufacturers is still as follows:

$$\max_{E_n > 0} J_{N_1}^C = \int_0^\infty e^{-\rho t} \left[\pi_n a - bp + \alpha G + \beta(R - P) - \frac{(1 - \phi)}{2} k_1 E_n^2 \right] dt. \quad (15)$$

Building materials retailers are based on the fairness of manufacturer; set your own profit function as follows:

$$\max_{E_m > 0} J_M^C = \int_0^\infty e^{-\rho t} \left[\pi_m(a - bp + \alpha G + \beta(R - P)) - \frac{1}{2} k_2 E_m^2 - \frac{\phi}{2} k_1 E_n^2 \right] dt. \quad (16)$$

However, because building materials manufacturers have fair concerns about profit distribution, what manufacturers pursue is no longer their own profit

maximization but the utility maximization brought about by the fairness of profit distribution. The formula for maximizing utility is

$$\left\{ \max_{E_n > 0} J_N^C = \int_0^\infty e^{-\rho t} + \varepsilon \left[\begin{array}{c} \pi_n(a - bp + \alpha G + \beta(R - P)) - \frac{(1-\phi)}{2} k_1 E_n^2 \\ - \left(\pi_m(a - bp + \alpha G + \beta(R - P)) - \frac{1}{2} k_2 E_m^2 - \frac{\phi}{2} k_1 E_n^2 \right) \end{array} \right] dt \right\}. \quad (17)$$

When the retailers are in the advantage of profit distribution, the retailers will pay more efforts to improve their own efficiency. Otherwise, they will go slow and reduce

efficiency. After sorting, the following formula can be obtained:

$$\max_{E_n > 0} J_N^C = \int_0^\infty e^{-\rho t} (1 + \varepsilon) \left[\begin{array}{c} \pi_n(a - bp + \alpha G + \beta(R - P)) - \frac{(1-\phi)}{2} k_1 E_n^2 \\ - \varepsilon \left[\pi_m(a - bp + \alpha G + \beta(R - P)) - \frac{1}{2} k_2 E_m^2 - \frac{\phi}{2} k_1 E_n^2 \right] \end{array} \right] dt. \quad (18)$$

Theorem 3. In the Stackelberg game with fairness concerns and cost bearing, the following results can be obtained:

(1) The equilibrium results of building materials manufacturers and retailers are as follows:

$$\left\{ \begin{array}{l} E_n^{C*} = \frac{r_n}{k_1(\rho + \delta)} \left(\alpha + \frac{\lambda\beta}{\rho + \theta} \right) \frac{(\pi_n + \varepsilon\pi_n - \varepsilon\pi_m)(2\pi_m + \pi_n)}{3\varepsilon\pi_n - 2\varepsilon\pi_m + 2\pi_n}, \\ E_m^{C*} = \frac{r_m\pi_m}{k_2(\rho + \delta)} \left(\alpha + \frac{\lambda\beta}{\rho + \theta} \right), \\ \phi = \frac{2\pi_m - \pi_n}{2\pi_m + \pi_n}. \end{array} \right. \quad (19)$$

(2) The moving track model of brand goodwill is as follows:

$$G^{C*}(t) = H^C - (H^C - G_0)e^{-\delta t}. \quad (20)$$

From the above equation,

$$H^C = \frac{r_n^2}{k_1\delta(\rho + \delta)} \left(\alpha + \frac{\lambda\beta}{\rho + \theta} \right) \frac{(\pi_n + \varepsilon\pi_n - \varepsilon\pi_m)(2\pi_m + \pi_n)}{(3\varepsilon\pi_n - 2\varepsilon\pi_m + 2\pi_n)} + \frac{r_m^2\pi_m}{k_2\delta(\rho + \delta)} \left(\alpha + \frac{\lambda\beta}{\rho + \theta} \right). \quad (21)$$

(3) The real optimal income function of building materials manufacturer is as follows:

$$\begin{aligned}
 V_n^{C*} = & \frac{1}{\rho + \delta} \left(\alpha + \frac{\lambda\beta}{\rho + \theta} \right) (\pi_n + \varepsilon\pi_n - \pi_m)G + \frac{\pi_n\beta + \varepsilon\beta - \varepsilon\pi_m\beta}{\rho + \theta} R \\
 & + \frac{1}{\rho} \left[(\pi_n + \varepsilon\pi_n - \varepsilon\pi_m) \left(a - bp - \beta - \frac{\theta\beta p}{\rho + \theta} \right) + \frac{r_m^2 \pi_m}{2k_2(\rho + \delta)^2} \left(\alpha + \frac{\lambda\beta}{\rho + \theta} \right)^2 (2\pi_n + 2\varepsilon\pi_n - \varepsilon\pi_m) \right] \\
 & + \frac{1}{\rho} \frac{r_n^2}{2k_1(\rho + \delta)} \left(\alpha + \frac{\lambda\beta}{\rho + \theta} \right)^2 (\pi_n + \varepsilon\pi_n - \varepsilon\pi_m)^2 \frac{(2\pi_m + \pi_n)}{3\varepsilon\pi_n - 2\pi_m + 2\pi_n}.
 \end{aligned} \quad (22)$$

The optimal effect function of building materials retailers is as follows:

$$\begin{aligned}
 V_m^{C*} = & \frac{1}{\rho + \delta} \left(\alpha + \frac{\lambda\beta}{\rho + \theta} \right) G + \frac{\pi_m\beta}{\rho + \theta} R + \frac{\pi_m(a - bp - \beta p)}{\rho} + \frac{\theta p \pi_m \beta}{\rho(\rho + \theta)} + \frac{r_m^2 \pi_m}{2\rho k_2(\rho + \delta)^2} \left(\alpha + \frac{\lambda\beta}{\rho + \theta} \right)^2 \\
 & + \frac{r_n^2}{\rho k_1(\rho + \delta)^2} \left(\alpha + \frac{\lambda\beta}{\rho + \theta} \right)^2 \frac{(\pi_n + \varepsilon\pi_n - \varepsilon\pi_m)(2\pi_m + \pi_n)(\pi_n^2 + \varepsilon\pi_n^2)}{3\varepsilon\pi_n - 2\varepsilon\pi_m + 2\pi_n}.
 \end{aligned} \quad (23)$$

The optimal effect function of building materials manufacturers is as follows:

$$\begin{aligned}
 V_{N_1}^{C*} = & \frac{\pi_n}{\rho + \delta} \left(\alpha + \frac{\lambda\beta}{\rho + \theta} \right) G + \frac{\pi_n\beta}{\rho + \theta} R + \frac{\pi_n(a - bp - \beta p)}{\rho} + \frac{\theta p \pi_n \beta}{\rho(\rho + \theta)} + \frac{r_m^2 \pi_m \pi_n}{\rho k_2(\rho + \delta)^2} \left(\alpha + \frac{\lambda\beta}{\rho + \theta} \right)^2 \\
 & - \frac{r_n^2}{\rho k_1(\rho + \delta)^2} \left(\alpha + \frac{\lambda\beta}{\rho + \theta} \right)^2 \frac{(\pi_n^2 + \varepsilon\pi_n^2 - \varepsilon\pi_m\pi_n)(2\pi_m + \pi_n)}{3\varepsilon\pi_n - 2\varepsilon\pi_m + 2\pi_n} \left(\frac{\varepsilon\pi_m - 2\varepsilon\pi_n - \pi_n}{3(\varepsilon\pi_n - 2\varepsilon\pi_m + 2\pi_n)} \right).
 \end{aligned} \quad (24)$$

The following inference can be obtained from Theorem 3.

Corollary 5. The building material manufacturer's fair concern for profit distribution will not affect the retailer's publicity level, because the manufacturer will have fairness negative effects because of jealousy of the retailer, but the manufacturer's fairness concern intensity information is not public information. When making a decision on the level of publicity, the retailer does not know the manufacturer's fairness concerns, so the retailer's publicity level is not affected by the manufacturer's fairness concerns.

Corollary 6. The effort level of building materials manufacturers will be affected by their own intensity of fairness concerns, and because $(\partial E_n^C / \partial \varepsilon) < 0$, as the intensity of fairness concerns increases, the effort level of manufacturers will decrease. This is because manufacturers are jealous of retailer's high profits. Manufacturer's dissatisfaction with

profit distribution and concern about fairness lead to negative production, and they are not willing to spend higher costs to improve product's quality and output.

3.5. Centralized Decision. In the case of centralized decision-making, the decision goal is to maximize the overall benefits of the building materials market supply chain. However, the intensity of the fairness concern of building materials manufacturers is to seek the fairness of the distribution of benefits, and it is the goal of the internal members of the supply chain to maximize their own interests. Therefore, under centralized decision-making, manufacturers do not have fair concerns.

Under centralized decision-making, building materials manufacturers and retailers work together to maximize the overall benefits of the system as the goal. The superscript S represents centralized decision-making. At this time, the objective function of the supply chain is as follows:

$$\max_{E_n > 0, E_m > 0} J_H^S = \int_0^\infty e^{-\rho t} \left[\pi_s (a - bp + \alpha G + \beta (R - P)) - \frac{1}{2} k_1 E_n^2 - \frac{1}{2} k_2 E_m^2 \right] dt. \quad (25)$$

Theorem 4. In the centralized decision game model, the following results can be obtained:

- (1) The equilibrium results of building materials manufacturers and retailers are as follows:

$$\begin{aligned} E_n^{S^*} &= \frac{r_n \pi_s}{k_1 (\rho + \delta)} \left(\alpha + \frac{\lambda \beta}{\rho + \theta} \right) \\ E_m^{S^*} &= \frac{r_m \pi_s}{k_2 (\rho + \delta)} \left(\alpha + \frac{\lambda \beta}{\rho + \theta} \right). \end{aligned} \quad (26)$$

- (2) The moving track model of brand goodwill is as follows:

$$G^{S^*}(t) = H^S - (H^S - G_0) e^{-\delta t}. \quad (27)$$

From the above equation,

$$H^S = \left(\alpha + \frac{\lambda \beta}{\rho + \theta} \right) \left(\frac{r_n^2 \pi_s}{\delta k_1 (\rho + \delta)} \right) + \left(\frac{r_m^2 \pi_s}{\delta k_2 (\rho + \delta)} \right). \quad (28)$$

- (3) The optimal effect function of supply chain is as follows:

$$\begin{aligned} V_H^{S^*} &= \frac{\pi_s}{\rho + \delta} \left(\alpha + \frac{\lambda \beta}{\rho + \theta} \right) G + \frac{\beta \pi_s}{\rho + \theta} R + \frac{\pi_s (a - bp - \beta p)}{\rho} \\ &\quad + \frac{\theta \beta \pi_s p}{\rho (\rho + \theta)} + \frac{\pi_s^2}{\rho (\rho + \delta)^2} \left(\frac{r_n^2}{2k_1} + \frac{r_m^2}{2k_2} \right) \left(\alpha + \frac{\lambda \beta}{\rho + \theta} \right)^2. \end{aligned} \quad (29)$$

4. Comparison and Analysis

Comparing and analyzing the inputs and benefits of building materials manufacturers and retailers in the production supply chain under different decisions, the following inferences can be obtained.

Corollary 7. According to formulas (5), (12), (19), and (26), we can clearly get $E_m^{S^*} > E_m^{D^*} = E_m^{A^*} = E_m^{C^*}$. Under the centralized decision-making, the retailer's publicity level can reach the best condition.

Corollary 8. When the strength of fairness concerns of the building material manufacturer $\varepsilon = 0$, there is $E_n^{C^*} = E_n^{A^*}$, so, in case 2 and case 3, the levels of effort of the manufacturer are the same. When $0 < \varepsilon < 1$, the manufacturer is more concerned about the fairness of profit distribution, and, with the increase of fairness concern intensity ε , the manufacturer's effort level $E_n^{C^*}$ will also decrease, so $E_n^{C^*} < E_n^{A^*}$. Therefore, when $\varepsilon = 0$, there is $E_n^{S^*} > E_n^{C^*} = E_n^{A^*} > E_n^{D^*}$. When $0 < \varepsilon < 1$, there is

$E_n^{S^*} > E_n^{A^*} > E_n^{C^*} > E_n^{D^*}$. The fairness concerns of producers not only are detrimental to improving their own efforts but also reduce the production effect and income.

Corollary 9. From equations (6), (14), (20), and (27), we can get $G^{S^*}(t) > G^{A^*}(t) > G^{C^*}(t) > G^{D^*}(t)$. Under the centralized decision-making, the stable value of brand goodwill is still in the best value, and the stable value of brand goodwill under the Nash noncooperative game is in the lowest state. The cost sharing of retailers to manufacturers is conducive to the further improvement of product brand goodwill, which can make Pareto improvement. However, the manufacturer's concern about the fairness of profit distribution will lead to negative production and reduce brand goodwill.

5. Simulation Analysis

In the standardized supply chain of building materials market, the ultimate goal of building materials manufacturers and retailers is to achieve the maximization of social and economic effects. In order to better verify the authenticity and reliability of the above theory, this article uses MATLAB software for numerical simulation analysis to verify the effectiveness of the model. Let the reference values be as follows:

$$\begin{aligned} \pi_n &= 0.8, \\ \pi_m &= 1, \\ r_n &= 0.9, \\ r_m &= 1.2, \\ k_1 &= 1, \\ k_2 &= 2, \\ \theta &= 0.7, \\ \delta &= 0.8, \\ \lambda &= 0.5, \\ \beta &= 0.7, \\ \alpha &= 0.6, \\ a &= 20 \\ b &= 1, \\ p &= 5, \\ G(0) &= 0, \\ R(0) &= 5, \\ \rho &= 0.3. \end{aligned} \quad (30)$$

This article only selects some parameters for sensitivity analysis. Substitute the benchmark parameters into the corresponding model and draw the relevant graphs. Take $t \in [0, 10]$, and draw the optimal trajectory graph of the

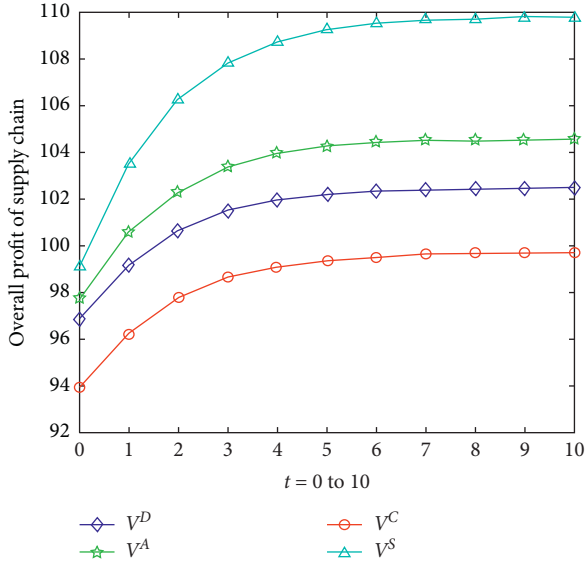


FIGURE 1: The optimal trajectory of supply chain profits under benchmark parameters.

overall benefits of the supply chain under four different decision-making situations, as shown in the figure below.

According to Figure 1, it can be clearly observed that, with the passage of time t , the overall benefits of the supply chain also increase, and the supply chain effect under centralized decision-making is much higher than the overall supply chain effect under the other three situations. The part of the cost of building materials retailers can further help realize the Pareto improvement of the supply chain. However, when manufacturers hold a fair concern attitude towards profit distribution (in order to make the overall gap between supply chains more intuitive, this paper sets the fairness concern degree of retailers as 50%), the overall efficiency of the supply chain declines significantly.

With the help of Figure 2, we can more clearly understand the impact of fairness concerns on supply chain effects. With the increase in the strength ε of building materials manufacturers' concerns about the fairness of profit distribution, it has had a serious negative impact on the manufacturers' own operating profits. This is because the retailers obtain higher profits in the process of brand promotion and sales. It has aroused the jealousy of building materials manufacturers and caused them to be unwilling to spend a higher level of effort to improve product quality and negatively sabotage work, which will affect their own income. However, retailers are not affected by the manufacturer's fairness concern psychology, because fairness concern is the manufacturer's subjective thinking. Retailers cannot understand the manufacture's subjective thinking well. When retailers make decisions, they will assume that the manufacturer's concern for fairness is zero.

Figure 3 reflects the impact of consumer reference price effects on brand goodwill, and, in the four game models, the brand goodwill under centralized decision-

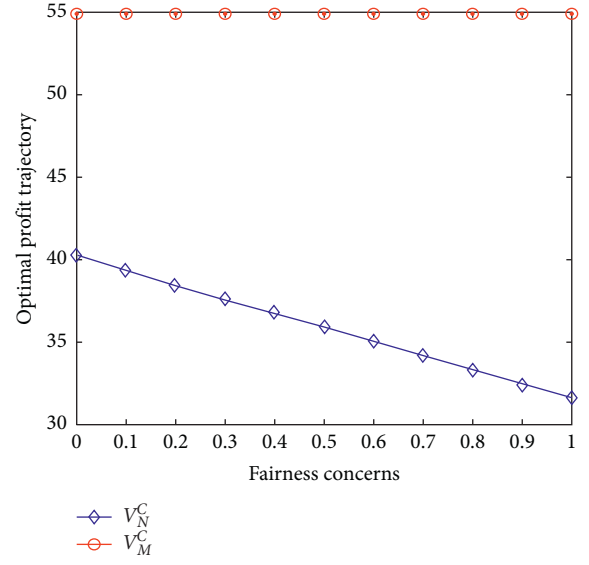


FIGURE 2: Profit trend chart under fairness concerns.

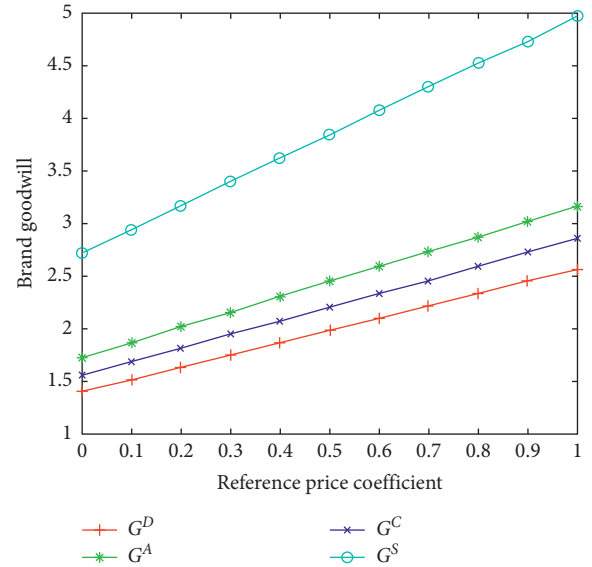


FIGURE 3: The impact of consumer reference effect on brand goodwill.

making still maintains the best level. The consumer's reference effect β has a positive correlation with the impact of changes in product brand goodwill. The higher the consumer's reference price effect β , the higher the brand goodwill $G(t)$.

From Figures 4 and 5, we can see that the reference price effect of consumers has a positive correlation with the effort level and publicity level of building materials manufacturers and retailers. The effort level and publicity level still have the highest effect under the centralized decision-making model. Building materials retailer's commitment to costs can improve the level of efforts of manufacturers, improve product quality, and achieve Pareto improvement.

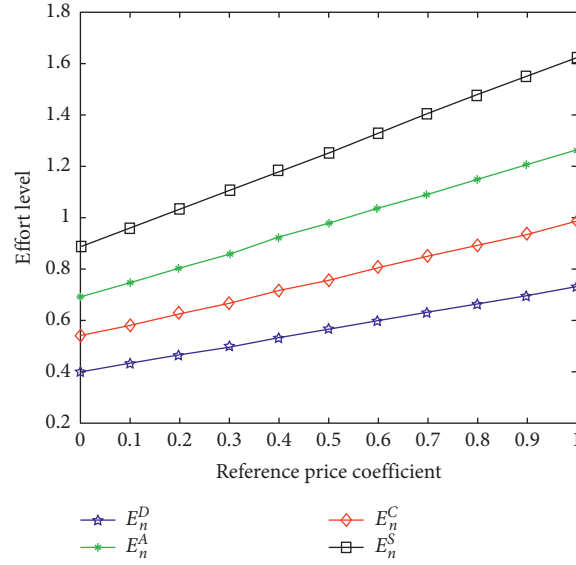


FIGURE 4: The impact of consumer reference price effects on effort level.

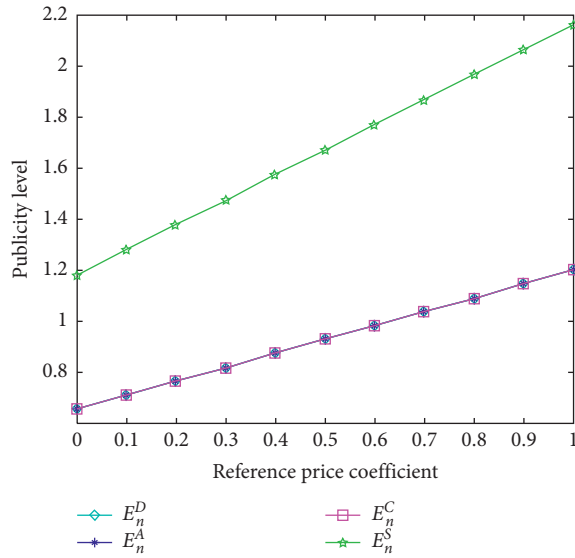


FIGURE 5: The impact of consumer reference price effects on the level of publicity.

6. Conclusion

With the help of differential game model, this article incorporates manufacturer's concerns about fairness in benefit distribution and consumer's reference price effects into the building materials market supply chain decision-making and cooperation issues. Under different decision-making models, different decision-making factors of manufacturers and retailers are discussed, and how to promote supply chain cooperation to achieve a win-win situation is also discussed. By constructing the NASH noncooperative game, the Stackelberg game model with cost sharing, the Stackelberg game model with fair concerns about the distribution of benefits, and the centralized

decision-making model are obtained. The optimal decision-making model, brand goodwill dynamic model, and supply chain effect model of manufacturer and retailer in four cases are obtained. Finally, the sensitivity of related parameters was tested through simulation analysis, and the final conclusions are as follows.

First, under the centralized decision-making model, building materials manufacturers and retailers can put a higher level of effort and publicity to achieve Pareto optimal and achieve the best stable value of brand goodwill. This is because, under the centralized decision-making model, the overall benefit of the supply chain is the common goal of both parties, effectively mobilizing the enthusiasm of manufacturers and retailers. Considering the effect of consumer's reference prices will help promote the production and supply chain to realize a virtuous circle of "increasing resource input-competing for market share-increasing corporate effect."

Second, building materials manufacturer's concerns about fairness in the distribution of benefits not only are detrimental to the improvement of their own interests but also reduce their own efforts and production effects and affect the overall effect of the supply chain. However, the fairness concern of the manufacturer will not affect the publicity level of the retailer, because the fairness concern of the building material manufacturer is a personal subjective thought and cannot be understood by the retailer. When retailers make decisions, they will assume that the fairness concerns of manufacturers are zero. Therefore, the unilateral fairness concerns of manufacturers will have a negative impact on the overall efficiency of the supply chain, and it is necessary to adjust their strategies to suppress the damage [22].

Third, building materials retailers will take the initiative to bear part of the manufacturer's costs only when their own marginal profit is higher than half of the manufacturer's own marginal profit, and the ratio is positively related to its own

marginal profit and inversely proportional to the marginal profit of the building material manufacturer. Cost-bearing helps manufacturers reduce cost pressures, so that more funds can be invested in product research and development to achieve the purpose of improving product quality and achieving better brand effects. Building materials retailers can make up for the cost through the increase of sales, so as to improve their own effect level and achieve a win-win situation.

Although this article considers the impact of fairness concerns on supply chain decision-making and effects, it does not consider the evolutionary game between supply chain companies. Building materials retailers will understand the fairness concern psychology of building materials manufacturers over time, so as to change enterprise decision-making and seek higher interests. In the future, we will

further discuss the evolutionary game of decision-making and effect among supply chain enterprises over time.

Appendix

Proof of Theorem A

After time t , the optimal value function of the profit of the producer and the retailer is as follow:

$$\begin{aligned} J_N^{D*}(E_n) &= e^{-\rho t} V_N^D(G, D), \\ J_M^{D*}(E_m) &= e^{-\rho t} V_M^D(G, D). \end{aligned} \quad (\text{A.1})$$

The sufficient conditions for static feedback equilibrium can be assumed. The optimal value function has a Hamilton-Jacobi-Bellman equation for any $G > 0, R > 0$, as follows:

$$\rho V_N^D(G, R) = \max_{E_n} \left[\pi_n(a - bp + \alpha G + \beta(R - P)) - \frac{1}{2} k_1 E_n^2 + V_{NG}^{D'}(r_n E_n + r_m E_m - \delta G) + V_{NR}^{D'}(\theta(P - R) + \lambda G) \right]. \quad (\text{A.2})$$

Take the partial derivative of the manufacturer's effort level on the right side of the above formula and set it to zero to obtain the first-order condition,

$$E_n^D = \frac{r_n V_{NG}^{D'}}{k_1}. \quad (\text{A.3})$$

Similarly, after time t , the profit optimal value function of building materials retailers also satisfies the HJB equation.

$$\rho V_M^D(G, R) = \max_{E_m > 0} \left[\pi_m(a - bp + \alpha G + \beta(R - P)) - \frac{1}{2} k_1 E_m^2 + V_{MG}^{D'}(r_n E_n + r_m E_m - \delta G) + V_{MR}^{D'}(\theta(P - R) + \lambda G) \right]. \quad (\text{A.4})$$

Find the partial derivative of E_m on the right side of the above formula and set it to zero to obtain the first-order condition.

By substituting E_n^D and E_m^D into the optimal value functions of building materials manufacturers and retailers, the authors can get the following results:

$$\begin{aligned} \rho V_N^D &= G \left(\pi_n \alpha - \delta V_{NG}^{D'} + \lambda V_{NR}^{D'} \right) + R \left(\pi_n \beta - \theta V_{NR}^{D'} \right) + \pi_n(a - bp - \beta p) + \frac{(r_n V_{NG}^{D'})^2}{2k_1} + \frac{r_m^2 V_{NG}^{D'} V_{MG}^{D'}}{k_2} + \theta P V_{NR}^{D'}, \\ \rho V_M^D &= G \left(\pi_m \alpha - \delta V_{MG}^{D'} + \lambda V_{MR}^{D'} \right) + R \left(\pi_m \beta - \theta V_{MR}^{D'} \right) + \pi_m(a - bp - \beta p) + \frac{(r_m V_{MG}^{D'})^2}{2k_2} + \frac{r_n^2 V_{NG}^{D'} V_{MG}^{D'}}{k_1} + \theta P V_{MR}^{D'}. \end{aligned} \quad (\text{A.5})$$

Therefore, it can be assumed that $V_N^D(G, R) = n_1 G + n_2 E + n_3$ and $V_M^D(G, R) = m_1 G + m_2 E + m_3$, where $n_1, n_2, n_3, m_1,$

m_2 , and m_3 are constants, according to the method of undetermined coefficients. The following formula can be obtained:

$$\begin{cases}
n_1 = \frac{\pi_n}{\rho + \delta} \alpha + \frac{\lambda \beta}{\rho + \theta}, \\
n_2 = \frac{\pi_n \beta}{\rho + \theta}, \\
n_3 = \frac{\pi_n - a - b\rho - \beta\rho}{\rho} + \frac{\theta p \pi_n \beta}{\rho(\rho + \theta)} + \frac{r_n^2 \pi_n^2}{2k_1 \rho(\rho + \delta)} \left(\alpha + \frac{\lambda \beta}{\rho + \theta} \right)^2 + \frac{r_m^2 \pi_m^2}{2k_2 \rho(\rho + \delta)} \left(\alpha + \frac{\lambda \beta}{\rho + \theta} \right)^2,
\end{cases}
\quad (A.6)$$

$$\begin{cases}
m_1 = \frac{\pi_m}{\rho + \delta} \alpha + \frac{\lambda \beta}{\rho + \theta}, \\
m_2 = \frac{\pi_m \beta}{\rho + \theta}, \\
m_3 = \frac{\pi_m(a - b\rho - \beta\rho)}{\rho} + \frac{\theta p \pi_m \beta}{\rho(\rho + \theta)} + \frac{r_m^2 \pi_m^2}{2k_2 \rho(\rho + \delta)} \left(\alpha + \frac{\lambda \beta}{\rho + \theta} \right)^2 + \frac{r_n^2 \pi_n \pi_m}{2k_1 \rho(\rho + \delta)} \left(\alpha + \frac{\lambda \beta}{\rho + \theta} \right)^2.
\end{cases}$$

From this, the effort level $E_n^{D^*}$ of the manufacturer and the level $E_m^{D^*}$ of the retailer can be derived.

Then, substituting $E_n^{D^*}$ and $E_m^{D^*}$ into equation (1) of the dynamic model of brand goodwill, the optimal trajectory model of brand goodwill can be obtained, as shown in equation (6), and Theorem 1 is verified. \square

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

Empirical Analysis of the Matching Degree between Energy Equipment Manufacturing and Market Demand: A Global Perspective

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The study of matching degree between energy equipment manufacturing and market demand is crucial for energy enterprises to adjust business strategies, expand market share, and develop sustainably. Considering that the current electricity market evaluation indicators are rarely selected from a global perspective and a single evaluation method may lead to one-sided results, this article takes the technology and equipment related to electric energy as the research object and selects six indicators, including technical standards, qualification certification, export methods, after-sales service, market concentration, and product concentration. By analyzing the supply and demand characteristics of major global regional markets and the situation of Chinese power enterprises in these markets, we propose matching model cluster including osculating value method, rank-sum ratio method, ideal point method, entropy value method, and efficacy coefficient method to conduct the matching degree study. The results show that the overall market matching degree of Chinese power companies is good, especially in Southeast Asia, Central Asia, and Africa. For markets with a low degree of matching, we analyze the reasons based on the matching indicators values to provide companies with corresponding strategies and recommendations.

1. Introduction

With the continuous advancement of energy technology, the world energy landscape is undergoing important changes [1]. The energy structure is gradually becoming low-carbon, diversified, and intelligent [2]; especially, the global power market is in a stage of deep transformation and rapid innovation. The interaction between supply and demand is the development trend under the new situation such as power market reform and smart grid construction, and it is also a necessary condition for building a complete, sound, and efficient power market [3]. In the background of uneven resource distribution and uneven demand, the mismatch between supply and demand has become a major energy problem in most countries around the world [4–6]. As one of the world's largest cross-border energy investment countries, China's energy companies have entered the international market with the global economic slowdown and

increasing overcapacity in China. In this context, performing the matching analysis between global energy equipment manufacturing and market demand became an important research content. By grasping the trend of the global power market, China power companies can deal with the opportunities and challenges of the power market calmly, which is of great significance to expand overseas markets and achieve industrial upgrading.

In order to explore the matching degree between energy equipment manufacturing and market demand, certain evaluation indicators and evaluation models need to be selected. On the selection of power market evaluation indicators, Dunnan et al. constructed the power market evaluation system from the perspective of the market and the supplier [7]. Rahimiyan and Mashhadi assessed the market according to the duration and size of market power [8]. Hellmer and Warell evaluated the dominant position of the Nordic electricity market-based market concentration [9].

In the above studies, few evaluation indicators are selected. Wang et al. divided the power market evaluation indicators into five categories: market structure, market security, market operation, market efficiency, and market risk [10]. Xue et al. evaluated the electricity sales market from four aspects: market structure, market performance, prosperity index, and welfare index [11]. Research by Gärling et al. showed that consumers choose suppliers from four perspectives: price, quality of information, market share, and availability of “green” electricity [12]. Woo et al. pointed out that product differentiation can meet the needs of consumers and improve grid operation [13]. Through the above research, we can see that there is no unified evaluation indicator system for the electricity market, and it is rare to select relevant evaluation indicators from the perspective of product exports based on a global perspective.

As far as the electricity market evaluation methods are concerned, analytic hierarchy process (AHP), fuzzy comprehensive evaluation method [14–18], entropy theory [19–21], and so forth are used widely. AHP is often combined with the fuzzy analysis method to comprehensively evaluate and analyze the power market [22, 23]: the fuzzy evaluation method determines the index membership degree, and AHP determines the weight of each index. The gray relational analysis has also been applied in power market evaluation in recent years. It measures the factors’ relevance degree according to the similarity or difference degree of factors’ development trends, that is, the “gray relational degree” [24]. Li et al. used an improved gray relational analysis to evaluate the service quality of power supply companies [25]. Tao and Shengyu evaluated the electricity market through the combination of the gray relational model and fuzzy comprehensive evaluation method [26]. Due to the ambiguity or uncertainty of the evaluation indicators in the electricity market, and because these evaluation methods are subjective, single evaluation method may have one-sidedness to a certain degree. Therefore, the combination of multiple methods should be tried.

Based on the deficiencies in the above research, this article takes electric power technology and equipment as the research object and selects six matching indicators, including technical standards, qualification certification, export methods, after-sales service, market concentration, and product concentration. On the basis of this, we analyze the characteristics of the power markets of Southeast Asia, Central Asia, Africa, Latin America, the Middle East, and Europe and the construction situation of Chinese power equipment enterprises in these regions. Then, we use our proposed method integration cluster, including the osculating value method, rank-sum ratio method, ideal point method, entropy method, and efficiency coefficient method, to conduct research on the matching degree of supply and demand. Finally, we give corresponding strategies and suggestions based on the matching results.

In short, our contribution to this research work has two aspects. One is that when we select matching indicators, we add some factors that need to be considered in exporting energy equipment based on a global perspective. The second is that we propose a matching model cluster to conduct an

empirical analysis of market matching, which makes up for the lack of one-sided results that a single evaluation method may bring.

The rest of this article is organized as follows. Section 2 introduces market matching indicators and proposes matching models based on the research object of this article. Section 3 is the empirical analysis of the six major market regions in the world. Section 4 summarizes the research conclusions and gives corresponding strategies and recommendations.

2. Matching Model

Based on the existing research results and combined with the actual situation of power market technology and equipment exports, we propose the corresponding matching indicators system and matching model cluster to study the matching degree of Chinese power companies’ global construction and market demand.

2.1. Indicators Selection. Market matching is the practical application of matching theory in the product-market scenario, that is, the process of matching products with customer needs in the market. According to the indicators that buyers mainly pay attention to in the market and the specific conditions of overseas exports in the electricity market, we select six indicators, including technical standards, qualification certification, export methods, after-sales service, market concentration, and product concentration, and divide them into four aspects: markets thresholds, entry methods, business strategies, and market layout. Each indicator is quantified, as shown in Table 1.

2.2. Model Design

2.2.1. Osculating Value Method. The osculating value method is an optimal method for multiobjective decision-making in systems engineering. The decision-making here is essentially an analysis and evaluation process. Because of its flexible and simple calculation, intuitive and clear results, and high resolution, it has been widely used in the fields of energy, economy, society, medicine, etc. and is an effective method for comprehensive evaluation.

The basic idea of the osculating value method is to divide the evaluation indicators into positive indicators (i.e., the higher the value, the better the result, such as cure rate) and negative indicators (i.e., the lower the value, the better the result, such as the mortality rate) and standardize all indicators. Then, it finds out the “best point” and “worst point” of each evaluation index, that is, the maximum and minimum value of each evaluation indicator and calculates the distance between each evaluation unit and the “best point” and “worst point,” respectively. These distances are transformed into a comprehensive index that can comprehensively reflect evaluation unit-osculating value. Finally, the order of each evaluation unit is determined according to the size of the osculating value. The smaller the osculating value,

TABLE 1: Matching indicators and quantification method.

| Level 1 indicators | Level 2 indicators | Quantification method |
|---------------------|-----------------------------|---|
| Markets thresholds | Technical standards | The proportion of power projects that adopt Chinese standards in the target market |
| | Qualification certification | The proportion of qualification certification types met by Chinese power companies in the target market |
| Entry methods | Export methods | The degree of overlap between the export methods of Chinese power companies in the market and the market-led export methods |
| Business strategies | After-sales service | The percentage of projects that Chinese power companies have after-sales services to the total projects in the target market |
| Market layout | Market concentration | The percentage of Chinese power companies' turnover in the target market |
| | Product concentration | The degree of overlap between the types of power technology and equipment exported by Chinese power companies and market requirements |

the higher the quality of the evaluation unit. The operation process is shown in Figure 1.

For a matching model including n evaluation units and m evaluation indicators, the osculating value D is calculated as equation (1), where i represents the evaluation unit and the distances of each evaluation unit to the “best point” and “worst point” are recorded as d_i^+ and d_i^- , respectively.

$$D = \frac{d_i^+}{d^+} - \frac{d_i^-}{d^-},$$

$$d^+ = \min_{1 \leq i \leq n} \{d_i^+\}, \quad (1)$$

$$d^- = \max_{1 \leq i \leq n} \{d_i^-\}, \quad i = 1, 2, \dots, n.$$

2.2.2. Rank-Sum Ratio Method. The rank-sum ratio (RSR) method is a statistical analysis method that combines classical parameter statistics and modern nonparametric statistics, which can be used for multi-index evaluation. The basic principle is to obtain the dimensionless statistic RSR through rank transformation in a n row (n evaluation units) and m column (m evaluation indicators) matrix and use the RSR value to rank the evaluation objects [27]. The RSR of the evaluation unit i is calculated as equation (2); $i = 1, 2, \dots, n, j = 1, 2, \dots, m, R_{ij}$ represents the rank of the element in the row i and column j . The larger the RSR, the better the comprehensive evaluation. The operation process is shown in Figure 2.

$$RSR_i = \frac{1}{n \times m} \sum_{j=1}^m R_{ij}. \quad (2)$$

2.2.3. Ideal Point Method. The ideal point (also known as TOPSIS, Technique for Order Preference by Similarity to Ideal Solution) method is a sorting method according to the closeness of the evaluation object to the idealized target, and the closeness is reflected by Euclidean distance. It forms a space with the positive ideal solution and the negative ideal solution in the finite scheme, and the scheme to be evaluated can be regarded as a certain point in the space, so that the Euclidean distance between the point and the positive ideal solution and the negative ideal solution can be obtained.

Then, according to the Euclidean distance, the evaluated units are ranked.

The operation process is shown in Figure 3, where the closeness of the ideal solution G is calculated as equation (3). S^+ and S^- , respectively, represent the distance from the target to the positive ideal solution and the negative ideal solution. The larger the closeness value, the better the target.

$$G = \frac{S^-}{S^+ + S^-}. \quad (3)$$

2.2.4. Entropy Value Method. Entropy is a measure of uncertainty: the greater the amount of information, the smaller the uncertainty, and the smaller the entropy; the smaller the amount of information, the greater the uncertainty, and the greater the entropy. By calculating the entropy value, the dispersion degree of an indicator can be judged. The greater the dispersion degree, the greater the influence of the indicator on the comprehensive evaluation.

The operation steps of the entropy method are shown in Figure 4. For an evaluation system with n evaluation units and m evaluation indicators, $p_{ij}, e_j, d_j, w_j, s_i$'s calculation formula is as follows: the original data matrix is $X = (x_{ij})_{n \times m}$, $i = 1, 2, \dots, n, j = 1, 2, \dots, m$.

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^n x_{ij}}, \quad (4)$$

$$e_j = -k \sum_{i=1}^n p_{ij} \ln(p_{ij}),$$

$$k = \frac{1}{\ln(n)}, \quad (5)$$

$$e_j \geq 0,$$

$$d_j = 1 - e_j, \quad (6)$$

$$w_j = \frac{d_j}{\sum_{j=1}^m d_j}, \quad (7)$$

$$s_i = \sum_{j=1}^m w_j \cdot p_{ij}. \quad (8)$$

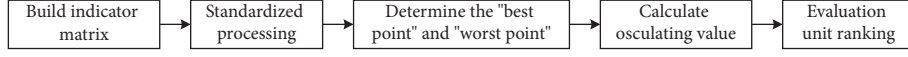


FIGURE 1: Osculating value method flowchart.

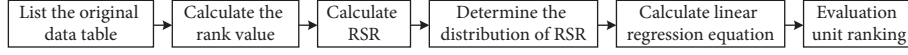


FIGURE 2: RSR method flowchart.

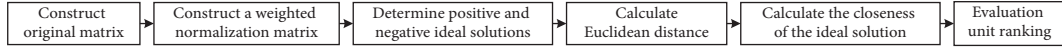


FIGURE 3: TOPSIS method flowchart.

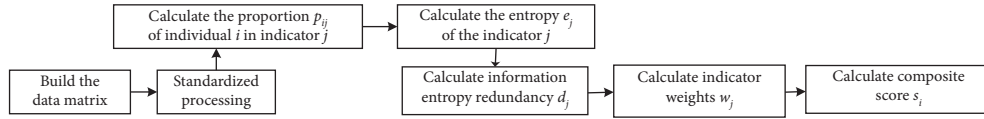


FIGURE 4: Entropy value method flowchart.

2.2.5. Efficacy Coefficient Method. The efficiency coefficient method is based on the principle of multiobjective planning. For each evaluation indicator, a satisfactory value and an unallowable value are determined as the upper and lower limits. The score of the indicator is determined by calculating the degree to which the indicator achieves the satisfactory value. Finally, the overall situation of the evaluated unit is obtained by weighted average.

If there are n evaluation units and m evaluation indicators, x_i^h and x_i^l represent satisfactory values and disallowed values, and the original data matrix is $X = (x_{ij})_{n \times m}$, then the efficiency coefficient x'_{ij} is calculated as equation (9). The operation process is shown in Figure 5.

$$x'_{ij} = \frac{x_{ij} - x_i^l}{x_i^h - x_i^l}. \quad (9)$$

2.2.6. Matching Method Cluster. In order to more accurately reflect the matching relationship between Chinese power companies and the target market demand, this article adopts a multimodel integrated spouse model, which includes the osculating value method, RSR method, ideal point method, entropy value method, and efficacy coefficient method. This matching model cluster measures the overall matching degree of the evaluation unit by forming a matching space.

The advantages and disadvantages of these five evaluation models are shown in Table 2. According to the content shown, combining these five models can achieve complementary advantages.

The complete matching process is shown in Figure 6. Firstly, quantify the 6 selected matching indicators according to 2.1. Secondly, conform them to the input data format of the model by certain data processing. Then, input them into the five models. Respectively, the result value of each matching object $R = \{R_1, R_2, R_3, R_4, R_5\}$ can be obtained. Normalize them and take the minimum r_{\min} and

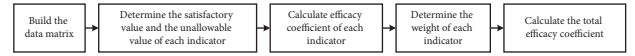


FIGURE 5: Efficacy coefficient method flowchart.

maximum values r_{\max} as the matching interval to obtain the final matching results.

3. Case Analysis

3.1. Data Source. We selected six regions, including Southeast Asia, Central Asia, Africa, Latin America, the Middle East, and Europe, then figured out the relevant projects in each regional power market, and analyzed the types of projects (thermal power, hydropower, wind power, photovoltaic power, and transmission and transformation.), the power technology and equipment involved, the company responsible for the project and its country, the project amount, the export method adopted (direct export, EPC, EPC + F, EPC + F + O, BOOT, BOT, joint ventures, etc.), technical standards adopted, and if there is special after-sales service organization or team. According to the power projects of Chinese power companies in these areas, we can get their specific value after quantifying six matching indicators, as shown in Table 1.

3.2. Result Analysis. According to the proposed matching model cluster, the matching results of Chinese power companies in each regional market are obtained. It can be seen that although the ranking results of different methods are not exactly the same, the overall trend remains consistent. Moreover, the length of the matching interval for each country is small, indicating that our model is feasible and effective.

3.2.1. Southeast Asia. From the results in Table 3 and Figure 7 and the specific indicator values in Table 4, it can be

TABLE 2: Characteristics analysis of five evaluation methods.

| Method | Advantages | Disadvantages |
|-----------------------------|---|---|
| Osculating value method | Simple principle, clear concept, an easy to implement process, and objective evaluation results | When performing multi-index evaluation, different dimension indexes should be quantified. |
| RSR method | Solving the problem of multiple indicators, comprehensive evaluation, and the influence of dimensions not considered | Some information of the original data will be lost when the index is converted to rank. |
| TOPSIS method | A selection technique based on the similarity of ideal goals, which is a very effective method in multiobjective decision analysis | The weight of each indicator needs to be determined artificially and has a certain degree of subjectivity. |
| Entropy value method | Determining the index weights according to the degree of variation of the index values and avoiding the deviation caused by human factors | It ignores the importance of the index itself, and the dimension of the evaluation index cannot be reduced. |
| Efficacy coefficient method | Calculating and scoring the evaluation object from different aspects according to the complexity of the evaluation object | The two evaluation criteria, satisfactory value and unallowable value, are difficult to decide and operate. |

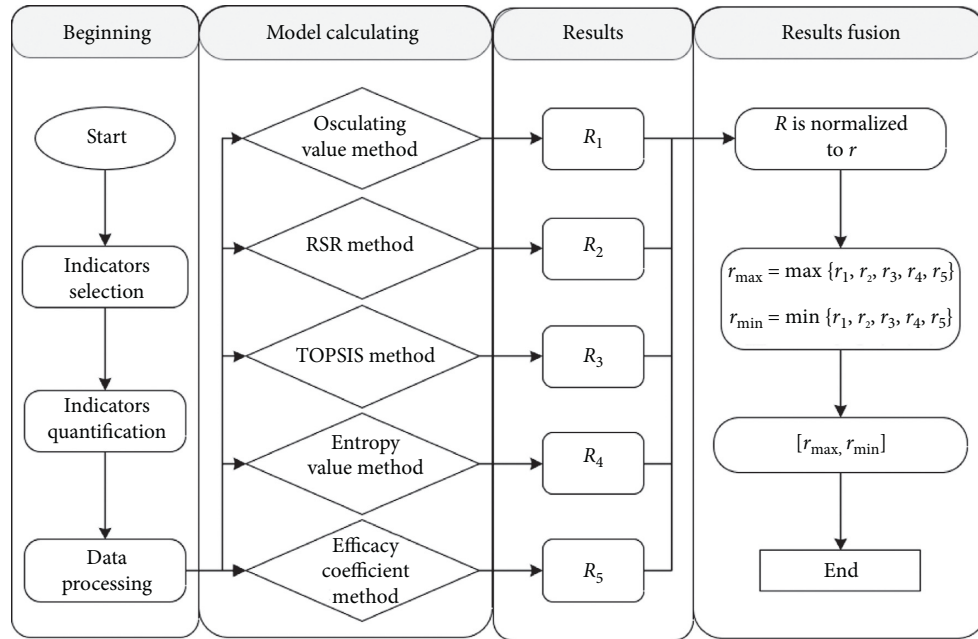


FIGURE 6: Matching model cluster architecture.

TABLE 3: Matching result of Chinese power companies in Southeast Asia.

| Country | Osculating value | RSR | TOPSIS | Entropy value | Efficacy coefficient | Min | Max | Interval length |
|-------------|------------------|------|--------|---------------|----------------------|-------------|-------------|-----------------|
| Laos | 0.99 | 1.00 | 1.00 | 0.99 | 1.00 | 0.99 | 1.00 | 0.01 |
| Cambodia | 1.00 | 0.96 | 0.98 | 1.00 | 0.99 | 0.96 | 1.00 | 0.04 |
| Indonesia | 0.61 | 0.44 | 0.43 | 0.74 | 0.67 | 0.43 | 0.74 | 0.31 |
| Myanmar | 0.67 | 0.41 | 0.71 | 0.50 | 0.61 | 0.41 | 0.71 | 0.30 |
| Philippines | 0.44 | 0.31 | 0.37 | 0.49 | 0.44 | 0.31 | 0.49 | 0.18 |
| Vietnam | 0.43 | 0.29 | 0.36 | 0.39 | 0.41 | 0.29 | 0.43 | 0.14 |
| Thailand | 0.33 | 0.27 | 0.28 | 0.49 | 0.37 | 0.27 | 0.49 | 0.22 |
| Malaysia | 0.08 | 0.06 | 0.06 | 0.14 | 0.06 | 0.06 | 0.14 | 0.08 |
| Singapore | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

seen that Chinese power companies have developed well in the power markets of Laos, Cambodia, Indonesia, and Myanmar. This is because the recognition and popularity of technical standards are high, the certification is perfect, the export method is in line with the local mainstream method, the after-sales service is in place, and the export products

meet the market demand. In the Philippines, Vietnam, and Thailand, they need to be improved, especially in terms of technical standard, qualification certification, and after-sales service. Since Singapore and Malaysia mostly use European and American standards, and Singapore is a high-end market, the equipment required is concentrated in areas

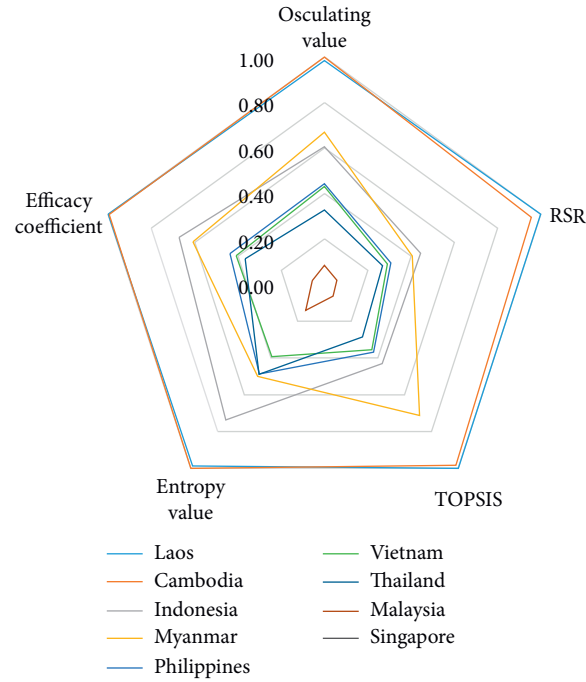


FIGURE 7: Matching effect picture of Chinese power companies in Southeast Asia.

TABLE 4: Matching indicators value of Chinese power companies in Southeast Asia.

| Country | Technical standards | Qualification certification | Export methods | After-sales service | Market concentration | Product concentration |
|-------------|---------------------|-----------------------------|----------------|---------------------|----------------------|-----------------------|
| Laos | 0.75 | 1.00 | 0.71 | 0.86 | 0.60 | 0.86 |
| Cambodia | 0.67 | 1.00 | 0.86 | 0.71 | 0.71 | 0.86 |
| Indonesia | 0.27 | 1.00 | 0.54 | 0.93 | 0.53 | 0.93 |
| Myanmar | 0.67 | 0.67 | 0.50 | 0.50 | 0.58 | 0.75 |
| Philippines | 0.43 | 1.00 | 0.67 | 0.17 | 0.38 | 1.00 |
| Vietnam | 0.43 | 1.00 | 0.43 | 0.25 | 0.44 | 0.88 |
| Thailand | 0.17 | 0.33 | 1.00 | 1.00 | 0.14 | 1.00 |
| Malaysia | 0.00 | 1.00 | 1.00 | 0.25 | 0.10 | 0.50 |
| Singapore | 0.00 | 0.33 | 0.00 | 1.00 | 0.20 | 1.00 |

where European and American power companies are better at control systems, automation, etc., which limits Chinese power companies development in these two countries.

3.2.2. Central Asia. From the results in Table 5 and Figure 8 and the specific indicator values in Table 6, we can see that Chinese power companies have the highest matching degree in Kyrgyzstan, but export methods need to be adjusted slightly. In Uzbekistan, Chinese power companies lack after-sales service. There are low recognition of technical standards and low market concentration in Turkmenistan and Kazakhstan, indicating that Chinese power companies are less competitive in these two countries. In Tajikistan, due to the large deviation between the export method and the mainstream export method, the overall matching degree is very low.

3.2.3. Africa. From the results in Table 7 and Figure 9 and the specific indicator values in Table 8, it can be seen that

Chinese power companies have developed best in the power markets of Ethiopia, Kenya, Cameroon, and Angola, and all indicators are well matched. It is necessary to further strengthen the promotion of technical standards in Mozambique, Tanzania, and Sudan. The market concentration of electricity in Senegal, Nigeria, Morocco, and Egypt is not high, and the target market positioning is not accurate. In Algeria and South Africa, the power market development situation is relatively tense, and competitiveness needs to be further improved.

3.2.4. Latin America. From the results in Table 9 and Figure 10 and the specific indicator values in Table 10, we can see that Chinese power companies have developed well in the power markets of Ecuador, Venezuela, and Argentina, but they need to further strengthen the promotion of Chinese technical standards. Development in Cuba, Bolivia, Brazil, and Peru is in good condition. In contrast, the development in Colombia, Mexico, Chile, and Uruguay is

TABLE 5: Matching result of Chinese power companies in Central Asia.

| Country | Osculating value | RSR | TOPSIS | Entropy value | Efficacy coefficient | Min | Max | Interval length |
|--------------|------------------|------|--------|---------------|----------------------|-------------|-------------|-----------------|
| Kyrgyzstan | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 |
| Uzbekistan | 0.36 | 0.45 | 0.45 | 0.78 | 0.69 | 0.36 | 0.78 | 0.42 |
| Turkmenistan | 0.38 | 0.29 | 0.29 | 0.36 | 0.41 | 0.29 | 0.41 | 0.12 |
| Kazakhstan | 0.34 | 0.24 | 0.42 | 0.25 | 0.32 | 0.24 | 0.42 | 0.18 |
| Tajikistan | 0.01 | 0.11 | 0.20 | 0.08 | 0.07 | 0.01 | 0.20 | 0.19 |

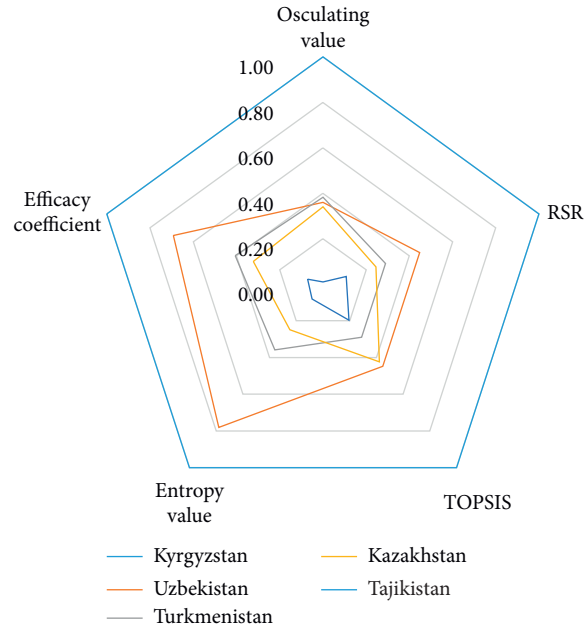


FIGURE 8: Matching effect picture of Chinese power companies in Central Asia.

TABLE 6: Matching indicators value of Chinese power companies in Central Asia.

| Country | Technical standards | Qualification certification | Export methods | After-sales service | Market concentration | Product concentration |
|--------------|---------------------|-----------------------------|----------------|---------------------|----------------------|-----------------------|
| Kyrgyzstan | 1.00 | 1.00 | 0.67 | 1.00 | 1.00 | 1.00 |
| Uzbekistan | 1.00 | 1.00 | 1.00 | 0.00 | 1.00 | 1.00 |
| Turkmenistan | 0.50 | 0.50 | 1.00 | 1.00 | 0.50 | 1.00 |
| Kazakhstan | 0.40 | 0.83 | 0.91 | 1.00 | 0.50 | 0.73 |
| Tajikistan | 0.20 | 1.00 | 0.33 | 0.83 | 0.60 | 0.83 |

TABLE 7: Matching result of Chinese power companies in Africa.

| Country | Osculating value | RSR | TOPSIS | Entropy value | Efficacy coefficient | Min | Max | Interval length |
|--------------|------------------|------|--------|---------------|----------------------|-------------|-------------|-----------------|
| Ethiopia | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 |
| Kenya | 0.90 | 0.73 | 0.87 | 1.00 | 0.94 | 0.73 | 1.00 | 0.27 |
| Cameroon | 0.66 | 0.63 | 0.66 | 0.91 | 0.88 | 0.63 | 0.91 | 0.28 |
| Angola | 0.74 | 0.53 | 0.68 | 0.83 | 0.77 | 0.53 | 0.83 | 0.30 |
| Mozambique | 0.56 | 0.52 | 0.52 | 0.82 | 0.75 | 0.52 | 0.82 | 0.30 |
| Tanzania | 0.67 | 0.51 | 0.66 | 0.76 | 0.74 | 0.51 | 0.76 | 0.25 |
| Sudan | 0.72 | 0.45 | 0.70 | 0.59 | 0.65 | 0.45 | 0.72 | 0.27 |
| Senegal | 0.46 | 0.38 | 0.42 | 0.59 | 0.53 | 0.38 | 0.59 | 0.21 |
| Nigeria | 0.45 | 0.38 | 0.36 | 0.60 | 0.52 | 0.36 | 0.60 | 0.24 |
| Morocco | 0.50 | 0.36 | 0.53 | 0.41 | 0.49 | 0.36 | 0.53 | 0.17 |
| Egypt | 0.37 | 0.34 | 0.29 | 0.48 | 0.45 | 0.29 | 0.48 | 0.19 |
| Algeria | 0.22 | 0.15 | 0.15 | 0.10 | 0.14 | 0.10 | 0.22 | 0.12 |
| South Africa | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

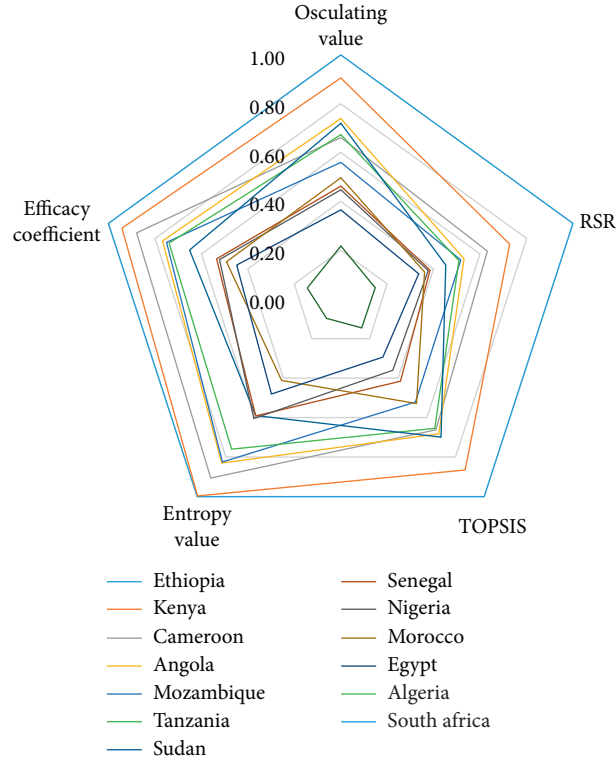


FIGURE 9: Matching effect picture of Chinese power companies in Africa.

TABLE 8: Matching indicators value of Chinese power companies in Africa.

| Country | Technical standards | Qualification certification | Export methods | After-sales service | Market concentration | Product concentration |
|--------------|---------------------|-----------------------------|----------------|---------------------|----------------------|-----------------------|
| Ethiopia | 1.00 | 1.00 | 0.67 | 0.83 | 1.00 | 0.83 |
| Kenya | 0.75 | 1.00 | 0.67 | 1.00 | 0.75 | 1.00 |
| Cameroon | 1.00 | 1.00 | 1.00 | 0.00 | 1.00 | 1.00 |
| Angola | 0.67 | 1.00 | 0.50 | 0.75 | 0.67 | 1.00 |
| Mozambique | 0.33 | 1.00 | 1.00 | 1.00 | 0.33 | 1.00 |
| Tanzania | 0.50 | 0.50 | 1.00 | 1.00 | 0.50 | 1.00 |
| Sudan | 0.75 | 1.00 | 0.75 | 0.50 | 0.75 | 0.50 |
| Senegal | 0.67 | 1.00 | 0.50 | 0.00 | 0.67 | 1.00 |
| Nigeria | 0.40 | 1.00 | 0.33 | 0.67 | 0.40 | 1.00 |
| Morocco | 0.43 | 0.50 | 1.00 | 1.00 | 0.29 | 0.50 |
| Egypt | 0.25 | 1.00 | 1.00 | 0.40 | 0.25 | 0.80 |
| Algeria | 0.11 | 0.67 | 0.50 | 0.50 | 0.29 | 0.50 |
| South Africa | 0.03 | 1.00 | 0.00 | 0.50 | 0.07 | 0.50 |

TABLE 9: Matching result of Chinese power companies in Latin America.

| Country | Osculating value | RSR | TOPSIS | Entropy value | Efficacy coefficient | Min | Max | Interval length |
|-----------|------------------|------|--------|---------------|----------------------|-------------|-------------|-----------------|
| Ecuador | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 |
| Venezuela | 0.83 | 0.50 | 0.73 | 0.75 | 0.74 | 0.50 | 0.83 | 0.33 |
| Argentina | 0.82 | 0.43 | 0.63 | 0.64 | 0.62 | 0.43 | 0.82 | 0.39 |
| Cuba | 0.72 | 0.51 | 0.79 | 0.72 | 0.76 | 0.51 | 0.79 | 0.28 |
| Bolivia | 0.68 | 0.47 | 0.66 | 0.69 | 0.70 | 0.47 | 0.70 | 0.23 |
| Brazil | 0.66 | 0.35 | 0.46 | 0.56 | 0.48 | 0.35 | 0.66 | 0.31 |
| Peru | 0.49 | 0.34 | 0.44 | 0.56 | 0.48 | 0.34 | 0.56 | 0.22 |
| Colombia | 0.40 | 0.26 | 0.32 | 0.46 | 0.33 | 0.26 | 0.46 | 0.20 |
| Mexico | 0.45 | 0.28 | 0.36 | 0.44 | 0.36 | 0.28 | 0.45 | 0.17 |
| Chile | 0.43 | 0.26 | 0.33 | 0.37 | 0.33 | 0.26 | 0.43 | 0.17 |
| Uruguay | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

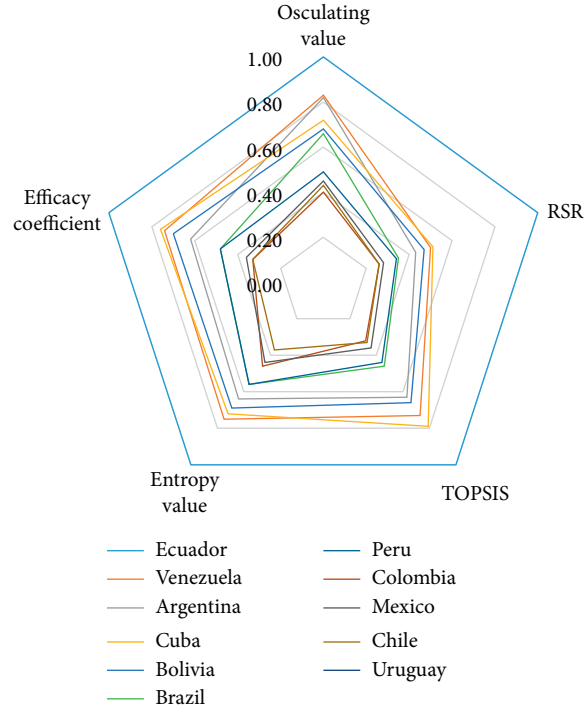


FIGURE 10: Matching effect picture of Chinese power companies in Latin America.

TABLE 10: Matching indicators value of Chinese power companies in Latin America.

| Country | Technical standards | Qualification certification | Export methods | After-sales service | Market concentration | Product concentration |
|-----------|---------------------|-----------------------------|----------------|---------------------|----------------------|-----------------------|
| Ecuador | 0.67 | 1.00 | 1.00 | 1.00 | 0.67 | 0.75 |
| Venezuela | 0.33 | 1.00 | 1.00 | 0.33 | 0.50 | 0.67 |
| Argentina | 0.30 | 0.60 | 0.75 | 0.50 | 0.36 | 0.75 |
| Cuba | 0.50 | 0.67 | 1.00 | 0.50 | 0.50 | 0.50 |
| Bolivia | 0.67 | 0.67 | 0.50 | 0.00 | 0.67 | 1.00 |
| Brazil | 0.11 | 0.25 | 0.50 | 0.83 | 0.14 | 1.00 |
| Peru | 0.33 | 0.33 | 0.00 | 1.00 | 0.20 | 1.00 |
| Colombia | 0.00 | 0.67 | 0.00 | 0.50 | 0.17 | 1.00 |
| Mexico | 0.11 | 0.60 | 0.00 | 1.00 | 0.18 | 0.33 |
| Chile | 0.25 | 0.50 | 0.00 | 0.50 | 0.29 | 0.33 |
| Uruguay | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

TABLE 11: Matching result of Chinese power companies in the Middle East.

| Country | Osculating value | RSR | TOPSIS | Entropy value | Efficacy coefficient | Min | Max | Interval length |
|--------------|------------------|------|--------|---------------|----------------------|-------------|-------------|-----------------|
| Iran | 0.91 | 1.00 | 0.74 | 1.00 | 0.99 | 0.74 | 1.00 | 0.26 |
| Oman | 0.69 | 0.66 | 0.51 | 1.00 | 1.00 | 0.51 | 1.00 | 0.49 |
| Yemen | 1.00 | 0.73 | 1.00 | 0.89 | 0.81 | 0.73 | 1.00 | 0.27 |
| Kuwait | 0.44 | 0.46 | 0.36 | 0.79 | 0.81 | 0.36 | 0.81 | 0.45 |
| Turkey | 0.63 | 0.47 | 0.46 | 0.79 | 0.79 | 0.46 | 0.79 | 0.33 |
| Iraq | 0.49 | 0.43 | 0.35 | 0.74 | 0.76 | 0.35 | 0.76 | 0.41 |
| Saudi Arabia | 0.43 | 0.37 | 0.30 | 0.66 | 0.68 | 0.30 | 0.68 | 0.38 |
| Bahrain | 0.42 | 0.34 | 0.30 | 0.63 | 0.66 | 0.30 | 0.66 | 0.36 |
| Qatar | 0.38 | 0.34 | 0.32 | 0.59 | 0.49 | 0.32 | 0.59 | 0.27 |
| UAE | 0.24 | 0.17 | 0.14 | 0.33 | 0.26 | 0.14 | 0.33 | 0.19 |
| Israel | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

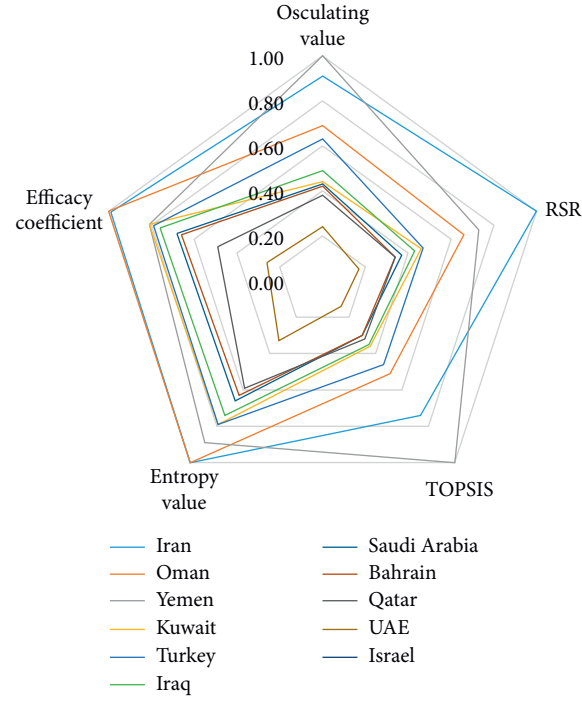


FIGURE 11: Matching effect picture of Chinese power companies in the Middle East.

TABLE 12: Matching indicators value of Chinese power companies in Middle East.

| Country | Technical standards | Qualification certification | Export methods | After-sales service | Market concentration | Product concentration |
|--------------|---------------------|-----------------------------|----------------|---------------------|----------------------|-----------------------|
| Iran | 0.50 | 1.00 | 0.75 | 1.00 | 0.50 | 0.75 |
| Oman | 0.25 | 1.00 | 1.00 | 1.00 | 0.25 | 1.00 |
| Yemen | 1.00 | 1.00 | 0.00 | 0.00 | 1.00 | 1.00 |
| Kuwait | 0.00 | 0.50 | 1.00 | 1.00 | 0.05 | 1.00 |
| Turkey | 0.25 | 0.75 | 0.78 | 0.63 | 0.33 | 0.80 |
| Iraq | 0.13 | 0.50 | 1.00 | 0.50 | 0.19 | 1.00 |
| Saudi Arabia | 0.00 | 0.67 | 1.00 | 0.20 | 0.26 | 0.83 |
| Bahrain | 0.00 | 0.50 | 1.00 | 0.00 | 0.33 | 1.00 |
| Qatar | 0.00 | 0.50 | 0.00 | 1.00 | 0.14 | 1.00 |
| UAE | 0.00 | 0.33 | 0.00 | 0.00 | 0.17 | 1.00 |
| Israel | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

TABLE 13: Matching result of Chinese power companies in Europe.

| Country | Osculating value | RSR | TOPSIS | Entropy value | Efficacy coefficient | Min | Max | Interval length |
|---------|------------------|------|--------|---------------|----------------------|-------------|-------------|-----------------|
| Poland | 0.61 | 0.44 | 1.00 | 0.66 | 0.73 | 0.44 | 1.00 | 0.56 |
| Belarus | 0.58 | 0.39 | 0.41 | 0.78 | 0.64 | 0.39 | 0.78 | 0.39 |
| Russia | 0.48 | 0.32 | 0.32 | 0.65 | 0.52 | 0.32 | 0.65 | 0.33 |
| Romania | 0.22 | 0.17 | 0.13 | 0.36 | 0.23 | 0.13 | 0.36 | 0.23 |
| UK | 0.26 | 0.17 | 0.24 | 0.25 | 0.23 | 0.17 | 0.26 | 0.09 |
| France | 0.06 | 0.04 | 0.05 | 0.11 | 0.05 | 0.04 | 0.11 | 0.07 |
| Hungary | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

relatively poor, and the export methods and types of products exported deviate greatly from market demand; thus, business strategies need to be further adjusted.

3.2.5. Middle East. From the results in Table 11 and Figure 11 and the specific indicator values in Table 12, it can be seen that Chinese power companies have developed well in

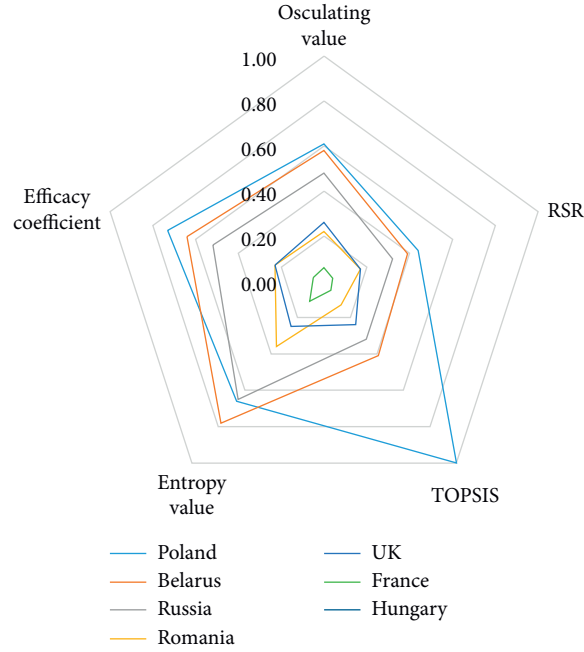


FIGURE 12: Matching effect picture of Chinese power companies in Europe.

TABLE 14: Matching indicators value of Chinese power companies in Europe.

| Country | Technical standards | Qualification certification | Export methods | After-sales service | Market concentration | Product concentration |
|---------|---------------------|-----------------------------|----------------|---------------------|----------------------|-----------------------|
| Poland | 1.00 | 0.33 | 1.00 | 0.00 | 0.14 | 1.00 |
| Belarus | 0.00 | 1.00 | 0.60 | 0.40 | 1.00 | 1.00 |
| Russia | 0.00 | 1.00 | 0.66 | 0.33 | 0.50 | 1.00 |
| Romania | 0.00 | 0.50 | 0.50 | 0.00 | 0.33 | 1.00 |
| UK | 0.00 | 0.33 | 0.67 | 0.33 | 0.11 | 0.33 |
| France | 0.00 | 0.20 | 0.00 | 0.00 | 0.10 | 1.00 |
| Hungary | 0.00 | 0.33 | 0.00 | 0.00 | 0.33 | 0.00 |

the Iran and Oman power markets, and their qualification certification and after-sales service are quite complete. There is room for improvement in Kuwait, Turkey, Iraq, Saudi Arabia, Bahrain, and Qatar, especially in terms of technical standards. For the UAE and Israeli power markets, the overall matching degree is very low. China's technical standards and qualification certification need to be strengthened, and export methods and after-sales services need to be adjusted.

3.2.6. Europe. From the results in Table 13 and Figure 12 and the specific indicator values in Table 14, we can see that Chinese power companies have developed well in the Polish power market but lack after-sales services. The development in Belarus and Russia is at a general level. For the power markets of Romania, the United Kingdom, France, and Hungary, Chinese companies need to vigorously promote Chinese technical standards and improve after-sales services to expand their business.

4. Conclusion

Through the analysis of the supply and demand characteristics in major regional power markets, it is found that the global power technology and equipment market demand is dominated by hydropower, thermal power, and power transmission and transformation equipment and related technologies. The demand for wind power, nuclear power, photovoltaic power generation equipment, and technology is increasing year by year. Under the influence of the "One Belt, One Road" strategy, China has established good cooperative relations with countries along the route, especially Central Asia, Southeast Asia, and other countries, providing opportunities for China's power technology and equipment to "go global." In addition, the power infrastructure in Africa is backward. Therefore, China's power technology and equipment exports are currently mainly concentrated in Southeast Asia, Central Asia, and Africa. There are fewer equipment exports and power contracting businesses in Latin America, Europe, and the Middle East. This also reflects the fact that

Chinese power companies are less competitive in Latin America and Europe, which are with a higher level of internationalization. In terms of export method, Chinese power companies mainly export directly through project contracting, such as EPC, BOT, and BOOT. In order to share risks and increase international competitiveness, the joint venture model of cooperation with other power equipment or construction companies has also begun to appear.

Through market matching analysis, it is found that China's power technology and equipment have a relatively good global market matching, especially in Southeast Asia, Central Asia, and Africa. Due to the low degree of data disclosure in some countries, it is difficult to find comprehensive and accurate data for analysis and the electricity market barriers in some countries are relatively high, making it difficult for Chinese power technology and equipment companies to enter their markets; thus, market matching degree is low to a certain extent.

In response to the above research conclusions, the following strategic suggestions are given. Firstly, improve the dynamic tracking and analysis mechanism of power technology and equipment markets in different regions of the world. Long-term continuous tracking of market characteristics such as technical standards, qualification certifications, and key supply and demand in target markets is important for power companies to make adjustments in the business models and business strategies in time. Secondly, accelerate the internationalization of China's power technology standards. Although China's power standards have been promoted in recent years, their recognition in certain regions is still very low, making Chinese power companies lack competitiveness. Therefore, China must accelerate the establishment of a domestic power standard linkage mechanism and promote more Chinese standards to become international standards. Thirdly, communicate with relevant government departments actively. Try best to obtain government policy support, which helps create conditions for expanding the output of enterprise power technology and equipment. Fourth, before entering the target market, understand the local political situation, security issues, economic risks, etc. and establish a risk prevention and control mechanism. In the meantime, be familiar with local laws and regulations to avoid losses due to poor understanding or deviations of local laws and regulations. Fifth, cultivate high-end compound talents. The electric power technology and equipment business involve many professional fields such as electric power technology, equipment manufacturing, and law. It is necessary to further strengthen the training of talents proficient in technology and foreign languages so as to drive the high-quality and rapid development of the electric power technology and equipment business.

In future research, we will study the matching degree of internationally renowned power companies in the energy equipment market. Thus, we can learn the operation and management experience from outstanding companies in the energy market.

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 regarding the publication of this article.

Acknowledgments

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Research Article

Reconstruction of ER Network from Specific Academic Texts for the Governance of MSW-NIMBY Crisis in China

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Along with urban development globally, the NIMBY (Not-In-My-Backyard) crisis has been a complex social problem, which requires urgent remedial action. The inevitable management of Municipal Solid Waste (MSW) has been one of the toughest risk management tasks in the worldwide modernization process. At present, certain fuzzy and unstructured results and methods have been formed for MSW-NIMBY crisis response, mainly focusing on the sociology and politics which scatter in complex and sensitive reports and news. Aiming at enhancing the effectiveness of data mining from specific sparse text of MSW-NIMBY crisis, an improved knowledge extraction method is developed. Through rule-based text mining and complex network analysis, the Entity Relationship (ER) network of MSW-NIMBY crisis is reconstructed. Meanwhile, a novel transitivity for relationship between entities in semantic analysis is proposed to improve the feasibility and accuracy of information extraction. Characteristics and regularity of MSW-NIMBY crisis evolution and experience of crisis governance could be identified effectively. Results show that knowledge integration and ER transitivity can enhance knowledge recognition and major other factors, which could help formulate the governance strategies of NIMBY crisis from academic texts.

1. Introduction

With the development of modernization and urbanization, environmental conflict has been a top global focus and an issue for urban sustainable development. It is generally believed that some facilities with negative effects were built in this process, such as nuclear power plants, waste incinerator plants, and sewage plants, etc. [1–3]. It widely causes resistance and conflict between surrounding residents and local authorities [4], and this phenomenon is named as “NIMBY” [5]. After the 1970s, as more and more countries and regions have realized industrialization, NIMBY gradually became a cosmopolitan problem. Taking the United States as an example, NIMBY caused almost half of all clean energy projects to be delayed or abandoned [6], and only 8 of 81 toxic waste disposal sites scheduled to be built between 1980 and 1987 were successfully completed [7]. The impacts of various types of NIMBY facilities on society are complex and diverse in nature [8], and the risks are constantly

changing due to the uncertainty of the types and interests of relevant stakeholders [9]. On the other hand, NIMBY crisis involves the interests of the masses and highly sensitive political decisions. It is difficult to be resolved once it has emerged, which has become one of the serious risks of “modernity” the transnational world faces [10]. The increases in public environmental awareness and community living standards, and the rapid development of media also have greatly accelerated the outbreak of the NIMBY crisis [11], especially in developing countries with a high population density. The rising NIMBY protest movement within the city caused by MSW has become a serious challenge during the process of urbanization in China [12].

Until 2019, there are about 330 MSW incineration facilities in China [13], but from 2007 to 2016 with more than five anti-incinerator demonstrations annually that claimed the relocation of MSW incineration facilities [14]. The continuous criticisms and protests that occurred in China in recent years show the significant characteristics of numerous

participants, unpredictable tendencies, strong diffusivity, and urgently required system solutions. Once the MSW-NIMBY crisis occurs, it usually creates tension between residents, local governments, and the private sector, and results in hindering waste disposal, causing trust crisis in the government and even triggering large-scale public events [15]. How to alleviate NIMBY crisis in MSW management would have a sustainable global impact. Although the existing literatures have not paid much attention to this issue, it has become the key point of managing MSW dilemma, strengthening the urban planning and development control, and promoting the construction of ecological civilization and environmental sustainability [16, 17].

The study of NIMBY crisis in the context of China shows hysteresis, compared with many western countries. It mainly focuses on related concepts [18], influence factors [15, 19], control measures [20], and relevant resolving experience [21], but most of them use qualitative and common methods, such as focus interviews to analyze effectiveness of public participation [22], case analysis to study government strategic orientation [23], and promotion of public participation [24], etc. There are relatively simple research types. The quantitative research just focuses on the site selection of NIMBY facilities [25] and other aspects mostly using structured interviews [26], questionnaires [27], and other positive methods for statistical analysis. Although scholars in this field are constantly innovating with regard to the research methods on MSW-NIMBY crisis, there is still a lack of scientific quantitative methods to enrich the theoretical basis of MSW-NIMBY crisis governance. This is because the problem of NIMBY generally has a strong political sensitivity, involving issues of national and social stability. It is difficult to obtain authoritative data or information from open access resources, such as the insufficient waste service in developing countries [28]. It results in research on such political sensitivity issues having certain limitations, and having not formed a complete method system yet. Therefore, the main contributions of our work could be summarized as follows:

- (i) Constructing a systematic method of knowledge integration for complex and scattered information, and providing the reference for textual research on politically sensitive issues.
- (ii) ER network of MSW-NIMBY crisis is reconstructed, which could help find key information and relationships, and a novel transitivity in semantic analysis is proposed to improve feasibility and accuracy of text analysis.
- (iii) The application of a novel transitivity in semantic analysis could help identify characteristics and regularity of MSW-NIMBY crisis effectively, which provides method support for other NIMBY crisis governance.

The remainder of this paper is organized as follows: It addresses an analysis of related works on MSW-NIMBY crisis along Section 2. Section 3 describes the proposed method of using network to research in detail. The complete

experiment and application of MSW-NIMBY crisis are presented in Section 4. In Section 5, analysis results show the mined information and knowledge in this field. Conclusions are given in Section 6.

2. Related Work

This research aims to obtain valuable knowledge from text information. This kind of text processing technology that extracts specified types of unstructured information from natural language text and converts it into structured data output is known as information extraction [29]. ER extraction is one of the most important and difficult contents, and it is also a key to the integration and analysis of Chinese text knowledge, especially such social science issues. The method of Chinese ER extraction is innovated based on the bidirectional maximum entropy Markov model [30], ontologies, and bidirectional long short-term memory [31], which all improve the precision or operability of extraction. Information extraction technology has extensive research and application in the fields of medicine, health, traffic, and artificial intelligence [32–34]. However, the current research in the field of MSW-NIMBY does not have a unified specification or standard expression, and the research of semantic analysis on Chinese is limited. A more accurate supervised extraction method is selected to identify the relationship between entities based on rules.

In addition, existing research on MSW-NIMBY crisis mostly focuses on explaining the outcome of NIMBY conflict and decision-making on NIMBY facilities, with the multiple theoretical and methodological approaches [35]. But all of them have largely neglected the role that non-human factors also played in such controversies and uncertain interactions within all factors [36], so that some scholars have called for social research on NIMBY crisis and its interaction with all factors [37, 38]. It has been discussed that NIMBY is a dynamic and complex problem involving mixed entities, including concepts, organizational departments, policy measures, influential factors [39], etc. It is characterized by inextricable relations among social, natural, and material factors [40], which have trouble in understanding and analyzing in sociological research. Among the approaches that have tried to develop a more complex analysis of the inherent relationship of NIMBY crisis, complex network occupies a prominent position because of its strong influence on theoretical and empirical sociological research [41].

Complex network not only focuses on the tight interdependence between an individual and others objectively in the system [42] but also keeps an eye on the overall interaction of the system from a holistic perspective [43]. It can analyze structural composition and relational components of evolving systems that cannot otherwise be identified using other techniques [44]. Complex network grasps the internal mechanism and system characteristics of complex systems, such as NIMBY, and provides reasonable indicators on quantitative analysis of network, namely, by the method of Social Network Analysis (SNA) [45], to tackle NIMBY problems. This kind of research in the form of network is

mostly used in information science, environmental science, geography, biomedicine, etc. [46]. In the fields of MSW and NIMBY, there are many scholars using network expression to research the public's acceptance of new energy infrastructure [47], the development of radicalism and organizational activities in NIMBY [48, 49], the relationship between stakeholders in waste management [50], etc. Most of the existing researches are mainly expressed in the form of ER network [51], that is, the entities and relationships between them are directly abstracted from the real world and presented in the form of network.

ER network can find the generality of a complex system under a unified framework by abstracting entities with different attributes into nodes, using links to represent relationships between entities, and then quantifying the indexes of network structure with nodes and links as components [52]. In natural language, the discontinuous structure of ER can represent semantic units such as words, sentences, and paragraphs, reflecting information from text as a network. This is based on the language-dependent constraint that each word or phrase is mapped into a node and edges are established according to syntactical relations [53]. Such textual representation has allowed the investigation of basic human behavior [54]. For example, expressing the words in the message set as an undirected graph [55], ranking events based on event relation graph for a single document [56], and expressing relationships between entities by Multi-Entity Bayesian networks [57], and so on. The method based on network model is effective because it can obtain the global information of network comprehensively, namely, the global information of text, through iterative calculation [58]. Note that there is an issue that the presence of specific words other than relevant entities in the network may hinder the accurate recognition of patterns. While several available methods grasp the ER between all words or specific classes of words as the characteristics of complex networks [59, 60], only a few researches focus on solving the problems of insufficient accuracy and difficulty in grasping the key points of the network constructed from text information. In this sense, this paper constructs a networked text representation by introducing the transitive expression of relationship, to analyze it more clearly.

The scientific literatures often contain a lot of information and knowledge, and store abundant research achievements. Inspired by the ER network, a series of rules for ER extraction and transitive relation model can be established to acquire overall information of MSW-NIMBY crisis from scientific literatures more accurately, and provide a solution for environmental conflicts like MSW-NIMBY crisis.

3. MSW-NIMBY Crisis Network

In this section, we present and explain all the methods used to construct the MSW-NIMBY crisis network. Rule-based ER extraction for MSW-NIMBY is proposed conforming to Chinese syntactic structures for information extraction. The transitive relation model is constructed by introducing

transitivity in order to optimize ER network. The ultimate purpose of this research is digging valuable information from ER network in the MSW-NIMBY crisis. SNA is a common method in network analysis, which focuses on graph-theoretic properties of social networks with mathematical methods [61, 62]. This analysis method for structural networks focuses on the structure, pattern, topological complexities, and implications of interacting entities [63, 64].

In order to build the MSW-NIMBY crisis network, we propose a series of methods adapted to the specific requirements of any administrative domain, as shown in Figure 1.

Beginning from extracting ER triples by the semantic annotation and customized sentence rules of extraction, the relation transmission of ER triples is reconstructed and reinterpreted by the novel transitive relation model. In the network analysis, the macro level and micro level of measurements and disciplines can be analyzed comprehensively by SNA [65].

3.1. Rule-Based ER Extraction for MSW-NIMBY. ER extraction is a crucial part of information extraction, which is a text-processing technology extracting entities, relationships, events, and other unstructured information from natural language and converting them into structured data output [66]. Its task is to extract the triple (*Entity1*, *Relationship*, *Entity2*) from text, where (*Entity1*, *Entity2*) is an entity pair with some relationship, and “*Relationship*” is the word or word-sequence that describes the semantic relationship between entities in the context. For example, in the text “*NIMBY facilities generate negative externality effects*,” the ER triple (*NIMBY facilities*, *Generate*, *Negative externality effects*) can be extracted to establish connection. That is, there is a relationship of “*Generate*” between “*NIMBY facilities*” and “*Negative externality effects*.”

It is inconvenient to specify the classification of relationships in advance in the open-domain information extraction. Besides, the content omission and semantic judgment are necessary in extraction of complex sentences. There is a common method that using the vocabulary in the corpus representing relationships to model the ER [67] and extract all types of relationships that exist in the text, because most of the syntactical connections occur between neighboring words in the same sentences [68]. This paper customizes the supervised extraction rules for open-domain information extraction. It includes formulating the template of semantic annotation in advance for word segmentation and semantic role labeling of Chinese language, and constructing the sentence rules to extract the ER triples.

3.1.1. Template of Semantic Annotation. The template is applied to deal with word segmentation and semantic role labeling. It uses specific labels to mark roles of semantic units such as words or phrases in the text [69], and completes the word segmentation when judging these semantic units. In this way, it can formally represent the role features and thematic connections of semantic units in the text. The

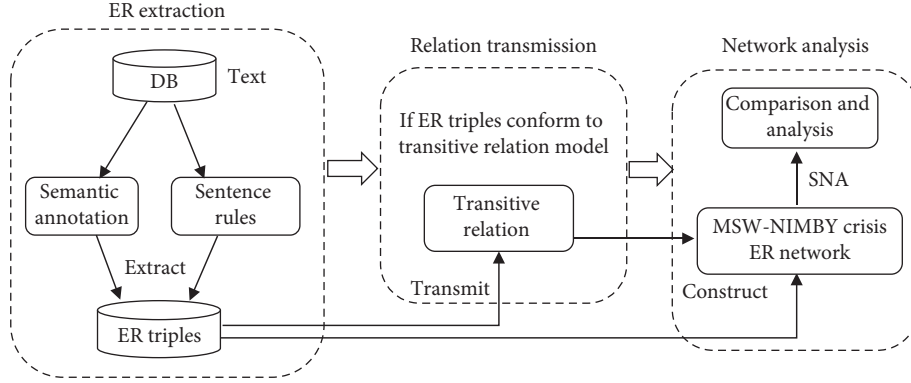


FIGURE 1: Overview of the research method proposed.

specified template of semantic annotation in the study of MSW-NIMBY, including the role label and its description, is shown in Table 1.

For the text of scientific research, the manual word segmentation and annotation for the semantic units in sentences can be done, according to their semantics and features. They are the premise of based-rules ER extraction. We use AE for action executor, which mostly represents the subject in sentences, and ACT for specific action of executor, including predicate verbs or linking verbs. AR is an action receiver and IAR is an indirect action receiver, which are expressed as direct object and indirect object, respectively, in the sentence structure. PREP and CONJ are conjunctions and prepositions, both of which are indispensable parts for analyzing structure and semantics of a sentence. In order to represent the preposition-object structure in English, POBJ is used to label object of preposition and expresses the action together with preposition. Besides, the component as an adverbial can be omitted in the manual annotation to simplify the extraction rules, or be retained to understand and extract sentences better, such as the adverbials of manner (MAN), purpose (PRP), reason (REA), background (BGD), condition (CND), time (TMP), location (LOC), etc. Because its definition is vague and it is not the key point of this research.

3.1.2. Sentence Rules for ER Extraction. ER triples almost only appear in stable syntactic structures, although the semantics in Chinese expression is very complex. There are many syntactic types containing characterization for relationship extraction, such as Subject-Predicate, Predicate-Object, Preposition-Object, and Coordinate and others [70]. A set of sentence rules for ER extraction of MSW-NIMBY in Chinese is constructed based on syntactic parsing [66]. It is based on 24 kinds of dependencies proposed by the LTP (language technology platform) of HIT-SCIR (Harbin Institute of Technology) [71]. It can be generalized into the combination of words, POS-tags, dependency paths, and dependency labels on paths [72]. We defined logical and graphical expression to display sentence rules in accordance with the above labels in the template of semantic annotation as well as extracted ER triples by the certain rules, as shown in Table 2. The rectangular block represents the annotated

TABLE 1: Template of semantic annotation in MSW-NIMBY.

| Number | Label | Description |
|--------|-------|--------------------------|
| 1 | AE | Action executor |
| 2 | ACT | Action |
| 3 | AR | Action receiver |
| 4 | IAR | Indirect action receiver |
| 5 | PREP | Preposition |
| 6 | CONJ | Conjunction |
| 7 | POBJ | Object of preposition |

semantic unit, and the arrowed curve represents the dependency relationship between these two units, which is used to explain the specific relationship (these are all listed below).

This kind of rule-based ER extraction can be used for text information: using the template of semantic annotation to clarify each semantic unit and its role, and then extracting the ER triples in the text information according to the sentence rules. The specific applications of Rule1-Rule6 are explained as follows:

- (i) *Simple Verbal Structure.* The Rule1 is often used in the verbal structure, in which the verb acts as the predicate phrase and may be the relationship word. For an entity pair, one is the subject of the predicate while the other is the object of the predicate, and both depend on the predicate word by labels SBV and VOB (these mean the kind of dependency labels defined by LTP from HIT-SCIR. <http://www.ltp-cloud.com/intro>). The triple (*NIMBY facilities*, *Generate*, *Negative externality effects*) can be extracted from the sentence “*NIMBY facilities generate negative externality effects.*” We can easily extract this kind of ER triples based on Rule1.
- (ii) *Double Object Structure.* The Rule2 applies to the double object structure. Taking the sentence “*Government gives inhabitant preferential policies*” as an example, it should be labelled as “[AE *Government*] [ACT *Gives*] [IAR *Inhabitant*] [AR *Preferential policies*]” according to Table 1. That is, there is a subject-predicate relationship (SBV) between [AE *Government*] and [ACT *Gives*], while [AR *Preferential policies*] is the direct receiver of the

TABLE 2: Sentence rules for ER extraction in MSW-NIMBY.

| Rule | Logical and graphical expression | ER triple (Entity1); relationship, Entity2) |
|-------|--|---|
| Rule1 | <p>[AE-SBV-ACT, AR-VOB-ACT] [AE-SBV-ACT, AR-VOB-ACT]</p> | (AE, ACT, AR) |
| Rule2 | <p>[AE-SBV-ACT, AR-VOB-ACT, IAR-IOB-ACT] [AE-SBV-ACT, AR-VOB-ACT, IAR-IOB-ACT]</p> | (AE, ACT, AR) (AE, ACT-AR, IAR) |
| Rule3 | <p>[AE-SBV-ACT, AR-VOB-ACT, PREP-ADV-ACT, PREP-POB-POBJ] [AE-SBV-ACT, AR-VOB-ACT, PREP-ADV-ACT, PREP-POB-POBJ]</p> | (AE, ACT, AR) (AE, ACT-[AR]?-PREP, POBJ) |
| Rule4 | <p>[AE-SBV-ACT, AR I-VOB-ACT, AR I-COO-AR II, CONJ-LAD-AR II] [AE-SBV-ACT, AR I-VOB-ACT, AR I-COO-AR II, CONJ-LAD-AR II]</p> | (AE, ACT, ARI) (AE, ACT, ARII) |
| Rule5 | <p>[AE-SBV-ACT, AR-VOB-ACT, AE-SBV-PREP, MNR-POB-PREP] [AE-SBV-ACT, AR-VOB-ACT, AE-SBV-PREP, MNR-POB-PREP]</p> | (AE, ACT, AR) |
| Rule6 | <p>[AE-SBV-ACT, AR-VOB-ACT, AE-SBV-PRP, PREP-POB-PRP] [AE-SBV-ACT, AR-VOB-ACT, AE-SBV-PRP, PREP-POB-PRP]</p> | (AE, ACT, AR) |

Note: – denotes the combination of two words. []?+ means the word occurring once or not.

action [ACT Gives] with the dependency relationship of VOB between them. [IAR Inhabitant] is the indirect receiver of the action [ACT Gives], namely, the indirect object (IOB) depends on it. The content should be retained at the greatest extent without violating the original intention of the sentence, so the two triples (*Government, Gives, Preferential policies*) and (*Government, Gives preferential policies, Inhabitant*) can be extracted.

- (iii) *Light Verb Structure*. There are many light verb structures in Chinese expression, which is expressed as preposition-object structure in English. For example, in the sentence “*Government made a deal with citizens*,” it is often expressed as “*Government with citizens made a deal*” in Chinese, and “*With...made a deal*” is a typical Chinese light verb structure. [AE Government] as the subject directly depends on the light verb [ACT Made] by SBV, and [AR A deal] as the object depends on the light verb [ACT Made] by VOB, which is obviously similar in the Rule1. Meanwhile [POBJ Citizens] follows the preposition [PREP With] as the prepositional object, indirectly depending on the light verb by POB and ADV. This structure can be handled with the Rule3, so the two triples (*Government, Made a deal, Citizens*) and (*Government, Made, A deal*) should be extracted. In addition, for the structure of the intransitive verb, it also can be treated as a light verb structure in ER extraction [73]. For example, the sentence “*The public protest in the street*” translated into Chinese gives us “*The public in the street protest*.” There is no verbal object following the intransitive verb [ACT Protest], [AE The public], [PREP In], and [POBJ The street] with the same dependency relationships as the abovementioned light verb structure. At this time, only one triple of (*The public, Protest in, The street*) can be extracted, and the preposition cannot be omitted to ensure the semantic integrity.
- (iv) *Coordinate Structure*. The Rule 4 adds a conjunction and an action receiver based on Rule1, used in the coordinate structure. This conjunction connects two action receivers expressing a coordinate relationship, both of which can be labelled as AR (distinguished by ARI and ARII in order to understand the extraction rules). The additional action receiver depends on the same role with another action receiver by COO, and depends on the conjunction by LAD. Other labels and dependency relationships are the same with the Rule1. This kind of sentence with coordinate structure can extract two ER triples. For example, the sentence “*The waste incineration plant provides employment opportunity and financial revenue*” can extract two triples of (*The waste incineration plant, Provides, Employment opportunity*) and (*The waste incineration plant, Provides, Financial revenue*). This rule also applies to the structure of action executors having a coordinate relationship between them, and the principle is the same.

- (v) *Multiple Structure*. There are multiple extraction methods that can be used for the same sentence. In particular, the Chinese expression is flexible and various, and one sentence often contains multiple structures. For example, the sentence “*This way through communication and understanding to make profits*” expressed in Chinese can be understood as an adverbial clause of manner. It is annotated as “[AE This way] [PREP Through] [MNR Communication and understanding] to [ACT Make] [AR Profits].” The clause usually follows a preposition and depends on it by POB, with the structure of Preposition-Object. So, the annotations of PREP plus adverbial clause are used to express the sentence structure more clearly, also applied to other adverbial clauses. The Rule5 is suitable for the above situation. “[MNR Communication and understanding]” meaning specific manners can be omitted in the extraction, and only considering the dependency relationship of [AE This way], [ACT Make], and [AR Profits] according to Rule1 can extract a triple (*This way, Make, Profits*). At the same time, this sentence can also be understood as the adverbial clause of purpose, annotated as “[AE This way] [ACT Through] [AR Communication and understanding] [PREP To] [PRP Make profits].” It accords with the dependency structure of the Rule6, so a triple (*This way, Through, Communication and understanding*) can be extracted in a similar manner. The extraction rules of Rule5 and Rule6 highlight that there are different extraction methods and results for the same sentence.

Following the writing styles of Chinese articles, there are abundant complex expression formats, which can be split into multiple simple sentences for more than one annotations and extractions. And, the structure of a simple sentence is mostly covered by Rule1–Rule6, which are suitable as the basis and rules for ER extraction.

In order to maximize the integrality and correctness of information, and ensure the feasibility of analysis, the rule-based ER extraction for MSW-NIMBY follows these principles:

- (i) Multiple methods of annotation and extraction can be implemented for the same sentence. For example, considering the subordinate clause as a single sentence to extract, all the extraction methods conforming to the sentence structure should be applied as much as possible, and all these results are retained.
- (ii) Manual semantic annotation needs to master semantics and parts of speech of Chinese, and the unified regulation can be formulated to train labeling personnel before annotation.
- (iii) Not all content appearing in the text need to be annotated. The main parts of the content should be retained when annotating, while the meaningless content is omitted as much as possible.

3.2. Novel Transitive Relation Model. The information of ER triples extracted from scientific literature is numerous and complicated, and it is difficult to find the key point of research. This section constructs the transitive relation model and demonstrates the effects with multiple relation transmission, in order to mine significant information in the text.

The principle of transitive relation model is that when the Entity1 in a triple is the same as the Entity2 in the other triple, a transitive relationship is established between these two triples. And, the new relationship is also generated connectedly, according to the characteristic of transitivity. The principle and example of the transitive relation model are shown in Figure 2.

Here is an example: with the transitive relation model, Triple1 (*Various ways, Confront, NIMBY project*) and Triple2 (*NIMBY project, Be faced with, Mass opposition*) can be expressed as (*Various ways, Confront, NIMBY project, Be faced with, Mass opposition*). Thus, an indirect relationship between “Various ways” and “Mass opposition” is constructed. There is no tense problem in Chinese expressions, as in English expressions, so it is easier to unify expression of entities to construct relationships. The relationship after transmission is an indirect relationship, the expression of which is more complicated and does not play a major role. Therefore, the specific indirect relationship between the entities can be omitted, and it is only regarded as an uncertain relationship between them. The novelty of transitive ER utilization could help the information receiver obtain major points rapidly without lots of noise screening work.

In order to depict the ER transmission network, the progress of pairwise relations is reconstructed, as shown in Figure 3. Obviously, the nonvital ER information in transitive relationship is discarded gradually. This reconstruction of transitive relation can be implemented iteratively. That is, there are three ER triples in the originals that can construct continuous transitive relation, which is treated as a second transitive relation. The multiple transitive relation is expressed in the same manner. After multiple relation transmission, the information of connections and changes between entities in the ER network is expressed as follows:

The nodes of A-F represent entities, while the edges between them represent relationships from Entity1 to Entity2 in the ER. The nodes and edges in the network after transmission have great changes, which relate to the number of times directly. It can intuitively reflect that the types of node decrease gradually while the edges between surviving nodes increase gradually, as the times of transmission increases. But, it should be noted, if the times of transmission is large enough, too many nodes and edges may be omitted, which cannot accomplish the aim of information mining in network analysis. The times of transmission needs to be determined according to actual effects of transitive relation in different problem.

In short, with the transitive relation model, entities are more closely connected, while its type is reduced and the number is increased. The primary and secondary status of entity information is still maintained, only amplifying the primary information and weakening the secondary information to some extent. In this way, it is possible to highlight

the important nodes and structural relationships between them in the network, so that it is easier to analyze and research the potential knowledge in MSW-NIMBY crisis based on text information.

4. Application Analysis of MSW-NIMBY Crisis

In this section, we demonstrate how to implement the ER network analysis process of the MSW-NIMBY crisis. First, the process of ER extraction is demonstrated in detail, by the rule-based ER extraction. Then, we perform multiple relation transmission to the extracted ER and analyze their actual effects, and determine the optimal times of transmission for ER network analysis of the MSW-NIMBY crisis ultimately.

4.1. ER Extraction. For the ER extraction of the MSW-NIMBY crisis, the relevant scientific literatures are obtained and screened from the literature database. Then, the ER triples are extracted based on rules, and finally the extracted entities are filtered and unified to improve the accuracy and standardization of entity information from literatures.

4.1.1. Dataset Selection. Due to the regional differences of NIMBY, the CNKI database (the most comprehensive database of paper collection in China on <https://www.cnki.net/>) is selected to be the data source of the MSW-NIMBY in China. With the theme of “Waste” and the keyword of “NIMBY,” 463 scientific literatures are collected before 2019 from the CNKI database by advanced search. The whole process is executed from the following seven aspects: removing all dissertations, positioning the Chinese core journal catalog of Peking University as the standard, and comprehensive consideration of publication time, times cited, times download, fund support, and core journal positioning.

As a rapidly developing country, the MSW-NIMBY emergency in China is a relative new issue in NIMBY field. But as long there is urbanization progress in China, the MSW-NIMBY could be a serious problem based on the history of developed countries. We derived pivotal literatures (see Table3) mainly containing management advices and social analysis for MSW-NIMBY events, which cover most of the views and strategies on the MSW-NIMBY crisis in China to some extent.

4.1.2. Annotation and Extraction. According to the above-defined method of rules-based ER extraction, extracting ER from 13 articles is related to the MSW-NIMBY crisis.

The content of these 13 articles is split roughly into a bulk of semantic units by using the Jieba Chinese Text Segmentation (a Python component of Chinese word segmentation on <https://github.com/fxsjy/jieba>). According to the template of semantic annotation, each semantic unit is manually judged and semantically labeled, before assigning it to a part of speech in the syntactic structure. Focusing on the syntactic structure of the annotated semantic units, the

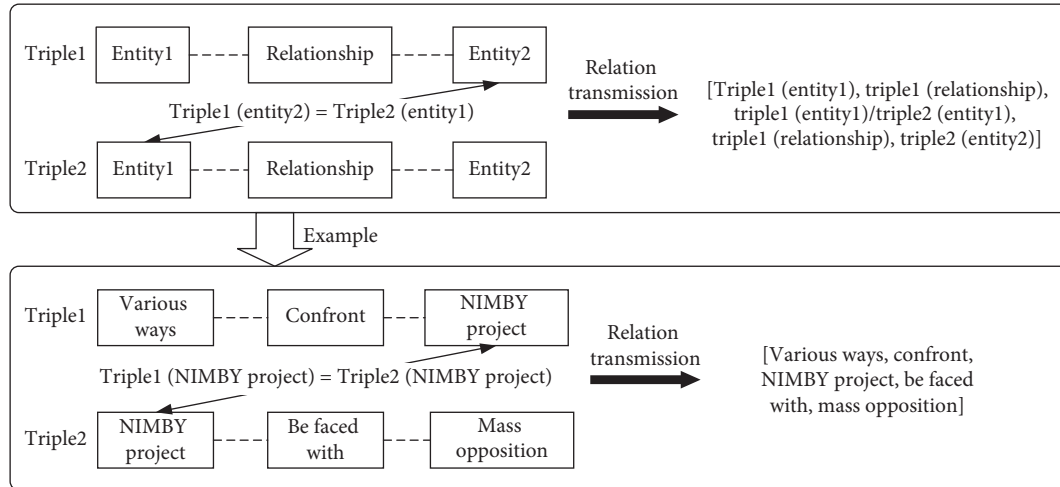


FIGURE 2: Transitive relation model and its example.

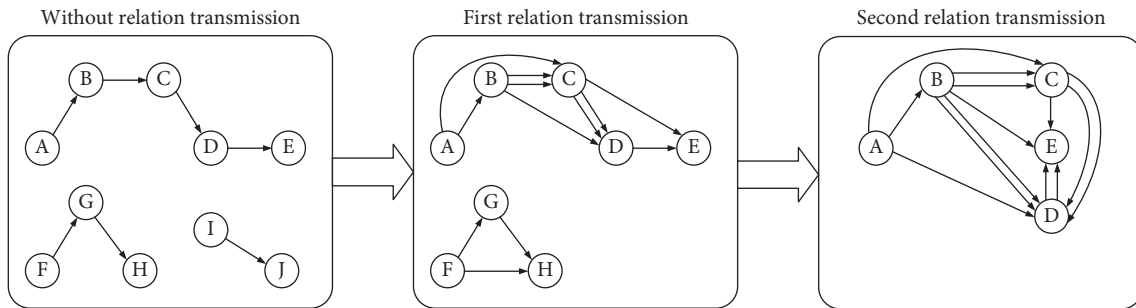


FIGURE 3: The changes of ER network with multiple relation transmission.

TABLE 3: Initial literature set in ER extraction.

| Number | Title | Journal | Publication date | Times cited | Times download | Fund support |
|--------|---|--|------------------|-------------|----------------|--------------|
| 1 | Effectively do a good job in the management innovation of waste incineration projects—turning “NIMBY” into “Neighbor benefit” | Consultation Report | 2019.09.27 | | | |
| 2 | Cause of environmental NIMBY conflicts and solution with dual-game structure as an analysis framework | City Planning Review | 2019-02-09 | 1 | 723 | 2 |
| 3 | Understanding the variation of government responses to NIMBY conflicts: from an urban governance perspective | Chinese Public Administration | 2018-08-01 | 16 | 1848 | 1 |
| 4 | Research on public participation in NIMBY conflicts caused by environmental pollution | Chinese Public Administration | 2017-12-01 | 18 | 1241 | 2 |
| 5 | Reflections on the “NIMBY” conflicts in environmental protection in the urban development—Based on the research of NIMBY conflicts in environmental protection projects in Shenzhen | Chinese Public Administration | 2017-08-01 | 2 | 760 | 2 |
| 6 | Manufacturing consent: strategies of the Guangzhou municipal government governing the NIMBY conflict | Wuhan University Journal (Philosophy & Social Science) | 2017-05-06 | 19 | 1211 | 3 |

TABLE 3: Continued.

| Number | Title | Journal | Publication date | Times cited | Times download | Fund support |
|--------|--|---|------------------|-------------|----------------|--------------|
| 7 | How to promote the NIMBY project in dilemma: analysis based on “benefit-risk” perception theory | Chinese Public Administration | 2017-04-01 | 22 | 1161 | 3 |
| 8 | Formation mechanism and governance strategy of the NIMBY effect of waste treatment project under information asymmetry | Social Science Front | 2016-04-01 | 11 | 654 | 3 |
| 9 | The cause of the NIMBY movement and its governance paradigm: an empirical analysis based on NIMBY movements in Chongqing | Urban Problems | 2016-02-27 | 46 | 1655 | 1 |
| 10 | Role of social organizations in the NIMBY crisis management in British and American countries and the enlightenment to China | Chinese Public Administration | 2016-02-01 | 21 | 1591 | 3 |
| 11 | Beyond predicament: the provision patterns reconstruction of NIMBY facilities in transitional China: Reflection of site selection of incineration power plants in Panyu, Guangzhou | China Soft Science | 2016-01-28 | 49 | 2303 | 5 |
| 12 | New public involvement in the NIMBY conflict: from the perspective of the framing process | Journal of Zhejiang University (Humanities and Social Sciences) | 2015-07-10 | 57 | 1860 | 1 |
| 13 | The conflict caused by “NIMBY” and its solution: analysis based on urban collective protest Yanling He | Public Management Research | 2006-12-15 | 319 | 4944 | 2 |

Note: The first report was adopted by the province-level government.

massive ER triples (Entity1, Relationship, Entity2) in the MSW-NIMBY crisis are extracted according to the sentence rules. All the above are done during manual handling. In order to improve the accuracy of ER extraction as much as possible, a strict extraction process is adopted in the actual extraction of ER triples:

- (i) First, unified regulation can be formulated to train labeling personnel before labeling.
- (ii) Second is the sampling inspection and consistency test after multiple rounds of labeling by multiple people repeatedly. If more than 3 people approve the same label, it is deemed available.
- (iii) In the end, multiple random screening is carried out by multiperson and reextracting it if there are more inexactitude.

In information extraction, entity disambiguation is also an important part, which is used to solve the problem of ambiguity caused by entities with the same name [74]. The entity disambiguation is completed when the triples are extracted after annotation, because the constructed semantic template and sentence rules are based on the semantic relationship of the context.

4.1.3. Filtration and Unification of Entity. Due to the strong subjectivity of manual annotation, the annotated content is more complicated. Besides, the expression of scientific literature is multifarious and involves a wide range of information. Entity is filtered and unified after the extraction of ER triple, in order to standardize the entity expression for mining information reflected in the text directionally and accurately.

In this process, the entity with a length of more than 10 characters is filtered, and all the triples that contain them are also removed at the same time. Then, the extracted ER triples are filtered and uniformly named by construction of stop word lists and synonym lists. The Baidu stop words that remove English words [75] are utilized. If an entity appears in these stop words, all the ER triples where it exists are filtered to identify the more accurate ER. Based on the frequency of each entity in the extracted information, synonym lists are customized for the MSW-NIMBY crisis to unify and standardize the expression of entities. This is accomplished by using the synonyms (Chinese synonyms for natural language processing and understanding on <https://github.com/huyingxi/Synonyms>), which can automatically provide synonym and similarity for the Chinese word based on Word2vec model [76]. By calculating the similarity between words, the entities with the same meaning in extracted triples are replaced by a unified expression of high-frequency entity based on word frequency statistics.

4.1.4. Validity Check of Extracted ER. The extracted ER information contains 1954 entities and 1660 ER ultimately, and the statistics of the entities with high-frequency are sorted by frequency, as shown in Table 4.

The information of a high-frequency entity reflects the main subject involved in the research of NIMBY problems, and it is the focus in this field generally. For example, “Public,” “Government,” and “Local government” are undoubtedly the inevitable subjects of MSW-NIMBY in the real world. What’s more, the frequency statistics conform to Zipf’s law [77]. That is, if the words are sorted by frequency of occurrence, the frequency is almost inversely proportional to the rank exactly.

TABLE 4: Entity information sorted by frequency.

| Rank | Entity | Frequency |
|------|------------------|-----------|
| 1 | Public | 230 |
| 2 | Government | 120 |
| 3 | Local government | 97 |
| 4 | Waste | 43 |
| 5 | Environment | 41 |
| 6 | NIMBY conflict | 28 |
| 7 | Countermeasure | 25 |
| 8 | Institution | 25 |
| 9 | Conflict | 23 |
| 10 | Project | 21 |
| ... | ... | ... |

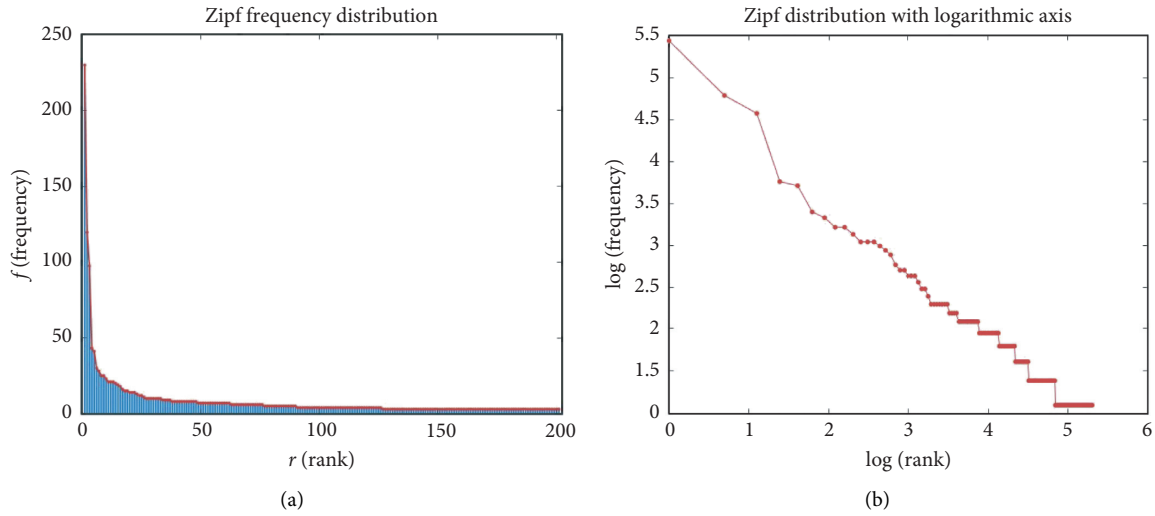


FIGURE 4: (a) Zipf distribution and (b) with logarithmic axis of top 202 high-frequency entities.

Zipf distribution of 202 high-frequency entity information with a frequency greater than 3 is shown in Figure 4, including Zipf frequency distribution with logarithmic axis. The logarithmic distribution between frequency and rank is close to a straight line, which can be regarded as conforming to Zipf's law on the whole. It shows that by covering a small part of the high-frequency words in the corpus, most of the information in the entire corpus can be understood. This fact also applies to a single article, so it is effective to use this entity information to analyze text information.

Table 5 reveals the excerpts of the ER output in the end. There is no tense problem of words in the Chinese sentence, so the meanings of ER triples are only expressed in English here, and their tense can be ignored.

4.2. Multiple Relation Transmission of the MSW-NIMBY Crisis. The network expressed by directly extracted ER from the text has defects of disordered hierarchy, intricate relationship, and ambiguous priority. These can be avoided by the transitive relation model, a method of relational data mining. Multiple relation transmission aims to transmit the extracted ER triples more than once, and then comparing and analyzing the topological parameter of nontransmitted and transmitted ER network to find out the most suitable times of transitive expression for research in the problem of MSW-NIMBY crisis.

4.2.1. ER Transmission. The extracted ER triples from the relevant literature are processed by the transitive relation model. If the same Entity1 and Entity2 are present in the two different triples, the association between these triples is established with the logic of transitivity. There is a relationship between each pair in these three different entities, and the triples that are not established are discarded. Repeating this operation, we can observe the changes of the output of transitive relationship during the experiment, about the number of entities and ER. The third transitive relationship has expressed the information of more concentrated entity and clear relationship, while the fourth transitive relationship expresses that the number of entities has been greatly reduced and run time for its operation is too long to achieve effective analysis. Therefore, only the ER information of original and the first three transmissions are retained for network analysis.

4.2.2. Comparison and Analysis of ER Network Attribute. The original ER and the transmitted ER are expressed in the form of a network, and the network of directed graphs is constructed by entities as nodes and their relationships between entities as edges. Gephi is used to calculate various parameters of ER network, which represent attributes of the network. Gephi is an open source network exploration and

TABLE 5: The ER triples of the MSW-NIMBY crisis (excerpts).

| Number | Entity1 | Relationship | Entity2 |
|--------|-----------------------------------|----------------|---------------------------------------|
| 1 | People | Carry out | The spirit of the 19th party congress |
| 2 | Countermeasure | Is | Strengthen expert management |
| 3 | MSW incineration project | Have | External risks |
| 4 | MSW incineration project | Be faced with | Mass opposition |
| 5 | External effect | Distribute | Imbalance |
| 6 | Common sense | Generate | Value conflict |
| 7 | Potential risk | Greater than | Potential profit |
| 8 | Government | Set up | Cooperation platform |
| 9 | Government | Organize | Stakeholder |
| 10 | Government | Participate in | Argument and decision |
| 11 | Government | Prevent | NIMBY crisis |
| 12 | Benefit compensation | Lack of | Coordination |
| 13 | Population | Express | Tendency |
| 14 | Report of the 19th party congress | Indicate | Direction |
| 15 | Benefit compensation | Is | Reason |
| 16 | Project | Guarantee | Right to know |
| 17 | MSW incineration project | Have | Pollution risk |
| 18 | People | Express | Willingness |
| 19 | People | Identify | Information |
| 20 | Countermeasure | Is | Design |

manipulation software, which provides features such as high-quality layout algorithms, clustering, and sample filtering by specific characteristics of the network [78]. It also provides functions of calculation and statistical distribution of topological parameters, and the calculation results are presented in Table 6.

Comparing and analyzing the parameters of ER network attributes under different times transmission are done, so as to get the best expression of transitive relation model. The changes and analysis of parameters are shown as Figures 5–7. It is observed that the transmitted network is endowed with more obvious characteristics.

(1) *Tighter Entity Connection.* Average degree represents the average number of connected edges of each node. Its linear rise indicates the remaining entities are connected to more and more other entities, and the more important the former is, as the times of transmission increase. Graph density reflects the closeness of nodes in the network, and its changes show that the relationship among entities is getting closer and closer. The network without transmission is too scattered and its density is almost zero, because it is composed of ER triples which are massive individuals extracted from natural language text directly. However, with the increase of transmission times, the graph density has a linear upward trend in the scattered structure. In the study of this complex problem, it reflects the ER network with the second transmission having a tighter entity connection to a certain extent.

(2) *Refined Module Division.* Modularity index is used to measure the strength of the network divided into modules (also called groups, clusters, or communities). This statistic shows that the modularity index is gradually decreasing, because the close connection of information between entities

reduces the number of communities where the entities belong, namely, the category or module. It indirectly reflects the refined module division with the increase of transmission times. The number of entities in each community is increasing, and the close entity connection in the same module will be affected negatively. In general, the modularity index is greater than 0.44, which means the network has reached a certain degree of modularity. For the complex problem of abundant entities, it is possible to grasp the key points with the refined module division under the second transmission.

(3) *Higher Cohesive Clustering.* Average network distance reflects the degree of separation among nodes in the network. It gradually decreases, indicating that the connection between entities is getting closer and closer, and the node which is more separated from others is filtered. Similarly, its decreasing trend also slows down after the second transmission. Clustering coefficient shows the effect of the so-called “small world” with average network distance together, so that they can display some overall signs of clustering or clumping of nodes. Compared with the ER network without transmission, each entity in the ER network tends to form a relatively higher cohesive clustering after transmission, but the times of transmission have little effect on the clustering coefficient.

Through the comprehensive analysis of various network attributes at different times of relation transmission, it is found that the ER network with the second transmission has the more obvious characteristics of tighter entity connection, refined module division, and higher cohesive clustering. At the same time, it does not weaken the effects of relation transmission. Therefore, it is more suitable for the study of MSW-NIMBY crisis. It can be directly used for analyzing the ER network structure and mining the potential information.

TABLE 6: ER network attributes with different times' transmission.

| Network attributes | The original | First transmission | Second transmission | Third transmission |
|--------------------------|--------------|--------------------|---------------------|--------------------|
| Nodes | 1954 | 735 | 479 | 415 |
| Edges | 1660 | 3875 | 4453 | 5515 |
| Average degree | 0.849 | 5.272 | 9.296 | 13.289 |
| Average weighted degree | 0.952 | 19.427 | 95.591 | 755.077 |
| Diameter | 7 | 4 | 3 | 2 |
| Graph density | 0 | 0.007 | 0.019 | 0.032 |
| Modularity index | 0.884 | 0.625 | 0.452 | 0.192 |
| Average network distance | 0.003 | 0.277 | 0.268 | 0.226 |
| Clustering coefficient | 2.807 | 1.712 | 1.5 | 1.46 |

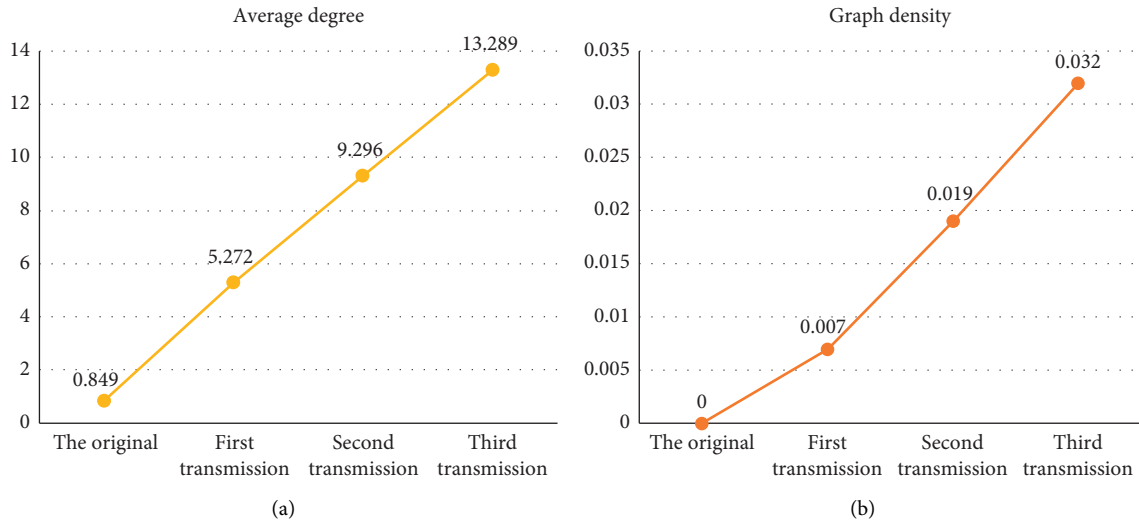


FIGURE 5: The changes in (a) average degree and (b) graph density of ER network.

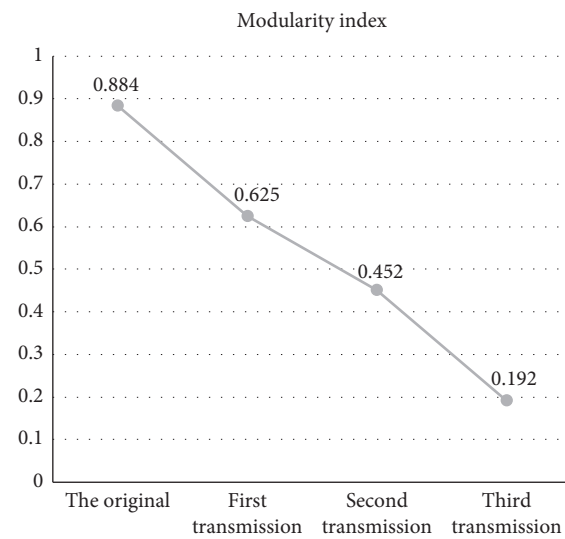


FIGURE 6: The changes in the modularity index of ER network.

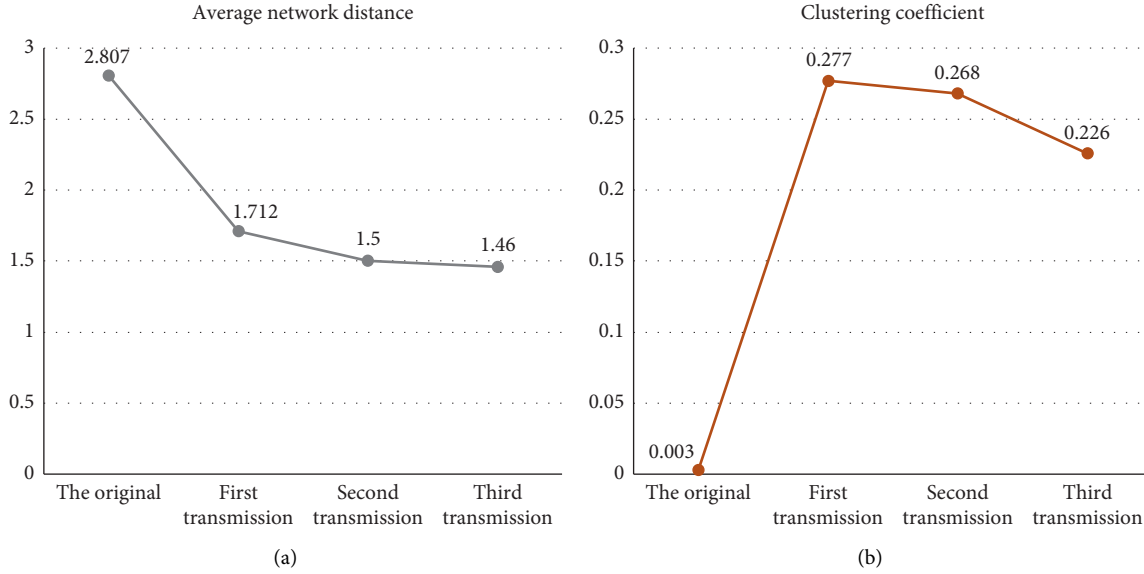


FIGURE 7: The changes in (a) average network distance and (b) clustering coefficient in the ER network.

5. Results and Discussion

The ER network with the second relation transmission is applied to analysis and mining information on detailed by the method of SNA, from the macro- and microlevels. It might be useful to reveal some general findings that provide knowledge of the MSW-NIMBY research field.

5.1. Macro Level of ER Network Analysis. Compared with the original ER network, the ER network with the second relation transmission is analyzed from the macro level of the ER network. It displays the optimization effects of the transitive relation model in text information extraction more intuitively.

There are two ER networks with the original and second transmission. Size of nodes set up by node degrees, color of nodes divided by different modules, and colors of edges depend on its connected nodes color. Then, the network structures of nontransmission and the second transmission are displayed in the layout of Fruchterman and Reingold [79], with greater symmetry and local aggregation. The comparison of these two networks is displayed in Figure 8.

From the macro level of view, ER network without transmission is too scattered under the same parameter settings and layout algorithms. According to statistics, it is divided into 442 communities. Even if the modularity index reaches 0.88, the clustering coefficient is only 0.03 because the modular structure has not been formed with too many small communities. Besides, the sizes of nodes are overall too small to judge the importance of different entities. There is a lot of interference of useless information in the analysis of the overall network structure, which results in difficulty in grasping the key point.

On the contrary, the modularity of the ER network with the second transmission is relatively clear, and it is divided into 9 communities. The main communities and entities are

more obvious than before transmission, even though the total number of entities in some communities is small. Therefore, under the same settings for the ER network, the key information mentioned in literature is more prominent with high cohesion and low coupling, and it is easier to research related issues by using the ER network.

5.2. Micro Level of ER Network Analysis. From the micro level of view, ER network analysis and knowledge mining can be implemented from multiple aspects, under the second relation transmission. The modularity and betweenness centrality of the ER network are selected to acquire knowledge, including general countermeasures of the MSW-NIMBY crisis proposed by experts, as well as research focus and general ideas.

5.2.1. ER Network Analysis with Modularity. For the ER network with the second relation transmission, the modularity is clear with the distinct color, and one community of network is selected for in-depth analysis to study one aspect of the complex problem.

Although the entities were filtered and unified during ER extraction, the result presented in the visualization still is slightly defective due to the subjectivity and incompleteness of manual annotation. In order to analyze local network better, the more obvious unfiltered and useless information is deleted manually, and nodes with similar meanings are merged. At last, there are 466 nodes and 2742 edges remaining in the network with the second relation transmission. Also, displayed under the same settings and layout as above, only one community of this ER network is displayed to grasp the key information of one aspect, which contains a total of 26 nodes (5.53% visible) and 70 edges (2.55% visible). Displaying the labels of its nodes in English, one community of ER network with the second transmission is shown in Figure 9.

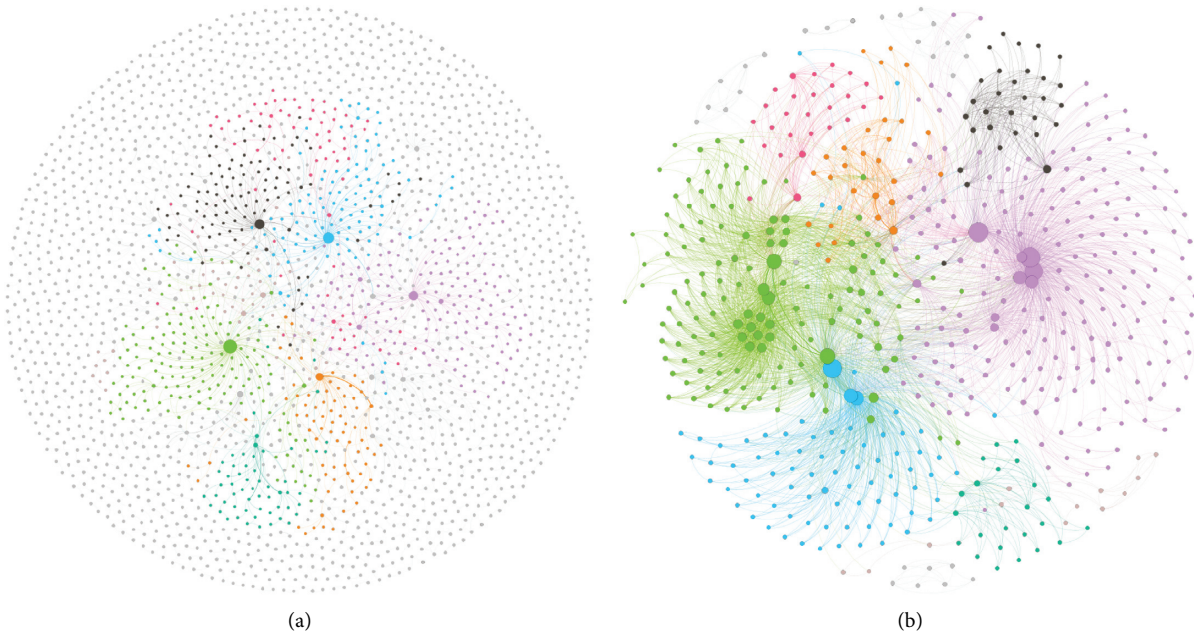


FIGURE 8: The comparison of (a) the ER network without transmission and (b) the ER network with the second transmission.

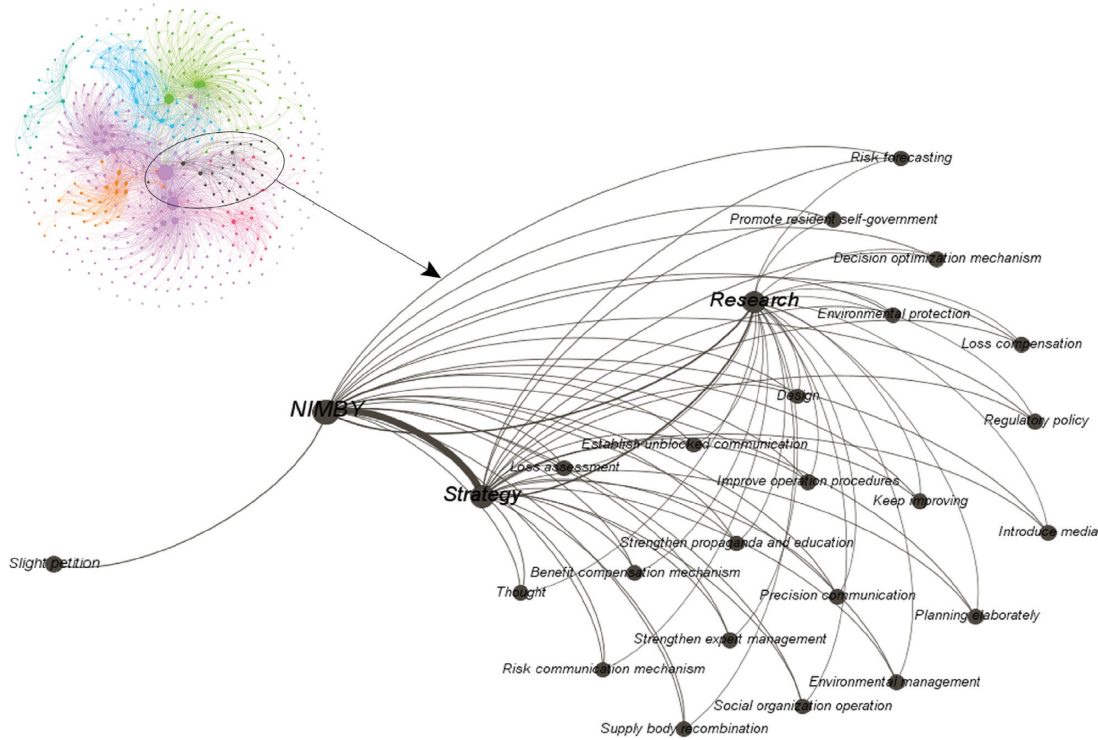


FIGURE 9: One community of ER network with the second transmission.

The labels of the largest nodes in this community are “NIMBY,” “Research” and “Strategy,” and other nodes that almost point out measures and suggestions. Obviously, from this community, the common and general strategies and suggestions on the MSW-NIMBY crisis can be acquired from the existing research results as follows:

- (i) Expert management could help improve operation procedures, risk forecasting, and ensure loss assessment in environment governance.
- (ii) Diverse decision optimizations like introducing media and regulatory policies should be applied in the supervision system.

TABLE 7: Top 20 betweenness centrality and frequency of nodes.

| Number | High betweenness centrality | | High frequency | |
|--------|-----------------------------|------------------------|------------------|-----------|
| | Node | Betweenness centrality | Node | Frequency |
| 1 | Public | 6079.9 | Public | 8009 |
| 2 | Local government | 2199.3 | Subject | 3539 |
| 3 | Benefit | 1474.0 | Environment | 1227 |
| 4 | NIMBY facilities | 525.0 | NIMBY conflict | 821 |
| 5 | Subject | 344.4 | Conflict | 732 |
| 6 | Waste | 146.7 | Project | 731 |
| 7 | NIMBY conflict | 146.6 | Local government | 715 |
| 8 | NIMBY | 145.3 | Government | 582 |
| 9 | Environment | 132.9 | Society | 437 |
| 10 | Project | 92.9 | Externality | 391 |
| 11 | Institution | 76.7 | Waste | 362 |
| 12 | Government | 60.0 | Institution | 349 |
| 13 | Conversation | 54.7 | Conflict event | 332 |
| 14 | Conflict | 48.4 | Participation | 259 |
| 15 | Countermeasure | 42.2 | City | 236 |
| 16 | Assessment | 42.0 | Inhabitants | 202 |
| 17 | Research | 28.8 | Source | 192 |
| 18 | Participation | 24.7 | Supply model | 192 |
| 19 | Inhabitants | 17.2 | Region | 190 |
| 20 | Expert | 12.8 | Dilemma | 186 |

- (iii) Necessary mechanisms of benefit compensation, risk communication and loss compensation, strengthening education, establishing unblocked communication channel, and self-organizing rules for residents could enhance the guarantee for residents' rights and interests.

The above results show that the filed focus mainly includes the perspectives of environment, supervision, and residents' rights and interests for the strategies on the MSW-NIMBY crisis.

These are the major parts mentioned in the existing articles on countermeasures of the MSW-NIMBY crisis. In addition, the node of "slight petition" is far away from other nodes of the network in location, and it also seems out of place in content. From the perspective of the network structure, this node penetrates into the area where the orange group is located in Figure 9. Most information of nodes in this area has some focus and reflections of public institutions on NIMBY events. It can be seen the petition incident relates to public institutions closely in general, such as the Ministry of Ecology and Environment, the National Environmental Protection Agency, because people often petition these institutions to meet their requirements. The petition incident is also one of the research points of scholars on the MSW-NIMBY crisis governance, so it still belongs to the community of strategies and suggestions.

5.2.2. ER Network Analysis with Betweenness Centrality.

The micro level of ER network analysis can reveal the characteristic of each node and acquire more valuable information, such as the betweenness centrality of the node, which means that if a node is traversed by many shortest paths, the node is very central in the network [80]. These entities of ER network are the key points in the existing research, which not only play significant roles in connecting

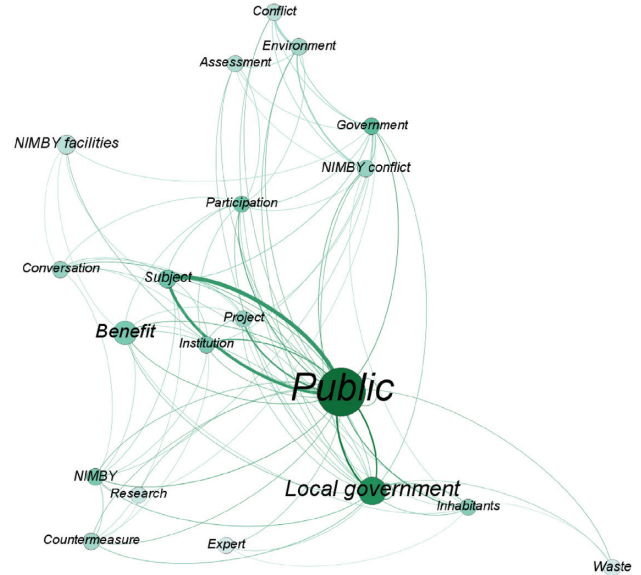


FIGURE 10: Top 20 betweenness centrality of nodes in the ER network.

other entities closely but also reflect most characteristics and phenomena on the MSW-NIMBY crisis.

The principle of relation transmission is to establish relationship through the same entity. So, the betweenness centrality of these entities is bound to become larger, and play a central role in the network with relation transmission. In the ER network of the MSW-NIMBY crisis with the second transmission, the betweenness centrality has a large distribution of values, and the highest 20 nodes are enough to analyze the focus. The Top 20 betweenness centrality and frequency of nodes (see Table 7) are highly overlapped, indicating that these key nodes are current hot topics in the research on MSW-NIMBY in China. The size of the node

represents betweenness centrality and the depth of color represents the frequency of entity, to construct an ER network. These two indicators can more intuitively present the information of the ER network as shown in Figure 10.

The statistical data and ER network show that the key point to constructing transitive relations in the study of MSW-NIMBY crisis is not only its keywords, such as “waste,” “NIMBY,” and “research,” but also mostly all kinds of subjects, including public or inhabitants, government or local government, institution, etc. Most experts prefer to explore the inherent characteristic and evolution of this complex problem from the perspective of different subjects. Most of the research on the NIMBY crisis has formed the general logic. Based on analyzing the causes of the problems, related to conflicts, benefit, environment, etc., the countermeasures for crisis governance were proposed. It includes assessment NIMBY projects and facilities for environmental concerns, clearing the channels of conversation between multiple subjects, guaranteeing the people’s participation right, and so on.

6. Conclusions

From different perspectives and concerns, more knowledge can be acquired from the ER network. It covers the theoretical research results for the MSW-NIMBY crisis, which is of great significance to a certain extent. The following findings can reflect the realities in MSW management along with urbanization:

- (i) From the perspective of scholars, the importance of “Public” in the influence of NIMBY is consistent universally, while the role of experts is erratic. The public’s awareness lacks professional guidance, so there will be high voices and too intense behavior from the public. As a result, the close connection between the public and government has become a kind of confrontation. For example, government would intitle waste incineration plants with obscure words, such as “Green energy.”
- (ii) From the perspective of the public, the activities of “Conversation,” “Participation,” and “Assessment” are too far away from each other, especially multi-agent associations are rarer. Therefore, the power of the public cannot be met effectively, the organization is broken up easily, and the sustainability of the public organization is challenged extremely. For example, there is no doubt that most of the protests organized voluntarily by the public come to an end easily.
- (iii) From the perspective of correlation, “Benefit” has been shelved. In fact, the NIMBY conflict is the result of unbalanced distribution of benefits and damages. However, the NIMBY event triggers other social conflicts and historical issues easily, but it weakens the initial interest disputes of the NIMBY issue. This also explains why “Benefit” is not the most critical link point between the government and public.

Furthermore, we can think at the present stage, the government has adopted a more flexible approach for the NIMBY, and the public organization still cannot develop continuously under the existing system. The evolution of the NIMBY event can produce derivative hazards and enlarge the scope of influence easily. Therefore, there is still a long way for transformation cities of deliberative democracy and open decision-making in the future.

The result shows that the developed methods of rule-based information extraction are universal and could be applied to manage the knowledge of other research fields, especially the fields of political sensitivity or speciality. In addition, the information-mining techniques with transitivity-enhanced ER expression overcomes the obstacles of complex semantics and sparse corpus, which help researchers have a comprehensive understanding about the hidden knowledge in a large amount of scientific literature. By this method, it can provide more information for decision-makers based on the limited data and make full use of it. Remarkably, the research focus and framework of scholars on the MSW-NIMBY crisis are obtained, as well as the countermeasures and management of crisis governance in existing research are integrated.

At present, there are few studies on the NIMBY crisis governance by information extraction, and the research on such issues with political sensitivity has not formed a complete method system. Although we introduce transitivity to mine information effectively, there are still challenges with heavy workload and strong subjectivity to extract valuable information from many scientific literatures, because of the numerous existing research results and their continuous growth. Accordingly, the future work should involve improving the efficiency and accuracy of information extraction from text, in order for mining and integrating existing research results better to acquire knowledge. Furthermore, it can continue to mine information in the ER network based on the more and newer research literatures, and further provide theoretical basis for the NIMBY crisis governance in MSW.

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 reported in this paper.

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Research Article

Energy Investment Potential and Strategic Layout in Countries along the “Belt and Road” Based on Principal Component Analysis

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It is important for energy enterprises to research on the investment potential of the energy markets in countries along the “Belt and Road,” which can help them optimize the regional investment structure, reduce investment risks, and conform to the development trend of “going global.” Therefore, we construct an investment potential assessment system of 29 indexes including five dimensions: politics, economy, society, energy, and cooperation and assess energy investment potential of 48 sample countries along the “Belt and Road” using principal component analysis to provide reference meanings for energy enterprises. The results show that the assessment results of investment potential are affected by a combination of multiple indexes. In addition, compared with Central Asia and South Asia, which have weak economic foundations and greater political and legal risks, the investment potential of Central and Eastern Europe and some emerging economies in Southeast Asia is higher.

1. Introduction

With the deepening implementation of the Belt and Road Initiative (BRI), China has made substantial investment in energy projects in BRI regions [1]. Many Chinese energy enterprises such as State Grid Corporation, China Southern Power Grid Corporation, and Power Construction Corporation have made direct investments in BRI countries by controlling interest and constructing greenfield projects. According to statistics from China Global Investment Tracker compiled by American Enterprise Institute, China invested 39.7 billion in the energy industry of countries along the “Belt and Road” in 2019, accounting for 38.36% of the total investment. Furthermore, direct investment in energy projects has long been regarded as one of the most complex international corporate activities. On the one hand, energy projects with long cycle, high cost, and wide influence range are extremely susceptible to many factors such as the host country’s political environment and social environment. On

the other hand, because of the different national conditions in different BRI countries, it is difficult to access their investment prospects. In contrast to the importance and complexity of energy investment, there are still few articles on the analysis of investment prospects in the energy market. Therefore, before outward direct investment in BRI countries, energy enterprises’ major task is to analyse the investment potential of each country to prevent investment risks, increase investment returns, and achieve regional economic planning [2, 3]. In addition, the assessment of the investment potential of BRI countries is helpful for energy enterprises to sort out the location factors of the investment market, clarify target investment markets, and cope with the complex and volatile international environment, thereby exploiting international markets and enhancing international competitiveness.

The Belt and Road Initiative aims to promote the connectivity of Asian, European, and African continents and their adjacent seas, establish and strengthen partnerships among the countries along the Belt and Road, set up all-dimensional,

multitiered, and composite connectivity networks, and realize diversified, independent, balanced, and sustainable development in these countries [4]. And, the roadmap of the Belt and Road Initiative is shown in Figure 1. BRI had already excited wide attention and became a research hotspot since the initiative was advocated in 2013 [5]. Wang confirms that China's investment cooperation with countries along the Belt and Road region had been growing amid the global economic downturn [6]. Adopting institutional theory, Chen et al. examined the effect of bilateral diplomatic activities, institutional distance, and common land borders on the selection of transport infrastructure locations [7]. Li et al. have found that technique and structural effects of China's investment have positive impact on cumulative CO₂ emission reduction of B&R region, while the scale effect has the negative contribution [8]. Ahmad et al. found that foreign investment has two contradictory effects on the environmental quality of BRI countries: energy consumption and urbanization process pollute the environment, while trade openness improves environmental quality [9]. In fact, there are relatively few studies on energy investment compared to transport infrastructure and environmental impact assessment. Based on the above analysis, we create an assessment model of energy investment potential about BRI countries.

Direct investment in energy projects is a complex international corporate activity, which is concerned with multifaced factors including politics, economy, and society [10–13]. Therefore, the key to assess energy investment potential is to establish a scientific, comprehensive, and multidimensional system of assessment [14]. The Worldwide Governance Indicators (WGI) developed by the World Bank is one of the comprehensive indicators with great influence, high rigor, and wide usage in many current quantitative research studies on governance [15], which is often used to evaluate the effect of the political environment on investment. By comparing 49 countries along BRI with 43 countries in other regions, Buckley et al. found that China's direct investment in BRI countries is highly sensitive to exchange rate level, market potential, openness, and infrastructure facilities of host countries [16]. Fedderke and Romm divided the factors that determine foreign direct investment into policy factors and nonpolicy factors. Nonpolicy factors include market size and political and economic stability, and policy factors include openness, product-market regulation, labour market arrangements, corporate tax rates, and infrastructure [17]. The study by Fan et al. indicates that China's direct investment positively correlates with nature resource endowment of host countries [18]. Wu and Hu presented that the cooperative relationship between host countries and China has influence on investment location selection [14]. In this paper, after analysing the above indexes, we create an investment potential assessment system of 29 indexes including five dimensions: politics, economy, society, energy, and cooperation.

At present, main methods of investment environment evaluation includes stochastic frontier gravity model, network analytic hierarchy process, and principal component analysis. [19]. Armstrong introduced the stochastic frontier into the gravity model, which has a good explanatory power for international investment activities [20]. Song and Zhou

used the stochastic frontier gravity model to analyse the efficiency of trade between Chinese provinces and Pakistan from 2010 to 2018 [21]. Zhao and Jia used the stochastic frontier analysis method to verify that China's import trade is related to the economic scale, population, geographical distance, and border situation of BRI countries [22]. Jiang used network analysis to compare Sudan, Iran, Iraq, and Venezuela from five dimensions: politics, economy, infrastructure, social culture, and physical geography [23]. In his study, Zhang analysed the investment facilitation level of 50 Asian, European, and African countries along the "Belt and Road" based on principal component analysis [24]. Qi and Ren used principal component analysis to study the impact of the host country's development level of digital economy on the location and scale of China's investment in the Belt and Road countries [25]. Fan et al. constructed an indicator system from the four dimensions of port efficiency, customs' environment, regulatory environment, and financial e-commerce and used principal component analysis to evaluate the trade facilitation level of the Belt and Road countries [26]. However, the stochastic frontier gravity model has weak theoretical foundations [18], and when setting inefficiency elements, due to human differences or omission of important factors, the investment potential under different indicators may vary greatly [14]. In other words, this method has defects in robustness and accuracy. Considering the complexity of the comprehensive index assessment system in this paper, principal component analysis is chosen to analyse investment potential.

Based on the above analysis, we focus on the assessment of energy investment potential and create an investment potential assessment system of 29 indexes including five dimensions: politics, economy, society, energy, and cooperation at first. Then, we assess energy investment potential of 48 sample countries using principal component analysis. Finally, we divide BRI countries into 8 major groups as Mongolia, Russia, Southeast Asia, CIS, South Asia, West Asia, North Africa, Central and Eastern Europe, and Central Asia and put forward the strategic layout to provide reference meanings for energy enterprises.

The rest of this paper is structured as follows. In Section 2, an assessment model of energy investment potential about BRI countries is created, which consists of indexes, samples, and method. In Section 3, assessment results of 48 sample countries using principal component analysis are illustrated based on data obtained from World Bank and International Labour Organization. In Section 4, the strategic layout is proposed based on assessment results. And, corresponding conclusions and advise are put forward in Section 5.

2. Assessment Model Design

2.1. Model Frame Design. The paper quantitatively analyses the investment potential of energy markets in countries along the "Belt and Road" using principal component analysis. The assessment model mainly includes three important parts: index analysis module, sample analysis module, and method design module [27, 28], as shown in Figure 2. First, it is vital to adopt a scientific and comprehensive assessment system for the

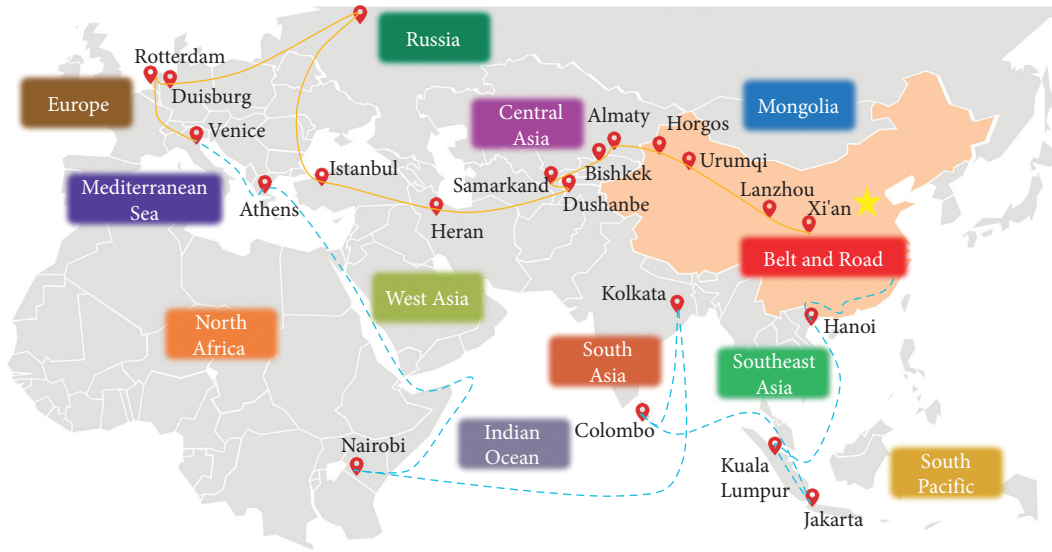


FIGURE 1: The Belt and Road Initiative roadmap.

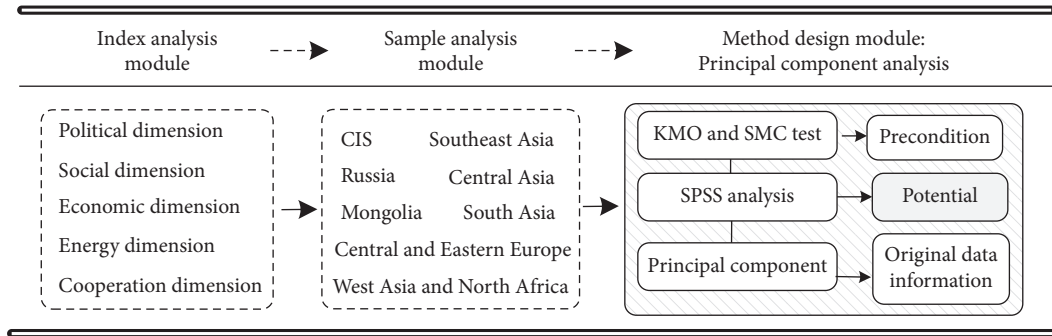


FIGURE 2: Model frame.

reliability of results [29, 30]; therefore, the factors affecting the energy investment in BRI countries are classified and sorted out in the index analysis module. After that, the list and number of sample countries to be analysed are finally determined based on the official data integrity in the sample analysis module. Finally, principal component analysis is used to cope with the data, and 48 sample countries are ranked according to the assessment results in the method design module.

2.2. Index Analysis. China's energy investment potential in BRI countries is affected by many factors such as the host country's political environment, social environment, economic environment, energy environment, and cooperative relationship between the host country and China [31]. Political factors refer to indexes that measure the efficiency of government work, such as the quality of handling national issues and supervision and the effectiveness of maintaining political stability and legal construction. Energy projects require various government licenses, so political factors have a major impact on energy investment. Social factors refer to indexes that affect the investment potential due to the social conditions of the host country, including social stability, employment levels, and many other aspects. Energy companies need to coordinate various social relations in the host

country, including local labour and various organizations. The host society's recognition degree of Chinese investment has a huge impact on the investment potential. Economic factors are indexes to measure the long-term stability of the host country's investment environment. Countries with a better economic environment have lower investment risks, which in turn lead to relatively higher investment profitability and security and higher investment potential. Energy factors refer to indexes such as energy resource endowment and energy cooperation with China, which measure the development prospects of the host countries' energy field and the energy cooperation potential with China. The richer the host country's energy reserves, the easier it is to attract foreign investment. The cooperative relationships between host countries and China reflect their closeness of trade and investment. The friendlier the relationships between the host countries and China, the higher the possibility of China's investment in them. The meanings and sources of 29 indexes from the above 5 dimensions are shown in Table 1.

2.3. Sample Analysis. This paper refers to the standard of classification for BRI countries in the Political Risk Assessment Report on "Belt and Road" Energy Resources Investment compiled by National Academy of Development and Strategy

TABLE 1: Description of indexes.

| Dimension | Index system | Index description | Data source |
|-------------|---------------------------------------|---|---------------------------------|
| Politics | Control of corruption | Reflects perceptions of the extent to which public power is exercised for private gain | WGI ¹ |
| | Government effectiveness | Reflects perceptions of the quality of public services, the quality of the civil service, the degree of its independence from political pressures, and the quality of policy formulation and implementation | WGI |
| | Political stability | Measures perceptions of the likelihood of political instability and/or politically-motivated violence | WGI |
| | Regulatory quality | Reflects perceptions of the ability of the government to formulate and implement sound policies and regulations that permit and promote private sector development | WGI |
| | Rule of law | Reflects perceptions of the extent to which agents have confidence in and abide by the rules of society | WGI |
| | Voice and accountability | Reflects perceptions of the extent to which a country's citizens are able to participate in selecting their government, as well as freedom of expression, freedom of association, and a free media | WGI |
| Society | Investment freedom | 1–100 points, the higher the score, the higher the investment freedom | ITC ² |
| | Trade freedom | 1–100 points, the higher the score, the higher the trade freedom | ITC |
| | Labour freedom | 1–100 points, the higher the score, the higher the labour freedom | IEF ³ |
| | Total labour force | Total labour force of the host country | ILO ⁴ |
| | Unemployment rate | Total unemployment/total population | WDI ⁵ |
| Economics | Electricity consumption | Electricity consumption level in host countries | CE ⁶ |
| | Electricity consumption per capita | Electricity consumption per in host countries | CE |
| | Electricity rate | Development level of electricity infrastructure in host countries | GCR ⁷ |
| | Average GDP growth rate | Average GDP growth rate in the past three years | WDI |
| | Industry's share of GDP | Gross industrial output value/GDP | WDI |
| | Investment openness | Inflow of investment/GDP | WDI |
| | Trade openness | (Total export + total import)/GDP | ITC |
| | Ease of doing business | 0–100 points, the higher the score, the better the business environment | Doing business |
| Energy | Energy resource endowment | Reserves of crude oil, natural gas, and coal | EIA ⁸ |
| | Attention degree of energy investment | China's energy investment/China's total investment | China Global Investment Tracker |
| Cooperation | Export dependence | Total export from China/total export | ITC |
| | Import dependence | Total import from China/total import | ITC |
| | Investment dependence | China's direct investment to the host country | China Global Investment Tracker |
| | Degree of nonperforming investment | Nonperforming investment/total import | |

¹Worldwide Governance Indicators, ²International Trade Centre (Trade Map), ³Index of Economic Freedom, ⁴International Labour Organization, ⁵World Development Indicator, ⁶Country Economy, ⁷Global Competitive Report, and ⁸Energy Information Administration of United States.

and concludes the strategic layout after dividing 64 BRI countries into 8 major groups: Mongolia, Russia, Southeast Asia, CIS, South Asia, West Asia, North Africa, Central and Eastern Europe, and Central Asia (as shown in Table 2). 16 countries (marked with ☆ in Table 2) including Brunei, Iraq, and Syria have serious data missing problems due to wars and economic backwardness, so principal component analysis is used to evaluate the investment potential of other 48 countries after removing the above 16 countries.

2.4. Method Design. The comprehensive index system constructed in this paper is complex and contains many variables. It is very important to choose a suitable assess method [32–34]. The principal component analysis method

can eliminate the correlation between variables and reduce the workload of calculation. In addition, the variance contribution rate of each principal component is determined according to the variance, which is relatively objective due to the elimination of human influence. Therefore, the principal component comprehensive assessment method is finally selected to analyse the investment potential. Principal component analysis is mainly used for data dimensionality reduction, and its basic thought is to maximize the projection variance of the dataset as much as possible, while reducing the dimensionality of the dataset. The data is orthogonally transformed to achieve the purpose of not only retaining most of the original data information but also removing the redundant information of the data, which is for data analysis and comparison.

TABLE 2: BRI countries.

| Number | Regions | Countries |
|--------|---------------------------------|---|
| 1 | Mongolia | Mongolia |
| 2 | Russia | Russia |
| 3 | Southeast Asia (11) | Indonesia, Thailand, Malaysia, Vietnam, Singapore, Laos, Philippines, Cambodia, Myanmar ^{0072*} , Brunei [*] , and East Timor [*] |
| 4 | CIS (6) | Ukraine, Belarus, Georgia, Azerbaijan, Armenia, and Moldova |
| 5 | South Asia (8) | India, Pakistan, Bangladesh, Sri Lanka, Nepal, Afghanistan [*] , Maldives [*] , and Bhutan [*] |
| 6 | West Asia and North Africa (16) | Saudi Arabia, Oman, Iran, Turkey, Israel, Egypt, Kuwait, Qatar, Jordan, Lebanon, Bahrain, Iraq [*] , Yemen Republic [*] , Syria [*] , The United Arab Emirates [*] , and Palestine [*] |
| 7 | Central and Eastern Europe (16) | Poland, Romania, Czech Republic, Slovakia, Bulgaria, Hungary, Latvia, Lithuania, Slovenia, Estonia, Croatia, Albania, Serbia, Macedonia [*] , Bosnia and Herzegovina [*] , and Montenegro [*] |
| 8 | Central Asia (5) | Kazakhstan, Kyrgyzstan, Tajikistan, Uzbekistan [*] , and Turkmenistan [*] |

In order to analyse and evaluate the investment potential index system of 48 BRI countries, this paper chooses principal component analysis to reduce the data dimension, calculates the synthesis score of each sample, and then rank and compare the samples. The basic steps of principal component analysis are as follows:

- (1) Construct a data matrix of 48×29 . The assessment model contains 48 samples, and each sample contains 29 indexes, so the paper constructs a data matrix $X = (x_{i,j})_{48 \times 29}$:

$$X = \begin{cases} x_{1,1}, x_{1,2} \dots x_{1,29}, \\ \dots \dots \dots \\ x_{48,1}, x_{48,2} \dots x_{48,29}. \end{cases} \quad (1)$$

- (2) Make dimensionless and standardized processing. In order to eliminate the influence of dimension and order of magnitude between indexes, the paper makes dimensionless and standardized processing of the data and obtains the matrix $Y = (y_{i,j})_{48 \times 29}$.
- (3) Construct the correlation coefficient matrix. The correlation coefficient reflects the correlation relation between standardized data:

$$R = \begin{cases} r_{1,1}, r_{1,2} \dots r_{1,29}, \\ \dots \dots \dots \\ r_{48,1}, r_{48,2} \dots r_{48,29}, \end{cases} \quad (2)$$

where $r_{i,j}$ represents the correlation coefficient between the index i and index j . And, its calculation formula is as follows:

$$r_{i,j} = \frac{\sum_{k=1}^{48} (y_{k,i} - \bar{y}_i)(y_{k,j} - \bar{y}_j)}{\sqrt{\sum_{k=1}^{48} (y_{k,i} - \bar{y}_i)^2 \sum_{k=1}^{48} (y_{k,j} - \bar{y}_j)^2}} \quad (3)$$

- (4) Calculate eigenvalues and eigenvectors of the correlation coefficient matrix. The paper obtains eigenvalue λ_i ($i = 1, 2, \dots, 29$) according to the characteristic equation $|R - \lambda E| = 0$ and then gets the eigenvectors based on the equation $R\mu_i = \lambda_i\mu_i$.
- (5) Select principal components. This paper sorts the principal components F_1, F_2, \dots, F_{48} according to the

value of eigenvalues and then calculates variance contribution rate and cumulative variance contribution rate of each principal component. The top p principal components with a cumulative contribution rate greater than 80% are selected to ensure that they can basically express the information in the original data:

$$\begin{cases} F_1 = \mu_{1,1}y_1 + \mu_{1,2}y_2 + \dots + \mu_{1,29}y_{29}, \\ \dots \dots \dots \\ F_{48} = \mu_{48,1}y_1 + \mu_{48,2}y_2 + \dots + \mu_{48,29}y_{29}, \end{cases} \quad (4)$$

where the variance contribution rate of the i th principal component can be expressed as $\alpha_i = \lambda_i / \sum_{i=1}^p \lambda_i$ and variance contribution rate can be expressed as $G(k) = \sum_{i=1}^k \lambda_i / \sum_{i=1}^p \lambda_i$.

- (6) Calculate the synthesis score.

3. Result Analysis and Strategic Layout

Before the principal component analysis, the paper first conducts the KMO test and SMC test on the investment potential index system to verify the correlation between the 29 subindicators and judge whether the data is suitable for this method. The higher the value of the KMO test and SMC test, the stronger the linear relationship and commonality between the subindicators and the more reliable the results of principal component analysis. Generally speaking, only when the KMO test result is greater than 0.5 and the SMC test result is less than 0.05, the index system is suitable for principal component analysis. It can be seen from Table 3 that the results of principal component analysis based on the investment potential index system of BRI countries are meaningful.

The paper uses SPSS 23.0 to process data from countries along the "Belt and Road." As shown in Table 4, the cumulative variance contribution rate of the first nine principal components is as high as 81.134%. In other words, the first nine principal components obtained after principal component analysis can express more than 80% of the original information which can then accurately evaluate the investment potential of the host country. The paper uses the range method to standardize the results of the principal

TABLE 3: Results of the KMO and SMC test.

| | | |
|----------------------------------|-------------------|----------|
| KMO measure of sampling adequacy | | 0.577 |
| | Chi-square | 1150.232 |
| Bartlett test of sphericity | Degree of freedom | 406 |
| | Significance | 0.000 |

TABLE 4: Variance contribution rate and cumulative variance contribution rate of principal components.

| Component number | Eigenvalue | Variance contribution rate | Cumulative |
|------------------|------------|----------------------------|------------|
| 1 | 7.608 | 26.234 | 26.234 |
| 2 | 3.534 | 12.186 | 38.421 |
| 3 | 2.919 | 10.066 | 48.486 |
| 4 | 2.688 | 9.268 | 57.754 |
| 5 | 2.301 | 7.936 | 65.690 |
| 6 | 1.398 | 4.821 | 70.511 |
| 7 | 1.228 | 4.234 | 74.745 |
| 8 | 0.970 | 3.346 | 78.091 |
| 9 | 0.883 | 3.044 | 81.134 |
| 10 | 0.780 | 2.690 | 83.824 |
| 11 | 0.736 | 2.537 | 86.361 |
| 12 | 0.660 | 2.275 | 88.636 |
| 13 | 0.527 | 1.818 | 90.454 |
| 14 | 0.458 | 1.580 | 92.034 |
| 15 | 0.419 | 1.445 | 93.479 |
| 16 | 0.365 | 1.258 | 94.737 |
| 17 | 0.285 | 0.982 | 95.719 |
| 18 | 0.278 | 0.960 | 96.679 |
| 19 | 0.203 | 0.701 | 97.380 |
| 20 | 0.181 | 0.625 | 98.006 |
| 21 | 0.154 | 0.532 | 98.538 |
| 22 | 0.125 | 0.431 | 98.969 |
| 23 | 0.091 | 0.315 | 99.284 |
| 24 | 0.059 | 0.205 | 99.489 |
| 25 | 0.057 | 0.195 | 99.685 |
| 26 | 0.042 | 0.144 | 99.829 |
| 27 | 0.027 | 0.092 | 99.921 |
| 28 | 0.016 | 0.057 | 99.978 |
| 29 | 0.006 | 0.022 | 100.000 |

component analysis, obtains the final evaluation results, and ranks the sample countries.

From the perspective of overall investment potential assessment results, there is an obvious difference in energy investment potential between 48 BRI countries: 12 countries' investment potential values are above 0.5, 15 countries' values are between 0.3 and 0.5, and 21 countries' values are below 0.3. Analysing Table 5, it can be found that Central and Eastern European countries and some Southeast Asian countries with great economic level are ranked higher in investment potential, and Central and South Asian countries with poor economic development and weak infrastructure are ranked lower.

From the perspective of regional evaluation results, the regions with the highest investment potential are Central and Eastern Europe, and the lowest are Central Asia and South Asia. The average value of investment potential in each region is shown in Figure 3. The stable political environment and perfect legal system in Central and Eastern Europe facilitate the inflow of foreign capital, so the

investment potential of countries in this region is generally high. In South Asia, India's high investment potential benefits from the vast energy market, and the generally low investment potential of other countries is caused by high political and legal risks. In Central Asia, Kazakhstan's higher investment potential is due to strategic resource factors. In Southeast Asia, the high investment potential of Singapore and Malaysia is mainly due to the large economy and high energy demand. The investment potential of West Asia and North Africa countries is generally in the middle.

4. Strategic Layout

Aiming at the investment potential evaluation results of 48 BRI countries, energy enterprises should tend to invest in countries with greater investment potential and reduce investment in countries with less investment potential to reduce nonperforming investment, increase the rate of return on funds, expand overseas markets, and enhance international competitiveness. The strategic layout is

TABLE 5: Ranking of BRI countries.

| Country | Score | Ranking |
|--------------|-------|---------|
| Singapore | 1.000 | 1 |
| Estonia | 0.731 | 2 |
| Czech | 0.662 | 3 |
| Slovenia | 0.652 | 4 |
| Slovakia | 0.622 | 5 |
| Latvia | 0.621 | 6 |
| Lithuania | 0.598 | 7 |
| Israel | 0.597 | 8 |
| Hungary | 0.593 | 9 |
| Malaysia | 0.570 | 10 |
| Georgia | 0.565 | 11 |
| Poland | 0.553 | 12 |
| India | 0.483 | 13 |
| Bahrain | 0.476 | 14 |
| Qatar | 0.467 | 15 |
| Oman | 0.459 | 16 |
| Croatia | 0.450 | 17 |
| Bulgaria | 0.447 | 18 |
| Romania | 0.421 | 19 |
| Kuwait | 0.415 | 20 |
| Russia | 0.384 | 21 |
| Jordan | 0.362 | 22 |
| Turkey | 0.358 | 23 |
| Serbia | 0.354 | 24 |
| Thailand | 0.335 | 25 |
| Albania | 0.317 | 26 |
| Armenia | 0.316 | 27 |
| Saudi Arabia | 0.293 | 28 |
| Vietnam | 0.260 | 29 |
| Sri Lanka | 0.255 | 30 |
| Kazakhstan | 0.244 | 31 |
| Moldova | 0.238 | 32 |
| Mongolia | 0.228 | 33 |
| Philippines | 0.224 | 34 |
| Indonesia | 0.210 | 35 |
| Kyrgyzstan | 0.178 | 36 |
| Egypt | 0.177 | 37 |
| Ukraine | 0.164 | 38 |
| Azerbaijan | 0.156 | 39 |
| Lebanon | 0.141 | 40 |
| Belarus | 0.126 | 41 |
| Nepal | 0.080 | 42 |
| Iran | 0.043 | 43 |
| Tajikistan | 0.026 | 44 |
| Cambodia | 0.010 | 45 |
| Pakistan | 0.009 | 46 |
| Laos | 0.009 | 47 |
| Bangladesh | 0.000 | 48 |

concluded after dividing 64 BRI countries into 8 major groups as Mongolia, Russia, Southeast Asia, CIS, South Asia, West Asia, North Africa, Central and Eastern Europe, and Central Asia in the following section.

4.1. Southeast Asia. In Southeast Asia, the investment potentials of 8 countries including Indonesia, Thailand, Malaysia, Vietnam, Singapore, Philippines, Myanmar, Cambodia, and Laos are assessed. Among the above-mentioned 8 countries, Singapore ranks first, Malaysia ranks

tenth, the other 6 countries are in the inferior position, and Laos ranks the worst at 47th. Compared with other Southeast Asian countries, Singapore and Malaysia's value of investment freedom, trade freedom, labour freedom, and trade openness are higher, but political risk is lower, which provides a powerful explanation for the evaluation results. From the aspect of Cambodia and Laos, the promotion of friendly relations with China has attracted a large amount of government capital inflow. However, these two countries have small territories, high political and legal risks, poor economic development, and low labour quality, which makes their future investment potentials small. Energy enterprises should formulate preventive measures in response to the above situations to avoid unnecessary losses.

4.2. Commonwealth of Independent States. The investment potentials of 6 CIS countries including Ukraine, Belarus, Georgia, Azerbaijan, Armenia, and Moldova are evaluated. Among the 6 countries, Georgia ranks the highest at 11th, and Ukraine, Azerbaijan, and Belarus rank the worst at 38th, 39th, and 41st, respectively. Like Singapore and Malaysia, Georgia's value of investment freedom, trade freedom, labour freedom, and trade openness are higher, but political risk is lower. In addition, Georgia has rich coal reserves. Russia's scores of corruption control, government effectiveness, political stability, regulatory quality, law rule, voice, and accountability are generally low, which shows that it has a high political risk. And, the high political risk is a major obstructive factor to capital inflows due to large-scale and irreversible characteristics of energy investment. Therefore, energy enterprises can first choose Georgia when they want to invest in the CIS countries.

4.3. South Asia. In South Asia, the investment potentials of 5 countries including India, Pakistan, Bangladesh, Sri Lanka, and Nepal are evaluated. Among them, India ranks the highest at 13th place, Sri Lanka ranks 30th, and the other three countries in the inferior position. The score of India's investment potential is close to 0.5, and the major indexes contributing much to it are market size, labour force, and coal reserves. However, due to the prevalence of "national protectionism" and the hindrance of the "national security investigation policy" in India [14], there is still greater uncertainty about whether energy enterprises can invest in India in the future. The indicators leading to the poor ranking of Pakistan, Bangladesh, and Nepal mainly include market size, investment freedom, trade freedom, labour freedom, and trade openness.

4.4. West Asia and North Africa. In West Asia and North Africa, the investment potentials of 11 countries including Saudi Arabia, Oman, Iran, Turkey, Israel, Egypt, Kuwait, Qatar, Jordan, Lebanon, and Bahrain are assessed. The investment potential scores of the countries in West Asia are relatively even; apart from Israel ranking 8th, most of which are ranked between 10 and 30. Therefore, energy companies can choose investment countries based on strategic needs. It

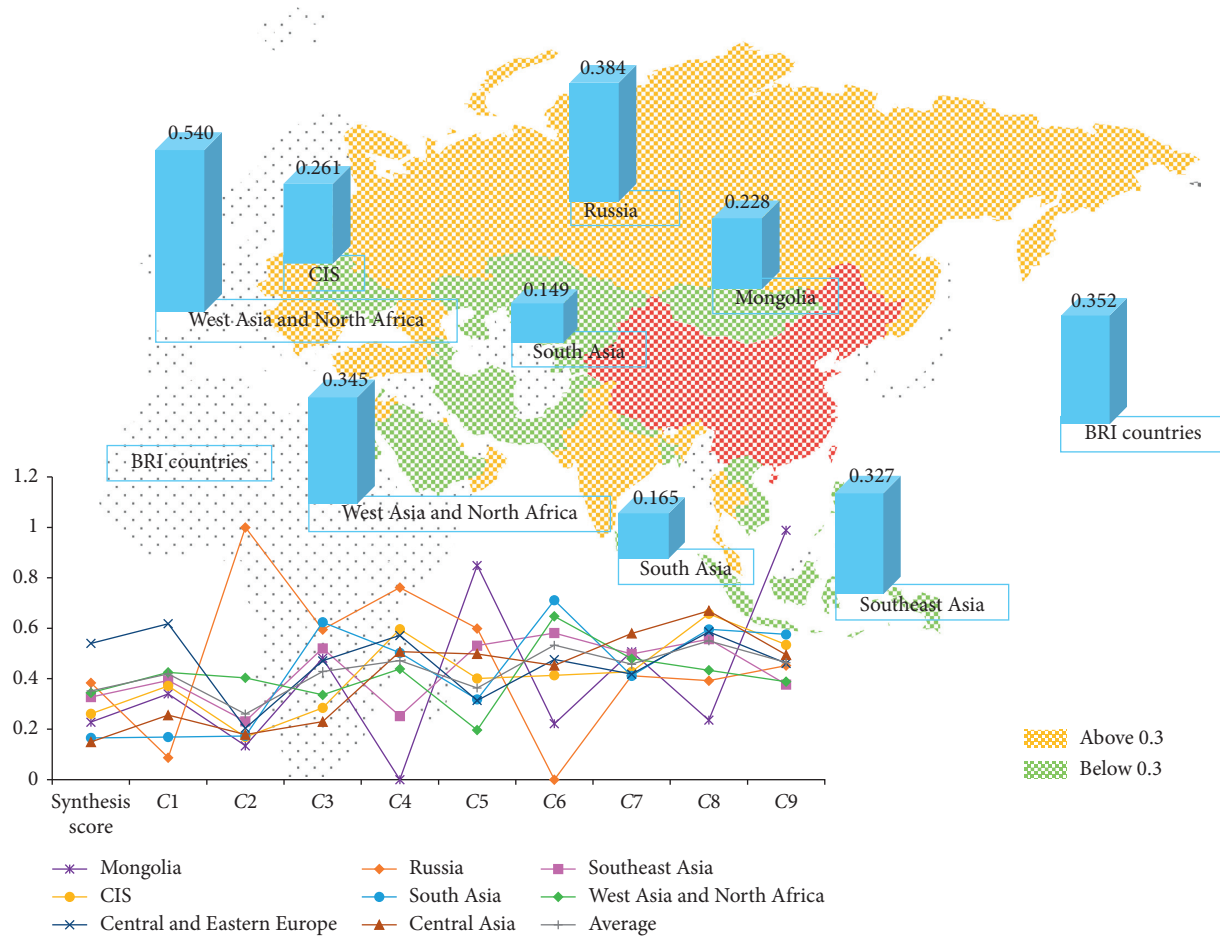


FIGURE 3: Regional assessment results of BRI.

should be noted that since West Asia and North Africa are important international oil-producing regions, trade competition and war risks are relatively high, and energy companies should formulate comprehensive risk control measures to ensure the efficiency of investment.

4.5. Central and Eastern Europe. In Central and Eastern Europe, the investment potentials of 13 countries including Poland, Romania, Czech Republic, Slovakia, Bulgaria, Hungary, Latvia, Lithuania, Slovenia, Estonia, Croatia, Albania, and Serbia are evaluated. Central and Eastern Europe is the region with the highest investment potential; except for Albania and Serbia, other countries are all ranked above the 20th. Central and Eastern European countries have the most complete political and legal systems and the highest degree of investment openness and trade freedom, which determine the much higher investment potential.

4.6. Central Asia. In Central Asia, the investment potentials of 3 countries including Kazakhstan, Kyrgyzstan, and Tajikistan are assessed due to serious data missing problems of Uzbekistan and Turkmenistan. And, the average investment potential scores of these three countries are poor, ranking 31st, 36th, and 44th, respectively. China and

countries in Central Asia are joined by common mountains and rivers, and the friendly relationship between them drives the inflow of Chinese capital. However, the future investment potentials of Central Asian countries are limited by their basic national conditions, such as low labour quality, poor economic level, and backward infrastructure.

4.7. Russia and Mongolia. Russia and Mongolia are, respectively, 21st and 33rd in the investment potential assessment results. They are both adjacent to China and have abundant reserves of natural resources. However, compared with Mongolia, Russia has a broader energy market and a lower degree of nonperforming investment, so Russia's investment potential is relatively high. In addition, the omnidirectional, multidomain, and multilevel strategic cooperation between Russia and China will drive Chinese capital to flow into Russia.

5. Summary

For one thing, we construct an investment potential assessment system of 29 indexes including five dimensions: politics, economy, society, energy, and cooperation in this paper and then assess energy investment potential of 48 sample countries along the "Belt and Road" using principal

component analysis. Finally, we propose the strategic layout, and we wish it can contribute reference to energy enterprises. Through empirical analysis, the following conclusions are concluded: (1) assessment results of investment potential are affected by a combination of multiple indexes, and different indexes contribute differently to assessment results. For example, political factors made more contribution to investment potential assessment results of Central and Eastern European countries, while economic factors made more contribution to India. (2) Energy investment potential measures the future investment value of the host country's energy field. By analysing the evaluation results, compared with Central Asia and South Asia which have weak economic foundations and greater political and legal risks, the investment potential of Central and Eastern Europe and some emerging economies in Southeast Asia is higher.

Aiming at the above conclusion, relevant suggestions are put forward in this section. First, before entering the overseas market, energy enterprises must actively conduct market research and have a full and thorough understanding of investment and financing projects. At the same time, it is also necessary to keep abreast of changes in the host country's policies and laws in order to effectively avoid overseas investment risks. Second, energy enterprises should clarify target investment markets, increase capital utilization, and focus on investing in countries with greater potential to avoid risky investment and reduce bad investment. Third, energy enterprises should improve the risk control system. It can be found that different countries along BRI face different risks by analysing the constructed assessment index system. Accordingly, energy enterprises should gradually establish risk database and formulate operable strategies of risk identification, risk analysis, risk evaluation, risk response, and risk supervision. Fourth, energy enterprises should actively broaden investment and financing channels. Energy projects have long investment cycles and high uncertainty; consequently, energy enterprises should flexibly use a variety of investment ways to improve the return on investment in accordance with the development stage and profitability of the project. Fifth, energy enterprises should choose investment strategies according to circumstances and conditions. Energy enterprises can choose various investment methods based on market characteristics and potential. For example, the investment method of obtaining partial equity is adopted in Central and Eastern Europe which has complete legal system and less cooperation with China, while the method of obtaining franchise rights is adopted in the emerging economies with broad market prospects and cooperation experience. Finally, energy enterprises must implement China's "Going Global" strategy, the "Belt and Road" initiative, and other policy recommendations. Energy enterprises should make full use of intergovernmental economic diplomacy, give full play to the advantages of China's power industry in financing and technology within the framework of diplomacy, and continuously expand the target market for China's power industry and technical standards.

Data Availability

The datasets generated and analysed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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Research Article

Development of a Territorial Planning Model of Wind and Photovoltaic Energy Plants for Self-Consumption as a Low Carbon Strategy

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Energy self-consumption is one of the strategies used for the optimization of renewable energy integration in electrical systems within a framework of sustainable energy policy development. Renewable energy self-consumption additionally contributes to the promotion of distributed generation. The aim of the present study is to develop a hybrid territorial planning model for the siting of areas suitable for the joint exploitation of wind and solar energy targeted principally at self-consumption. The methodology employed was based on the analytic hierarchy process (AHP) and geographical information systems (GIS), and the general area considered was the island of Gran Canaria (Spain). This island has an isolated electrical system. The case study involved locating areas close to populated settlements which are generally cut off from areas commonly marked out for large-scale wind and solar energy exploitation. The areas located with the model were differentiated according to the municipality they were in. The model that has been developed can be applied to any territory. The results obtained with the model can then be incorporated into territorial planning documents and/or national and regional and/or municipal files with the aim of optimizing the integration of renewable energy for self-consumption and advancing distributed electrical energy systems.

1. Introduction

Countries worldwide are becoming increasingly aware of the importance of renewable energy (RE) sources for their energy supply. Directive 2018/2001, on the promotion of the use of energy from renewable sources [1] and within a framework of a low-carbon energy transition (article 3.5 of Directive 2018/2011), established a series of strategic objectives in relation to the contribution of renewables to energy demand. The target set for the European Union (EU) as a whole was for renewable energies to meet 32% of energy demand by 2030. In addition, a series of short-term and 2030-based specific targets were set for the different EU member states (articles 3.4 and 3.2 of Directive 2018/2011). With respect to the particular case of the contribution of REs to meeting the electricity demand in the

framework of the EU, Directive 2018/2001 sets out, among others, the following strategic lines:

- (a) The large-scale generation of electrical energy from renewable sources is directly connected to the electrical power transmission networks
- (b) Energy self-consumption: this strategic line is new in the regulatory framework of the EU

Three distinct figures are considered with respect to the promotion of energy self-consumption: (1) renewables' self-consumer, (2) jointly acting renewables' self-consumers, and (3) renewable energy community (article 2, points 14–16, respectively, of Directive 2018/2001). In this regard, the aim is to promote not only self-consumption by individual or

small and medium enterprises (SMEs) but also the joint self-consumption of renewable energy by individuals, SEMs, and/or local bodies, including municipalities.

The participation of renewable energies in the generation of electrical energy as a strategy for a low-carbon energy transition has been the object of study in several recent scientific publications [2–6]. In their studies, Nakazawa et al. [2] and Wang et al. [3] analysed the case of a 100% renewable strategy in residential areas in a transition to low-carbon energy policies. Nikasa et al. [4] developed a methodology for the large-scale integration of photovoltaic solar energy in Greece. These authors considered this to be a key tool for a low-carbon energy transition. Nuwan et al. [5] underlined that a low-carbon economy requires low-carbon consumption on the part of the population. They undertook a study with a sample of the population of Sri Lanka, highlighting the importance of drawing up specific plans and proposing the use of renewable energies as one of the key strategic lines in this respect. Dorotic et al. [6] stressed the major importance of developing energy plans in island electrical systems and territories with limitations in their resources, aimed at achieving energy self-sufficiency and sustainability with zero carbon emissions. They undertook a case study on the island of Korcula (Croatia). To achieve their objectives, they developed a model of the electrical system in which wind and solar energy were incorporated as key elements.

Various authors have also highlighted energy self-consumption with renewable energies as a key tool for low-carbon energy policies [7–9]. Campos et al. [7] stressed the existing link between energy self-consumption and the low-carbon strategy, studying a case with the incorporation of renewable energy sources in a wine-producing industry in the Mediterranean area. In their study, Jimenez-Castillo et al. [8] considered the concept of net zero energy building, highlighting the importance of the incorporation of renewable energy sources and, more specifically, of photovoltaic solar energy for electrical energy generation. For their part, Lopez and Steininger [9] analysed the regulation of self-consumption with photovoltaic solar energy in Spain, reaching the conclusion, among others, that energy self-consumption plays a key role in the transition to a low-carbon energy system.

In article 15.3, Directive 2018/2001 states that member states must ensure the inclusion of provisions for the integration and deployment of renewable energy at national, regional, and local level, including for renewables' self-consumption and territorial planning necessary for that purpose. Taking into account these requirements, Spain has drafted its own Integrated National Energy and Climate Plan (INECP) 2021–2030 [10]. Among other aspects, strategic targets are set out in the Plan with respect to RE, including a nationwide renewable-sourced energy end use contribution of 42% and a 74% renewable share in electrical energy generation by 2030 (which presently stands at 36.8%).

The INECP of Spain specifically promotes energy self-consumption (see pp. 69–71 in [10]) and, in particular, joint self-consumption through the establishment of local energy communities. In Spain, electrical energy self-consumption is regulated through Royal Decree 244/2019 [11].

In self-consumption energy systems, the points of generation and consumption are relatively close, which thus contributes to distributed generation and the consequent improvement in the quality and cost of the electricity supply. The concept of distributed energy generation (DEG) and its incorporation in electrical system planning has been studied by numerous authors [12–16]. Notably, in all these studies, it is reported that the use of DEG improves the operational quality of electrical systems and is a beneficial strategy in the optimization of RE integration.

Ackermann et al. [12] defined the concept of distributed generation and its importance in electrical systems. In their work, they discussed various aspects that need to be considered for the incorporation of DEG in a competitive electricity market.

Specht and Madlener [15] studied a case for the German electrical system. They concluded that the incorporation of DEG is essential to optimize RE integration in the electrical system. They also considered it interesting to promote RE self-consumption. The same conclusion was reached in a study undertaken by Zhang et al. [16] on the electrical system in China. In their work, an analysis was carried out of the national electrical system, with one of the focuses of the study centred on the importance of DEG at the provincial and municipal level.

Dhakouani et al. [13] applied the so-called Open Source Energy Modeling System (OSeMOSYS) to the electrical system of Tunisia, with the aim of optimizing RE integration. They concluded that, in a framework of sustainability, the proper development of planning initiatives was fundamental for energy transitions. Navon et al. [14] reached similar conclusions in their study on the electrical system of Israel. They studied congestion in the Israeli transmission network as a result of RE integration and proposed the development of long-term planning criteria to promote DEG as a strategy to resolve the problem.

In the work undertaken by Uche-Soria and Rodríguez-Monroy [17] on energy poverty in the Canary Islands (Spain), the authors highlighted six basic pillars which need to be considered for the attainment of energy sustainability, including the exploitation of RE sources, the promotion of energy self-consumption facilities, and the electrification of energy demand. They also underlined the significant potential for RE exploitation in the Canary Islands, particularly solar and wind energy. Finally, they reported on the need for further research to be carried out on the possibility of increasing RE penetration while ensuring the quality of the electricity supply.

With respect to energy self-consumption, Van der Waal [18] carried out a case study on the Scottish island of Shapinsay in the Orkney archipelago, assessing the local impacts of a community self-consumption wind energy project.

The Canary Archipelago (Spain) is a geographical region of Spain which is a considerable distance from the mainland and not connected to the national electrical system. There are 7 main islands in the archipelago, each of which has its own independent electrical system, except for Lanzarote and Fuerteventura which are interconnected. At regional level,

the Autonomous Government of the Canary Islands has set a strategic target that RE should contribute 45% to the electrical energy demand of the islands by 2025 [19]. According to the latest data available, the corresponding contribution at the end of December of 2018 was just 11.8% [20].

Gran Canaria is the second most populated island in the archipelago. The island includes zones that are among the world's most prolific in terms of wind and solar energy potential, with mean annual wind speeds (at 10 m above ground level) of over 8 m/s and a solar energy potential which often exceeds 5,000 Wh/m²/day. Generally, the areas of high wind potential are found near the coast and on occasions at some distance from the island's populated settlements.

The islands in the Canary Archipelago are environmentally fragile territories, and 49.2% of the territory forms part of either the Canary Islands Network for Protected Natural Areas or the EU Nature 2000 network [21, 22].

Wind and solar energy are RE sources which are widely used for the supply of electricity. Their participation in the energy mix of electrical systems is continually rising. Optimizing the integration of RE in electrical systems can be tackled in a number of ways. These include the design of precise models to estimate the RE resource power output [23], the use of optimized smart grids [24] and, very importantly, the development of detailed and precise territorial planning studies for the demarcation of areas of interest for the installation of wind and solar energy facilities. Such studies are particularly important in island territories, where available land tends to be more limited and the electrical systems are generally small and weak. In the demarcation process, the planners need to consider, among many other aspects, the land use in the territory, the access to the areas in question, the potential of the renewable resource, the electrical infrastructure, and the location of areas of energy demand.

Various studies have been published in the literature which propose methodologies to demarcate areas for the installation of wind and/or solar energy infrastructures. These studies concentrate fundamentally on the identification of areas for the large-scale exploitation of these energy sources. In other words, the focus is on the implementation of large-scale facilities whose purpose is to directly dump all the electrical energy they generate into the transmission networks. The areas identified are usually situated in areas with a high renewable resource potential.

In many regions and/or countries, there are populated settlements with considerable energy requirements that are located at some distance from areas commonly demarcated for the implementation of large-scale wind and/or solar infrastructures. It may be possible for RE self-consumption plants to cover the electrical energy demand of these communities, including the demand of municipal facilities and of SEMs established there. However, for this, specific territorial planning has to demarcate areas relatively close to such settlements that have good potential for the joint exploitation of wind and solar energy and where energy self-consumption facilities can be built. Finding appropriate sites for such facilities is a decision-making problem which needs

to examine and take into account a wide range of issues. In this regard, multiple-criteria decision-making (MCDM) is a widely used tool in the field of energy planning. Thanks to its flexibility, it allows decision makers to find optimum results in complex scenarios which involve numerous conflicting indicators, targets, and criteria [25, 26]. The application of MCDM requires the support of geographical information systems (GIS), primarily for georeference of the geographical data that are of interest for the study [27, 28]. Various studies have used these tools to identify areas for the large-scale implementation of wind farms [29–35] and photovoltaic solar plants [36–40]. The aims pursued in such studies are generally related to providing assistance in the decision-making processes of governmental institutions. They usually involve assessing the suitability of an area in terms of its energy potential and the economic, social, and environmental impact of any facilities built there. However, all the studies that have been analysed have as their goal the large-scale generation of electrical energy through the direct connection of the wind or photovoltaic facilities with the transmission networks of the existing electrical systems in the study area. No studies have been found in which the specific objective is the siting of areas for the installation of wind or photovoltaic infrastructures aimed at energy self-consumption. At the same time, very few studies have focused on territorial contexts and small insular electrical systems (e.g., [34]). In these cases, it is of fundamental importance to consider factors related to territorial planning because the territory itself is a scarce resource. There are also very few studies which have tackled the joint siting of wind and photovoltaic facilities (e.g., [41, 42]). The most noteworthy study of this type of study was carried out by Aydin et al. [43], who presented a methodology for the siting of hybrid facilities (wind/photovoltaic). This approach favours the optimization of renewable resources in isolated areas because it provides a more stable energy supply by combining both energy sources.

The analytic hierarchy process (AHP) method was found to be the most widely used MCDM technique. In general, the AHP approach weighs the relative importance of each of the set of factors with a view to attaining a specific objective. The most important difference between the different consulted works concerns the criteria adopted for the weighing process. In some of the studies, no explanation is provided as to who assigns the respective weights (e.g. [30, 34]), or the authors themselves assign the weights in accordance with their own experience (e.g., [33]). In some MCDM-based studies, AHP is not used (e.g., [29, 35]), so no weights are applied to the different criteria considered. However, to give practical relevance to the results obtained, the most appropriate action would be to assign weights based on consultations with experts and organizations that know the local context in terms of energy generation and/or planning (e.g., [31, 32, 38, 39, 44]). Another aspect to consider is the sensitivity analysis that is used. In the case of studies related to the siting of wind RE installations, the approach commonly used involves modification of the weights, as site suitability is based on scores for each criterion given by the consulted experts. More specifically, one or a combination of

the following techniques is used: (a) an equal weighting is assigned to all the criteria (e.g., [32, 34, 44]), (b) a weighting of zero is assigned to one or more criteria (e.g., [34, 44]), and (c) the weightings of the criteria are modified in a defined interval (e.g., [45, 46]).

The study proposed in the present paper has as its main aim the development of a hybrid model for the siting of territorial areas that are suitable for the joint installation of wind and solar facilities targeted fundamentally at energy self-consumption. For this purpose, the AHP methodology was employed in conjunction with GIS.

The original contributions of this study are as follows:

- (a) In the definition of the AHP-GIS model for area demarcation, consideration is given to the fact that the wind and/or photovoltaic installations will be used fundamentally for energy self-consumption. In this way, such systems are promoted as a strategy for the optimization of the contribution of RE sources to meeting energy demand.
- (b) The case study focuses on the siting of areas close to populated settlements which are generally some distance from areas commonly demarcated for the large-scale exploitation of wind and solar energy.
- (c) The case study is targeted at a limited territory with an isolated and weak electrical system.
- (d) The study undertaken in the present paper also includes an original analysis of the sensitivity of the results of the hybrid model to modification of the threshold value in the minimum score criterion. This criterion is taken into account in the fitting stage of the wind and solar models to the hybrid model.

2. Data and Methodology

2.1. Study Area. The study area is the island of Gran Canaria, part of the Canary Islands Archipelago (Spain) (see Figure 1). This archipelago is found off the northwest coast of Africa between latitudes $27^{\circ}37'$ and $29^{\circ}25'$ N and longitudes $13^{\circ}20'$ and $18^{\circ}10'$ W. The surface area of Gran Canaria is $1,560 \text{ km}^2$ and its population is 846,717 [47]. Mean solar radiation is approximately $1,900 \text{ kWh/m}^2/\text{year}$ and mean wind speed is 6.4 m/s at a height of 40 m above ground level (see Data Availability). At the end of 2018, the island's installed wind and photovoltaic capacities were 154.3 and 41.5 MW , respectively. This is equivalent to 100% of the total installed renewable power on the island. Total installed electrical power was $1,219.9 \text{ MW}$. RE-sourced electricity generation on the island corresponds to a weight of 11.8% in the island's electrical energy demand [20].

Of the total installed wind capacity, only 20.8 MW is self-consumption installation. In the case of solar capacity, the proportion of installations for self-consumption is minimal.

2.2. Methodological Framework. Finding suitable sites for the installation of wind and PV plants, targeted principally at energy self-consumption and the promotion of DEG, is a decision-making problem which requires consideration of

different criteria. Normally, a combination of MCDM and GIS is used to analyse and resolve the problem [27, 28, 39]. Pohekar and Ramachandran [48] carried out a review of GIS-MCDM methods and concluded that AHP was the most extensively used technique in RE studies. AHP is an MCDM approach which is based on decomposing, comparative judging, and synthesising the priorities of the decision problem [49]. According to the literature related to the identification of areas for the exploitation of wind and solar energy, an AHP is used because of its flexibility in combining qualitative and quantitative criteria [50] because it allows clear identification of the relative importance of each criterion [51]. In addition, it is intuitive and easy to implement in a GIS.

The suitability analyses of wind and solar installations were carried out separately (see Figure 2). The process began with a review of the literature related to the siting of each energy type in order to select the criteria that need to be considered. These criteria were classified into factors, which favour or condition the location and constraints, which limit the location.

2.2.1. Identification of Factors. Nine factors used to identify the most suitable sites were found in the review of the literature. Each factor (Table 1, and see Data Availability for sources) was standardised through a linear membership function considering the critical points shown in Table 1.

Consideration was given to wind speed and solar radiation as factors related to the renewable resource potential. Wind speed is the key factor for wind energy exploitation [30–32, 34, 35, 44, 45]. In this study, the areas considered most suitable for exploitation were those with mean annual wind speeds above 7 m/s , while those below 4 m/s were discarded. For its part, solar radiation is the key variable for the generation of photovoltaic energy [36–38, 42, 43]. Based on the references that were consulted, although solar radiation was above $4,000 \text{ Wh/m}^2/\text{day}$ in all the selected areas, those considered most suitable enjoyed over $5,000 \text{ Wh/m}^2/\text{day}$.

With respect to environmental criteria, factors such as visual impact, slope, and slope direction were considered. The first of these is related to wind energy [30, 32, 34, 44, 52]. Bearing in mind the importance of the tourist sector in Gran Canaria, consideration was also given to the visual impact that wind turbines could have on the historical points of interest of the island. The criterion to evaluate this factor was that areas with a visual impact on more than 4 points of interest would not be considered suitable, while areas not visible from any point of interest would be considered the most suitable. In this case, the ArcGIS Viewshed Analysis was used to determine the degree of visibility, considering the observation points (historical sets) to be at a person's eye level (1.7 m) and a 40 m tall wind turbine in each of the digital elevation model (DEM) cells. It was also considered that areas with steep slopes (greater than 30%) were unfeasible locations for the construction of wind farms [30–32, 34] or PV plants [36, 38, 43], as access for construction would be extremely difficult and have a major

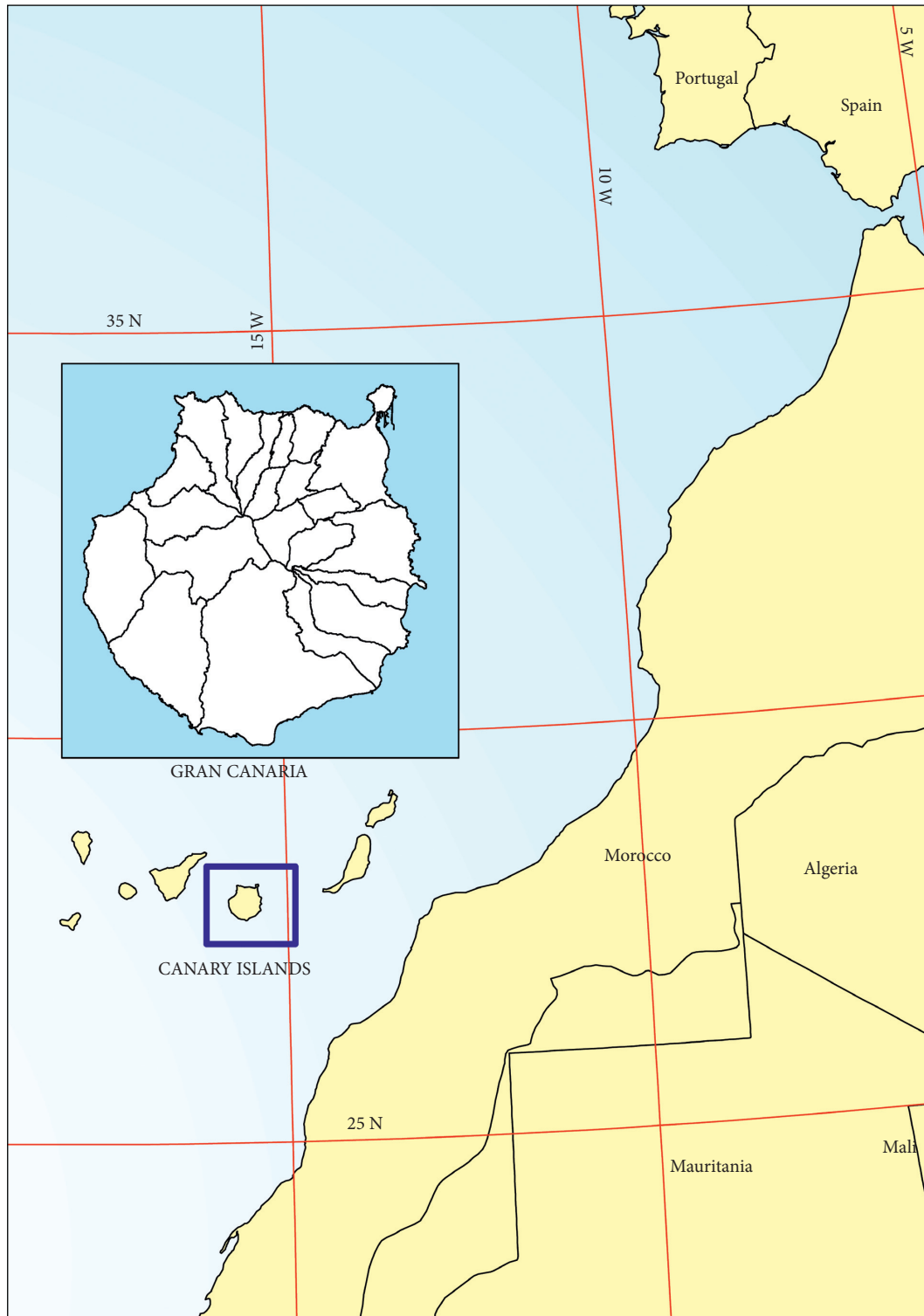


FIGURE 1: Geographical location of Gran Canaria island.

economic and environmental impact. In this case, it was considered that areas with a slope below 10% were the most suitable for wind farms. The constraint for solar plants was greater, with a 3% limit, as the infrastructure required to install solar panels requires a large surface area and the earthworks to condition the land which could generate

significant shaded areas. Finally, slope direction was additionally considered with respect to solar installations [36–38, 44]. It was determined that south-facing areas would have a considerably larger solar resource than north-facing areas. In this case, different critical points were established: one section between 337.5° and 22.5° , with a degree of

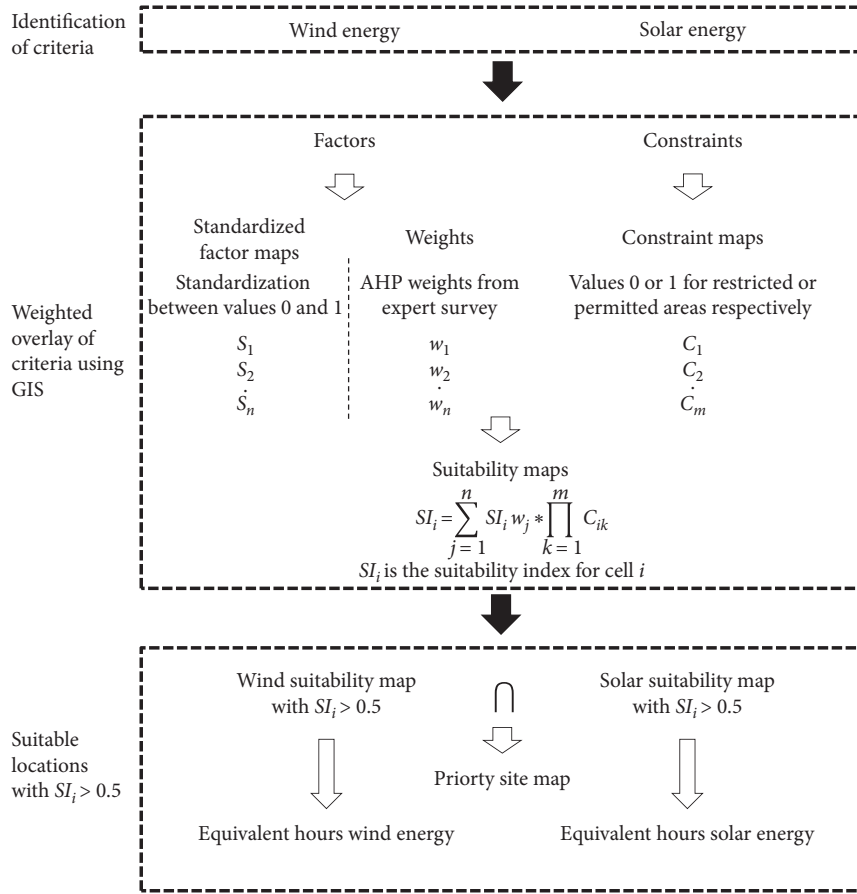


FIGURE 2: Methodological framework.

TABLE 1: Classification of factors.

| Type of criterion | Factors | | Critical points |
|-------------------|---------|---|--|
| Energy potential | F1 | Wind speed (*) | Less than 4 m/s = 0 More than 7 m/s = 1 |
| | F2 | Solar radiation (**) | Less than 4,000 Wh/m ² /day = 0 More than 5,000 Wh/m ² /day = 1 |
| Environmental | F3 | Visual impact (*) | Visible from more than 4 places of interest = 0 Visible from 0 places of interest = 1 |
| | F4 | Slope | Less than 10% = 1 (wind) Less than 3% = 1 (solar) More than 30% = 0 |
| | F5 | Slope directions (**) | Between 337.5° and 22.5° = 0 Between 157.5° and 202.5° = 1 |
| | F6 | Territorial planning | Incompatibility with IDP = 0 Compatibility with IDP = 1 |
| Economic | F7 | Proximity to road access | More than 2,000 m = 0 Less than 200 m = 1 |
| | F8 | Proximity to the potential electricity self-consumption | More than 2,000 m = 0 Less than 200 m = 1 |
| | F9 | Demand | More than 500 inhabitants = 1 Less than 100 inhabitants = 0 |

(*) is only for wind suitability maps. (**) is only for solar suitability maps.

suitability of 0, and a second section between 157.5° and 202.5°, with a degree of suitability of 1.

A total of four factors were considered in relation to the economic criterion: territorial planning, proximity to roads, proximity to the self-consumer, and potential volume of energy demand. With respect to territorial planning, land organization and use in Gran Canaria is based on the Island Development Plan (IDP) [47]. In addition, each municipality on the island has its own development plan which is dependent on the IDP. The ultimate aim of these plans is to guarantee sustainable development on the island. The IDP incorporates the coordination of supra-municipal actions and reflects the direction that the authorities are taking in terms of public investment policies. Land classification in the IDP is based on differentiation between the following groups or categories: Zones A (land of high natural value), Zones B (areas where natural values of importance coexist with traditional production activities), Zones C (land used for infrastructures and services of importance for the island), and Zones D (urban or developable land). Each of these groups is further divided into subcategories. After analysing the IDP, the areas that were considered most compatible for the installation of wind and solar plants for energy self-consumption were the following: Ba3 (low natural value and scarce productive value), Bb1.1 (potential productive value), Bb3 (moderate agricultural value), Bb4 (abandoned rural land), C (infrastructures, facilities, and installations of island-wide interest), and D1 (developable industrial land). The availability of a road network close to the potential wind farm and solar plant sites was also considered advantageous as it would reduce the construction costs of new access roads [30–32, 34, 44, 53]. In this study, roads with a minimum width of 4 m were considered. As the study area is an island of very uneven orography, the distance to any communication road was considered in terms of a maximum value ranging between 200 m and 2,000 m. The proximity of these types of installations to populated settlements also enhances their feasibility due to lower cabling costs and energy transmission losses. In the literature, this criterion is usually associated with proximity to the distribution grid [30, 32, 34, 36, 38, 44]. The ideal distance was determined to be between 200 m and 2,000 m. Finally, areas with a higher population evidently require more energy than less populated areas [34, 36, 42, 45], so the demand for self-consumption installations increases, as does their feasibility. Bearing in mind the demographic characteristics of the territory in question, it was estimated that population concentrations of more than 500 inhabitants would be the most suitable, while populations below 100 would not be sufficiently attractive for the installation of this type of infrastructure.

2.2.2. Identification of Constraints. Based on a review of the literature and the regulations applicable to the study area, the constraints shown in Table 2 were considered (see Data Availability):

- (i) The location of wind farms and solar plants must not conflict with territorial biodiversity conservation policies. These exclusion zones include the Canary Islands Network for Protected Natural Areas and the EU Nature 2000 network.
- (ii) These types of infrastructure cannot be installed on water-covered surfaces and, therefore, elements such as lagoons, lakes, marshland, dams, or reservoirs were discounted.
- (iii) The Canary Islands Road Regulation Act [54] was taken into account, especially in relation to article 45 which sets out the recognised minimum distances from public domains.
- (iv) For the case of wind energy, the Autonomous Government of the Canary Islands stipulates in article 29.2 of Decree 6/2015 that the distance between a wind turbine and an inhabited area must be no less than 250 m for turbines with a unit power of less than 900 kW. The aim is to minimize the possibility of acoustic pollution. This was taken as the constraint distance for this study given that the power range of wind turbines that would be installed with respect to the purposes of the present study would be below 900 kW. With respect to solar energy, consideration was given to the perimeter of urban areas which would make the implementation of this type of installation impossible.
- (v) In Royal Decree 1471/1989 on coastal regulations, article 43 establishes a sea-land construction limit that extends 100 m inland from the shoreline.
- (vi) In Framework Law 5/2005, article 30 establishes limitations for the construction of civil installations in designated military zones.
- (vii) A safety area needs to be established with respect to airports to limit air space and ensure the required area is free of obstacles. The approach and departure areas were taken into consideration in this regard for the present study.
- (viii) The Special Territorial Plan for Infrastructure Development (PTE-32) of Gran Canaria allocates three specific zones for large-scale RE exploitation. These three zones were excluded. In any case, the aim of the present study is not concerned with large-scale electricity generation, but rather the generation of electrical energy for self-consumption targeted, in general, at meeting the electrical energy demands of municipal facilities and agricultural, livestock, tourist and small industrial activities, etc., in rural areas.
- (ix) With a view to avoiding an excessive number of scattered RE installations constructed on small plots which could have an excessive visual impact, the constraint imposed on plot size was that there must be sufficient space for solar energy

TABLE 2: Constraints.

| Constraints | Constraint area |
|---|---|
| Protected areas | |
| Canary network of protected natural spaces | The perimeter of protected areas |
| Special areas of conservation | |
| Areas of special protection for birds (wind only) | |
| Water bodies | |
| Roads | The perimeter of reservoirs 20 m from the centre axis |
| Urban area | Acoustic pollution >250 m urban area (wind only) |
| Sea-land limits | The perimeter of the urban area (solar only) 100 m inland from the shore |
| Military areas | The perimeter of military areas |
| Airports | Approach and departure areas |
| Special territorial plan-32 (STP-32) | The perimeter of designated areas |
| Minimum surface area | Plots with surface area >30,000 m ² |

installations of over 2.5 MWp (30,000 m²). According to technical specialists, an area of 12 m² is required to install 1 kWp.

2.2.3. The AHP Method. The relative importance of each factor was evaluated by a group of experts. These were selected to reflect different approaches and interests related to energy planning and/or the implementation of RE installations. In this respect, assessments were received from the following institutional bodies and enterprises:

- (i) The Technological Institute of the Canary Islands (Spanish initials: ITC): this R & D enterprise is managed by the Autonomous Government of the Canary Islands and specialises in RE technologies and sustainable development [55].
- (ii) Gran Canaria Island Energy Board, responsible for, among other questions, the design of the energy model for the ultimate goal of the island's energy sovereignty [56].
- (iii) The Consortium of Municipalities of the southeast of Gran Canaria: this Consortium represents 3 of the 21 municipalities of the island. This Consortium has a particular interest in territorial sustainability, for which it has been given three awards: 3rd prize in the Whole City category of the international Livcom Awards, Chicago USA (2010), the Eolo prize for the rural integration of wind energy, awarded by the Wind Enterprise Association of Spain (2012 and 2018), and the National Sustainable City Award (2008 and 2010) [57].

The factors considered were compared pairwise, one by one and on a scale of 1 to 9. For this comparison, a matrix was used in which the relative importance of each criterion was calculated as the normalised geometric mean of each row of the matrix. Subsequently, the consistency of the result obtained was measured using the consistency index (CI):

$$CI = \frac{\lambda_{\max} - n}{n - 1}, \quad (1)$$

where λ_{\max} is the largest eigenvalue and n is the number of criteria considered.

Finally, an estimation was made of the coherence of the comparisons using the consistency ratio:

$$CR = \frac{CI}{RI}, \quad (2)$$

where CR and RI are the consistency ratio and the random index (average CI of the randomly generated comparisons [58]), respectively. The CR must be below 0.1 for the result to be considered acceptable [59].

Tables 3 and 4 show the value of the weights for each of the factors obtained on the basis of the criterion of relative importance as evaluated by the consulted experts.

As determined by the experts consulted, wind speed and solar radiation were the most important factors, with final respective weights of 41.08% and 39.97%. Demand and proximity to potential RE self-consumption sites were classified at a second level, with these factors more closely related to the economic viability of the project. The CR in the case of wind energy was 8.5% and in the case of solar energy was 7.8%, values which are below the threshold value of 10%.

As each factor is expressed in different measurement units, it was necessary to standardise these variables in order to facilitate their joint analysis. Standardisation of the factors was carried out using a linear membership function [43, 45], considering the critical points shown in Table 1. Each constraint was classified with a Boolean criterion, where 0 represents the presence of a constraint and, therefore, the area in question is not feasible, and 1 represents the absence of a constraint and is, therefore, potentially feasible.

2.2.4. Suitability Maps. The wind and solar energy suitability maps were obtained multiplying each standardised factor by its weight. In these maps, the most suitable areas will have a score approaching 1 and the least suitable a score approaching zero. The implementation and visualization of the results was performed with ArcGIS 10.6.

One of the main drawbacks of the use of RE is its dependence on meteorological and climate conditions, and its consequent intermittent nature. It is therefore difficult to

TABLE 3: Pairwise comparison matrix and relative importance weights of the factors associated with wind energy.

| | F1 | F3 | F4 | F6 | F7 | F8 | F9 | Weights |
|----|----|----|-----|-----|-----|-----|-----|---------|
| F1 | 1 | 9 | 8 | 6 | 7 | 4 | 3 | 0.4108 |
| F3 | | 1 | 1/2 | 1/5 | 1/3 | 1/6 | 1/8 | 0.0252 |
| F4 | | | 1 | 1/3 | 1/2 | 1/5 | 1/6 | 0.0373 |
| F6 | | | | 1 | 2 | 1/3 | 1/4 | 0.0857 |
| F7 | | | | | 1 | 1/4 | 1/5 | 0.0553 |
| F8 | | | | | | 1 | 1/2 | 0.1589 |
| F9 | | | | | | | 1 | 0.2268 |

$$\lambda_{\max} = 7.675; CI = 0.113; RI = 1.32; CR = 0.085 < 0.1.$$

TABLE 4: Pairwise comparison matrix and relative importance weights of the factors associated with solar energy.

| | F2 | F4 | F5 | F6 | F7 | F8 | F9 | Weights |
|----|----|----|-----|-----|-----|-----|-----|---------|
| F2 | 1 | 9 | 6 | 5 | 7 | 4 | 3 | 0.3997 |
| F4 | | 1 | 1/3 | 1/4 | 1/2 | 1/6 | 1/8 | 0.0262 |
| F5 | | | 1 | 1/2 | 3 | 1/3 | 1/6 | 0.0652 |
| F6 | | | | 1 | 4 | 1/2 | 1/3 | 0.0976 |
| F7 | | | | | 1 | 1/5 | 1/6 | 0.0369 |
| F8 | | | | | | 1 | 1/2 | 0.1480 |
| F9 | | | | | | | 1 | 0.2264 |

$$\lambda_{\max} = 7.615; CI = 0.103; RI = 1.32; CR = 0.078 < 0.1.$$

provide a stable energy supply if using only one RE source. However, combining two or more RE sources in a hybrid system helps to overcome this limitation as, when production from one resource decreases, it may be possible for the other resource to compensate for this decrease. Bearing in mind the aim of the present study and taking [43] as reference, it was decided to prioritise the selection of areas in which the installation of both wind and solar energy (hybrid model) was permitted. This entails considering the factors and constraints which affect both energy sources simultaneously. In this study, the criterion was used for choosing priority areas which were allowed to have both types of installation which have values above 0.5 in the suitability analysis of the two energy sources.

2.2.5. Wind and Solar Equivalent Hours. The equivalent hours' parameter was used to provide an overview of the energy potential, both wind and solar, of the areas obtained as results of the hybrid model. This parameter reflects the equivalent annual specific energy generated in a particular area by a wind installation (in kWh/kW) or solar installation. The latter is expressed in kWh/kW_p, where kW_p is the power measured on the basis of the power specified for the photovoltaic modules.

A tool developed by the ITC was used for the calculation of equivalent hours (see Data Availability for sources of factor: "wind speed"). One of the applications of this tool contains information about the wind resource parameters required to estimate the Weibull function [60] in any point of the Canary territory in a 10 × 100 m mesh. Based on this information and in combination with another of the tool's

applications which makes use of wind turbine power curves, it was possible to estimate electrical energy generation.

For the particular case of equivalent solar hours, direct use was made of data accessible through the web portal developed by GRAFCAN (see Data Availability for sources of factor: "Solar radiation").

2.2.6. Sensitivity Analysis. After the above described process was concluded, it was necessary to carry out a what-if sensitivity analysis to provide information about the robustness of the results [61]. In the case of studies related to the siting of wind RE installations, the approach commonly used involves modification of the weights, as site suitability is based on scores for each criterion given by the consulted experts. More specifically, one or a combination of the following techniques is used: (a) an equal weighting is assigned to all the criteria (e.g., [32, 34, 44]), (b) a weighting of zero is assigned to one or more criteria (e.g., [34, 44]), and (c) the weightings of the criteria are modified in a defined interval (e.g., [45, 46]).

In the present study, it was decided to undertake the sensitivity analysis by considering two different approaches:

- According to the criterion of weights assigned to the factors of the model: in this case, the results obtained with the expert-assigned weights were compared with the results obtained on the basis of the criterion of equal weighting for each factor. This allowed evaluation of the impact of the relative importance assigned to each factor.
- According to the criterion of assigning a minimum suitability score in the hybrid model: the aim behind this second analysis was to evaluate the sensitivity of the final area available according to the different minimum scores assigned to the hybrid model.

Both analyses were undertaken considering the additional importance, for the case study, of surface area optimization due to land limitations in an island environment.

3. Results and Discussion

3.1. Wind and Solar Suitability Maps. The wind and solar evaluation maps were obtained (see Figures 3 and 4) by overlaying the factors corresponding to wind and solar energy shown in Table 1 (see factor maps in figure 5) and applying the weights according to the pairwise comparison matrices (Tables 3 and 4). In the case of wind energy (see Figure 3), the most suitable areas were the NW, E, and SE of the island. These areas have high wind speeds and are close to important population centres and road networks. In addition, the E area is one of low slope terrain. In the case of solar energy (see Figure 4), it can be estimated that 68% of the island has a score above 0.8 and only 31% has a score below 0.5. These high scores are due to the fact that 79% of the surface area of the island has solar radiation values above 5,000 Wh/m²/day because there is a homogenous distribution of populated settlements which favourably affects the

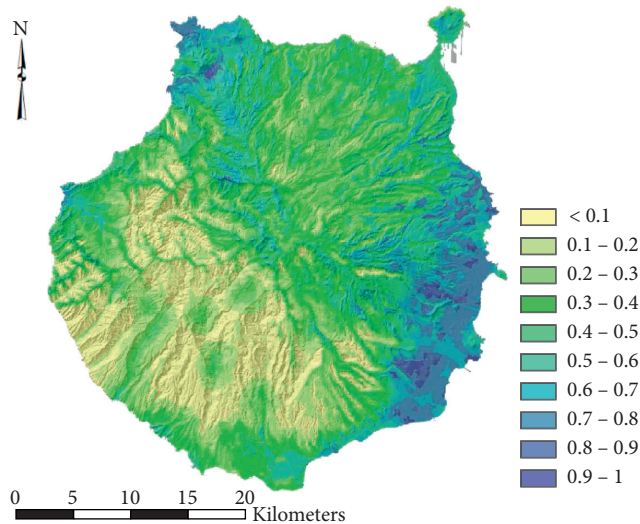


FIGURE 3: Wind evaluation map.

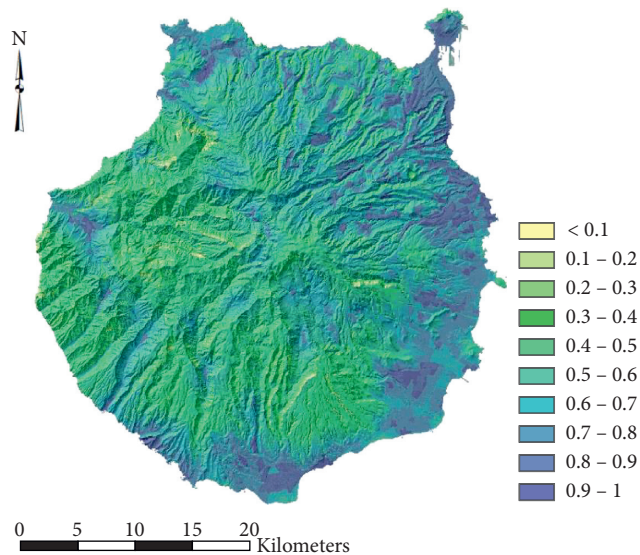


FIGURE 4: Solar evaluation map.

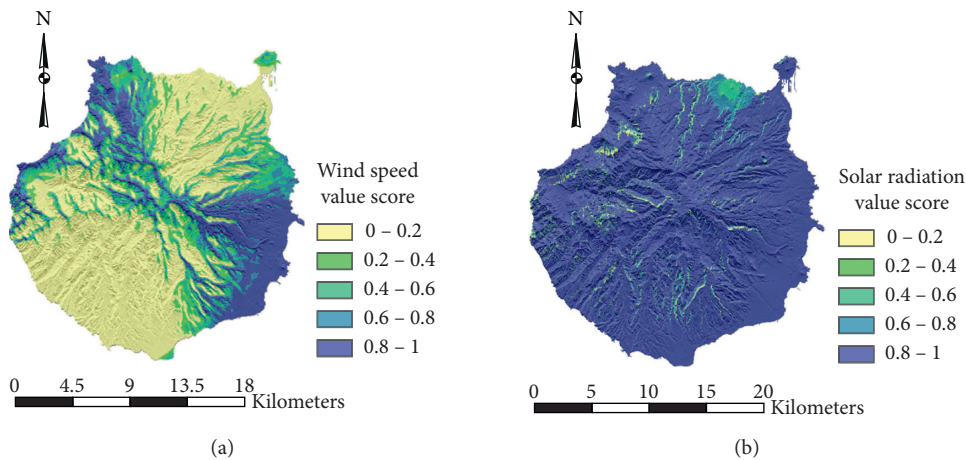


FIGURE 5: Continued.

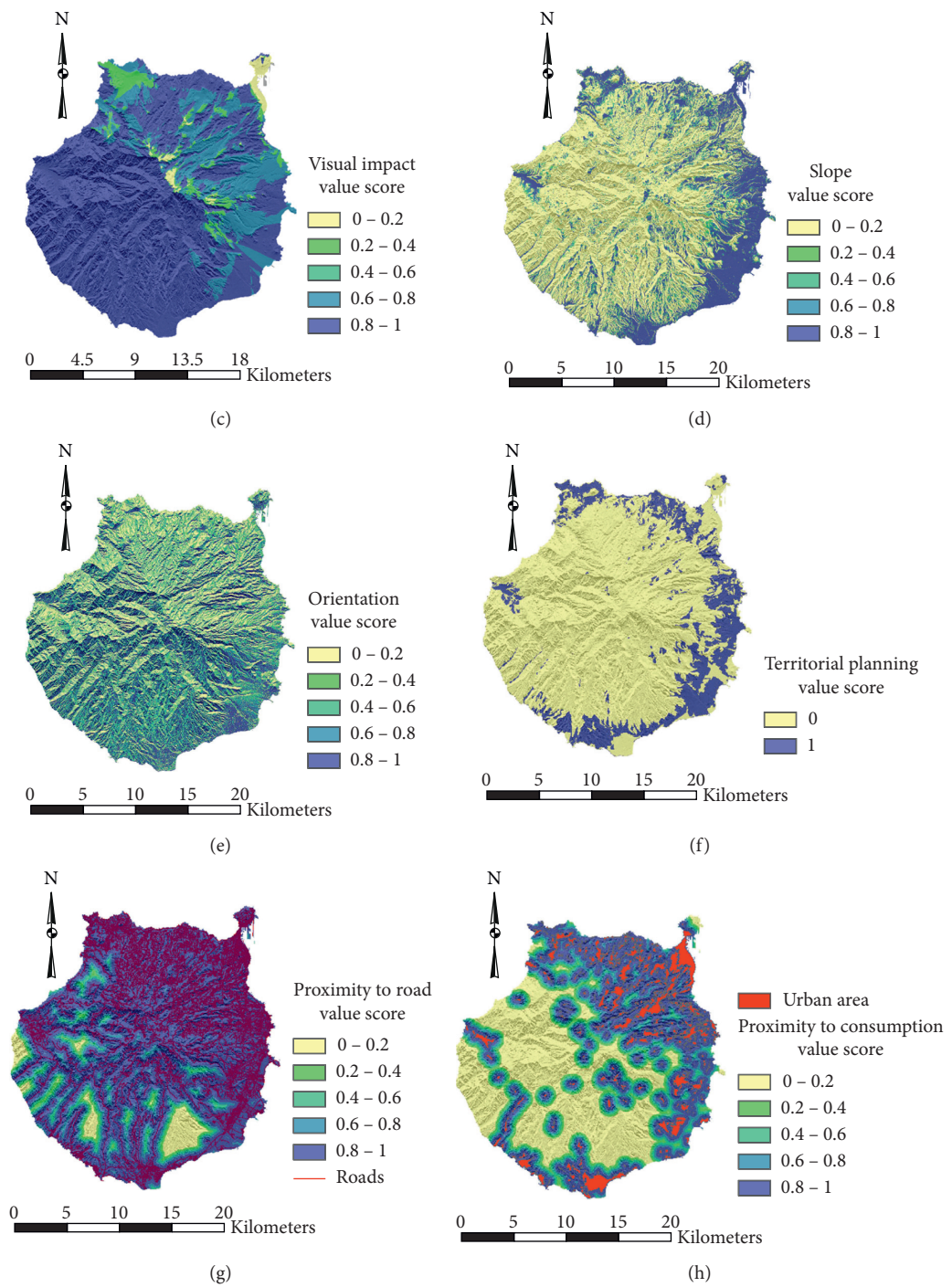


FIGURE 5: Continued.

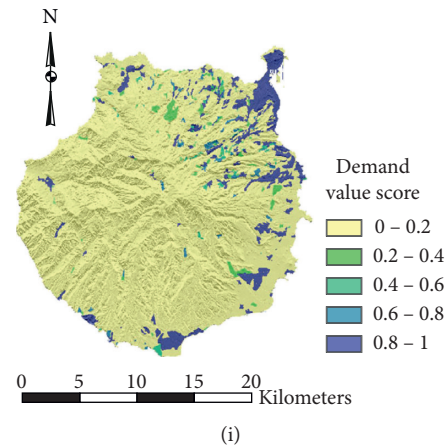


FIGURE 5: Factors: (a) wind speed, (b) solar radiation, (c) visual impact, (d) slope, (e) orientation, (f) territorial planning, (g) proximity to road access, (h) proximity to potential electricity self-consumption, and (i) demand.

scores in the factors of demand and proximity to potential self-consumption.

The wind and solar constraint maps were obtained (see Figures 6 and 7) taking into consideration the constraints corresponding to wind and solar energy shown in Table 2 (see constraint maps in figure 8). In this case, available surface areas of 282.34 km² and 388.91 km² were obtained for wind and solar energy, respectively. These areas represent 18.1% and 24.9% of the total surface area of the island, respectively.

The wind and solar suitability maps were finally obtained (see Figures 9 and 10) after eliminating the restricted areas from the respective evaluation maps. In the case of wind energy, 81% of the suitable area has a score below 0.5, 18% has a score of between 0.5 and 0.8, and only 1% has a score of above 0.8. In the case of solar energy, only 16.7% has a score below 0.5, the majority (80%) of the suitable area has a score between 0.5 and 0.8, and 3.3% has a score above 0.8. That is, in general, the score for available terrain in the case of wind energy is mostly low, whereas solar energy is characterised by a medium suitability. However, it is important to take into account the fact that the aim of the present study is concerned with DEG in areas distant from large-scale RE infrastructures connected to the transmission network. With this in mind, the STP-32 areas, which are the areas most favourable for the large-scale exploitation of wind energy on the island and therefore reserved for this purpose, were excluded.

3.2. Priority Sitemap (Hybrid Model). As previously indicated, one of the drawbacks of using only one RE modality (wind or solar) is that neither type generates energy continuously, as they are dependent on meteorological factors. The integration of both types of technology in a hybrid system favours the continuity of energy production as they can complement each other. However, the suitable areas with respect to each RE type do not necessarily overlap, as they depend on different factors and constraints (see Figures 9 and 10). It was therefore necessary to carry out a

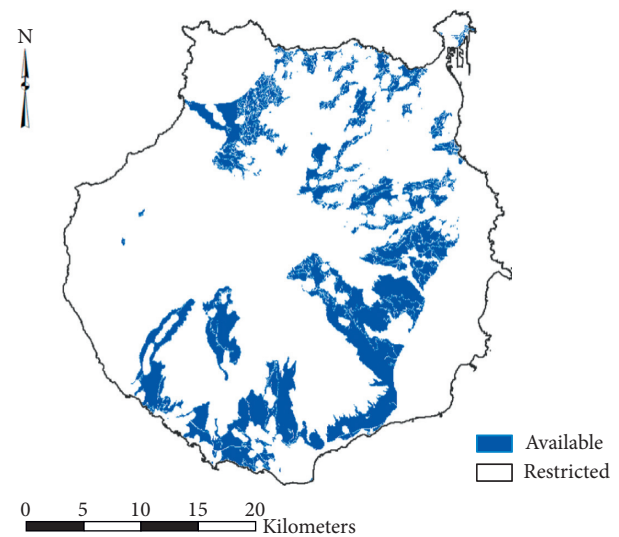


FIGURE 6: Wind constraint map.

selection of the most suitable common areas (priority areas). The criterion used was the simultaneous occurrence of values above 0.5 for both energy sources [43]. The result obtained is shown in Figure 11.

In addition, the location of each of these areas was determined by municipality, as such information could be extremely useful for local administrations in the elaboration of strategic plans at municipal scale. A total available priority surface area of 45.26 km² was obtained. The distribution of this area by municipality is shown in Table 5.

3.3. Maps of Equivalent Solar and Wind Hours. Figures 12 and 13 show the annual distribution of equivalent hours (EH) of the areas with a score above 0.5 for wind and solar energy, respectively. These results were obtained on the basis of Figures 9 and 10 and after eliminating the areas with a score below 0.5. In both maps, the areas which form part of the priority area (wind > 0.5 ∩ solar > 0.5, see Figure 11) are enclosed by a red line. According to Figure 12, with respect

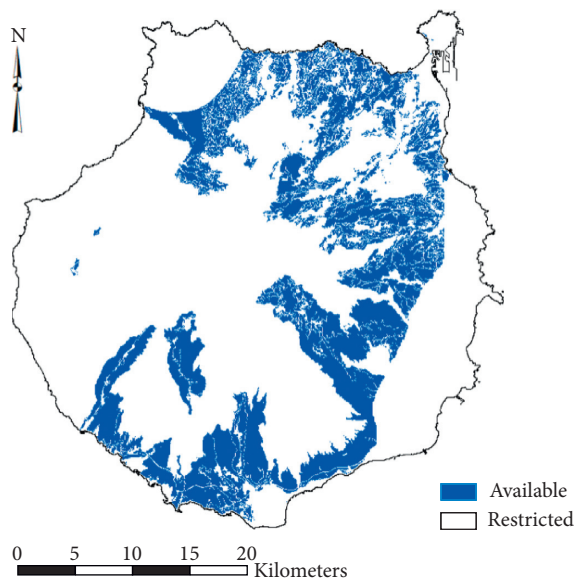


FIGURE 7: Solar constraint map.

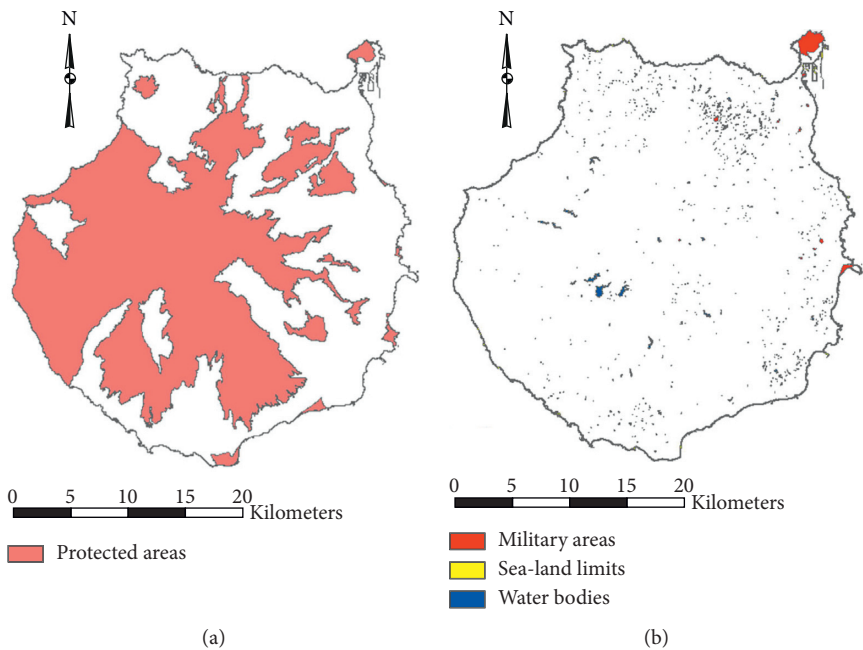


FIGURE 8: Continued.

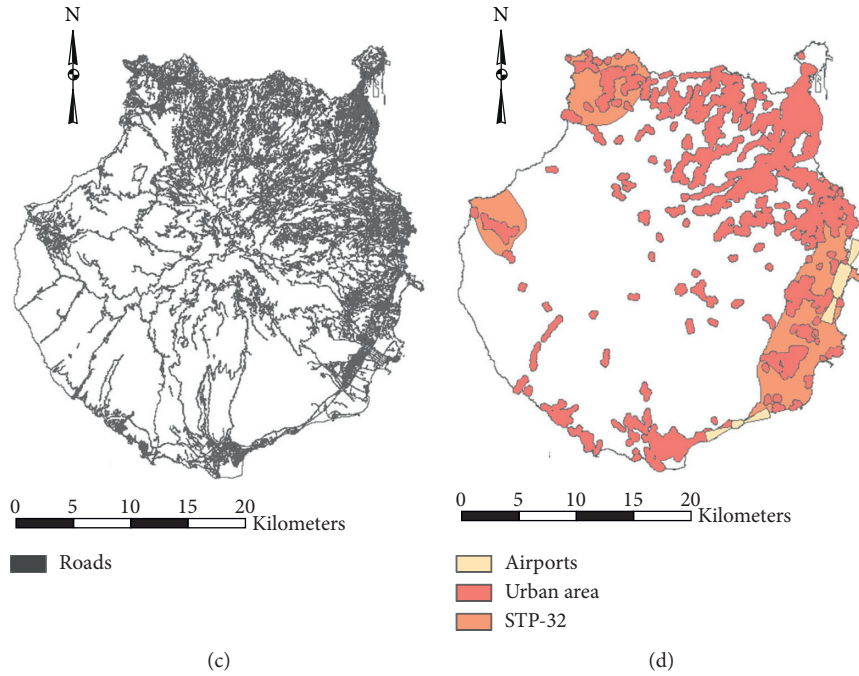


FIGURE 8: Constraints: (a) protected areas, (b) military areas, sea-land limits (100 m), and water bodies, (c) roads (20 m), and (d) airports, urban area (250 m), and special territorial plan-32.

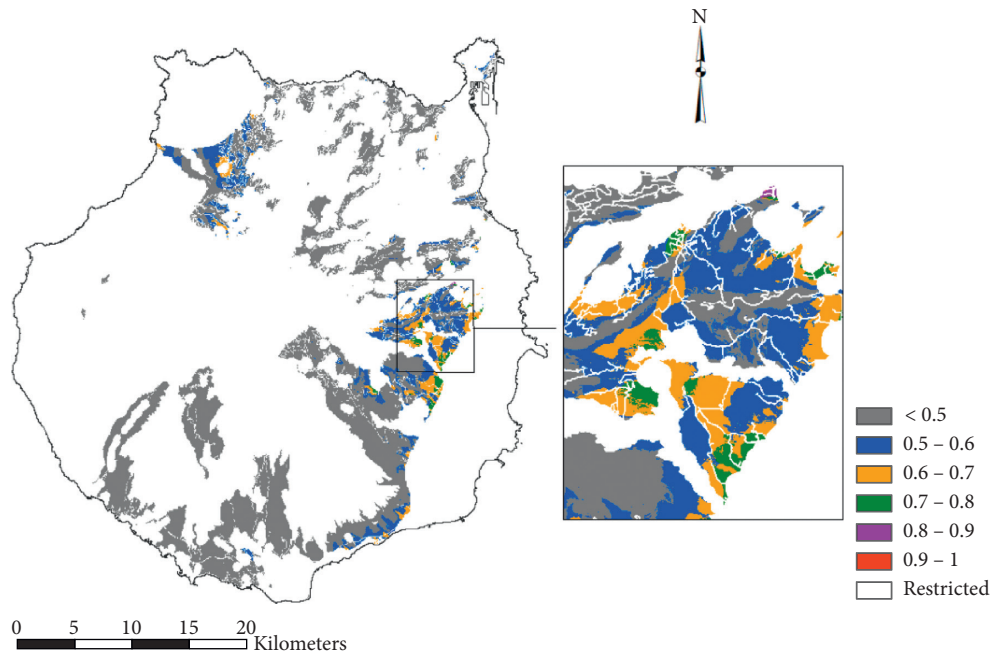


FIGURE 9: Wind suitability map.

to territorial distribution, 6% (2.9 km^2) has less than 2,000 EH, 43.3% (21.4 km^2) between 2,000 and 3,000 EH, 47.9% (23.6 km^2) between 3,000 and 4,000 EH and 2.8% (1.4 km^2) more than 4,000 EH.

In the case of solar energy, 14.5% of the total area (see Figure 10) forms part of the priority areas in the hybrid model. According to Figure 13, with respect to territorial distribution, 12.3% (38.4 km^2) has less than 1,800 EH, 26.4%

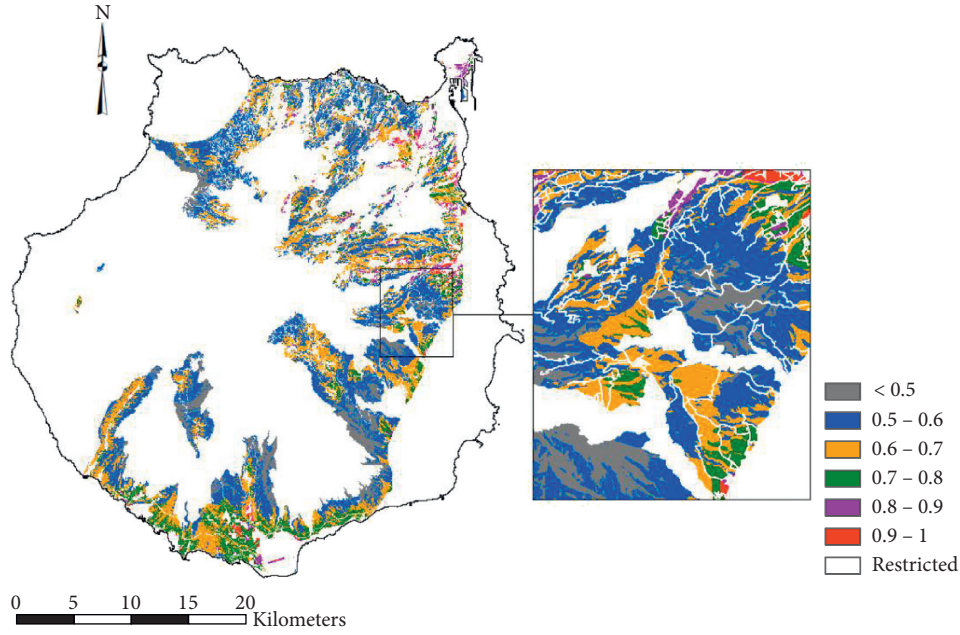


FIGURE 10: Solar suitability map.

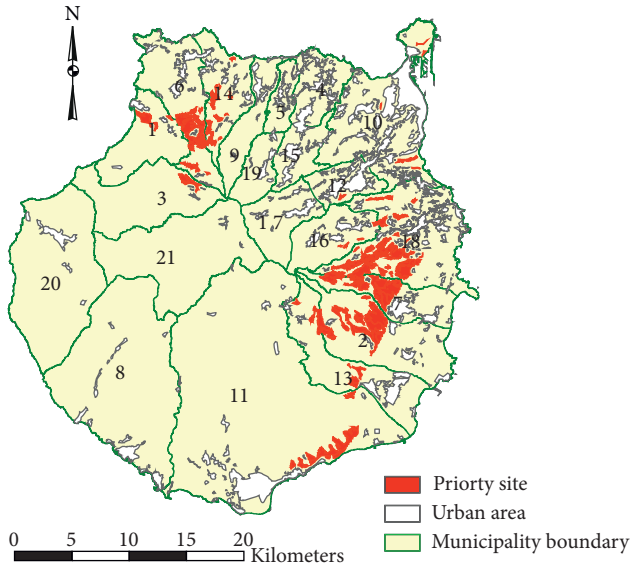


FIGURE 11: Priority sitemap (hybrid model).

(82.4 km²) between 1,800 and 1,900 EH, 51.4% (160 km²) between 1,900 and 2,000 EH, and 9.9% (30.7 km²) more than 2,000 EH.

3.4. Sensitivity Analysis

3.4.1. Sensitivity to the Expert-Assigned Weight Criterion. For this approach, the results obtained according to the expert-assigned weight criterion (see Figures 10 and 11) were compared with those obtained with the criterion of equal weights for each factor [32]. For this latter criterion and bearing in mind that there are 7 specific factors for each renewable resource, the relative weight of each factor is equal

TABLE 5: Distribution of available priority surface area by municipality.

| Municipality | No. | Surface area (km ²) |
|-----------------------------|-----|---------------------------------|
| Agaete | 1 | 1.36 |
| Agüimes | 2 | 8.88 |
| Artenara | 3 | 0.94 |
| Gáldar | 6 | 5.21 |
| Ingenio | 7 | 7.50 |
| Las Palmas de G. C. | 10 | 0.57 |
| San Bartolomé de Tirajana | 11 | 4.97 |
| Santa Brígida | 12 | 0.11 |
| Santa Lucía de Tirajana | 13 | 2.10 |
| Santa María de Guía de G.C. | 14 | 2.00 |
| Telde | 18 | 11.33 |
| Valsequillo de G.C. | 19 | 0.29 |
| TOTAL | | 45.26 |

to 14.3%. Figures 14 and 15 show the wind and solar suitability maps obtained when applying the criterion of equal weights.

Tables 6 and 7 compare the results obtained in the AHP models with the criterion of equal weights (see Figures 14 and 15) with the results obtained in the AHP model developed according to the criterion of expert-assigned weights (see Figures 9 and 10). A series of observations can be made after analysing the results. In both the wind and solar energy cases, the results obtained for areas with a low evaluation (<0.5) are highly sensitive, with respective variations of 11.49% and 35.31%. This would have a significant impact on the final result obtained in the hybrid model, where the hypothesis taken is to select areas with values above 0.5. Therefore, it was considered to be of fundamental importance to establish reasoned and expert-assigned weights for the different factors that intervene in the model, considering the particularities and requirements of the regions where it is applied.

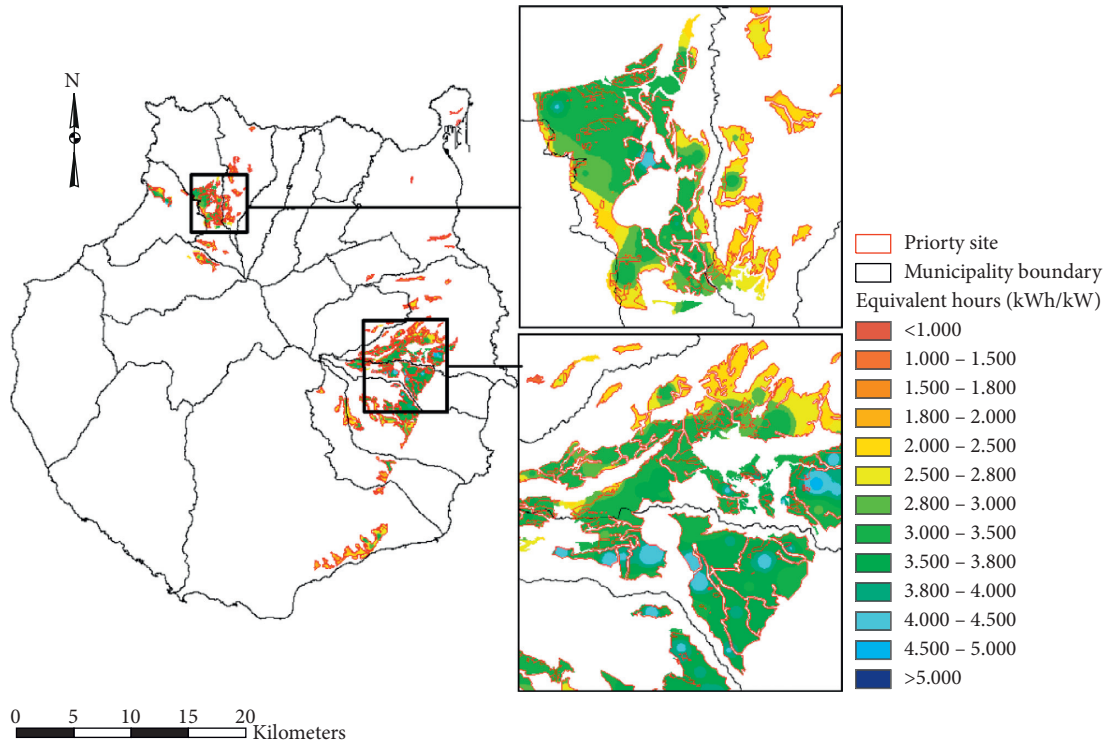


FIGURE 12: Wind equivalent hours.

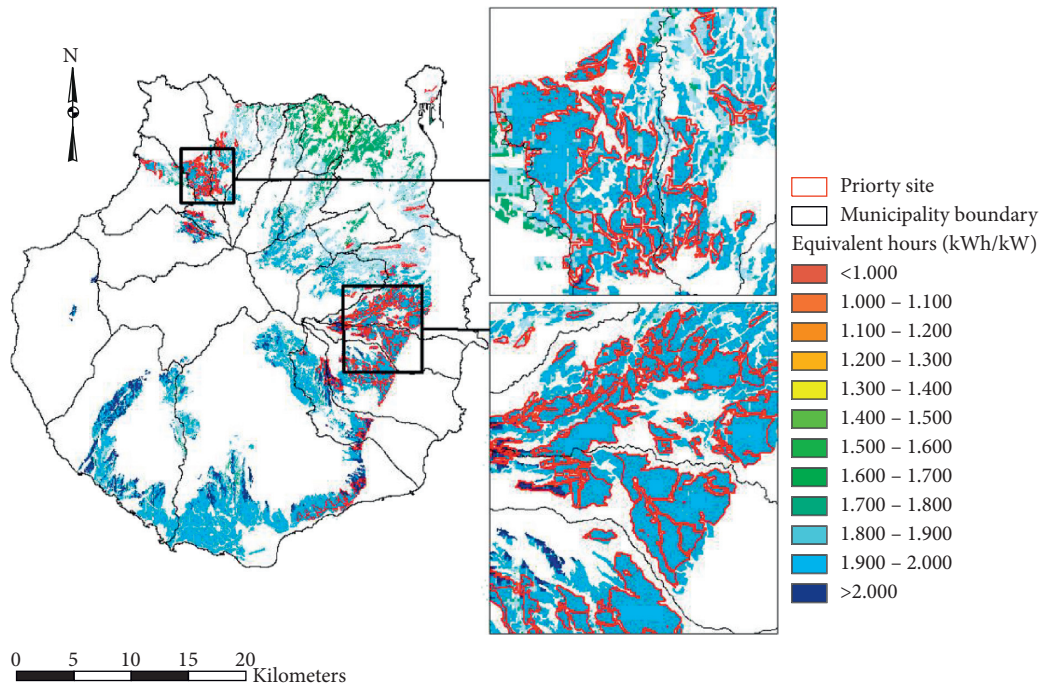


FIGURE 13: Solar equivalent hours.

3.4.2. Sensitivity to the Minimum Score Criterion to Determine Priority Areas in the Hybrid Model. Another of the critical aspects in the results of the model is the assignment of the minimum score for the selection of priority areas. With this in mind, a further sensitivity analysis was performed in which the results of available

land area were compared according to the minimum score applied. In this respect, the results obtained for a minimum score of 0.5, used for the priority sitemap (see Figure 11), were compared with the surface areas that would be obtained if minimum scores of 0.6, 0.7, and 0.8 were applied.

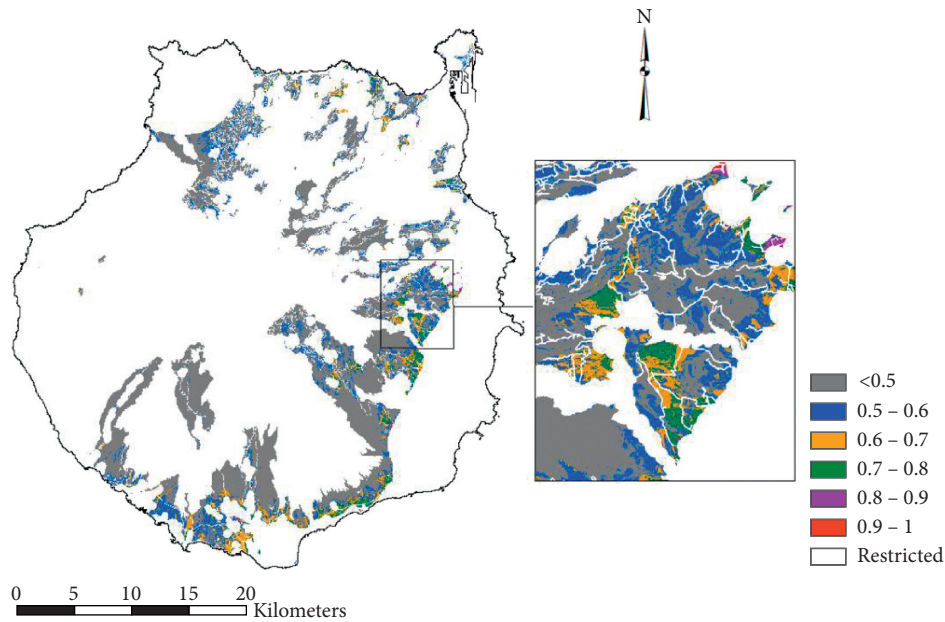


FIGURE 14: Wind suitability map (equal weights' criterion).

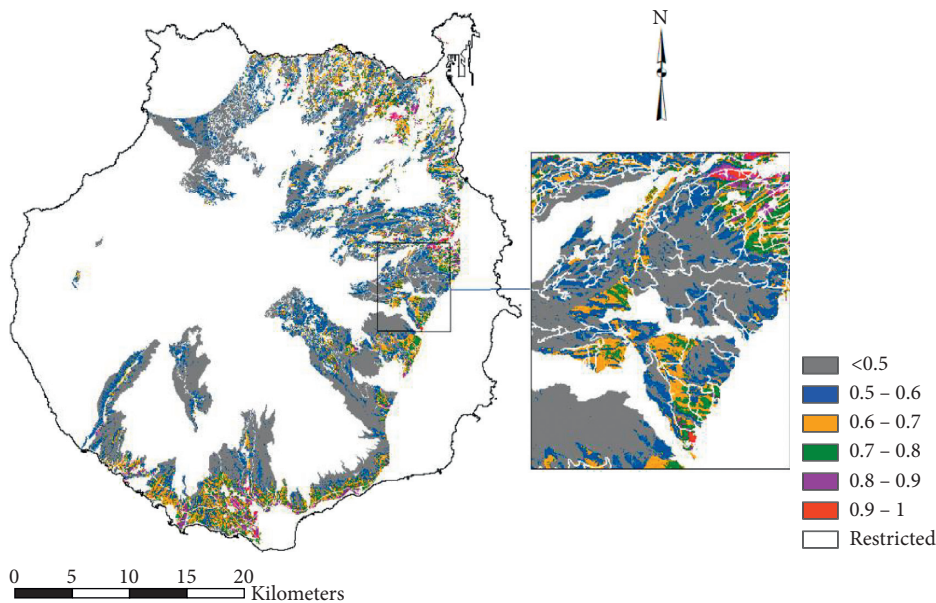


FIGURE 15: Solar suitability map (equal weights' criterion).

Figure 16 shows the graphic result of this comparative analysis.

Table 8 shows the numerical values obtained for the surface areas of Figure 16. It can be seen that the results for the hybrid model are markedly sensitive to the minimum score which is assigned for its generation. A 76.89% reduction in available surface area is obtained by simply changing from a minimum score of 0.5 to 0.6. Bearing in

mind that the weights assigned to the factors of wind speed and solar radiation are the highest, increasing the constraint for the generation of the hybrid model entails increasing the importance of these factors in the results of the hybrid model. In this respect and considering separately the results obtained for the wind and solar models (see Figures 9 and 10), for this case study, wind speed was determined as the limiting factor in the results for the hybrid model.

TABLE 6: Wind sensitivity analysis results.

| Suitability value score | | AHP model (according to equal weights criterion) | | AHP model (according to expert-assigned weights' criterion) | | Sensitivity | |
|-------------------------|---------|--|--------|---|--------|-----------------|--------|
| | | km ² | % | km ² | % | km ² | % |
| Low | <0.5 | 197.08 | 69.80 | 229.51 | 81.29 | -32.44 | -11.49 |
| | 0.5-0.6 | 49.85 | 17.65 | 37.34 | 13.23 | 12.50 | 4.43 |
| Medium | 0.6-0.7 | 24.42 | 8.65 | 12.64 | 4.48 | 11.79 | 4.17 |
| | 0.7-0.8 | 10.37 | 3.67 | 2.81 | 0.99 | 7.56 | 2.68 |
| High | 0.8-0.9 | 0.60 | 0.21 | 0.04 | 0.01 | 0.56 | 0.20 |
| | 0.9-1 | 0.02 | 0.01 | 0.00 | 0.00 | 0.02 | 0.01 |
| Total | | 282.34 | 100.00 | 282.34 | 100.00 | | |

TABLE 7: Solar sensitivity analysis results.

| Suitability value score | | AHP model (according to equal weights criterion) | | AHP model (according to expert-assigned weights criterion) | | Sensitivity | |
|-------------------------|---------|--|--------|--|--------|-----------------------------|--------------|
| | | km ² | % | km ² | % | Δ (km ²) | Δ (%) |
| Low | <0.5 | 202.67 | 52.11 | 65.36 | 16.81 | 137.31 | 35.31 |
| | 0.5-0.6 | 93.99 | 24.17 | 150.40 | 38.67 | -56.41 | -14.51 |
| Medium | 0.6-0.7 | 51.06 | 13.13 | 116.16 | 29.87 | -65.10 | -16.74 |
| | 0.7-0.8 | 30.81 | 7.92 | 44.14 | 11.35 | -13.33 | -3.43 |
| High | 0.8-0.9 | 8.93 | 2.30 | 9.06 | 2.33 | -0.13 | -0.03 |
| | 0.9-1 | 1.46 | 0.37 | 3.79 | 0.97 | -2.33 | -0.60 |
| Total | | 388.91 | 100.00 | 388.91 | 100.00 | | |

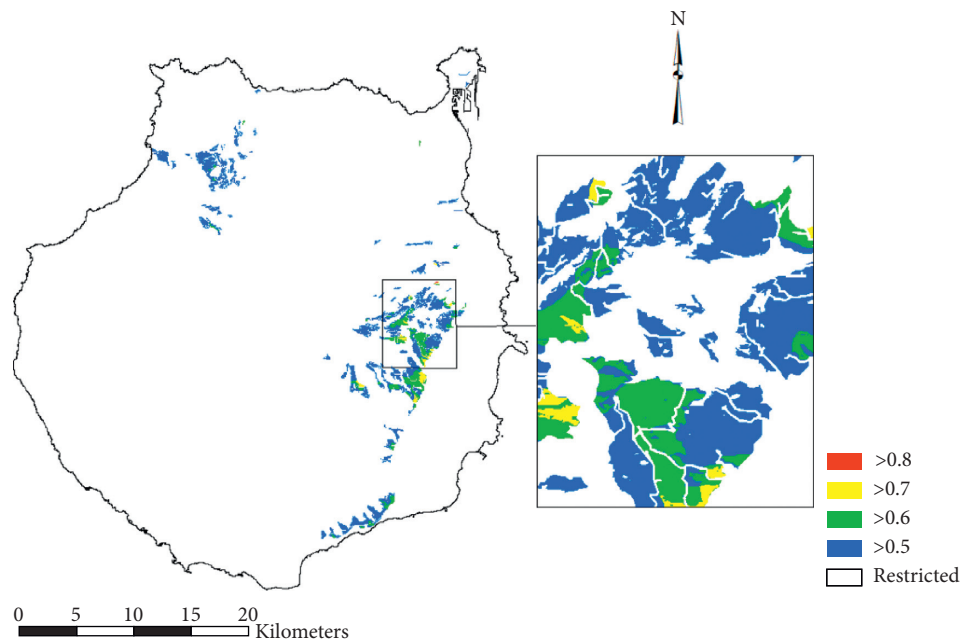


FIGURE 16: Sensitivity analysis map (minimum score for priority site).

TABLE 8: Sensitivity analysis results of minimum score for priority site.

| Assigned value for minimum score | Sensitivity analysis | | |
|----------------------------------|----------------------|-----------------------------|--------------|
| | km ² (%) | Δ (km ²) | Δ (%) |
| >0.5 | 45.26 | | |
| >0.6 | 10.46 | −34.8 | −76.86 |
| >0.7 | 1.54 | −43.72 | −96.60 |
| >0.8 | 0.03 | −45.23 | 99.97 |

4. Conclusions

In this work, a GIS-MCDM-based model has been developed for use in territorial planning targeted at the joint implementation (hybrid model) of wind and solar installations for energy self-consumption. The model that has been developed can be applied to any territory. In this paper, the hybrid model that was developed was applied to the particular case of an insular electrical system (Gran Canaria, Canary Islands, Spain). The model can be incorporated as an energy planning tool to optimize the integration of renewable energy resources and to promote DEG systems, which are important goals in the framework of the development of sustainable and low-carbon energy policies.

To generate the model, territorial constraints were imposed and factors which were considered priority were identified in the siting of suitable areas. Weights were additionally assigned to each factor in accordance with their relative importance. For this ultimate requirement, consideration was given to the opinion of external experts connected to the energy sector and territorial and/or energy planning on the island. In this respect, a total of 9 factors were taken into consideration, related to technical, environmental, and economical aspects.

As a result of the models that were developed, potential sites were identified for the joint exploitation of wind and solar energy resources in areas relatively close to populated settlements with significant energy demand. These are urban and/or rural communities generally at some distance from the coast where wind and solar potential is high.

In the results of the model, the suitable areas were differentiated by the municipality in which they are located. In this way, the results can be incorporated in future territorial planning modifications at both island and municipality level.

Based on the assigned factors and weights, suitable areas were initially demarcated in terms of their potential for wind or solar energy exploitation. The demarcated areas were evaluated on a scale of 0 to 1, with 0 equivalent to zero viability and 1 to high viability. For the results of the hybrid model, which are identification of the areas suitable for joint solar and wind energy exploitation, the areas selected were those with a score above 0.5 for both wind and solar exploitation. In this way, suitable areas were identified in 12 of the 21 municipalities of the island. The total demarcated

surface area amounted to 45.3 km², which corresponds to approximately 3% of the total area of the island.

In the results of the models, two elements were considered to be critical: the allocation of weights to the different factors and the minimum score considered for the generation of the hybrid model. With this in mind, an additional sensitivity analysis of the results to these two elements was performed. With respect to the weights assigned to the different factors, the results that were obtained on the basis of an expert-assigned weights criterion (see Figures 9 and 10) were compared with those obtained on the basis of a criterion of equal weights for all factors (see Figures 14 and 15). From the results obtained for the individual wind and solar models, a decrease of 14.13% was observed in the wind model for areas with a score below 0.5, and in the solar model, an increase of 210% (Tables 6 and 7, respectively) was observed. These results would have a significant impact on the results of the definitive hybrid model. With respect to the sensitivity of the results to the chosen minimum value for the generation of the hybrid model, it was observed that a change from 0.5 to 0.6 would result in a decrease in the available suitable area in the hybrid model of 76.89%, from an initial 45.3 km² to 10.46 km². In short, the results of the hybrid model are highly sensitive to the two elements considered, which should therefore be carefully established according to the case study in question.

Abbreviations

| | |
|--------------------|--|
| λ_{\max} : | Largest eigenvalue (equation (1)) |
| AHP: | Analytic hierarchy process |
| CI: | Consistency index (equation (1)) |
| CR: | Consistency ratio (equation (2)) |
| DEG: | Distributed electricity generation |
| DEM: | Digital elevation model |
| EH: | Equivalent hours (kWh/kW and kWh/kW _p for wind and solar energy, respectively) |
| GIS: | Geographical information systems |
| GRAFCAN: | Public enterprise run by the autonomous government of the Canary Islands for the production and management of geographic and territorial information |
| ITC: | Instituto Tecnológico de Canarias; Technological Institute of the Canary Islands, an R & D enterprise run by the autonomous government of the Canary Islands |
| MCDM: | Multiple-criteria decision-making |
| INECP: | Integrated national energy and climate plan 2021–2030 |
| RE: | Renewable energy |
| RI: | Random index, average CI of the randomly generated comparisons (equation (2)) |
| STP-32: | Special territorial plan of the island of Gran Canaria. |

Data Availability

The data used to support the findings of wind speed are available at <http://www.itccanarias.org/recursoeolico/> (Instituto Tecnológico de Canarias (ITC): Technological Institute of the Canary Islands), solar radiation are available at http://www.idecanarias.es/listado_servicios/mapa-radiacion-solar (Spatial Data Infrastructure of the Canary Islands), visual impact are available at <http://www.gobiernodecanarias.org/cultura/actividades/cantierradecult09/10PATRIMONIO%20CULTURAL.pdf> (Autonomous Government of the Canary Islands), slope/orientation/road/potential self-consumption is available at <http://tiendavirtual.grafcan.es/index.jsf> (Cartografía de Canarias, S.A.- GRAFCAN), territorial planning are available at <https://www.idegrancanaria.es/catalogo> (Spatial Data Infrastructure of Gran Canaria), demand are available at <https://www.ine.es/> (Spanish Statistical Office), protected areas are available at https://www.miteco.gob.es/es/biodiversidad/servicios/banco-datos-naturaleza/informacion-disponible/ENP_Descargas.aspx (Ministry for Ecological Transition of the Government of Spain) and <http://catalogo.idecanarias.es/geonetwork/srv/spa/catalog.search#/search?resultType=details&inspiretheme=Lugares%20protegidos&from=1&to=20&sortBy=relevance> (Spatial Data Infrastructure of the Canary Islands), and roads/urban area/water bodies/sea-land limits/airports are available at <http://tiendavirtual.grafcan.es/index.jsf> (Cartografía de Canarias, S.A.- GRAFCAN) and <https://planesterritoriales.idegrancanaria.es/config/planes.xml> (Gran Canaria Regional Government).

Disclosure

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Conflicts of Interest

The authors declare that there are no conflicts of interest.

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Research Article

The Effect of Product-Harm Crises on the Financial Value of Firms under the Concept of Green Development

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Product-harm crises can trigger product recalls or product discards, which is very likely to cause secondary pollution to the environment. Also, these crises may harm customers' health and threaten firms' survival. To foster low-carbon economy and green development in such complex systems, this paper studies the internal mechanism of the product crisis and its impact on the firm value. It proposes a two-stage model to avoid the endogeneity of product-harm crises. In the first stage, this paper assesses the effect of firms' leverage on their capacity to produce higher quality products. In the second stage, this paper conducts the impact of these crises on stock prices. Then, it depicts the financial effects of product-harm crises over time, and analyzes the differences of such effects based on brand equity. Results show that book leverage can positively impact firms' capacity to produce high-quality products. In addition, the market's response to product-harm crises is significant at 1% level, and with the increase in severity, the market reaction is more prominent. Furthermore, its negative effect is persistent for a firm experiencing a severe crisis. Luckily, brand equity can mitigate this negative impact. These findings provide some ways to improve product performance and firm value in the green context.

1. Introduction

The Chinese government advocates harmonious coexistence between humans and nature, and sticks to the path of green and sustainable development. A huge amount of related work has been conducted [1, 2]. However, limited product-harm work has been conducted under the concept of green development. When a product-harm crisis occurs, it causes product recalls or product discards, resulting in a secondary pollution to the environment. The secondary pollution goes against the company's low-carbon economy and green development. Also, a product-harm crisis is potential for customers' economic loss, serious illness or injury, and even death [3]. Moreover, the crisis can affect a firm's reputation and value, and interrupt the supply and financial chain, leading to its bankruptcy, such as the Sanlu group [4, 5]. In such a complex context, it is worth exploring the underlying mechanism and external influence of the product-harm crisis.

The product-harm crisis is a knotty issue created by defective or dangerous products [6, 7]. As shown in a

previous study [8], the episode of a product-harm crisis includes initial negative event, firm's recovery strategy, and post-recovery. Much work has been done in the firm's recovery field, including the analysis of product recalls [9–12], the classification of firms' behavior [13–15], and the analysis of brand attributes [16–19]. However, limited work has been conducted in the stage of initial negative events, such as the type of crises or the severity of crises [8].

Furthermore, lots of recent work has focused on firms or investors [10, 11, 20], although early product-harm work focused on consumers [19, 21, 22]. The reason is that the overall effect of these crises is reflected in the stock returns immediately and directly [23]. Such an effect reveals investor perceptions of firm value [24]. As seen in the recent case of the Changsheng group (<http://news.windin.com>), the dangerous lyophilized human rabies vaccine has caused many infants to be disabled or even die. Following that, its stock price plunged sharply, from 24.55 yuan to 1.51 yuan, a drop of nearly 94 percent.

Research has found that most studies concerning the impact of product-harm crises are limited to developed

countries [25]. Still, some industries with frequent product-harm crises receive much less attention (e.g., clothing and information technology industries). Thus, this paper includes a variety of industries from China. It covers 208 cases from different industries, such as medicine products, machinery equipment, clothing, food, as well as information technology industry. Then, the paper examines the factor and effect of the incidence and severity of initial crises.

In addition, regarding the product-harm work, the majority treats time as a control factor, and not much literature considers the impact of such crises over time [8]. Therefore, it is valuable to depict the financial effect of product-harm crises over time. Moreover, extant work of product-harm crisis has to pay much attention to brand-related mediators. But, the findings are contradictory [18]. These two contradictory findings are as follows: brand equity buffers the negative effect affected by a crisis [3, 19, 21, 26], and brand equity is a trouble in the case of a crisis [27, 28]. From a new perspective, the investors' standpoint, this paper can provide a new evidence for the buffer effect of brand equity, by analyzing the differences in the negative effect between high brand equity and low brand equity.

In a nutshell, this paper aims to examine the internal factors and financial effects of incidence and severity of product-harm crises from a wide range of industries in a developing country. This paper firstly considers financial leverage influencing product-harm crises to address the endogenous issue. By doing so, it provides more conclusive and persuasive evidence that supports negative market reaction to initial product-harm crises. This paper then pictures the financial impact of these crises over time. Furthermore, through analyzing the differences in financial impact of most severe crises, this study finds that high brand equity can mitigate this financially negative effect.

2. Hypothesis

The effect of product-harm crises is reflected in the stock market directly. Extant studies have explored the financial effect of product-harm crises from different viewpoints. Firstly, from the perspective of industry, it is discussed that the fluctuations of stock prices in different industries after the product recall, especially in the automotive and pharmaceutical industries [4, 29–31]. Secondly, from the characteristics of the firm, the impact of product-recall strategies or CEO characteristics on the stock price of the firm has been discussed [11, 20, 32]. Thirdly, from the characteristics of crisis, such as the severity of product recall, the literature explores the impact of crisis characteristics on stock price movements [23].

Almost all these studies identify product-harm crises by product recalls and encompass the field of firm's recovery. However, as developing countries lack sound rules and regulations, the cases of product recalls per year are very limited. Research has only found 42 cases of product recalls from various industries in China, spanning 10 years [4]. Among these product recalls, 20 cases were in the automobile industry. Furthermore, limited product-harm work has focused on the initial negative events. Thus, this paper

focuses on the initial product-harm crises amid the green development scenario. The top priority is to study the internal factors of product-harm crises. Then, it examines the negative impact of such crises and to find effective solutions based on firm characteristics.

2.1. Financial Conditions Contributing to Product-Harm Crises. Some firms are more likely to experience product-harm crises due to their inherent characteristics. A string of articles prove that financial leverage may boost investments in firms, which will reduce the probability of such crises. Brander and Lewis [33] have suggested that leverage usage to shareholders can provide risk-shifting incentives at the expense of benefits to bondholders. By doing so, managers have the motivation to take out debt and increase their investments in firms to get a strategic advantage over their industry counterparts [34]. Furthermore, financially poor firms improve their investments through money subsidized by debt holders. As a consequence, these firms are more likely to get out of financial trouble and produce high product quality in the future using "someone else's money" [35]. In addition, another benefit of levered firms is that leverage can motivate managers and their organizations to be more competitive in operational management and more attentive to product market concerns [36]. Specially, debt taking forces managers to bond their promises to debt service payments. The threat posed by crises to repay debt is an effective motivation to make these managers and organizations more effective, thus leading to high product quality. These theoretical predictions have been supported by the empirical evidence presented by Campello and Fluck [37], which shows that firms with more debt have outperformed their industry counterparts. Thus, the following hypotheses are proposed:

Hypothesis 1a: the incidence of product-harm crises is negatively related to the financial leverage.

Hypothesis 1b: the severity of product-harm crises is negatively related to the financial leverage.

2.2. The Impact of Product-Harm Crises on Stock Prices of Firms. A product-harm crisis means that there are problems in the firm's production and operation process. Such a crisis can seriously damage a firm's image. Even worse, the quality of the product and the underlying information behind it will hit investors' confidence, which will immediately be reflected in the stock price. Thus, these investors make negative expectations about the development of the firm based on signal theory [38]. Then, investors will throw out their shares of the firm, which will lead to a decline in the stock price. What's more, investors' reaction to damage is more drastic than the reaction to an equivalent earnings, supported by the prospect theory [39]. Applied to product-harm crises, it is expected that investors focus more on potential losses than on potential gains in revenues [40]. Based on investors' loss aversion, this paper assumes that the incidence of product-harm crisis is negatively associated with stock prices.

Furthermore, the severity of product-harm crises is the degree of potential harm resulting from a product hazard. Rogers has noted that people will take more intense measures to protect themselves from external harm as the risks they face increase, suggested by the theory of protection motivation [41]. As a source of risk for consumers, product-harm crises will undoubtedly cause psychological panic and worry among the public. This psychological state leads to the unsalable products of the involved firm and the decline of the market position. In addition, a serious hazard is more likely to get much media attention [28, 42]. It conveys more frequent and vivid signals to consumers about harm to their health, resulting in greater circumspection about purchasing products from the affected firm. Investors incorporate these messages, intensified by their loss aversion, into their assessment of sales in the future [23]. Thus, the following hypotheses are proposed:

Hypothesis 2a: the incidence of product-harm crises is related to a negative stock market response.

Hypothesis 2b: the more severe the product-harm crises, the more negative the stock market response will be.

3. Sample Construction and Data Characteristics

3.1. Sample Construction. This paper identifies product-harm crises by searching the Wind database, China Food and Drug Administration (CFDA), State Administration for Market Regulation (SAMR), and Sina. We include A-share listed corporations from 2014 to 2017. The sample of firms needs to be China based and either listed on the Shanghai Stock Exchange (SHSE) or the Shenzhen Stock Exchange (SZSE). Stock prices are secured from the CSMAR database.

This paper then reports the distribution of sample by year in Panel A, industry in Panel B, and manufacturing industry in Panel C of Table 1. Panel A comprises 207 final samples. Of these, 34.78% of the samples occurred in 2017. Some firms have undergone more than one product-harm crisis during 2014–2017. Regarding the distribution of industries, manufacturing industry is the top list with the most reported subindustries. Thus, it represents the subindustry distribution of the manufacturing sector in Panel C. And, there are 9 two-level INC industries (industry classification code) in manufacturing sector. The frequency of events occurring in C8, C7, C1, and C0 industries decreases successively.

3.2. Data Characteristics of Product-Harm Crises and Control Firms. Table 2 reports univariate comparisons between product-harm crises and control firms on the basis of financial condition and other variables that can impact product-harm crises [43] and CARs [44]. The variables that could impact product-harm crises include Book leverage, Size, Sales, and the Number of suppliers [43–45]. Other variables that can impact CARs consist of R & D intensity, Book to market, and Net income. More specially, Book

leverage, Size, Sales, R & D intensity, Book to market, and Net income are calculated at the end of the previous year and are obtained from the CSMAR database. The number of suppliers is obtained from the WIND database.

Table 2 reports the univariate comparisons between product-harm samples and control samples. The sample period is 2014–2017. Control samples are the firms that belong to the same 3-level INC industry (industry classification code) as the product-harm firm provided and they were not announced with product-harm crises during 2014–2017. The total assets of control firms are similar to that of product-harm firms. T-Stat provides the t-statistic from a *t*-test for equality in means between the product-harm firms and control firms. Z-Stat provides the z-statistic for the equality of medians between the product-harm firms and control firms. ***, **, and * indicate significance at 1%, 5%, and 10%, respectively.

Of all these, Book leverage represents the sum of the long-term debt and debt in current liabilities divided by total assets. The logarithm of the total asset is regarded as a proxy for firm size. Sales represents the logarithm of sales as an indicator for firm's continuing income. Number of suppliers presents the number of key suppliers of the firm, which is obtained from the WIND database. Because it is difficult to get the number of suppliers of the firm every year, this paper assumes that the number of suppliers is constant in different years. R & D intensity is defined as R & D spending over total assets.

Book to market is the firm's book-to-market ratio as an indicator for the firm's value. High Book to market means high value and low growth, and vice versa. Net income is the logarithm of net income from operating activities, which represents a net sustainable income.

In Table 2, the univariate statistics on the variables for product-harm crises and control firms are presented. Control firms are firms belonging to the same 3-level INC industries as the product-harm firms with a similar total asset but have not experienced a product-harm crisis in any of the years during 2014–2017. This paper then performs a *t*-test to test for the equality of means between the product-harm samples and control samples. A Wilcoxon rank-sum test is also performed to test for the equality of medians. As a result, this paper finds that product-harm firms have significantly higher Size, Sales, and Net income than control firms.

4. Market Reaction upon Announcement of Product-Harm Crises

Event study methodology (ESM) [46–49] is a well-established approach that has been widely applied to assess the effect of particular events on firms or investors, such as product recalls [32, 43], merger and acquisition announcements [50], CEO scandals [44], and banking crises [51]. Therefore, this paper utilizes ESM to assess the impact of product-harm crises on stock returns in China [4].

In essence, an unexpected event is observed to generate significant abnormal stock returns (AR), which indicate the market's estimate of a firm's value in the future. The

TABLE 1: Frequency of product-harm crises and industries covered in product-harm sample.

| A: frequency of product-harm crises by crisis type | | | | |
|--|---|-------------------------------|---------|--------|
| Year of product-harm crises | | Freq. | Percent | Cum. |
| 2014 | | 38 | 18.27 | 18.27 |
| 2015 | | 55 | 26.44 | 44.71 |
| 2016 | | 72 | 34.62 | 79.33 |
| 2017 | | 43 | 20.67 | 100.00 |
| 2014–2017 | | 208 | 100.00 | 100.00 |
| B: industries covered in product failure sample at 1-level INC level | | | | |
| 1-level INC | Description of industry | Number of product-harm crises | Percent | Cum. |
| A | Agricultural | 1 | 0.48 | 0.48 |
| C | Manufacturing industry | 165 | 79.71 | 80.19 |
| D | Water production and supply | 2 | 0.97 | 81.16 |
| G | Information technology industry | 19 | 9.18 | 90.34 |
| H | Whole income and retail trade | 18 | 8.70 | 99.03 |
| J | The real estate industry | 1 | 0.48 | 99.52 |
| M | Comprehensive industry | 1 | 0.48 | 100 |
| C: industries covered in manufacturing product failure sample at 2-level INC level | | | | |
| C0 | The food and beverage industry | 19 | 11.52 | 11.52 |
| C1 | Textile clothing and fur | 29 | 17.58 | 29.10 |
| C3 | Paper and printing | 1 | 0.61 | 29.71 |
| C4 | Petroleum, chemicals, and plastics | 18 | 10.91 | 40.62 |
| C5 | Electronic engineering | 1 | 0.61 | 41.23 |
| C6 | Metal and nonmetal | 11 | 6.67 | 47.90 |
| C7 | Machinery, equipment, and instrumentation | 32 | 19.39 | 67.29 |
| C8 | Medicine and biological products | 52 | 31.52 | 98.81 |
| C9 | Other manufacturing | 2 | 1.21 | 100 |

In Table 1, panel A presents the frequency and percent of product-harm crises in our product-harm sample by public traded corporations during 2014–2017. Panel B shows the different 1-level INC (industry classification code) industries covered in our product-harm sample, as well as the number and percent of product-harm crises under each 1-level INC industry. Panel C reports the different 2-level INC (industry classification code) industries covered in our manufacturing product-harm sample, as well as the number and percent of product-harm crises under each 1-level INC industry.

TABLE 2: Univariate comparisons between product failure samples and control firms.

| Variable | Product failure sample | | | | Control sample | | | | T (Z) Stat |
|---------------------|------------------------|--------|--------|-------|----------------|--------|--------|-------|-----------------------|
| | Obs | Mean | Median | S.D. | Obs | Mean | Median | S.D. | |
| Book leverage | 207 | 0.393 | 0.360 | 0.181 | 207 | 0.400 | 0.393 | 0.198 | −0.390 (0.241) |
| Size | 207 | 22.703 | 22.554 | 1.189 | 207 | 22.591 | 22.417 | 1.128 | −5.092*** (−4.853***) |
| Sales | 207 | 22.413 | 22.168 | 1.355 | 207 | 22.014 | 21.970 | 1.297 | −7.270*** (−6.848***) |
| Number of suppliers | 180 | 3.222 | 3.000 | 2.244 | 170 | 3.741 | 5.000 | 2.392 | 1.601 (1.624) |
| R & D intensity | 195 | 0.021 | 0.015 | 0.054 | 185 | 0.020 | 0.016 | 0.015 | −0.487 (0.916) |
| Book to market | 199 | 0.813 | 0.543 | 0.748 | 207 | 0.803 | 0.535 | 0.844 | −0.067 (−0.756) |
| Net income | 188 | 19.966 | 20.035 | 1.431 | 176 | 19.666 | 19.795 | 1.539 | −2.931*** (−2.669***) |

advantage of ESM is that it identifies stock price volatilities due to a firm-specific event [52]. Utilizing ESM, this paper calculates abnormal returns (AR) of the product-harm crisis, which reflect the financial impact of such an event. The value of Abnormal returns (AR) is measured as the difference between actual returns and expected returns around the time of the event. Cumulative abnormal returns (CARs) reflect the cumulative effects of the firm-specific event. When the value of CARs is negative, it indicates that the event is unfavorable. In this case, the event usually leads to the prediction of negative future profitability.

To test the market reaction to the incidence and severity of product-harm crises, this paper uses the event study methodology. The earliest announced day of product-harm crisis is treated as the event date. Then, it measures

Cumulative Abnormal Returns (CARs) over a few days around the publicity of product-harm crises. The value of CARs is the sum of the abnormal returns during our windows of interest. Since many product-harm crises are first discovered before public date, the information has been leaked to the market before being made public. This paper then computes CARs prior to the event date to cover for the news leakage. Thus, the windows include (−5, +1), (−10, +1), (−10, +5), (−1, +10), and (−10, +10), with day 0 representing the day that the product-harm crisis is made public.

To predict forecasted daily returns, this paper uses four approaches as given below. The paper firstly utilizes the Fama-French three-factor model to predict daily returns [53]. Then, it computes the abnormal return for firm i on day t (AR_{it}) as given below.

$$AR_{it} = R_{it} - (\alpha RP_t + \beta SMB_t + \gamma HML_t + RF_t). \quad (1)$$

R_{it} is the return of firm i on day t . RP_t is the market risk premium factor, the difference between the daily market return rate of the cash dividend reinvestment (the total market capitalization weighted average method) and the daily risk-free interest rate (the central bank announces the three deposit benchmark interest rate). SMB_t (small minus big) is the result of the returns of small-stock portfolios minus the returns of big-stock portfolios. HML_t (high minus low) is the difference between the returns of high and low book-to-market equity portfolio with about the same weighted average size. RF_t is the daily risk-free interest rate. Because the change of RF is small, the biggest change is only 0.004% during our sample period of 2014–2017; this paper assumes that it is constant. α , β and γ are parameters to estimate. The model is evaluated by utilizing the daily returns over the estimation period (−200, −11) as presented in

$$R_{it} = \alpha RP_t + \beta SMB_t + \gamma HML_t + RF_t + \varepsilon_{jt}. \quad (2)$$

Second, the research also calculates CARs using the method of Fama-French five-factor model to predict daily returns [24]. This model is constructed by adding two factors to the Fama-French three-factor model. The two additional factors are profitability and investment factors.

In addition, this paper uses the average of the daily returns over the estimation period (−200, −11) as forecasted returns to measure CARs [44]; calling it the e-period model here. Furthermore, the market model is utilized to predict daily returns. This paper then computes the abnormal return for firm i on day t (AR_{it}) as follows:

$$AR_{it} = R_{it} - (\alpha RP_t + \beta R_{mt}). \quad (3)$$

R_{it} is the return of firm i on day t , R_{mt} is the return of the CSMAR equally weighted Index, α and β are parameter estimates. The model is estimated using daily returns over the period (−200, −11) as presented in

$$R_{it} = \alpha RP_t + \beta R_{mt} + \varepsilon_{it}. \quad (4)$$

Next, product-harm crises are classified into three categories referring to FDA (U.S. FOOD & DRUG ADMINISTRATION) severity classification criteria. Class I events are the least severe; Class II events can induce temporary, medically reversible adverse health consequences or major financial loss; and Class III events being the most severe are likely to induce adverse health consequences or death [43]. For events that are not sufficiently detailed, the paper cannot judge the severity from the announcements and do not classify them. Then, two subsamples are obtained, one including Class II and Class III, and the other including Class III only. A t -test is performed to test for the means of CARs equal to zero, containing the whole sample and two

subsamples, respectively. Panel A of Table 3 presents the means and t -test of CARs. More specifically, this paper measures CARs for event periods surrounding the public dates of the product-harm crises. Findings demonstrate that the mean CARs are negative across all the event periods, either for the whole sample or for the other two subsamples. Of the 60 mean CARs, 59 are significant at the 10% level or better and 31 are significant at the 1% level. Thus, the negative CARs confirm the hypothesis that investors respond unfavorably to public product-harm crises. For the overall sample of product-harm crises, 9 of the 20 mean CARs are significant at the 1% level. For the subsample of Class II & Class III, 10 of the 20 mean CARs are significant at the 1% level. For the subsample of Class III, 12 of the 20 mean CARs are significant at the 1% level. This supports the fact that severity of product-harm crises can contribute to CARs.

However, results find that the mean CARs computed by the Fama-three model and the Fama-five model are not affected by severity of product-harm crises. Furthermore, for overall samples, their (−1, +10) event windows have mean CARs of −2.187%, −2.400%, respectively, with the highest t -Stat. But the mean CARs by the e-period model and market model are contributed by severity of product-harm crises. For product-harm samples, their (−5, +1) event windows have mean CARs of −1.800%, −1.963%, respectively, with the highest t -Stat. To further verify whether the severity of product-harm crises has an impact on stock price anomalies, a nonparametric test, Kruskal–Wallis, is performed to test CARs computed by the e-period model and the market model. The results are presented in panel B of Table 3, which also support the fact that severity of product-harm crises can contribute to CARs.

Moreover, this paper needs to disentangle the impact of the financial condition, firm size, sales, and the number of suppliers from incidence/severity of the product-harm crises to determine the true effect of the latter on the firm's share price. This paper then uses the two-stage procedure to control for this endogenous issue. In the first stage, a probit regression model and an ordered probit regression model are applied, respectively, to estimate the propensity that a firm is influenced by incidence/severity of product-harm crises. In the second stage, this paper derives the R & D intensity, Book to market, and Net income that are employed in the cross-sectional analysis of the CARs.

4.1. The Likelihood Being Affected by Product-Harm Crises.

Firstly, the hypotheses about the factors that impact the incidence/severity of product-harm crises are empirically investigated. The main models are probit regressions and ordered probit regressions, respectively. They are shown as follows:

TABLE 3: Announcement effects of product-harm crises.

| A: parameter test | | | | | | | | | | |
|-----------------------|---------------|-------------------------|-----------------|-------------------|--------------------------|---------------------|-----------------|---------------|-----------------|----------|
| Estimation method | Event windows | (1) product-harm crises | | | (2) class II & class III | | | (3) class III | | |
| | | Mean (%) | <i>t</i> -Stat. | <i>N</i> | Mean (%) | <i>t</i> -Stat. | <i>N</i> | Mean (%) | <i>t</i> -Stat. | <i>N</i> |
| Fama-three | (−5, +1) | −1.618 | −3.07*** | 209 | −2.214 | −3.05*** | 134 | −2.279 | −2.78*** | 107 |
| | (−10, +1) | −1.699 | −2.07** | | −3.154 | −2.67*** | 134 | −3.246 | −2.34** | |
| | (−10, +5) | −2.343 | −2.30** | | −3.815 | −2.54** | 134 | −3.855 | −2.30** | |
| | (−1, +10) | −2.187 | −4.10*** | | −2.112 | −2.97*** | 134 | −2.430 | −3.31*** | |
| | (−10, +10) | −3.266 | −3.03*** | | −4.647 | −2.96*** | 134 | −4.724 | −2.77*** | |
| Fama-five | (−5, +1) | −1.646 | −2.74*** | 208 | −2.285 | −2.64*** | 133 | −2.268 | −2.24** | 106 |
| | (−10, +1) | −1.570 | −1.71* | | −3.078 | −2.29** | 133 | −2.910 | −1.86* | |
| | (−10, +5) | −2.209 | −1.97* | | −3.836 | −2.29** | 133 | −3.681 | −1.92* | |
| | (−1, +10) | −2.400 | −3.76*** | | −2.412 | −2.69*** | 133 | −2.636 | −2.69*** | |
| | (−10, +10) | −3.229 | −2.62*** | | −4.696 | −2.55** | 133 | −4.523 | −2.21** | |
| E-period | (−5, +1) | −1.800 | −2.99*** | 209 | −2.602 | −3.42*** | 134 | −3.579 | −4.13*** | 107 |
| | (−10, +1) | −1.505 | −1.81* | | −3.075 | −2.87*** | 134 | −3.878 | −3.30*** | |
| | (−10, +5) | −1.812 | −1.72* | | −2.938 | −2.06** | 134 | −4.073 | −2.70*** | |
| | (−1, +10) | −1.717 | −1.72* | | −1.400 | −1.17 | 134 | −2.531 | −1.84* | |
| | (−10, +10) | −2.551 | −1.88* | | −3.560 | −1.95* | 134 | −5.053 | −2.52** | |
| Market model | (−5, +1) | −1.963 | −3.80*** | 210 | −2.818 | −4.29*** | 136 | −3.612 | −4.95*** | 109 |
| | (−10, +1) | −1.502 | −1.98** | | −3.141 | −3.12*** | 136 | −3.736 | −3.32*** | |
| | (−10, +5) | −1.724 | −1.82* | | −3.191 | −2.41** | 136 | −3.899 | −2.75*** | |
| | (−1, +10) | −2.446 | −2.72*** | | −2.568 | −2.26** | 136 | −3.647 | −2.84*** | |
| | (−10, +10) | −2.957 | −2.37** | | −4.371 | −2.50** | 136 | −5.493 | −2.85*** | |
| B: nonparametric test | | | | | | | | | | |
| Estimation method | Event windows | Kruskal–Wallis test | | Estimation method | Event windows | Kruskal–Wallis test | | | | |
| | | chi2-value | <i>P</i> -value | | | chi2-value | <i>P</i> -value | | | |
| E-period | (−5, +1) | 15.927 | 0.0003*** | Market model | (−5, +1) | 18.705 | 0.0001*** | | | |
| | (−10, +1) | 19.090 | 0.0001*** | | (−10, +1) | 24.004 | 0.0001*** | | | |
| | (−10, +5) | 14.039 | 0.0009*** | | (−10, +5) | 13.565 | 0.0011*** | | | |
| | (−1, +10) | 4.582 | 0.1011 | | (−1, +10) | 6.080 | 0.0478** | | | |
| | (−10, +10) | 10.312 | 0.0058*** | | (−10, +10) | 11.181 | 0.0037*** | | | |

In panel A, CARs are shown for the windows in days around the event date. The windows are as follows: (−5, +1), (−10, +1), (−10, +5), (−1, +10), and (−10, +10). In methods 1 and 2, this paper utilizes Fama-French three-factor model and Fama-French five-factor model, respectively. In addition, it uses E-period and Market model in methods 3 and 4. In panel B, Kruskal–Wallis is employed to test the impact of severity of product-harm crises on stock price anomalies, which is calculated from e-period model and market model.

$$\begin{aligned}
\frac{\text{Incidence}_{i,t}}{\text{Severity}_{i,t}} \left(\frac{\text{Incidence}_{i,t} = 0, 1}{\text{severity}_{i,t} = 0, 1, 2, 3} \right) &= \alpha_0 + \alpha_1 \text{Book leverage}_{i,t-1} + \alpha_2 \text{Size}_{i,t-1} + \alpha_3 \text{Sales}_{i,t-1} + \alpha_4 \text{Number of suppliers}_{i,t-1} \\
&+ \frac{\text{Year and}}{\text{or industry dummies}} + \varepsilon_{i,t}.
\end{aligned} \tag{5}$$

In the above model, the dependent variables are Incidence and Severity, respectively. Incidence is a dummy variable that takes the value 1 if a product-harm crisis occurs for firm i in year t , and 0 for control firms in our sample. Severity is a dependent variable, which is set to 1 for Class I events (the least severe product-harm crises), 2 for Class II events, 3 for Class III events (the most severe product-harm crises), and 0 for control firms in our sample. All independent variables are lagged by one year to help ease concerns about reverse causality [43].

The regression results are presented in Table 4. Columns (1) and (4) include Book leverage, Size, Sales, and

calendar year dummies. Number of suppliers is added in Columns (2) and (5), and 1-level INC industry dummy is added in Columns (3) and (6). The table shows marginal effects with their P -values in parentheses. These P -values are based on heteroskedasticity robust standard errors and are clustered by firm. The results are showed in the six columns.

Specifically, results find that the relation between the Incidence/Severity and book leverage is negative in all models. The coefficient is higher when the model includes Number of suppliers and 1-level INC industry dummies in Columns (3) and (6). Such results imply that higher leverage

TABLE 4: The likelihood being affected by incidence/severity of product-harm crises.

| Dep. variables | Incidence | | | Severity | | |
|---------------------|----------------------|---------------------|---------------------|-----------------------|-----------------------|-----------------------|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Book leverage | -0.836* (0.084) | -1.035* (0.067) | -1.037* (0.068) | -0.669 (0.159) | -0.924* (0.086) | -0.995* (0.071) |
| Size | -0.468*** (0.004) | -0.402** (0.028) | -0.402** (0.030) | -0.387*** (0.006) | -0.345** (0.029) | -0.351** (0.026) |
| Sales | 0.566*** (0.000) | 0.541*** (0.001) | 0.541*** (0.001) | 0.505*** (0.000) | 0.495*** (0.000) | 0.496*** (0.000) |
| Number of suppliers | | -0.052 (0.209) | -0.052 (0.210) | | -0.046 (0.221) | -0.047 (0.216) |
| Year dummies | Yes | Yes | Yes | Yes | Yes | Yes |
| Industry dummies | No | No | 1-level INC | No | No | 1-level INC |
| Observations | 413 | 350 | 350 | 407 | 343 | 343 |
| Wald | 17.96*** (0.0063) | 15.74** (0.0276) | 15.81** (0.0453) | 558.07*** (0.0000) | 553.29*** (0.0000) | 530.31*** (0.0000) |

Table 4 presents estimation results of the incidence and severity for product-harm events by listed firms during 2014–2017. The dependent variables are incidence and severity. Incidence is a dummy variable, which is set to 1 for firms in the product-harm sample, and 0 for control firms. Severity is an ordered rank variable, which is set to 1, 2, or 3 for firms in the product-harm sample according to the severity of the event, and 0 for control firms. Columns (1) and (4) contain estimation results when they include Book leverage, Size, Sales, and calendar year dummies. Columns (2) and (5) contain estimation results when they add Number of suppliers. Columns (3) and (6) contain estimation results when they add 1-level INC industry dummies. Marginal effects are presented in the table. Presented *P*-values in the parentheses are based on heteroskedasticity robust standard errors. These *P*-values are clustered by firm. ***, **, and * indicate significance at 1%, 5%, and 10%, respectively.

for China' firms can hinder the incidence of failures and degrade the hazard of crises. These findings are consistent with the view that higher debt can help firms get out of financial trouble, and get a strategic advantage over their industry counterparts. These findings also agree with the notion that higher leverage may motivate managers and their organizations to be more efficient in operational management and more attentive to product market concerns, which lead to higher product quality. Our hypothesis 1a and 1b are supported by these.

Furthermore, there is a significant negative relation between the Incidence/Severity and Size in all models. The smaller firms are more likely to have product-harm crises and their severity is higher. An explanation for this is that a large firm might have more to lose from product-harm crises than a smaller firm, and may therefore have stricter product quality control processes than smaller firm. Hence, the probability and severity of product-harm crises decrease in larger firms compared to smaller firms. Results then find that there exists a positive relation between the Incidence/Severity and Sales. Higher sales may imply greater production output, increasing the probability of incidence and severity for product-harm crises. Finally, results do not find a relation between the incidence/severity of product-harm crises and the Number of suppliers.

4.2. The Short-Term CARs Being Affected by Product-Harm Crises

4.2.1. CARs Being Affected by Product-Harm Crises. Results find that the mean CARs computed by the Fama-three model and the Fama-five model are not affected by severity of product-harm crises. For overall samples, their (−1, +10) event windows have mean CARs of −2.187%, −2.400%, respectively, with the highest *t*-Stat. Thus, this section uses (−1, +10) CARs computed by the Fama-three model and the Fama-five model as dependent variables. But the mean CARs calculated by the e-period model and the market model are contributed by severity of product-harm crises. For product-harm samples, their (−5, +1) event windows have mean CARs of −1.800%, −1.963%, respectively, with the highest *t*-Stat. Therefore, this section uses (−5, +1) CARs computed by the e-period model and the market model as dependent variables.

Multiple regression analysis is employed to account for the variations in the CARs as presented in equation (6). The regression enables us to establish whether the variable incidence/severity of product-harm crises is significantly associated with the CARs after controlling for other firm characteristics. It is expected that the value of the coefficient of incidence/severity is significantly negative. This negative coefficient reflects the unfavorable share price reaction to public product-harm crises.

$$\begin{aligned}
 CARs_{i,t} = & \alpha_0 + \frac{\alpha_1 \text{Incidence}_{i,t}}{\text{Severity}_{i,t}} + \alpha_2 \text{Book to market}_{i,t-1} + \alpha_3 \text{R\&D intensity}_{i,t-1} \\
 & + \alpha_4 \text{Net income}_{i,t-1} + \frac{\text{Year and}}{\text{or industry dummies}} + \varepsilon_{i,t}.
 \end{aligned} \tag{6}$$

In equation (6), Book to market is the firm's book-to-market ratio, an indicator for firm's value—low-value firms are related to low book-to-market, and vice versa. R & D intensity is the research & development spending divided by total assets. Net income is the logarithm of net operating income. Book to market, R & D intensity, and Net income are calculated at the end of the prior year and downloaded from the CSMAR database. R & D intensity and Net income are included in control variables.

4.2.2. Cross-Sectional Analysis of CARs. As product-harm crises may be attributed to various factors including the financial condition, firm size, sales, and the number of suppliers, there exist a self-selection issue in product-harm samples. For instance, a firm with small size is more likely to have a product-harm crisis, thus making it more likely to be included in the sample. By examining the impact of product-harm crises on CARs, this section would have introduced a risk of endogeneity into the analysis, caused by potentially omitted variables that could affect the predicted variable. If the endogeneity cannot be statistically corrected, biased coefficient estimates and faulty conclusions will follow [54]. To address this potential endogenous problem, this section uses the two-step regressions approach [55]. Table 5 presents the findings of the two-step regressions on the firms' CARs [56].

In the first stage, this section estimates the probability of a firm being affected by incidence/severity of a product-harm crisis, based on model (3) and model (6) from Table 4. In the second stage, the dependent variables (−1, +10) CARs is from the Fama–French three-factor model and the Fama–French five-factor model in Columns (1) and (2). Then (−5, +1) CARs are computed by the e-period model and the market model as dependent variables in Columns (3) and (4). Incidence/Severity is an endogenous variable. Incidence is set to 1 for firms in the product-harm crises sample, and 0 for the control sample. Severity is set to 1 for Class I events (the least severe product-harm crises), 2 for Class II events, 3 for Class III events (the most severe product-harm crises), and 0 for control firms in our sample. Book to market, R & D intensity, and Net income are included as exogenous variables in the CARs regressions. R & D intensity and Net income are regarded as control variables. Panel A contains results from the 2nd stage of the two-stage estimation utilizing book leverage, size, sales, and the number of suppliers as instruments from Panel B. All estimations include year dummies and 1-level INC industry dummies.

The primary focus is Incidence, which is employed to test whether the product-harm crisis elicits an unfavorable share price reaction. Results show that there exists a negative relation between the CARs and the likelihood of a product-harm crisis. Its coefficient is significantly different from zero at 5% in both Columns (1) and (2). This confirms that the incidence of product-harm crises is related to negative CARs, which also supports the univariate results reported earlier in Table 3.

The second focus is Severity, which is established to test whether the severity of product-harm crisis elicits an

unfavourable stock market reaction. The coefficient of Severity is consistently negative and significant at least at 5% in Columns (3) and (4). This confirms that the severity of product-harm crises is related to negative CARs and also supports the univariate results reported earlier in Table 3. The finding means that a serious event is more likely to cause a fall in share price. Furthermore, results find that the relation between the CARs and Book to market is positive and significant at the 10% level in Column (4). This suggests that value firms can relieve the effect of the severe hazard and growth firms deepen it. This is because growth firms' products are often early in their product life cycle, with uncertain revenues in the future [23]; investors react more strongly to it when such a firm experiences a product-harm crisis. Meanwhile, this result is consistent with the value effect concept, which believes that value stocks outperform growth stocks globally.

4.3. The Differences in Negative Effect Affected by Product-Harm Crises

4.3.1. The Duration of the Negative Effect Based on Crisis Severity. To further explore whether the effect of the product crises is temporary or permanent, this section has examined the duration of the negative effect based on its severity. Since Class II has a small number of samples, we put Class I and Class II in the second group. Cumulative average abnormal returns (CAARs) of Class I, Class II and Class II, and Class III are plotted across event time for the event windows (−5, 90) in Figure 1. The figure shows that the stock price fell upon publicity of the product-harm crisis. But the pattern of CAARs diverged by severity of product-harm events. For firms experiencing a Class I event (the least severe), their stock prices stopped decreasing after 60 days. A similar pattern was found for the second group (Class I and Class II), although the decline in stock prices halted at about 70 days. The nadir of its CAARs was roughly −0.1. Following the firms with a Class III event (the most severe), the trend line was steeper. Still, the stock price did not recover and the CAARs reached roughly −0.17 within 90 days after the event. Such a result suggests that its negative effect is persistent when a product-harm event with a Class III hazard occurs. Therefore, the duration of the negative reactions varied with the severity of product-harm crises. This result provides evidence to further support H2a and H2b.

4.3.2. The Difference of Negative Effects Based on Brand Equity. As the negative effect of a firm with Class III hazard is persistent and significant, this section compares the 25 firms experiencing the lowest drops in stock prices with 25 firms having the highest drops in stock prices, based on brand equity. These drops in stock returns are measured during the event window (−5, +1) by the market model.

Brand equity has been defined as an added value that is given to a product [57, 58]. More comprehensively, brand equity is identified as the brand value that stems from a high level of brand loyalty, perceived quality, name recognition, and strong brand associations as well as assets related to the

TABLE 5: CARs being affected by incidence/severity of product-harm crises.

| Panel A Dep. variables CARs | CARs from Fama3 (1) | CARs from Fama5 (2) | CARs from e-period model (3) | CARs from market model (4) |
|---------------------------------------|------------------------|------------------------|---------------------------------|-------------------------------|
| Incidence/severity | -0.025** (0.017) | -0.023*** (0.010) | -0.008** (0.014) | -0.008*** (0.003) |
| Book to market | 0.004 (0.246) | 0.001 (0.790) | 0.004 (0.420) | 0.007* (0.092) |
| Control variables | Yes | Yes | Yes | Yes |
| Panel B instrument in the first stage | | | | |
| Book leverage | -1.023* (0.071) | -0.996* (0.079) | -0.911* (0.096) | -0.995* (0.071) |
| Size | -0.396** (0.031) | -0.408** (0.026) | -0.379** (0.015) | -0.351** (0.026) |
| Sales | 0.532*** (0.001) | 0.535*** (0.001) | 0.487*** (0.000) | 0.496*** (0.000) |
| Number of suppliers | -0.055 (0.180) | -0.055 (0.187) | -0.047*** (0.215) | -0.047 (0.218) |
| Industry dummies | 1-level INC | 1-level INC | 1-level INC | 1-level INC |
| Observations | 398 | 397 | 391 | 392 |
| Wald | 38.29*** (0.0014) | 30.97*** (0.0089) | 51.29*** (0.0000) | 1636.95*** (0.0000) |

Table 5 shows results for the cross-sectional analyses of the $(-1, +10)$ CARs from the Fama–French three-factor model and the Fama–French five-factor model, and the $(-5, +1)$ CARs from the e-period model (Compared to estimation period) and the market model during our sample period. Incidence is an endogenous variable. It is set to 1 for firms in the product-harm sample, and 0 for the control sample. Severity is an ordered rank variable, which is set to one, two, or three for firms in the product-harm samples according to the severity of the event, and zero for control firms. All estimations include year dummies and 1-level INC. Column (1) and Column (2) are the results run in the Fama3 and Fama5 models, respectively, and Incidence is the endogenous variable. Column (3) and Column (4) are the results run in the e-period model and the market model, respectively, and Severity is the endogenous variable. Presented P -values in the parentheses are based on heteroskedasticity robust standard errors and are clustered by firm. ***, **, and * indicate significance at 1%, 5%, and 10%, respectively.

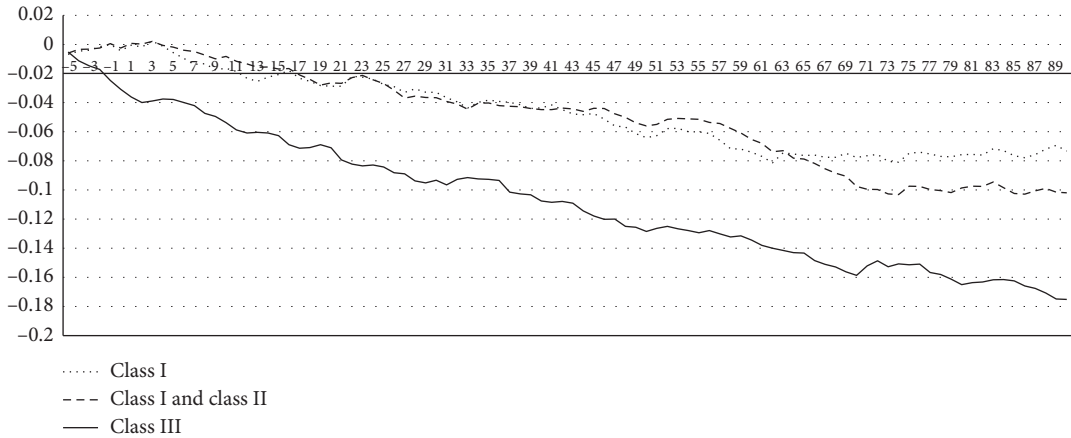


FIGURE 1: Cumulative average abnormal returns over time.

brand, such as trademarks, patents, and distribution channels [59]. This paper thereby treats brand equity and brand value equally. Also, these two terms can be used interchangeably and high brand equity means a valuable brand [60]. Furthermore, higher brand equity of a firm is called strong brand, otherwise it is a weak brand.

In the product-harm research, there exist two different claims regarding the effect of brand equity. Some scholars found that brand equity buffers against the negative impact, but others claimed that brand equity is a liability when faced with crises. For instance, some research has found that strong brands are less vulnerable to the negative impact of

corporate crises [19–21]. But some literature documents that higher brand equity means higher expectation, which can be a trouble in case of a product-harm event [27, 28]. Then, this section examines whether high brand equity can resist the harmful effect of product-harm crises in China from an investor perspective.

Next, this section identifies those brands that appeared on the China's 500 Most Valuable Brands (CMVB) list at least once from our sample period as strong brands [20]. The remaining brands are classified as weak brands. It sets a dichotomous variable that takes the value 1 to present a strong brand and 0 otherwise. Among the firms with lowest

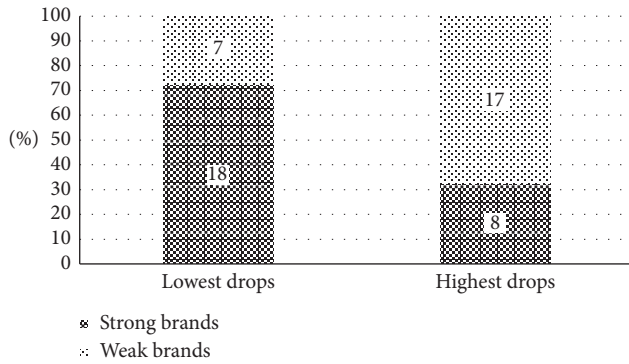


FIGURE 2: The difference of CARs affected by firms' brand equity.

drops in the stock price, 18 firms are strong brands, accounting for 72%. In another group, 17 firms are weak brands, accounting for 68%. These findings in Figure 2 suggest that strong brands can resist the negative effect of the severe hazards. In the long run, building a strong brand is very valuable. It can not only mitigate event risks but also benefit firms and investors.

5. Conclusion

Under the concept of green development, this study focuses on the initial stage of the product-harm crises to prevent secondary pollution caused by product recall or product disposal. To disentangle the effect of the inherent characteristics of firms from incidence/severity of the product-harm crises, it utilizes the two-stage procedure to control for this endogenous issue.

Firstly, this paper documents that firms hit by product-harm crises usually have a higher debt, and those with higher leverage are less likely to be mired by product-harm crises. Furthermore, such firms are less likely to undergo serious crises. These findings imply that higher leverage can encourage managers and organizations to focus on product issues. Moreover, results show that a large firm is less likely to have crises. This result is contrary to that of extant research [43]. An explanation is that a large firm might have more to lose from product-harm crises than a smaller firm. Hence, the probability of incidence and the severity of crises should decrease in larger firms, compared to smaller firms.

Secondly, the results of this study demonstrate that the incidence and severity of product-harm crises have a significant impact on the stock prices. Although previous literature has examined the effects of the incidence and severity of product recall on stock market [4, 23], little research has been conducted on the financial effect of initial crisis rather than its recovery strategy. Also, this paper demonstrates the financial effect of the incidence and severity of product-harm crises and offers a precise "size" of negative effect of its initial crisis. Results show that investors react adversely to product-harm crises. Furthermore, the drops in stock price are positively associated with the severity of product hazards. The result shows that firms with high potential growth appear to have more negative stock prices. This implies that growth firms should take some appropriate actions to

reassure investors. For instance, such firms can announce specific remedies for product issues when faced with product-harm crises.

Moreover, regarding the differences of CARs over time based on its severity, the duration of the negative reactions varied with the severity of product-harm crises. Results show that its negative effect is persistent when faced with the most severe crisis. If they are not life-threatening crises, the losses in the stock market will stop in the near future. These findings help firms to better understand the financial loss brought by crisis over time, because most studies consider the effect over time [8]. Then this paper firstly considers the buffer effect of brand equity from investors' perspective. Results confirm that brand equity can mitigate the negative effect in case of serious crisis. Such results give a new support for the fact that brand equity is a buffer rather than a trouble when faced with a crisis [19, 21, 26, 27].

In short, this paper evaluates the probability of a firm being influenced by incidence/severity of a crisis. Then, results find that firms with higher debt, larger size, and small sales are less likely to undergo product-harm crises. This provides new ideas for firms to better implement low-carbon economy and green development. After that, it explores the financial effects of incidence and severity of product-harm crises as well as the potential growth. Next, this paper analyzes the differences of CARs in cross section and that over time based on its severity. Our findings give new insights for firms to improve product performance amid the green context. Furthermore, the findings present some ways to enhance firm value in complex social networks.

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.

Acknowledgments

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Research Article

The Influence of Academic Independent Directors and Confucianism on Carbon Information Disclosure: Evidence from China

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As global warming has received widespread attention, the disclosure of firms' carbon information has been expected by increasing stakeholders. This study extends the previous literature on the determinants of firms' carbon information disclosure by examining the influence of academic independent directors and Confucianism on the quality of carbon information disclosure. Using a sample of Chinese listed firms in the CSI 300 Index during the period of 2012–2018, our empirical results show that academic independent directors have a significantly positive association with the quality of carbon information disclosure. The results also reveal that Confucianism positively affects the quality of carbon information disclosure. Moreover, Confucianism positively moderates the relationship between academic independent directors and the quality of carbon information disclosure. The results imply that Confucianism, as an informal system, can promote the governance effect of academic independent directors on firms' carbon information disclosure behaviour. Our findings offer shareholders, regulators, and other stakeholders an integrating perspective on motivating firms to disclose high quality carbon information.

1. Introduction

Global warming is one of the greatest concerns in the twenty-first century, and firms can be both the main culprit and problem solver of the greenhouse effects [1]. Several countries have implemented mandatory schemes that require disclosure of greenhouse gas (GHG) emissions, such as Australia, Canada, France, Japan, the United Kingdom, and the United States. China has not formulated mandatory carbon information disclosure (CID) requirements yet; thus, the carbon information disclosed by firms can be regarded as voluntary [2]. It is widely known that China's economy has developed rapidly and its international status has been improved at a high speed. However, China's environmental problems in recent years have attracted worldwide attention [3]. China has become the largest carbon emitter, with its emissions of CO₂ accounting for 28% of the total amount [4]. To reverse the situation, China made a significant U.S.-

China Joint Presidential Statement on Climate Change on 25 September 2015, pledging to lower carbon dioxide emissions per unit of GDP by 60% to 65% from 2015 level by 2030 [5], which leads China to a tremendous pressure of energy saving and emissions reduction [6]. Therefore, shareholders intend to monitor and supervise firms' carbon emissions better, which is one of the biggest motivators that China's CID has grown steadily in both quality and quantity in recent years [7].

Previous research on CID either used Carbon Disclosure Project (CDP) data [8–10] or content analysis method [7, 11, 12] for measuring the quality of CID. In view of the relatively low level of response to CDP by Chinese firms [13], we choose the content analysis method to measure the quality of CID. The research on the influencing factors of CID mainly focuses on the following aspects: (1) the firm's internal factors, such as profitability, leverage, size, and industry [12], environmental committee [14], environmental

management accounting [15]. (2) The firm's external factors, such as stakeholder engagement [16], and environmental legitimacy [13]. Nevertheless, there are very few studies on the influencing factors of CID from a cultural perspective. The motivation of this study arises from that so little research focuses on the role of culture in CID, especially Confucianism. And, previous research also provides little evidence on the effect of academic independent director (AID) on firms' CID.

According to agency theory, corporate governance can reduce agency conflicts and protect the interests of stakeholders in the information disclosure behaviour of firms [17]. Independent directors may be a trustworthy mechanism in resolving agency conflicts on this issue [18]. They can supervise as well as advise. Explicitly, academics are the incarnation of wisdom [19], an independent thinker [20], and have a higher sense of morality and social responsibility [21]. Due to the unique characteristics and role of AIDs, there is sufficient reason to believe that they are environmentally sensitive and have a positive effect on CID.

Unity of Man and Nature (天人合一) is one of the creative wisdom achievements of Confucianism ecological concept. The emphasis on the virtues of Confucianism that human should respect for nature has a positive influence on ecological education [22]. Studies have found that ecological awareness affects people's sense of social responsibility, which in turn affects people's behaviour and practices [23]. And, corporate social responsibility induces firms to create value for the environment and society and reduce the occurrence of environmental problems [24]. Therefore, it is reliable that Unity of Man and Nature will affect the management's attitude and decision-making towards energy conservation and emission reduction, which in turn affects corporate social responsibility behaviour and enables firms to accelerate the pace of carbon emission reduction. Based on signaling theory, managers will release information that is beneficial to firms. Firms with good environmental performance are more inclined to disclose environmental information. Therefore, Unity of Man and Nature will make firms more inclined to disclose carbon information.

Moreover, Confucianism emphasizes Respecting Teachers (尊师重道), which is also a traditional Chinese virtue. In the ethics between people advocated by feudal morality, children must obey their father absolutely (父为子纲). However, another famous saying in traditional culture is "one-day teacher, life-long father" (一日为师, 终身为父), which is a powerful explanation of Confucianism on respecting for teachers. Especially, the work of faculty professors mainly covers three aspects, teaching students, doing research work, and serving the school. The first identity of the AID is the faculty professor. Thus, Respecting Teachers connects Confucian culture with AIDs deeply. Hence, regions that are heavily influenced by Confucianism are more likely to appreciate the value of AIDs; thus, they are expected better performance in their monitoring and advising roles, thereby improving the quality of firms' CID.

Based on agency theory and signal theory, this research analyses the governance effect of AID and Confucianism on promoting the quality of firms' CID and explores the

moderating role of Confucianism in the relationship between AID and the quality of firms' CID. This study makes the following contributions to the existing literature. First, to the best of our knowledge, this study is the first to empirically investigate whether Confucianism may influence low carbon behaviour of firms with a specific focus on CID. Existing research have explored the influence of Confucianism on business ethics, gender diversity of the board of directors, expropriation of minority shareholders, and over investment, but they provide little evidence on the effect of Confucianism on particular low carbon behaviour of firms (CID in our case). This study finds that the concept of Unity of Man and Nature helps explain the positive association between Confucianism and CID.

Second, this study extends existing research on AIDs. Existing research have investigated the effect of AIDs on firm performance, innovation, acquisition performance, and CSR performance ratings, but they provide little evidence on the impact of AID on the quality of CID. Thus, the academia and practical circles know little about the relationship between AID, an important component of independent directors in China (account for one third of the independent directors of Chinese A-share listed firms), and the quality of CID.

Third, to the best of our knowledge, this study is the first to explore the moderating role of Confucianism in the governance effect of AIDs. Confucianism emphasizes respect for teachers. And, most AIDs are teachers in universities. But, previous literature provides little evidence on the influence of Confucianism on the governance effect of AIDs [25–27]. This study incorporates the Respecting Teachers in Confucianism into the theoretical framework of the governance effect of AID on CID. This study finds that Confucianism can positively moderate the relationship between AID and the quality of CID, implying that Confucianism can promote the governance effect of AIDs.

Fourth, this study complements the extant studies on the determinant of CID. Extant studies have investigated the influencing factors of CID such as CEO characteristics, female directors, board committee structures, and regulatory pressure of governments. Most of the influencing factors in extant studies belong to formal systems. Extant literature provides little evidence on the influencing mechanism of informal systems such as traditional culture. This study finds that Confucianism, as an informal system, can work together with AIDs to promote firms' CID behaviour.

Finally, focusing on the Chinese context, this study can better investigate the influence of AIDs and Confucianism on CID. There are a large number of AIDs in China, which account for one third of the independent directors in Chinese A-share listed firms. And, China is the cradle land of Confucianism. Using the context of China, this study can better investigate how AIDs (a formal system) and Confucianism (an informal system) work together to motivate firms' CID behaviour. And, the findings based on the context of China can add value to theoretical completeness of previous research on CID based on more developed countries.

The rest of this paper is organized as follows: Section 2 provides the literature review. Section 3 proposes the hypothesis of this research. Section 4 discusses the research

methodology. Section 5 presents the empirical results. Section 6 draws the conclusions.

2. Literature Review

2.1. Independent Directors and Environmental and Social Disclosure. In the existing literature, there are few studies exploring the role played by the board of directors in environmental and social disclosure [28, 29]. Some studies focus on the characteristics of the board of directors on environmental information disclosure. Empirical studies show that the size of the board of directors is positively correlated with the environmental performance of the firm [30]. Gender diversity is also one of the hot topics in voluntary disclosure research. Firms with more women on board are more likely to disclose climate change information [31, 32].

In the field of corporate governance, the existence of independent directors is widely concerned and discussed. Previous research has shown that the independence of the board of directors is positively related to environmental and social performance [33, 34]. Independent directors are positively related to environmental and social disclosure [35, 36]. More independent directors are on the board, a firm is more likely to disclose carbon information [37, 38]. If the board of directors has more seats of independent directors or an environmental committee exists, firms are more likely to pay attention to environmental transparency and disclose GHG emission information. However, when the independent directors are not active enough and the environmental committee is not large enough, the effect will not be obvious [8]. Some studies also find that independent directors may be reluctant to disclose GHGs and accurate information [39].

2.2. Determinants of Carbon Information Disclosure. Previous research has explored the determinants of CID behaviour of the firm. The research mainly covers two aspects. First, the internal influencing factors of disclosing carbon information. The decision to respond to CDP is associated with the firm's existing financial resources, the setting of a certified environmental management system, and the publicity of corporate social responsibility reports [10]. Firm's profitability, leverage, size, and industry are also important determinants of GHG emission disclosure [12]. Lewis et al. find firms led by newly appointed CEOs and those with MBAs are more likely to respond to CDP; nevertheless, those led by lawyers show less interest [40]. The influence of institutional investors is positively associated with the extent and quality of climate change disclosure [41]. The existence of an environmental committee can improve the level of climate change disclosure [14, 38]. However, the establishment of a separate risk committee has no impact on the firm's voluntary GHG emissions disclosure [42]. Firms in high-emission industries as well as firms with better performance are more willing to disclose carbon information, and when competitors increase, firms tend to disclose more carbon information [7].

Second, in addition to the internal characteristics of firms, the firm's CID will also be affected by the external

environment. The institutional pressure, such as the EU's emissions trading scheme and the GRI guidelines, has a positive effect on the quality and scope of firms' GHG emissions reporting [43]. Environmental regulations and legal sources are extremely important to a firm's decisions on CID [44]. The CIDs of state-owned enterprises are more sensitive to the regulatory pressure of local governments, while non-state-owned enterprises are more sensitive to social pressure [2]. Firms registered in countries that ratified the Kyoto Protocol are more likely to disclose GHG emissions information [45].

2.3. Confucianism and Business Practice. As a Chinese traditional culture, Confucianism has an impact on regions that recognize and practice Confucian culture and can serve as a good foundation for the business practices and management models of Chinese firms in the 21st century [46]. Most studies focus on the theoretical value of Confucianism. There are studies on comparing the correlation and worth of Confucian ethics and contemporary business ethics [47]. Some studies have linked interpersonal harmony in Confucian culture with corporate social responsibility [25]. The value of trustworthiness in Confucian culture is also explored [48].

When focusing on how culture works in practice, empirical research shows that culture plays a decisive role in corporate social performance and corporate financial performance [49]. A high-integrity corporate culture can help reduce the burden of external transaction costs for firms [50]. The impact of culture on ethical sensitivity is a decisive factor for corporate governance practices in different areas [51]. There is evidence that Hofstede's cultural dimensions have a significant correlation with corporate social performance [52].

There are few studies on the practical value of Confucian culture. Extant literature shows that Confucianism has a negative correlation with the gender diversity of the board of directors; however, regions with high GDP per capita can weaken this negative impact [27]. Confucianism can also reduce the expropriation of minority shareholders, and this effect enhances in non-state-owned enterprises [26]. Similarly, Confucianism has a negative correlation with over investments; the negative link strengthens in non-state-owned enterprises [53].

Based on the above, the effect of AID on the firm's CID quality has not been explored. And, there is no research on how the firm's CID behaviour is influenced by Chinese traditional culture. This paper explores the effects of AID and Confucianism on the quality of firms' CID. This research has theoretical and practical values for studying the influencing factors of firm's CID in China and for improving the internal governance efficacy of AID and external governance efficacy of Chinese traditional culture.

3. Theory and Hypotheses

3.1. Academic Independent Directors and the Quality of Carbon Information Disclosure. Agency theory believes that

managers may abuse their power and exploit the interests of shareholders. And, agency theory [17] proposes that disclosure behaviour is closely related to corporate governance. Agency theory encourages the use of corporate governance mechanisms to coordinate the contradictions between the principles and agents [37]. Based on this theory, firms will improve the effectiveness of its own corporate governance to enhance its' internal control level and provide a monitoring role to decrease opportunistic behaviour and information asymmetry [54]. Enhancing the independence of the board is a good way to promote the firm's long-term and stable development [35], such as promoting the firm's Environmental, Social, and Governance (ESG) disclosure behaviour [37].

In general, independent directors perform supervisory functions as well as an advising role. However, beyond the independence of directors, the influence of different types of independent directors on corporate governance is not equivalent. Among them, AID has a unique value. Academic directors have a positive relationship with firm performance [20] and corporate social responsibility performance [55]. The impact of AID on corporate governance has three levels. (1) What they can do? Most AIDs are professors with doctoral degrees and possess a wealth of professional knowledge and individual abilities. Undoubtedly, doctoral degrees represent the highest level of education in most countries around the world. The education level of AIDs speaks for their abilities and skills. And, highly educated directors are more likely to understand environmental issues; it is therefore more inclined to contribute to CID. (2) How they do? AIDs have the ability to think independently and objectively. Professors with doctorates generally have a deeper world view and can sagaciously distinguish good ideas from bad ones [19]. AIDs and non-AIDs have different ways of thinking, which can bring fresh and diverse perspectives to the board. Compared with other types of outside directors, AIDs have fewer internal social connections and are more likely to achieve independent thinking [20]. (3) Why they do? Because AIDs have higher moral standards, a stronger sense of social responsibility [55], and care more about their own reputation [56]. The above-mentioned characteristics of AIDs have inspired them to care about environmental issues and promote firms to take action. Based on these, they are expected to make greater contributions to the firm's CID. Therefore, we formulate the following hypothesis:

Hypothesis 1. Academic independent directors positively affect the quality of carbon information disclosure.

3.2. Confucianism and the Quality of Carbon Information Disclosure. Confucianism is one of the most significant philosophical and moral systems in China [27]. In the pre-Qin era, Confucius and other representatives created Confucianism which became the mainstream cultural consciousness of Chinese society after being institutionalized. After more than two thousand years of baptism and development, it has gradually become the essence and core of Chinese traditional culture.

Confucianism has some outstanding theories like Confucian traditional ecological consciousness. Confucianism believes that human society exists in the natural environment. Nature provides humans with a series of raw living materials such as food and shelter, and human beings are part of the natural environment. In view of Confucianism, man and nature are essentially similar and common. Based on this theory, Confucianism has developed some superior ecological consciousness such as the Unity of Man and Nature. According to the Unity of Man and Nature, understanding the human-nature relationship as a consumer-commodity relationship is void of sacredness or moral association of the human-nature relationship [57]. Some studies believe that the supreme essence of the Unity of Man and Nature is to bring peace and security to future generations and promote the sustainable development of global society, and the combination of Confucianism and science can help fix the thorny problem of global environmental degradation [58]. Generally speaking, Confucian ecological thinking can affect the decision-making of managers. In particular, firms in areas that are more deeply radiated by Confucianism will pay more attention to energy conservation and emission reduction, and furthermore, improve carbon performance.

Signaling theory emphasizes solving the problem of asymmetry of information between two parties. According to the signaling theory, when a firm's environmental performance is excellent, it will have a strong motivation to break the barriers of information asymmetry and actively disclose environmental information, to distinguish itself from firms with poor environmental performance in front of investors and stakeholders [59]. Furthermore, previous empirical studies believe that signaling theory is a key factor in influencing managers' options regarding CID [7, 60]. To sum up, the Confucian concept of Unity of Man and Nature will affect the behaviour of managers and promote firms to improve their carbon performance. Based on signaling theory, firms with good carbon performance are more willing to disclose carbon information. Therefore, we formulate the following hypothesis:

Hypothesis 2. Confucianism positively affects the quality of carbon information disclosure.

3.3. Academic Independent Director, Confucianism, and Quality of Carbon Information Disclosure. In Chinese history, some representatives of Confucianism discussed the topic of respecting teachers. Xunzi believes that "For a country to prosper, it must respect its teachers." Confucian classic, the Book of Rites, wrote "Teachers should not only teach students knowledge, but also teach students the principles of life." It is self-evident that the Confucianism of respecting teachers plays an important role in the growth of Chinese people. The first identity of AID is teacher. There are a few researches on the role of AIDs in corporate governance [19, 20, 55]. AIDs have objective thinking and are less affected by others and thus can better supervise the manager's decisions [56, 61], and they may bring reputation capital to a

firm. From the above analysis, it can be seen that firms in areas that are deeply radiated by Confucianism may more praise respecting teachers and may more value the significance of AIDs. When a firm is located in an area with strong Confucianism atmosphere, the advices of AIDs on CID will be more valued and easier to adopt by managers. When a firm is located in an area with weak Confucianism atmosphere, even if the proportion of AIDs is relatively high, their advices on CID are likely to be ignored because they are not valued by managers. Therefore, we formulate the following hypothesis:

Hypothesis 3. Confucianism positively moderates the relationship between academic independent directors and the quality of carbon information disclosure.

4. Methods

4.1. Sample and Data Sources. The sample of the study involves large firms, since they hold a greater economic significance, as well as face larger public, political, and institutional pressure than medium and small ones [62], and they are more concerned about their reputation and show more propensity to disclose information voluntarily [59]. For the above two reasons, our initial sample consists of 610 firms in the CSI 300 Index covering a period of 7 years (2012–2018). We collect financial data from the CSMAR database. Subsequently, the CID quality was obtained from the firms' corporate social responsibility reports and annual reports. Following Du [27], we manually collect and compute the data on Confucianism by means of Google-earth map. Of all these 610 firms, 4 firms belonging to the finance and insurance industries were eliminated from the sample. Then, 203 firms were excluded due to missing corporate social responsibility reports and 10 firms were excluded due to unavailable data. The final sample covers 2194 observations from 393 firms.

4.2. Variables and Models

4.2.1. Variables. The dependent variable is the quality of CID. Content analysis is a common measurement method in CID research [14, 59]. Considering the objectivity and comparability of the research results, we adopt the CID index used in the previous research to measure the quality of CID [11]. A score of one is assigned if a disclosure is related to items in CID index. We use content analysis to evaluate the total score of 22 items. The specific scoring rules are shown in Table 1.

The independent variable is AID and Confucianism. We download the firms' annual reports from the official website of the Shanghai and Shenzhen Stock Exchange and manually collect the detailed information of each independent director in the reports to see if he or she is a professor or an associate professor in the university. Consistent with prior research, in this study, we employ the percentage of AIDs on board (ACARATIO) as the proxy of AID [55]. We use Google-earth map to find the longitude and latitude of the firm's registered address and the Confucianism center separately and then use the geographic distance between the two to construct Confucianism variables [26, 27].

This research controls for the effect of several variables which have been acknowledged in the extant literature to affect the firm's CID quality, including firm size (SIZE), leverage (LEV), whether the corporate social report is verified by a third party (VERIFICATION), high-carbon industry (HIGH_CARBON), board of directors (BOARDSIZE), return on equity (ROE), firm age (AGE), and the concentration of ownership (CONCENTRATION). The definitions of variables are shown in Table 2.

4.2.2. Models. In this study, ordinary least squares (OLS) regression analysis is used to test our hypotheses. To test Hypothesis 1, we estimate the following regression model:

$$\begin{aligned} \text{CID} = & \alpha_0 + \alpha_1 \text{ACARATIO} + \alpha_2 \text{SIZE} + \alpha_3 \text{LEV} + \alpha_4 \text{ROE} + \alpha_5 \text{AGE} + \alpha_6 \text{BOARDSIZE} \\ & + \alpha_7 \text{HIGH_CARBON} + \alpha_8 \text{VERIFICATION} + \alpha_9 \text{CONCENTRATION} + \text{YEAR_DUMMIES} \\ & + \text{INDUSTRY_DUMMIES} + \varepsilon_{i,t}. \end{aligned} \quad (1)$$

To test Hypothesis 2, we estimate the following regression model:

$$\begin{aligned} \text{CID} = & \alpha_0 + \alpha_1 \text{CONF_R} + \alpha_2 \text{SIZE} + \alpha_3 \text{LEV} + \alpha_4 \text{ROE} + \alpha_5 \text{AGE} + \alpha_6 \text{BOARDSIZE} + \alpha_7 \text{HIGH_CARBON} \\ & + \alpha_8 \text{VERIFICATION} + \alpha_9 \text{CONCENTRATION} + \text{YEAR_DUMMIES} + \text{INDUSTRY_DUMMIES} + \varepsilon_{i,t}. \end{aligned} \quad (2)$$

To test Hypothesis 3, we estimate the following regression model:

TABLE 1: Items included in the carbon information disclosure index.

| ID | Category/item | |
|-----|---|---|
| CC | <i>Climate change-related risks, opportunities, and actions</i> | |
| 1 | CC1 | Risks associated with climate changes |
| 2 | CC2 | Description of the actions initiated or planned as a result of identification of risks associated with climate change |
| 3 | CC3 | Opportunities associated with climate change |
| 4 | CC4 | Actions initiated or planned as a result of identification of opportunities associated with climate change |
| GHG | <i>GHG emissions accounting</i> | |
| 5 | GHG1 | Methodology used to calculate GHG emissions |
| 6 | GHG2 | External verification/assurance status that applies to GHG emissions |
| 7 | GHG3 | Total GHG emissions |
| 8 | GHG4 | Breakdown of GHG emissions |
| 9 | GHG5 | GHG emission intensity |
| 10 | GHG6 | Strategies to reduce GHG emissions |
| 11 | GHG7 | GHG emission reduction plans |
| 12 | GHG8 | GHG emission intensity reduction |
| EC | <i>Energy consumption accounting</i> | |
| 13 | EC1 | Total energy consumption |
| 14 | EC2 | Breakdown of energy consumption |
| 15 | EC3 | Total renewable energy consumption |
| 16 | EC4 | Breakdown of renewable energy consumption |
| 17 | EC5 | Strategies to increase renewable energy use |
| 18 | EC6 | Strategies to reduce energy use |
| ACC | <i>Climate change-related governance and accountability</i> | |
| 19 | ACC1 | Board committee responsible for climate change risk management |
| 20 | ACC2 | How the board reviews progress on firms carbon performance |
| 21 | ACC3 | Incentives for managing GHG emissions and energy use |
| 22 | ACC4 | Staff development programs to encourage reduction of emissions and energy use |

The index is adopted from Liu et al. [11].

TABLE 2: Variable definition.

| Variables | Description |
|---------------|---|
| CID | The total score of CID index. |
| ACARATIO | Percentage of academic independent directors on the board of directors. |
| CONF_R | The number of Confucianism centers within a radius of R kilometers ($R = 200, 220, 240, 260, 280, 300$ km) around a firm's registered address. |
| SIZE | Logarithm of the number of employees. |
| LEV | Debt-to-equity ratio. |
| ROE | Return on equity. |
| VERIFICATION | Whether the corporate social responsibility report is verified by a third party. |
| HIGH-CARBON | Dummy variable that equals 1 if the firm belongs to a high-carbon industrial sector. High-carbon industries include automobiles and components, chemicals, forest products, gas and electrical utilities, oil and gas, mining, pipelines, precious metals, steel, and transportation. |
| BOARDSIZE | Total number of board members. |
| AGE | The number of years that have passed since a firm's IPO. |
| CONCENTRATION | The percentage of total common stocks owned by the largest shareholders. |

TABLE 3: Descriptive statistics.

| Variables | (1) N | (2) Mean | (3) SD | (4) min | (5) max |
|---------------|------------|-------------|-----------|------------|------------|
| CID | 2,194 | 2.572 | 2.252 | 0 | 15 |
| ACARATIO | 2,194 | 0.207 | 0.114 | 0 | 0.600 |
| CONF_R200 | 2,194 | 0.423 | 0.633 | 0 | 2 |
| CONF_R220 | 2,194 | 0.484 | 0.700 | 0 | 2 |
| CONF_R240 | 2,194 | 0.527 | 0.722 | 0 | 2 |
| CONF_R260 | 2,194 | 0.553 | 0.744 | 0 | 2 |
| CONF_R280 | 2,194 | 0.588 | 0.769 | 0 | 2 |
| CONF_R300 | 2,194 | 0.648 | 0.819 | 0 | 2 |
| SIZE | 2,194 | 4.005 | 0.563 | 1.602 | 5.739 |
| LEV | 2,194 | 0.525 | 0.193 | 0.0156 | 0.982 |
| ROE | 2,194 | 0.0660 | 0.614 | -20.74 | 0.566 |
| AGE | 2,194 | 13.70 | 6.247 | 1 | 33 |
| BOARDSIZE | 2,194 | 9.521 | 2.210 | 5 | 18 |
| HIGH-CARBON | 2,194 | 0.426 | 0.495 | 0 | 1 |
| VERIFICATION | 2,194 | 0.0351 | 0.184 | 0 | 1 |
| CONCENTRATION | 2,194 | 41.58 | 16.36 | 3.620 | 88.55 |

TABLE 4: Correlation analysis.

| Variables | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) | (16) |
|--------------------|-----------|-----------|-----------|-----------|---------|-----------|-----------|----------|----------|--------|----------|----------|----------|----------|----------|------|
| (1) CID | 1 | | | | | | | | | | | | | | | |
| (2) ACARATIO | 0.056*** | 1 | | | | | | | | | | | | | | |
| (3) SIZE | 0.256*** | -0.080*** | 1 | | | | | | | | | | | | | |
| (4) LEV | 0.140*** | 0.006 | 0.286*** | 1 | | | | | | | | | | | | |
| (5) ROE | 0.024 | 0.004 | 0.009 | -0.115*** | 1 | | | | | | | | | | | |
| (6) AGE | -0.080*** | 0.043** | -0.116*** | 0.102*** | -0.022 | 1 | | | | | | | | | | |
| (7) BOARDSIZE | 0.081*** | -0.084*** | 0.105*** | 0.099*** | -0.035* | 0.026 | 1 | | | | | | | | | |
| (8) HIGH_CARBON | 0.119*** | -0.094*** | 0.203*** | 0.091*** | -0.039* | 0.026 | 0.262*** | 1 | | | | | | | | |
| (9) VERIFICATION | 0.252*** | 0.051** | 0.129*** | 0.039* | 0.013 | -0.036* | 0.017 | 0.021 | 1 | | | | | | | |
| (10) CONCENTRATION | 0.122*** | -0.008 | 0.176*** | 0.072*** | 0.004 | -0.134*** | 0.072*** | 0.162*** | 0.077*** | 1 | | | | | | |
| (11) CONF_R200 | 0.082*** | 0.087*** | -0.090*** | -0.033 | 0.034* | 0.111*** | -0.089*** | -0.035* | 0.037* | -0.001 | 1 | | | | | |
| (12) CONF_R220 | 0.079*** | 0.106*** | -0.123*** | -0.02 | 0.035* | 0.145*** | -0.114*** | -0.052* | 0.042* | 0.011 | 0.940*** | 1 | | | | |
| (13) CONF_R240 | 0.083*** | 0.098*** | -0.109*** | -0.019 | 0.039* | 0.120*** | -0.107*** | -0.044** | 0.039* | -0.006 | 0.892*** | 0.954*** | 1 | | | |
| (14) CONF_R260 | 0.083*** | 0.082*** | -0.106*** | -0.03 | 0.040* | 0.112*** | -0.106*** | -0.022 | 0.051** | -0.003 | 0.872*** | 0.928*** | 0.977*** | 1 | | |
| (15) CONF_R280 | 0.075*** | 0.090*** | -0.096*** | -0.049** | 0.044** | 0.106*** | -0.101*** | -0.026 | 0.041* | -0.006 | 0.842*** | 0.898*** | 0.945*** | 0.971*** | 1 | |
| (16) CONF_R300 | 0.039* | 0.093*** | -0.096*** | -0.062*** | 0.045** | 0.097*** | -0.101*** | -0.027 | 0.046** | -0.005 | 0.811*** | 0.860*** | 0.905*** | 0.934*** | 0.957*** | 1 |

Notes. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

TABLE 5: Regression results of Hypothesis 1.

| Variables | The dependent variable: CID | |
|---------------|-----------------------------|-----------|
| | Coefficient | (t value) |
| ACARATIO | 1.109*** | (2.86) |
| SIZE | 0.713*** | (7.52) |
| LEV | 1.447*** | (4.93) |
| ROE | 1.043** | (2.28) |
| AGE | -0.038*** | (-4.96) |
| BOARDSIZE | 0.033 | (1.59) |
| HIGH_CARBON | -0.326*** | (-2.70) |
| VERIFICATION | 2.406*** | (10.16) |
| CONCENTRATION | 0.005* | (1.80) |
| Constant | -2.806*** | (-4.57) |
| Year | Yes | |
| Industry | Yes | |
| Observations | 2,194 | |
| R-squared | 0.190 | |

Notes. t statistics in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

$$\begin{aligned}
 \text{CID} = & \alpha_0 + \alpha_1 \text{ACARATIO} + \alpha_2 \text{CONF_R} + \alpha_3 \text{ACARATIO} * \text{CONF_R} + \alpha_4 \text{SIZE} + \alpha_5 \text{LEV} + \alpha_6 \text{ROE} \\
 & + \alpha_7 \text{AGE} + \alpha_8 \text{BOARDSIZE} + \alpha_9 \text{HIGH_CARBON} + \alpha_{10} \text{VERIFICATION} \\
 & + \alpha_{11} \text{CONCENTRATION} + \text{YEAR_DUMMIES} + \text{INDUSTRY_DUMMIES} + \varepsilon_{i,t}.
 \end{aligned} \tag{3}$$

5. Results

5.1. Descriptive Statistics and Correlation Analysis. Table 3 presents the descriptive statistical analysis on our sample firms' AIDs, Confucianism, CID, and other variables. The results show that there exists a great gap in CID among firms (the maximum and minimum values are 15 and 0, respectively). AIDs hold on 20.7% of the board seats in the board of directors in our sample firms. No matter it is within 200 or 300 kilometers from the registered address of the firm, there are at most two Confucianism centers and at least zero Confucianism center. On average, firms in the CSI 300 Index listed over 13 years. Table 3 also shows that 42.6% of our sample firms belong to high-carbon industries. Eventually, on average, only 3.51% of firms have a third-party verification of their social responsibility reports.

The Pearson correlation results are presented in Table 4, as well as the results of the significance test performed to detect whether there is collinearity between the variables in the table. Particularly, the relationship between ACARATIO and CID was found to be equal to 0.056 along with statistical significance at the 1% level. Therefore, AIDs positively encourage the CID of firms. Moreover, there is also a positive and significant correlation between Confucianism and CID, which means that the ecological concept of Unity of Man and Nature can indeed make the firms more concerned about environmental issues and more willing to disclose carbon information.

5.2. Hypothesis Tests

5.2.1. Regression Results of Hypothesis 1. Our first hypothesis confirmed that CID is affected in a statistically significant

way by AIDs. All continuous variables were winsorized at the 1% level to avoid potential outlier effects. The aforementioned result is presented in Table 5. The results show that the coefficients of ACARATIO are positive and significant at the 1% level across all regression models, which supports the prediction of our first hypothesis. In terms of control variables, we find SIZE, LEV, ROE, VERIFICATION, and CONCENTRATION are all significantly associated with CID in our regression model; we also found that AGE is negatively correlated with CID. HIGH-CARBON has a negative association with CID.

Our regression result shows that AIDs decrease the barriers of communication between the firm and stakeholders and reduce information asymmetry, thus well-playing their role to stimulate firms to disclose more carbon information. Moreover, the same as the previous study [63], we find that AGE is negatively correlated with CID, this may be because firms with less listing years are more likely to care about their reputation; thus, they intend to increase CID to attract investors' attention. Consistent with Prado-Lorenzo and Garcia-Sanchez [39], the result shows that high-carbon industries have a significant negative correlation with CID; this may be due to the poor carbon performers are reluctant to disclose; nevertheless, good carbon performers possess more willingness to disclose, which supports the signaling theory explanations in the literature [29, 60].

5.2.2. Regression Results of Hypothesis 2. The regression results for testing Hypothesis 2 are reported in Table 6. The results show that the regression coefficients for CONF_RN ($R = 200, 220, 240, 260, 280$, and 300) are significantly positively associated with the CID ($p < 0.01$), which means that firms that are heavily influenced by Confucian culture

TABLE 6: Regression results of Hypothesis 2.

| Variables | The dependent variable: CID | | | | | | | | | | | |
|---------------|-----------------------------|-----------|-------------|-----------|-------------|-----------|-------------|-----------|-------------|-----------|-------------|-----------|
| | (1) | | (2) | | (3) | | (4) | | (5) | | (6) | |
| | N = 200 | | N = 220 | | N = 240 | | N = 260 | | N = 280 | | N = 300 | |
| | Coefficient | (t value) | Coefficient | (t value) | Coefficient | (t value) | Coefficient | (t value) | Coefficient | (t value) | Coefficient | (t value) |
| CONF_RN | 0.363*** | (5.25) | 0.329*** | (5.20) | 0.312*** | (5.12) | 0.290*** | (4.90) | 0.266*** | (4.66) | 0.167*** | (3.08) |
| SIZE | 0.745*** | (7.87) | 0.755*** | (7.95) | 0.750*** | (7.91) | 0.749*** | (7.89) | 0.737*** | (7.78) | 0.728*** | (7.65) |
| LEV | 1.452*** | (4.97) | 1.442*** | (4.94) | 1.432*** | (4.90) | 1.444*** | (4.94) | 1.476*** | (5.05) | 1.475*** | (5.03) |
| ROE | 0.862* | (1.89) | 0.869* | (1.90) | 0.847* | (1.85) | 0.846* | (1.85) | 0.837* | (1.83) | 0.916** | (1.99) |
| AGE | -0.042*** | (-5.46) | -0.043*** | (-5.57) | -0.041*** | (-5.41) | -0.041*** | (-5.35) | -0.041*** | (-5.31) | -0.039*** | (-5.14) |
| BOARDSIZE | 0.038* | (1.83) | 0.040* | (1.94) | 0.039* | (1.89) | 0.039* | (1.88) | 0.038* | (1.84) | 0.035* | (1.68) |
| HIGH_CARBON | -0.357*** | (-2.98) | -0.352*** | (-2.94) | -0.356*** | (-2.97) | -0.370*** | (-3.09) | -0.374*** | (-3.12) | -0.372*** | (-3.09) |
| VERIFICATION | 2.392*** | (10.15) | 2.381*** | (10.10) | 2.384*** | (10.11) | 2.374*** | (10.06) | 2.391*** | (10.13) | 2.403*** | (10.15) |
| CONCENTRATION | 0.005* | (1.73) | 0.005 | (1.63) | 0.005* | (1.73) | 0.005* | (1.72) | 0.005* | (1.73) | 0.005* | (1.76) |
| Constant | -2.959*** | (-4.88) | -2.972*** | (-4.89) | -2.942*** | (-4.85) | -2.924*** | (-4.81) | -2.867*** | (-4.73) | -2.732*** | (-4.49) |
| Year | Yes | | Yes | | Yes | | Yes | | Yes | | Yes | |
| Industry | Yes | | Yes | | Yes | | Yes | | Yes | | Yes | |
| Observations | 2,194 | | 2,194 | | 2,194 | | 2,194 | | 2,194 | | 2,194 | |
| R-squared | 0.197 | | 0.197 | | 0.197 | | 0.196 | | 0.195 | | 0.191 | |

Notes. t statistics in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

(within 300 kilometers) prefer to disclose carbon information on account of following the philosophical ecological concept of Unity of Man and Nature. The significance of SIZE, LEV, ROE, AGE, HIGH-CARBON, VERIFICATION, and CONCENTRATION has not changed; the sign of the correlation coefficient has not changed either. Thus, Hypothesis 2 is supported. In short, we found that Confucianism has a positive impact on CID.

5.2.3. Regression Results of Hypothesis 3. Table 7 shows that the coefficients of ACARATIO and CONF_RN ($R=200, 220, 240, 260, 280, \text{ and } 300$) are positive and significant at the 1% level, suggesting that they both engender favourable effects on CID, consistent with our expectations in Hypotheses 1 and 2. The interaction term regression coefficients for ACARATIO*CONF_RN ($R=200, 220, 240, 260, 280, \text{ and } 300$) are significantly positively associated with CID ($p < 0.01$), Hypothesis 3 is therefore supported. AIDs and Confucian culture each have their own special characteristics to positively influence CID. Additionally, the concept of Respecting Teachers in Confucian culture will make firms in areas deeply influenced by Confucianism pay more attention to the value of AIDs. AIDs along with Confucianism can create greater sparks and deepen the promotion of the firm's CID behaviour.

5.2.4. Robustness Tests. One of the purposes of this research is to analyze the correlation between AIDs and CID as presented in Table 5; however, the baseline regression results may be influenced by a potential endogeneity. This is because firms with high levels of CID may have a propensity to recruit AIDs, and AIDs may also be attracted to firms with high levels of CID. Nevertheless, based on the fact that we are studying the largest firms in the Shanghai and Shenzhen stock markets in China, these firms are better than other firms in terms of firm performance, social responsibility, and environmental performance; thus, it is hard to say which factor attracts AIDs. Our sample itself avoids the endogeneity issues to some extent. Hence, as a robust test, first, we use the instrumental variables 2SLS regression analysis approach to alleviate this endogeneity concern. This instrumental variable should be associated with AIDs but not with the error term of the regression results of CID.

According to Francis et al. [20], the distance between the firm headquarter and the university where the professor is appointed is related to the professor director but is unlikely to be related to firm performance. Based on this idea, we choose the number of universities in project 985 (world-class universities) in the city where the firm's registered address is located as our instrumental variable, on account of the large number of universities in project 985 may signify that there will be more AIDs working here; thus, it is related to the AIDs, but is less likely to be related to the quality of the firm's CID. After this test, we find that after considering the potential endogeneity issue, AID is still positively and significantly associated with CID ($p < 0.1$), which again supports our hypothesis.

In addition, we also run further analysis by applying completely different standards to measure our main variables. CID-DUM is a dichotomous variable (a dummy variable that equals one if the firm gets a score, and zero otherwise), which represents the firm's decision to disclose carbon information. The results of this test are consistent with our hypotheses. The measure of Confucianism is also changed to study whether its impact on CID is robust. Following Du [26], we use CONF_R_DUM to reevaluate Confucianism, a dummy variable of CONF_R, equaling 1 if there is one or more Confucianism centers within a radius of R kilometers, $R=200, 220, 240, 260, 280, \text{ and } 300$ km. The results of this test are consistent with those of our hypotheses. We also use the number of AIDs as a new measure to test; the regression results are consistent with our hypotheses. These robustness tests above indicate that our empirical results are robust and credible.

6. Conclusions

As the largest carbon emitter, the world's carbon emission reduction trend strongly depends on China's carbon emission reduction status. This paper focuses on large Chinese firms to seek for the key factors related to their CID behaviour. In addition, along with China's unique traditional cultural thoughts which have been passed down for thousands of years and have imperceptibly influenced the Chinese people's ideological system, there are differences between Chinese firms and firms in other countries in how to encourage voluntary CID.

In this paper, we study the influencing factors of CID from a new perspective. We integrate the external governance factor, the traditional Chinese culture (Confucianism, an informal system), and the internal governance factor, the AID (a formal system), into a unified research framework. The results of our research indicate that there is a strong positive correlation between AIDs and CID and provide a significant input to the ongoing discussion on the role of academics on board. Our results contribute to this discussion by showing that academics are not only can take an important part in playing the supervisory and advising roles to reduce the asymmetry of information between the firms and investors but also as a representative of high wisdom independent thinkers and high sense of social responsibility. Our results document that academics can perform excellent on issues related to CID.

Another key finding of our study is that when cultural factor is incorporated into the influencing factors of CID, it produces a positive relationship as well. As the traditional Chinese culture, Confucianism has formed many excellent ecological concepts in the long historical development, such as the Unity of Man and Nature, which emphasizes that man and nature should live in harmony and man should respect and revere nature. Since Confucian culture teaches people to respect nature and thoughts can shape human's behaviour, this ecological concept will also make managers pay more attention to environmental issues and take practical actions to reduce emissions. According to the signaling theory, firms with good carbon emission reduction performance will be

more prefer to disclose and advertise themselves. Based on this principle, we observe that Confucianism promotes firms to disclose carbon information.

As regards Confucian culture, there is another marvelous tradition of respecting teachers. As the old saying goes, “respecting the teacher is the same as respecting one’s father and brother.” The teaching profession is generally respected in China with a long history, and AIDs are also university professors, which helps explain that firms in areas heavily affected by Confucianism can better understand the meaning of respecting teachers and they can see the value of AIDs. Therefore, we investigate the moderating role of Confucianism on the relationship between AIDs and CID. We find that Confucianism can enhance the positive impact of AIDs on CID.

In addition to the theoretical contributions listed in the “Introduction” section, the findings of this paper also have some practical implications. First, since AIDs promote firms’ CID quality, firms can improve their level of information disclosure related to climate change through appointing AIDs. Second, this study finds that Confucianism can influence the thought of managers and thus affect firm CID behaviour in the context of China. Therefore, Confucianism should not be ignored in academic research and policy-making. Scholars, practitioners, and government should pay more attention to the impact of Confucianism and other traditional cultures on firm behaviour. Third, since Confucianism affects the importance of AIDs, Confucianism, as an informal system, can promote the governance effect of AID. The academia, the practical circle, and regulators should pay attention to the external environment of AIDs. Academia and the government should actively promote the dissemination of Confucianism, which can promote the governance effect of AIDs and improve corporate governance. For listed firms in areas with a strong Confucianism atmosphere, appointing AIDs will be beneficial.

As in all empirical studies, our study has several limitations. First, the CID index used in our study may not have captured all necessary information which can measure the quality of CID. Second, aiming at capturing the influence of Confucianism atmosphere around a firm, we use the number of Confucianism centers within a particular radius around a firm as the proxy of Confucianism to capture the influence level of Confucianism atmosphere around a firm, which based on the assumption that the Confucianism atmospheres around different Confucianism centers are the same. In fact, the levels of Confucianism atmosphere around different Confucianism centers may be different. Third, our study focuses on a sample of relatively large firms in China (CSI 300). Therefore, our results may not hold for small firms, or firms outside China. The role and influences of AIDs and Confucianism may vary across countries. But, our findings may be applied to other Asian countries where Confucianism historically existed, such as Japan, Korea, Singapore, and Vietnam, which inspires further discussion and testing by scholars.

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

Urban Green Development towards Sustainability in Northwest China: Efficiency Assessment, Spatial-Temporal Differentiation Characters, and Influencing Factors

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For achieving the sustainable development goals, green development has been raised to a high position for cities in China. The economic development in Northwest China is slow, the ecological environment is fragile, and the mineral resources are rich. Only through green development can we realize the comprehensive income of regional production development, rich life, and good ecology. This paper measures the green development efficiency of 30 prefecture-level cities in Northwest China by using DEA-SBM model of unexpected output, explores the differences and causes of green development efficiency from the perspective of time and space through convergence coefficient, coordination matrix, GIS, and other methods, and empirically tests the impact of industrial structure, technological progress, and other driving factors on green development efficiency by using panel Tobit model. The results show that, on the whole, the efficiency of green development in Northwest China is low, path dependence is serious and unbalanced, the coordinated development effect of different regions is weak, and the spillover effect of core urban agglomerations has not been effectively exerted; from the perspective of driving factors, economic development, population density, traffic situation, and education investment can significantly improve the efficiency of urban green development, and the second is that the proportion of industries significantly hinders the improvement of green development efficiency, while the impact of scientific and technological innovation is not significant. Based on the empirical results, this paper believes that the harmonious development of natural environment and economic society can be realized only by improving the coordinated development effect among cities, implementing the optimization and upgrading of industrial structure, introducing excellent talents, and promoting the technological upgrading.

1. Introduction

Since the beginning of the 21st century, the ecological environment capacity and resource carrying capacity have gradually become the main factors restricting economic development. A green economy based on traditional industries, coordinated economic and environmental development, and market oriented has become an inevitable choice for China's development strategy. British economist Pearce's "Green Economy Blue Book," published in 1989, first proposed the concept of a green economy. He believed that economic development must not be at the expense of

environmental damage. At the same time, the exhaustion of resources was never the cause of economic stagnation, and green development was a breakthrough in resources' environmental constraints, transforming environmental advantages into development advantages, transforming the dynamic mechanism of economic growth, changing the way economic growth is focused, unifying economic growth, social development, and eco-friendliness to achieve high-quality economic growth, and the coordination and fairness of society as a whole effective sustainable development. Green development is the era of China's development, and it is a key move in the construction of ecological civilization.

Since 2012, ecological civilization construction has been fully promoted, and the process of green development has accelerated significantly. Green development, low-carbon development, and cyclic development have become the basic requirements for economic construction. The five concepts of innovation, coordination, greenness, openness, and sharing became the core of development. The implementation of a series of policies provided adjustments for the economic structure and green development which make the northwest region with strong kinetic energy support.

Northwest China has a complex and diverse terrain, a fragile ecological environment, and abundant mineral resources. The environmental pressures and social problems caused by predatory development in the last century have continued to appear in recent years, becoming a major bottleneck restricting development. The five northwestern provinces of China have an area of about 30% of China's total area and a population of about 130 million. In 2018, the total economic volume was 51.46 billion yuan, accounting for only 5.7%, which is lower than the provinces of Zhejiang and Shandong. At present, China's industrial upgrading is accelerating. The implementation of the "Belt and Road" initiative and the comprehensive management of the Yellow River Basin has provided a platform for the rise of the Northwest region. Therefore, seizing the opportunity to realize green development and improve the quality of economic development are the biggest opportunities of the five Northwest provinces.

This paper takes the main prefecture-level cities in the five Northwestern provinces of China as the main research body, measures its green development efficiency, analyzes its equilibrium characteristics from two aspects of time and space, and combines technical measures such as convergence coefficient, GIS, and coordinated equilibrium matrix to green the city cluster coordinated development which is analyzed. Finally, Tobit regression is used to explore the factors affecting its green development efficiency from economic development, industrial structure, and other aspects. Based on this, it provides the Northwest region with the goal of improving green development efficiency and achieving coordinated economic, social, and ecological development.

2. Materials and Methods

2.1. Literature Review of Green Development. With the continuous emergence of resources and environmental issues and the increasing awareness of environmental protection, green economy has gradually become the theme of world development. In terms of functional definition, green development is the second-generation sustainable development concept, and it is an economic, social, and natural system of integrated and coordinated system [1]. The development of the concept of green development is a change in development value. The goal of people-oriented, social progress, respect for nature, and ecological development is the ultimate goal of green development [2]. China's green development is formed on the basis of continuous summarization of traditional economic development and has

experienced a dynamic process from elementary to advanced, from simple to complex [3, 4]. In the 21st century, if China is to achieve high-quality economic growth and a win-win situation for ecological well-being, it must change its development model and take a green development path to promote a green economy [5]. Therefore, it is particularly important to evaluate the effect of green development from a quantitative perspective.

At present, the research subjects of green development practice evaluation focus on two aspects. On the one hand is to measure the green development of the entire country or key areas. Kunanuntakij, based on the green GDP accounting logic, used the EIO-LCA method to establish Thailand's green GDP model and conducted in-depth research on consumption costs, degradation costs, and defense costs in green GDP [6]. Ezici evaluated the impact of nonrenewable resources and renewable resources on the green development of US manufacturing from the perspectives of ecology and efficiency. From the perspective of input and output [7], Laura evaluated the sustainable development capacity of urban society and economy and tested the impact of economic development and technological innovation on green development [8]. Some scholars use China as the research area and discuss the industrial development level and green development in different regions of Chinese cities from 2005 to 2016. Nonlinear relationship [9] and the impact of environmental regulations on industry and its intermediary effects on green development were studied, through evaluating the effectiveness of green development in other countries combined with the DDF and Durenberger index analysis methods based on relaxation measures, the low-carbon and green development status of the 52 countries along the "Belt and Road" in 1995–2016 was explored, and socio-economic factors affecting the growth of low-carbon and green TFP in the region were analyzed by panel regression [10]. Zhang studied the impact of environmental regulation policy on the transfer of the whole industry and five pollution intensive industries and discussed the impact of local government environmental regulation on green development [11]. However, macro-research finds it difficult to avoid the endogenous nature of the data, and the analysis of influencing factors is often superficial. Therefore, the research on green development focusing on hot economic areas or special background areas is the main research interest at present. Tian takes the Yangtze River Economic Belt for measurement, and based on the greening measurement index and the extreme value entropy method, the greening index of the Yangtze River Delta urban agglomeration is calculated systematically and the influencing factors of the greening development of the Yangtze River Delta urban agglomeration based on the panel Tobit model are calculated [12, 13]. Some scholars have made the green development of China's impoverished areas and constructed an ecological index system [14] and explored the role of industrial structure changes in underdeveloped areas to promote green development efficiency [15, 16]. Si analyzed the impact of environmental regulations in the Yellow River basin on green technology innovation [17]. Generally speaking, the green development effect of

China's regions is U-shaped, and there are differences in the East, the middle, and the west, but there is a convergence trend.

On the other hand, research on green development focuses on measurement methods and indicator systems for green development; currently existing research mainly uses DEA and indicator system to construct two types of methods. The input-output data envelopment analysis (DEA) is used more frequently. Farrell [18] used the input-output method for the first time to measure the output efficiency of multiple inputs, but the existence of unintended outputs limited the further use of the model. In 1983, Pittman [19] added unintended output to the model, and the model gradually developed into a hot model for studying efficiency issues. With the continuous improvement of this model by scholars, its analysis and application boundaries for green development issues continue to expand. On the basis of combining the concept and connotation of green development, Zhou used DEA-SBM-undesirable model and other methods to measure and characterize the spatiotemporal characteristics of green development efficiency in Chinese cities from 2005 to 2015 [20, 21]. Lin used a nonradial direction distance function to construct and evaluate green economic efficiency indicators for cities at the prefecture level and above in the Super-DEA framework and further empirically studied the impact of economic agglomeration on green economic efficiency [22]. Measuring the green development index by building an indicator system and adopting an empowering method is another method which combines data and theoretical foundations better and can comprehensively evaluate the effect of green development [23, 24].

2.2. Theoretical Basis. The concept of green development is formed in the criticism of the traditional development path. With the development of human society, the pressure on resources and the environment has gradually increased, and the phenomenon of "humanity's impact in many aspects has exceeded the environmental tolerance" has appeared. The imbalance between resources, environment, and economic and social development has become a challenge for all mankind and even threatens the survival of mankind. Therefore, scholars first reflect on the relationship between humans and the environment and explore human production and development models. The concept of green environmental protection has begun to emerge. From green production to green consumption, the embryonic form of sustainable development has been formed, and its obvious characteristic is that it is separated from the economic system and, instead, focuses on environmental issues. With the development of society, the theory of green economy and sustainable development has been gradually improved. British scholar Pierce first put forward the concept of "green economy" and regarded resource protection and environmental conservation as important aspects of economic development. Ecological issues should not be ignored for economic growth. Economic development should follow the principles of sustainability, eco-friendliness, and rational

allocation of resources, focusing on how economic and social development affects the environment, solving pollution problems, and achieving overall development [25]. Since the 21st century, the theoretical system of green development has become more mature and has been continuously promoted in international organizations. In 2011, the United Nations Environment Program's "Green Economy Report" was released, stating that green development "means better use of natural resources and sustainable growth: a more effective and fairer economic model." As the largest developing country in the world, with the rapid development of economy, the continuous emergence of resource and environmental problems, and the increasing awareness of environmental protection, green economy has gradually become the theme of national development. The harmony and unity of man and nature is the realization of green development. Basically, from the perspective of function definition, green development is the second generation of sustainable development concept, which is the systematic, integrated, and coordinated development of economy, society, and nature. The proposal of green development concept is the transformation of development value, putting people first and society. The value goal of progress, respect for nature, and ecological development is the ultimate goal of green development.

2.3. Assessment Method. This paper uses the DEA-SBM model based on undesired output to measure the green development efficiency of cities in Northwest China. Based on this, the green development coordination of major urban agglomerations in Northwest China is measured through a convergence coefficient. Tobit regression is used to analyze the driving effects of the driving factors of green development efficiency.

2.3.1. Green Development Efficiency Measurement. Measuring the green development efficiency of a city based on a data model is an important method in academia at present. Its advantage is that it can measure efficiency through input and output, thereby avoiding the impact of price indexes and production functions. The measurement results are more objective. The current commonly used development efficiency methods include data envelope analysis and stochastic frontier analysis. Data envelopment analysis takes the effectiveness of different resource allocations as the efficiency of economic development and incorporates environmental factors, resource factors, and factor endowments into the research system to improve the rationality and effectiveness of the calculation. After years of continuous development, the data envelopment analysis method has continuous improvement. Tone [26] introduces nonradial relaxation variables into the DEA data envelope analysis model so that nonzero relaxation factors are included in the efficiency calculation, which solves the radial problem of the traditional DEA model and improves the accuracy of the calculation. Unexpected output is introduced into the nonradial DEA-SBM model, thus forming a more comprehensive and efficient measure of green development

efficiency. Fukuyama [27], on the basis of Tone, proposed a more operable DDF model based on relaxation measures, which further improves the application range of the data envelope analysis method. Based on the research purpose of this paper, the DEA-SBM method based on undesired output was selected to measure the urban green development efficiency in Northwest China.

This article considers each city as a production unit, and its different input volume decisions and its output determine the efficiency of green development. The optimal input-output situation of each period of output is constructed by multiple production units, assuming that there are n production decision-making units, whose factors are input factors, expected output factors, and undesired output factors and are represented by different vector matrices when the returns to scale are unchanged. $X \in R^m$, $X = [X_1, X_2 \dots X_n] \in R^{m \times n}$; $Y^g \in R^{s^1}$, $Y^g = [Y^{g^1}, Y^{g^2}, \dots, Y^{g^n}] \in R^{s^1 \times n}$; $Y^b \in R^{s^2}$, $Y^b = [Y^{b^1}, Y^{b^2}, \dots, Y^{b^n}] \in R^{s^2 \times n}$, assume $X > 0$, $Y^g > 0$, and $Y^b > 0$. The set of production possibilities is $P = \{(x, y^g, y^b) | x \geq X\alpha, y^b \geq Y^b\alpha, y^g \geq Y^g\alpha\}$, $\alpha \in R^n$ is the intensity vector. According to the above definition, a DEA-SBM model based on undesired output is obtained:

$$\rho^* = \min \frac{1 - (1/m) \sum_{i=1}^m s_i/s_{i0}}{1 + (1/(s_1 + s_2))(\sum_{r=1}^{s_1} s_r^g/y_{r0}^g + \sum_{r=1}^{s_2} s_r^b/y_{r0}^b)} \quad (1)$$

$x_0 = X\alpha + s^-$, $y_0^g = Y^g\alpha - s^g$, and $y_0^b = Y^b\alpha + s^b$, $s^- \geq 0$, $s^g \geq 0$, $s^b \geq 0$, and $\alpha \geq 0$. The optimal solution is $(\alpha^*, s^{*-}, s^{g*}, s^{b*})$. In the presence of unexpected output, only $\rho^* = 1$, $s^{g*} = 0$, and $s^{b*} = 0$ and production units are efficient.

2.4. Regional Difference Measure. Urban agglomerations are important engines for regional development. Four major urban agglomerations were formed in the Northwest during the 13th Five-Year Plan period, including the Guanzhong plain urban agglomeration (Xian, Tongchuan, Baoji, Xi'an, Weinan, and Yan'an), the Ningxia urban agglomeration (Yinchuan and Shizuishan), Lanxi urban agglomeration (Lanzhou, Jinchang, and Xining), and the northern slope urban agglomeration (Urumqi and Karamay); the coordinated green development of the urban agglomeration will form a strong driving force for the entire region. To measure the degree of green coordinated development, the convergence coefficient is used to measure the change in the dispersion of the green development efficiency of important urban agglomerations in Northwest China. When the convergence coefficient gradually decreases over time, it means that the degree of dispersion is gradually reduced, and the coordination efficiency of green development in urban agglomerations is gradually improved [28]. The calculation formula is

$$\begin{aligned} \sigma_1 &= \sqrt{\frac{1}{S-1} \sum_1^S (y_{it} - y_i^-) * (y_{it} - y_i^-), y_i^-} \\ &= \frac{1}{S} * \sum_1^S y_{it}, \quad i = 1, 2, \dots, S, t = 1, 2, \dots, T. \end{aligned} \quad (2)$$

In the formula, y_{it} is the green development efficiency of each prefecture-level city in year t and y_i^- is the average green development efficiency of all regions in year t ; if $\sigma_t > \sigma_{t+1}$, it means it is convergent.

At the same time, in order to further explain the comprehensive development of the coordination and efficiency of the urban agglomeration during the measurement period, this article measures the coordination within the urban agglomeration by the coordination coefficient [29]:

$$\begin{aligned} \phi &= -\sqrt{\frac{1}{S} \sum_1^S (y_{it} - y_i^-) * (y_{it} - y_i^-) + \varepsilon} \\ i &= 1, 2, \dots, S, t = 1, 2, \dots, T, \end{aligned} \quad (3)$$

where y_{it} is the green development efficiency of each prefecture-level city in year t , y_i^- is the average green development efficiency of all regions in year t , and ε is the equilibrium constant, which is taken as 0.5.

2.4.1. Green Development Performance-Driven Measure. Because the value of green development efficiency ranges from 0–1 and the degree of green development in the northwest region is low, there is a low possibility of being completely effective or superefficient. Therefore, this paper uses the panel Tobit model to empirically test the urban development potential influencing factors, with a view to make useful policy recommendations for improving the efficiency of green development in Northwest China [30]. This paper takes the green development efficiency as the explanatory variable and uses the level of economic development, industrial structure, technological innovation, population density, transportation status, and education investment as explanatory variables to construct the following model:

$$\begin{aligned} \text{TP}^* &= \beta_0 + \beta_1 * \ln \text{GDP}_{it} + \beta_2 * \ln \text{Indu str} + \beta_3 * \ln \text{Tech} \\ &+ \beta_4 * \ln \text{Ds peo} + \beta_5 * \ln \text{Traffic} + \beta_6 * \ln \text{Education} + e_{it}. \end{aligned} \quad (4)$$

In order to reduce the effect of sample data heteroscedasticity, the study variables are treated as logarithms, β_0 is the intercept term, β_1 – β_6 is the coefficient to be evaluated for image factors, and e_{it} is the random interference term.

2.5. Index Selection

2.5.1. The Input-Output Indexes. According to the theory of neoclassical economics, it can also be extended to technology input and resource input. Capital investment is an important driving force for green development. This article uses the amount of investment in fixed assets at the end of the year as capital input; labor input is an important basis for promoting the greening process. Because data on labor time and labor efficiency are difficult to obtain, this paper uses the number of employees which represents labor input; resource input is the endowment foundation of a region. Good resource input can effectively promote development. Considering the availability of data, this article uses the area of the built-up area to represent the input of urban land resources, uses annual water supply to indicate the input of urban water resources, and uses the annual power supply to represent the input of urban power resources.

Expected output variable: the objective indicator of economic development in a region is GDP. Therefore, this article uses urban GDP to indicate the expected output. Unexpected output: the most important factor affecting green development in the development of a region is wastewater, harmful gas, and harmful solid waste, so this article uses wastewater emissions, sulfur dioxide emissions, and smoke dust emissions to represent the unintended output of urban green development.

2.5.2. The Driving Factors' Indexes. Based on the measurement of the urban green development efficiency in the Northwest region, the most important driving factors for the preliminary judgment of urban green development include economic development level, industrial structure, scientific, technological innovation capabilities, population density, traffic conditions, and education investment. Clarifying the impact of different driving factors is important for deeper analysis, so the following variables are selected for measurement in this article.

Economic development level: this article uses GDP per capita to measure the level of urban economic development. The Kuznets curve (EKC) theory shows that environmental pollution presents an “inverted U-shaped” curve that first increases and then decreases with the continuous growth of the economy. The economic growth of cities on the left side of the curve will continue to negatively affect the environment, but with the further implementation of national policies, the further implementation of green industry and green energy-related policies by local governments will greatly reduce the impact on the environment while promoting economic development. With the further prosperity of the economy, more funds will be invested in environmental governance and the degree of green development in cities may increase.

Industrial structure, this article uses the proportion of the secondary industry to measure the city's industrial structure. Due to historical reasons and dependence on the path of economic development, the secondary industry in Northwest China accounts for a relatively high proportion.

At the same time, the discharge of waste related to the secondary industry greatly affects the construction of ecological civilization, continuous advancement of industrialization, and production of wastewater, waste gas, and solid waste. The rapid increase will have a negative impact on green efficiency, but with the continuous implementation of the green development concept and the continuous upgrading of the industry, the emissions of the three wastes are reduced, and the green development efficiency may gradually increase.

Scientific and technological innovation capabilities and the effects of innovation results can effectively spill over to highly polluting industries such as industry and construction, innovate pollution control methods, promote the upgrading of industrial structure and the construction of ecological civilization, and improve the efficiency of green development. Because there are no precise statistics on innovation efficiency in different regions and innovation requires a large amount of capital investment, this article uses urban science and technology expenditure to measure innovation capacity.

Population density and human resources are the most basic of many resources. There are enough talents for the future. Human resources in the Northwest are relatively lacking. There is a mismatch of resources, environment, economy, and human capital. An important factor is that an increase in population density can increase urban vitality and promote the improvement of green development efficiency. Similarly, an excessively high population density will bring urban problems such as serious urban pollution and traffic congestion and will also adversely affect green development.

Traffic conditions are the basis of regional industrial development. Good traffic conditions will reduce industrial energy consumption and improve the efficiency of green development to a certain extent. Due to the lack of relevant statistical data of roads at different levels in various cities, this article uses road area to represent urban traffic conditions.

Education investment: this article takes education expenditure in local fiscal investment as a measure of education investment. Continuous investment in education will lead to the continuous enrichment of educational resources, thereby outputting more high-quality talents, and high-quality talents have a higher level of self-literacy and knowledge and are willing to pay more for green products. Capital is more willing to invest in green development industries, so education investment may have a positive effect on green development, but there is a certain time lag between education investment and high-quality talent output.

2.6. Data and Study Areas. The relevant data in this article comes from the “China City Statistical Yearbook,” “China Energy Statistical Yearbook,” provincial and municipal statistical yearbooks, and the National Energy Administration and National Bureau of Statistics. For the missing data, this paper uses expectation-maximum to estimation.

Combining the availability of data and considering different categories of government authority and administrative levels, this article selects 30 prefecture-level cities in the Northwest region as the research object (Table 1).

3. Results

3.1. Current Situation of Green Development in Various Regions

3.1.1. Status Quo of Input Factors. Resource inputs and nonresource inputs are an important driving force for green development and a key factor affecting the efficiency of green development. Higher inputs can only achieve reasonable efficiency if they produce outputs that match them (Figure 1). From the perspective of nonresource input, fixed assets in the Northwest have shown a steady upward trend. In 2007, fixed asset investment was 613.678 billion yuan. In 2017, fixed asset investment increased by 3.925267 trillion yuan, an increase of 6.4 times. The urban labor supply of Northwest China showed a trend of rising first and then falling. In 2014, the urban labor supply peaked at 9.721 million. From the perspective of resource input, the supply of land resources, power resources, and water resources has been slowly increasing, but the growth rate is lower than the input of fixed assets.

3.1.2. Status Quo of Output Factors. Expected output and undesired output are important results of regional green development (Figure 2). From the perspective of expected output, the total growth rate of Northwest China's total GDP in the eleven years from 2007 to 2017 reached 7%. In the Northwest, sulfur dioxide emissions, smoke and dust emissions, and industrial wastewater emissions generally showed a declining trend. In some years, the emissions of three wastes increased, which inhibited the improvement of the efficiency of green development. At the same time, the three wastes are 10.9%, 1.5% and 4.6%. The reduction efficiency of the unexpected output is generally lower than the increase efficiency of the expected output, which may lead to the lower efficiency of the input-output.

3.2. Time Analysis of Green Development Efficiency in Different Regions. The analysis of the original data through MATLAB 2018a yields the green development efficiency scores of prefecture-level cities in the Northwest region. Due to the lack of unexpected output data of Zhongwei City in 2018, the data is interpolated through SPSS. So, exclude this score and finally get the data results of this article (Table 2).

3.2.1. The Unbalanced Characteristics of Green Development Efficiency. The overall efficiency of green development in Northwest China is relatively low, but there is an obvious upward trend in 2007–2017. The average green development efficiency of Shaanxi Province is higher, with an average annual value of more than 0.5 and an increase of 24.8% in 2007–2017, with the best green development efficiency.

From 2007 to 2017, the growth rate of green efficiency in Ningxia reached 31.2%, with the fastest growth.

From the provincial level, Shaanxi Province has the highest green development efficiency, while Gansu Province, Ningxia Autonomous Region, Xinjiang, and Qinghai Province have lower green development efficiency. From the perspective of the internal development of Shaanxi Province, the green development efficiency of all cities in Shaanxi Province is relatively balanced. The green development efficiency of Xi'an, Xianyang, Weinan, and Baoji is in the first echelon. The internal development of Gansu Province is quite different. The green development efficiency of Lanzhou is in the first echelon, but the green development efficiency of Jinchang, Jiuquan, Zhangye, and other cities is poor. The green development efficiency of Yinchuan Guyuan and Zhongwei is gradually increasing. In general, the efficiency of urban green development in Northwest China is characterized by low level, large gap, imbalance, and rapid growth.

3.2.2. Path Dependence and Matthew Effect in Green Development Efficiency. From the perspective of the green development efficiency of prefecture-level cities, since the green development efficiency of Shaanxi Province is generally higher than that of other regions, the change of the top five cities which include Xi'an, Xianyang, Weinan, Ankang, and Baoji is relatively small. And, the last five cities are mainly heavy industry cities with poor natural conditions, so this paper selects the middle 6–20 prefecture-level cities' green development efficiency to reflect the change of the cities in Northwest China (Table 3). Generally speaking, the sixth to eighth places of green development efficiency have little change, and they are all cities of Shaanxi Province. Lanzhou city of Gansu Province has high green development efficiency, ranking 10 to 11, with little change, ranking 12 to 20 cities with more intense change, and the ranking of Shizuishan, Jiayuguan, Yinchuan, Karamay, and other cities has changed greatly from 2007 to 2017. The high-efficiency and low-efficiency areas of urban green development in Northwest China have changed a little, while the medium-efficiency cities have changed a lot, and the path of green development efficiency of prefecture-level cities depends heavily, which forms Matthew effect. The high-efficiency development areas rely on the development advantages to form scale advantages and then promote the further green development of the areas. The low-efficiency areas have high pollution and high energy consumption industries. A large number of the existence of green development leads to low efficiency, which brings more negative effects, but more restrictions on the improvement of green development efficiency.

3.2.3. Provincial Capital Cities Will Play an Important Role. Intercept the data of 2007, 2012, and 2017 and compare it with the average green development efficiency of that year to explore the change of green development efficiency of prefecture-level cities in Northwest China over time (Figure 3). From the perspective of trend, the green development

TABLE 1: Data source cities.

| Province | Cities |
|----------|---|
| Shanxi | Xi'an, Tongchuan, Baoji, Xianyang, Weinan, Yan'an, Hanzhong, Yulin, Ankang, and Shangluo |
| Gansu | Lanzhou, Jiayuguan, Jinchang, Baiyin, Tianshui, Wuwei, Zhangye, Pingliang, Jiuquan, Qingyang, Dingxi, and Longnan |
| Qinghai | Xi'ning |
| Ningxia | Yinchuan, Shizuishan, Wuzhong, Guyuan, and Zhongwei |
| Xinjiang | Urumqi and Karamay |

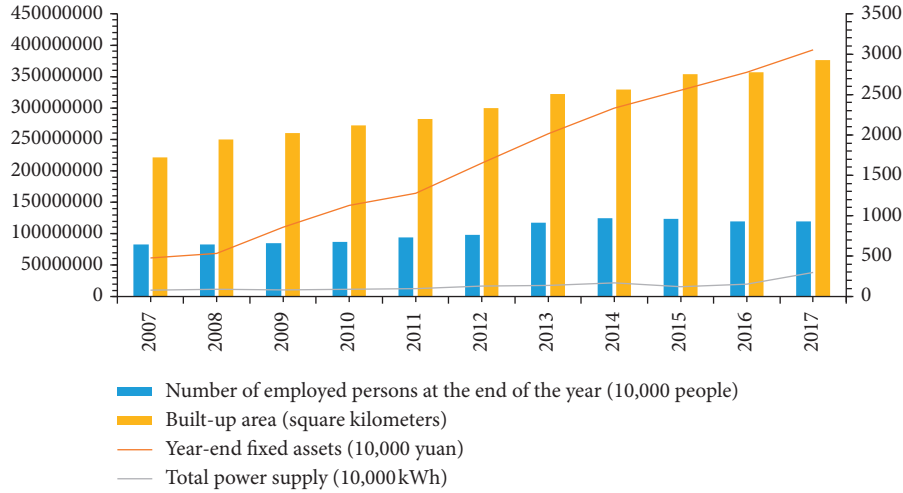


FIGURE 1: Input factors of prefecture-level cities in Northwest China.

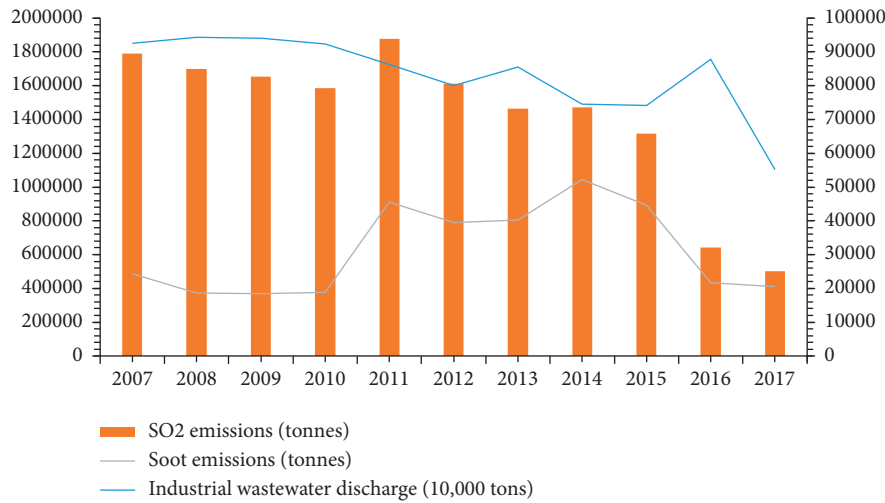


FIGURE 2: Unexpected output in prefecture-level cities.

efficiency of prefecture-level cities in Northwest China is developing well. In 2007, the green development efficiency of ten prefecture-level cities exceeded the average, accounting for only 33% of all prefecture-level cities. In 2012, 12 prefecture-level cities exceeded the average. Lanzhou and Longnan were new cities. In 2017, 14 prefecture-level cities exceeded the average, accounting for 47% of all cities, 14% higher than 2007, Including Xining, Yinchuan, Urumqi, and other provincial capitals. The efficiency of green development has been improved. It can be clearly seen from the green development efficiency of cities in Northwest China

that the green development efficiency of provincial capital cities has increased rapidly and become the locomotive of green development efficiency of Northwest China. It is a feasible path to achieve the improvement of green development efficiency of all cities in the province through the promotion of provincial capital cities.

3.3. Spatial Analysis of Green Development Efficiency in Different Regions. In 2007, the overall urban pattern in Northwest China situation was “strong in the East and

TABLE 2: Green development efficiency of prefecture-level cities in Northwest China.

| | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 |
|------------|--------------|--------------|--------------|--------------|--------------|---------------|--------------|--------------|--------------|--------------|--------------|
| Xi'an | 0.553 | 0.592 | 0.619 | 0.503 | 0.511 | 0.503 | 0.526 | 0.541 | 0.587 | 0.623 | 0.692 |
| Tongchuan | 0.434 | 0.436 | 0.416 | 0.494 | 0.501 | 0.424 | 0.417 | 0.512 | 0.552 | 0.528 | 0.576 |
| Baoji | 0.488 | 0.461 | 0.455 | 0.524 | 0.549 | 0.538 | 0.571 | 0.580 | 0.579 | 0.593 | 0.624 |
| Xianyang | 0.532 | 0.528 | 0.549 | 0.559 | 0.582 | 0.593 | 0.601 | 0.638 | 0.668 | 0.673 | 0.685 |
| Weinan | 0.539 | 0.546 | 0.572 | 0.567 | 0.578 | 0.552 | 0.537 | 0.584 | 0.618 | 0.611 | 0.623 |
| Yan'an | 0.504 | 0.513 | 0.538 | 0.569 | 0.566 | 0.596 | 0.579 | 0.591 | 0.610 | 0.615 | 0.605 |
| Hanzhong | 0.547 | 0.533 | 0.546 | 0.523 | 0.571 | 0.549 | 0.557 | 0.576 | 0.582 | 0.607 | 0.591 |
| Yuling | 0.408 | 0.432 | 0.486 | 0.454 | 0.488 | 0.523 | 0.544 | 0.529 | 0.564 | 0.579 | 0.587 |
| Ankang | 0.511 | 0.519 | 0.533 | 0.527 | 0.526 | 0.531 | 0.557 | 0.545 | 0.579 | 0.592 | 0.583 |
| Shangluo | 0.485 | 0.499 | 0.482 | 0.533 | 0.514 | 0.541 | 0.546 | 0.559 | 0.533 | 0.586 | 0.551 |
| Shaanxi | 0.508 | 0.513 | 0.525 | 0.536 | 0.548 | 0.534 | 0.539 | 0.574 | 0.602 | 0.607 | 0.634 |
| Lanzhou | 0.312 | 0.323 | 0.349 | 0.391 | 0.426 | 0.422 | 0.456 | 0.476 | 0.503 | 0.512 | 0.572 |
| Jiayuguan | 0.216 | 0.228 | 0.269 | 0.242 | 0.258 | 0.282 | 0.277 | 0.284 | 0.292 | 0.328 | 0.319 |
| Jinchang | 0.167 | 0.159 | 0.156 | 0.178 | 0.184 | 0.179 | 0.178 | 0.198 | 0.195 | 0.203 | 0.214 |
| Baiyin | 0.177 | 0.195 | 0.183 | 0.186 | 0.215 | 0.209 | 0.219 | 0.215 | 0.214 | 0.223 | 0.206 |
| Tianshui | 0.264 | 0.253 | 0.264 | 0.288 | 0.291 | 0.288 | 0.315 | 0.321 | 0.317 | 0.322 | 0.338 |
| Wuwei | 0.168 | 0.112 | 0.138 | 0.179 | 0.155 | 0.225 | 0.213 | 0.231 | 0.235 | 0.267 | 0.228 |
| Zhangye | 0.174 | 0.129 | 0.147 | 0.182 | 0.177 | 0.182 | 0.218 | 0.227 | 0.253 | 0.247 | 0.244 |
| Pingliang | 0.228 | 0.216 | 0.218 | 0.212 | 0.223 | 0.252 | 0.286 | 0.277 | 0.301 | 0.338 | 0.311 |
| Jiuquan | 0.183 | 0.187 | 0.152 | 0.168 | 0.207 | 0.211 | 0.233 | 0.228 | 0.213 | 0.235 | 0.241 |
| Qingyang | 0.237 | 0.216 | 0.253 | 0.213 | 0.241 | 0.232 | 0.244 | 0.235 | 0.254 | 0.274 | 0.282 |
| Dingxi | 0.196 | 0.198 | 0.215 | 0.218 | 0.236 | 0.244 | 0.241 | 0.231 | 0.208 | 0.217 | 0.204 |
| Longnan | 0.262 | 0.273 | 0.308 | 0.322 | 0.343 | 0.372 | 0.351 | 0.382 | 0.426 | 0.428 | 0.431 |
| Gansu | 0.215 | 0.207 | 0.221 | 0.232 | 0.246 | 0.258 | 0.269 | 0.275 | 0.284 | 0.299 | 0.299 |
| Xi'ning | 0.252 | 0.279 | 0.348 | 0.265 | 0.292 | 0.273 | 0.295 | 0.329 | 0.368 | 0.339 | 0.444 |
| Qinhai | 0.252 | 0.279 | 0.348 | 0.265 | 0.292 | 0.273 | 0.295 | 0.329 | 0.368 | 0.339 | 0.444 |
| Yinchuan | 0.258 | 0.262 | 0.312 | 0.344 | 0.333 | 0.342 | 0.331 | 0.286 | 0.339 | 0.356 | 0.392 |
| Shizuishan | 0.241 | 0.289 | 0.242 | 0.192 | 0.199 | 0.189 | 0.219 | 0.303 | 0.262 | 0.257 | 0.263 |
| Wuzhong | 0.262 | 0.276 | 0.229 | 0.200 | 0.249 | 0.272 | 0.280 | 0.317 | 0.308 | 0.303 | 0.314 |
| Guyuan | 0.297 | 0.293 | 0.379 | 0.362 | 0.344 | 0.246 | 0.346 | 0.390 | 0.474 | 0.447 | 0.331 |
| Zhongwei | 0.281 | 0.273 | 0.283 | 0.248 | 0.251 | 0.258 | 0.256 | 0.322 | 0.292 | 0.266 | |
| Ningxia | 0.25 | 0.276 | 0.277 | 0.268 | 0.266 | 0.2655 | 0.275 | 0.295 | 0.300 | 0.307 | 0.328 |
| Urumqi | 0.297 | 0.264 | 0.281 | 0.273 | 0.285 | 0.271 | 0.298 | 0.317 | 0.313 | 0.325 | 0.340 |
| Karamay | 0.285 | 0.287 | 0.291 | 0.297 | 0.314 | 0.308 | 0.315 | 0.357 | 0.420 | 0.454 | 0.435 |
| Xinjiang | 0.291 | 0.276 | 0.286 | 0.285 | 0.299 | 0.29 | 0.306 | 0.337 | 0.367 | 0.389 | 0.387 |

weak in the west.” Except for some prefecture-level cities in Shaanxi Province, the green development efficiency of other prefecture-level cities in the northwest was similar, and the overall level was relatively low (Figure 4). At the same time, the green development efficiency of cities in the south central part of Shaanxi Province was significantly higher than that in the north of Shaanxi such as Yulin and In 2012, the overall trend of green development efficiency in Northwest China did not change significantly (Figure 5). The development efficiency in eastern is still much higher than that in western. In 2012, the gap of green development efficiency in Western Shaanxi Province narrowed, especially in northern cities. At the same time, there are obvious differences in the green development efficiency among the cities in Gansu Province, Ningxia autonomous and Xinjiang autonomous. The green development efficiency of the provincial capital city circle headed by Lanzhou, Yinchuan, Xining, and Urumqi is much higher than that of other prefecture-level cities. At the same time, affected by the industrial transfer and the construction of Guanzhong City Cluster, the green development efficiency of Tianshui and other cities in the eastern part of Gansu province is

gradually compared with that of Guanzhong Urban Agglomeration convergence; in 2017, the difference of green development efficiency of prefecture-level cities in Northwest China further expanded, Shaanxi Province formed a high-efficiency area centered on Xi'an and Xianyang, and the gap between the green development efficiency of capital cities in Gansu Province and Ningxia Autonomous Region and other prefecture-level cities further widened (Figure 6). From the perspective of local cities, the green development efficiency of northern prefecture-level cities in Shaanxi Province is faster than that of central and southern cities, and the gap between the green development efficiency of prefecture-level cities in Shaanxi Province is narrowed, especially the green development efficiency of northern cities is significantly improved.

In general, the green development efficiency of prefecture-level cities in Northwest China shows a trend of rapid concentration from relative balance to provincial capital cities. Under the stimulation of a series of policies, the improvement rate of green development efficiency of provincial capital cities is far higher than that of other prefecture-level cities. In addition, Guanzhong City cluster led

TABLE 3: 6–20 cities with green development efficiency in Northwest China.

| 序号 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 |
|----|------------|------------|-----------|-----------|-----------|-----------|-----------|------------|-----------|-----------|-----------|
| 6 | Yan'an | Yan'an | Ankang | Baoji | Ankang | Baoji | Shangluo | Shangluo | Baoji | Baoji | Hanzhong |
| 7 | Baoji | Shangluo | Yulin | Hanzhong | Shangluo | Ankang | Yulin | Ankang | Ankang | Ankang | Yulin |
| 8 | Shangluo | Baoji | Shangluo | Xi'an | Xi'an | Yulin | Weinan | Xi'an | Yulin | Shangluo | Ankang |
| 9 | Tongchuan | Tongchuan | Baoji | Tongchuan | Tongchuan | Xi'an | Xi'an | Yulin | Tongchuan | Yulin | Tongchuan |
| 10 | Yulin | Yulin | Tongchuan | Yulin | Yulin | Tongchuan | Lanzhou | Tongchuan | Shangluo | Tongchuan | Lanzhou |
| 11 | Lanzhou | Lanzhou | Guyuan | Lanzhou | Lanzhou | Lanzhou | Tongchuan | Lanzhou | Lanzhou | Lanzhou | Shangluo |
| 12 | Guyuan | Guyuan | Lanzhou | Guyuan | Guyuan | Longnan | Longnan | Guyuan | Guyuan | Karamay | Xi'ning |
| 13 | Urumqi | Shizuishan | Xi'ning | Yinchuan | Longnan | Yinchuan | Guyuan | Longnan | Longnan | Guyuan | Karamay |
| 14 | Karamay | Karamay | Yinchuan | Longnan | Yinchuan | Karamay | Yinchuan | Karamay | Karamay | Longnan | Longnan |
| 15 | Tianshui | Xi'ning | Longnan | Karamay | Karamay | Tianshui | Tianshui | Xi'ning | Xi'ning | Yinchuan | Yinchuan |
| 16 | Longnan | Wuzhong | Karamay | Tianshui | Xi'ning | Jiayuguan | Karamay | Tianshui | Yinchuan | Xi'ning | Urumqi |
| 17 | Wuzhong | Longnan | Urumqi | Urumqi | Tianshui | Xi'ning | Urumqi | Wuzhong | Tianshui | Pingliang | Tianshui |
| 18 | Yinchuan | Urumqi | Jiayuguan | Xi'ning | Urumqi | Wuzhong | Xi'ning | Urumqi | Urumqi | Jiayuguan | Guyuan |
| 19 | Xining | Yinchuan | Tianshui | Jiayuguan | Jiayuguan | Urumqi | Pingliang | Shizuishan | Wuzhong | Urumqi | Jiayuguan |
| 20 | Shizuishan | Tianshui | Qingyang | Dingxi | Wuzhong | Pingliang | Wuzhong | Yinchuan | Pingliang | Tianshui | Wuzhong |

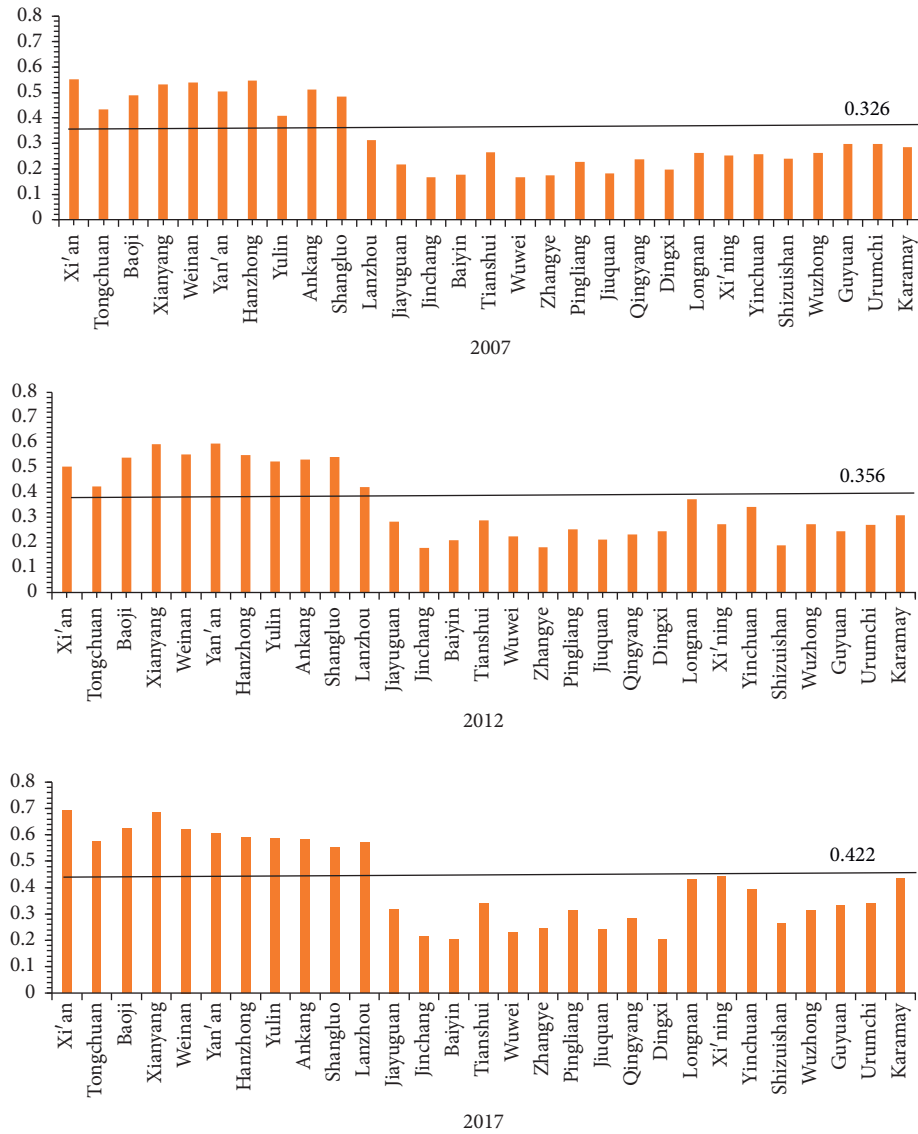


FIGURE 3: Green development efficiency of prefecture-level cities in Northwest China in 2007, 2012, and 2017.

by Xi'an has become the highest green development efficiency in Northwest China.

4. Discussion

4.1. Analysis of Convergence and Coordination of Green Development Efficiency. In Northwest China, there are four urban agglomerations centered on Xi'an (and Tongchuan, Baoji, Xianyang, Weinan, and Yan'an), Lanzhou (and Xining and Jinchang), Yinchuan (and Shizuishan), and Urumqi (and Karamay), which are Guanzhong urban Agglomerations, Lanxi urban agglomerations, Yanhuang urban agglomerations, and Tianshanbeipo urban agglomerations (Figure 7). Through the above spatial analysis, we can clearly see that the provincial capital city is the core area of green development efficiency. At the same time, the city cluster led by the provincial capital city has a high degree of industrial

agglomeration and close economic and social ties. The green development of the city cluster will certainly drive and improve the green development efficiency of the whole region. The convergence index is used to measure the difference degree of green development efficiency in urban agglomerations, and the coordination and efficiency coordinate chart is used to measure the coordination and efficiency relationship of green development efficiency in urban agglomerations.

According to the average value of green development efficiency of urban agglomerations in Northwest China (Figure 8), the overall trend is fluctuating and rising. The green development efficiency of Guanzhong urban agglomerations is far ahead of other urban agglomerations, and the convergence index of Guanzhong urban agglomerations shows a stable trend, indicating that the internal gap of green development efficiency of Guanzhong urban

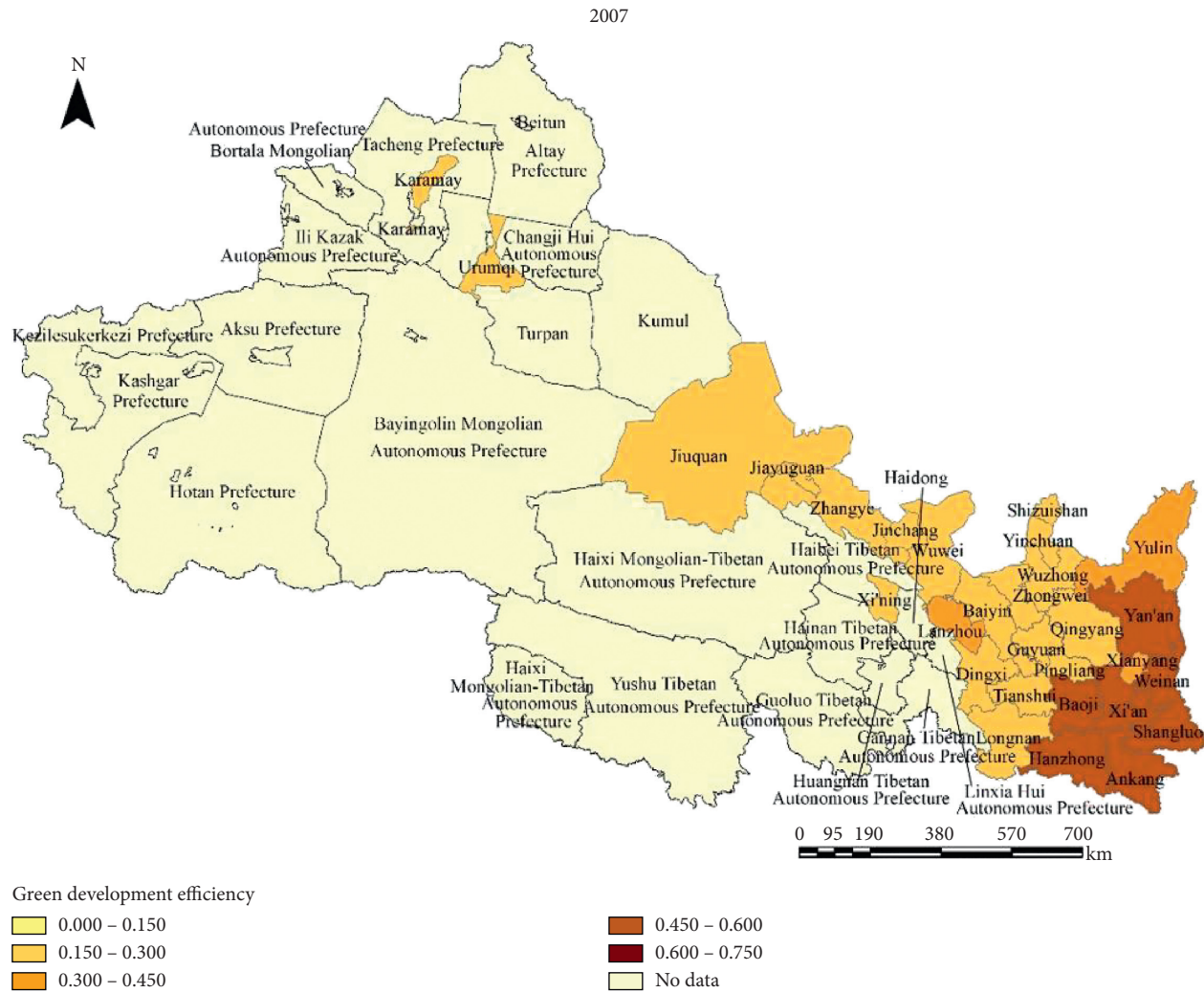


FIGURE 4: 2007 green development efficiency spatial map of prefecture-level cities in Northwest China.

agglomerations has not changed greatly in recent years. During the average green development of Lanxi urban agglomerations in 2007, the efficiency is the lowest among the urban agglomerations in Northwest China, but with the change of time, the average green development efficiency of Lanxi urban agglomerations ranked second in the Northwest China in 2017, and the convergence index of Lanxi urban agglomerations showed a divergent trend, which was 149% higher than that in 2007, with a significant gap in the efficiency of green development within the urban agglomerations; the convergence coefficient of Ningxia urban agglomerations along the Yellow River showed a fluctuating trend. During the period of 2012–2014, the gap in the efficiency of green development within urban agglomerations gradually narrowed, but gradually expanded after 2014; the convergence index of urban agglomerations on the northern slope of Tianshan Mountain remained stable from 2007 to 2013, but the divergence trend was obvious after 2013, and the efficiency gap within urban agglomerations gradually expanded. After 2014, the Northwest provinces began to gradually expand and

strengthen the provincial capital cities. The concentration of many resources has led to a significant increase in the green development efficiency of the provincial capital cities compared with the ordinary low-level cities, and the green development efficiency within each city cluster has obvious characteristics of divergence.

Take the coordination and efficiency values of urban agglomeration in Northwest China during 2007–2017 which are represented in the coordinate system (Figure 9). On the whole, the efficiency value of urban agglomerations in Northwest China has increased well, but the coordination is still at a medium level. It can be seen from the figure that the urban agglomerations in Northwest China are in the middle coordination degree and middle efficiency value range with more coordination and efficiency, and there are few years in the middle coordination, low-efficiency value and middle coordination, and high-efficiency value range. From the perspective of development trend, the urban agglomerations in Northwest China show an obvious momentum of development towards the middle coordination and high-efficiency value (Figure 10).

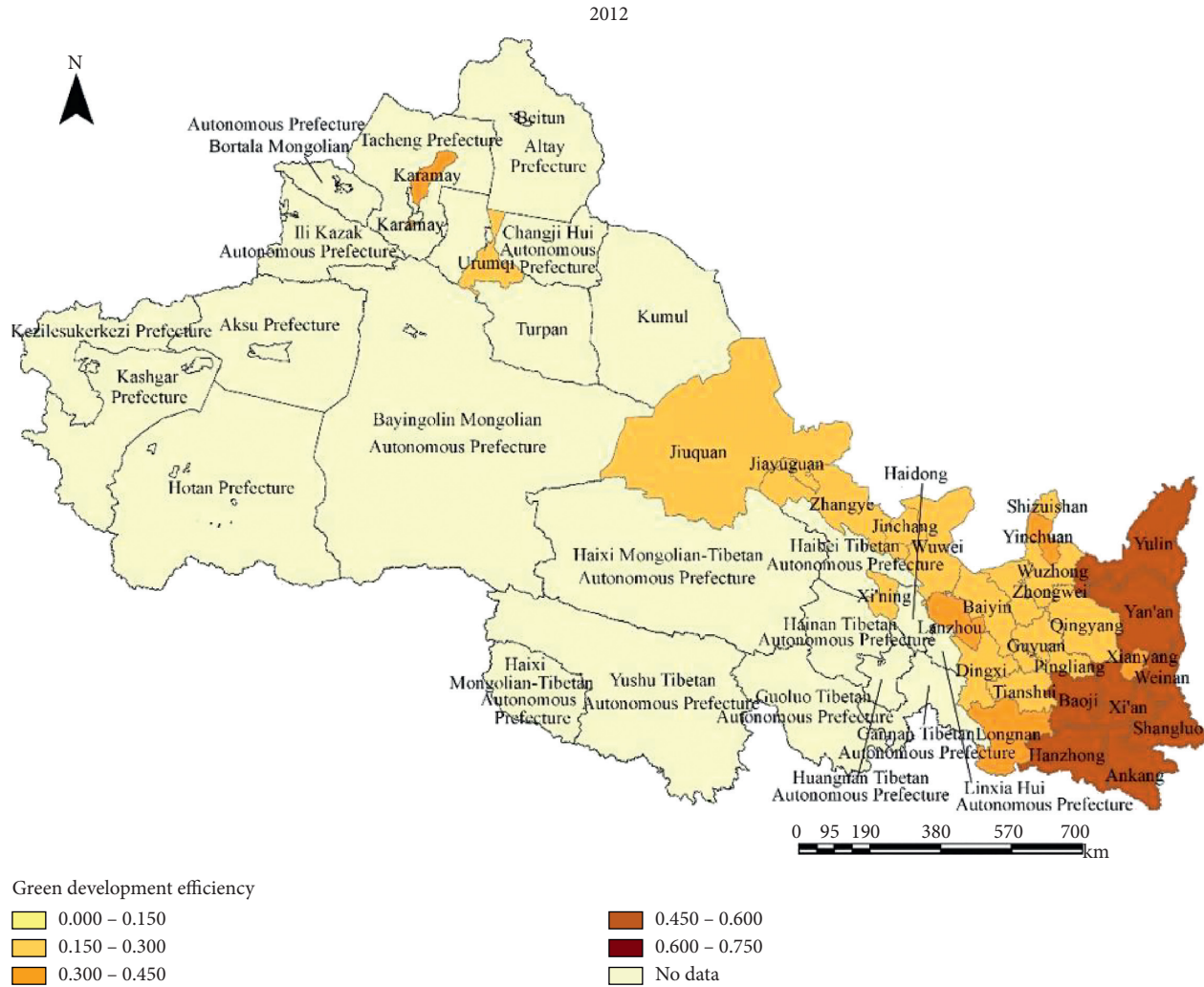


FIGURE 5: 2012 green development efficiency spatial map of prefecture-level cities in Northwest China.

4.2. Analysis of Driving Factors of Green Development Efficiency. The results of green development efficiency measurement of the northwest prefecture-level cities by SBM undesirable model show that there is an overall loss of efficiency in the northwest prefecture-level cities, and there is no case where the efficiency is more than 100% but expressed as 1. Therefore, the panel Tobit regression of random effects is applicable to the data characteristics of this paper (Table 4).

The economic development level of Northwest China has a positive impact on the green development efficiency at a significant level of 10%, with an impact coefficient of 0.023. It shows that the relationship between economic development and environmental pollution of prefecture-level cities in Northwest China has reached the right side of “Kuznets Curve.” The continuous development of economy promotes the improvement of people’s living standards, thus promoting the transformation of their demand relationship. The green consciousness is gradually awakened and the green consumption concept is gradually rooted in the hearts of the people. With the further deepening of the national green development policy, the continuous implementation of

relevant provincial and municipal policies, the sustainable development of green economy, the expansion of green market, and the reduction of environmental pollution, the coordination of economy, ecology, and society has been further enhanced, and the efficiency of green development has been continuously improved.

The economic structure has a negative impact on the green development efficiency at a significant level of 1%, with an impact coefficient of -0.034. Northwest China is rich in mineral resources, which has good conditions for the development of secondary industry. Therefore, it has formed the industrial structure dominated by the secondary industry. At the same time, due to the slow development of Northwest China, the development of green industry, the cultivation of emerging industry, and the adjustment of industrial structure have not been completed. The secondary industry is still dominated by mining, chemical industry, and other raw material processing industries, which is high. The characteristics of pollution, high energy consumption, and high emission are outstanding, which have a relatively bad impact on the environment and seriously inhibit the improvement of green development efficiency. What cannot be ignored is that,

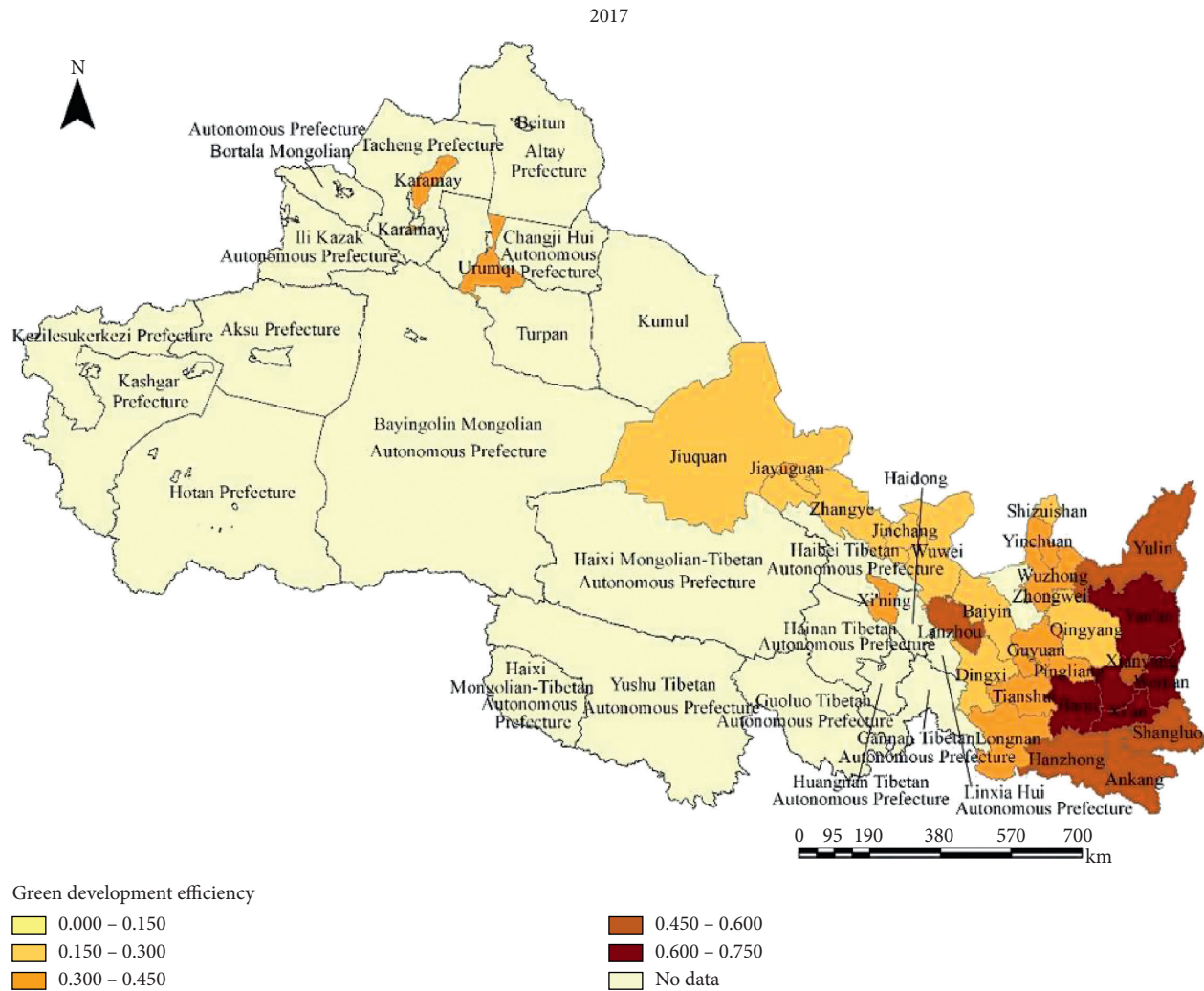


FIGURE 6: 2017 green development efficiency spatial map of prefecture-level cities in Northwest China.

as the pillar industry of most cities in Northwest China and the important source industry of government tax revenue, the process of adjusting the structure and changing the mode of the secondary industry must be accelerated. Only when the green of the secondary industry is realized can the green development in Northwest China go on the fast lane and realize the real sustainable development, green development, and harmonious development.

The impact of technological innovation on the green development level of cities in Northwest China is not significant, and cities in Northwest China fail to make full use of the progress of science and technology to promote green development. Northwest China is the lowland of China's higher education. There is only one 985 Engineering University in four provinces except Shaanxi Province. It has the characteristics of low education level and low stock of excellent talents. At the same time, due to the limitations of natural conditions and economic development in Northwest China, the contradiction between the introduction of excellent talents and excellent technology companies is also acute. The lack of higher education resources and the difficulty of introducing technical talents make it difficult for Northwest

China which has been trapped in a cycle in which the ability of scientific and technological transformation is difficult to improve. However, the progress of technology is the indispensable power to realize green development. Good technology development and transformation can improve the comprehensive utilization rate of resources, and it is the most effective way to improve the green development efficiency of the second industry in Northwest China. Therefore, how to improve the scientific and technological innovation ability of Northwest China has become the key to solve the problem of green development in Northwest China.

Traffic and education investment have a positive impact on the efficiency of urban green development in Northwest China under the condition of 1%, the impact coefficient of traffic is 0.063, and the impact level of education investment is 0.086. As the infrastructure of urban development, traffic conditions can improve the efficiency of urban value creation in unit time. Good and efficient traffic conditions can connect different regions, which is conducive to capital flow, technology exchange, and talent flow. It is an important basic condition to solve the problem of poor technological innovation ability and slow industrial structure adjustment



FIGURE 7: Location of urban agglomerations in Northwest China.

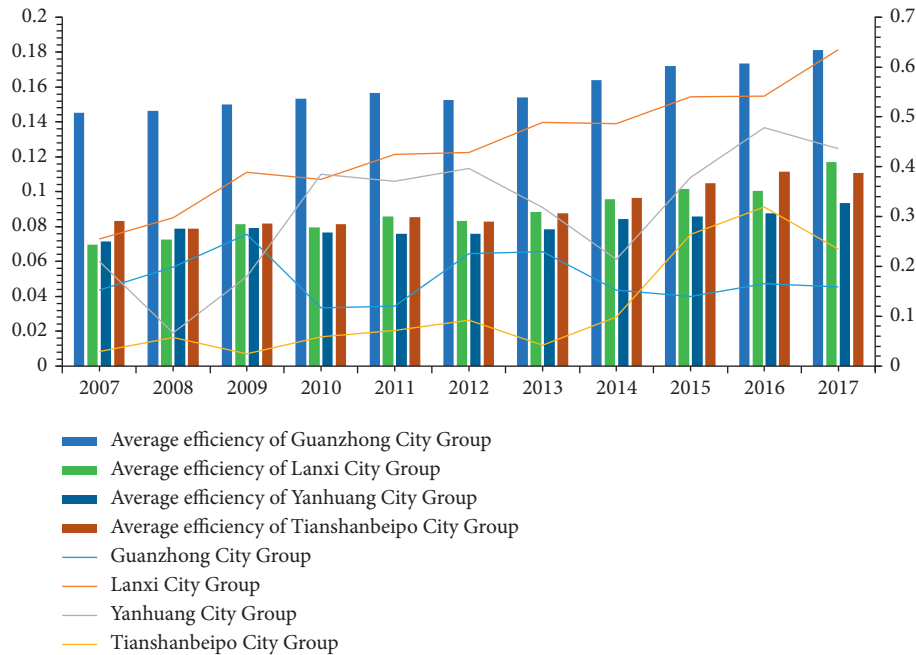


FIGURE 8: Average green development efficiency and convergence coefficient of northwest urban agglomeration, 2007–2017.

in Northwest China. It is an important engine to increase the endogenous power of urban green development in Northwest China. Education is the future of the development of a region. Good investment in education will improve the quality of the population. A large number of undergraduate

and graduate students have made an important foreshadowing for the future introduction of talents in Northwest China. It is an important human resource reserve for the realization of green sustainable development in Northwest China.

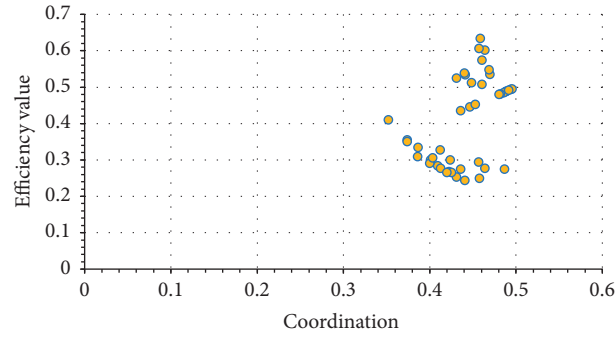


FIGURE 9: Coordination and efficiency matrix of urban agglomerations in Northwest China.

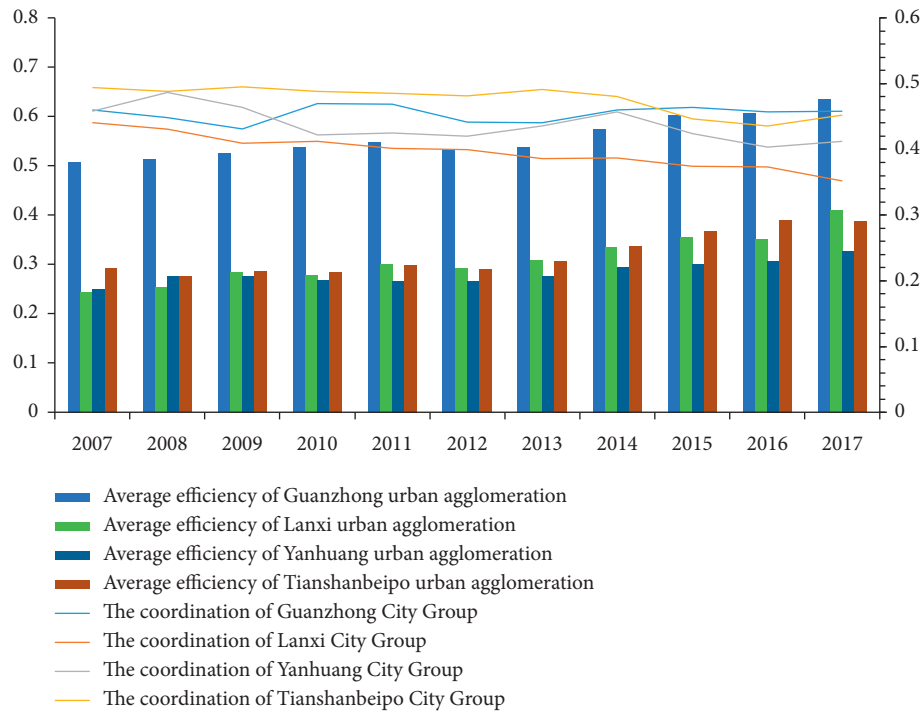


FIGURE 10: Efficiency and coordination of green development of urban agglomerations in Northwest China, 2007–2017.

TABLE 4: Tobit regression results.

| $T\rho^*$ | Coefficient | Standard deviation | T Test | P |
|-----------|-------------|--------------------|----------|------------|
| Per GDP | 0.023 | 0.013 | 1.85 | 0.065 |
| Industr | -0.034 | 0.008 | -4.14 | $P < 0.01$ |
| Tech | 0.002 | 0.011 | 0.22 | 0.828 |
| Dspeo | 0.096 | 0.024 | 3.95 | $P < 0.01$ |
| Traffic | 0.063 | 0.012 | 7.48 | $P < 0.01$ |
| Education | 0.086 | 0.139 | 7.16 | $P < 0.01$ |

Population density has a positive effect on the urban green development of Northwest China at a significant level of 1%, with an impact coefficient of 0.096. According to Williamson's hypothesis, the impact of population enrichment on economic development is inverted U-shaped. Population agglomeration in the early stage of economic development brings human capital and other resources,

which effectively promotes economic development. However, when the population is over concentrated, the cost of living pollution and traffic jams will offset its advantages, so as to green development has a negative impact. Obviously, population agglomeration in Northwest China is still on the left side of the curve, and effective population agglomeration has a strong role in promoting green development.

TABLE 5: Tobit regression of urban agglomerations.

| Tp* | Guanzhong urban agglomeration | | Lanxi urban agglomeration | | Yanhuang urban agglomeration | | Tianshanbeipo urban agglomeration | |
|-----------|-------------------------------|-------|---------------------------|-------|------------------------------|-------|-----------------------------------|--------|
| | Coefficient | P | Coefficient | P | Coefficient | P | Coefficient | P |
| Per GDP | 0.034 | 0.021 | 0.051 | 0.000 | 0.102 | 0.015 | −0.027 | 0.260 |
| Industr | −0.076 | 0.000 | −0.092 | 0.000 | −0.309 | 0.001 | −0.192 | 0.000 |
| Tech | −0.001 | 0.911 | 0.154 | 0.004 | 0.039 | 0.138 | −0.073 | 0.000 |
| Dspeo | −0.007 | 0.487 | 0.001 | 0.921 | −0.264 | 0.138 | −0.027 | 0.0192 |
| Traffic | 0.049 | 0.281 | 0.021 | 0.254 | −0.096 | 0.050 | −0.164 | 0.000 |
| Education | 0.033 | 0.000 | 0.004 | 0.625 | −0.062 | 0.221 | 0.141 | 0.0000 |

In order to better study the factors affecting the efficiency of urban green development, the samples were grouped according to the radiation range of the aforementioned urban agglomerations and further regression (Table 5). From the perspective of the influence direction of the influencing factors, per capita GDP in Guanzhong Urban Agglomeration, Lanxi Urban Agglomeration, and Yanhuang Urban Agglomeration has the same influence as the full sample, but in Tianshanbeipo Urban Agglomeration, it has the opposite influence from all samples; the economic structure influences the urban agglomeration sample which is the same as the full sample; technological innovation is the same as the full sample in Lanxi urban agglomeration and Yanhuang urban agglomeration and opposite to the full sample in other urban agglomerations; the direction of population density in Lanxi urban agglomeration is the same as the full sample, and other urban agglomerations are the same as the full sample. On the contrary, the traffic situation in Guanzhong urban agglomeration and Lanxi urban agglomeration affects the same direction as the full sample, and other urban agglomerations are opposite to the full sample; education investment in Guanzhong urban agglomeration, Lanxi urban agglomeration, and Tianshanbeipo urban agglomeration affects the same direction as the full sample, and other city groups are the opposite of full sample. From the perspective of the significance of the influencing factors, technological innovation is significantly correlated in Lanxi urban agglomeration and Tianshanbeipo urban agglomeration; population density is significantly uncorrelated in Guanzhong urban agglomeration, Lanxi urban agglomeration, and Yanhuang urban agglomeration; traffic conditions are significantly uncorrelated in Guanzhong urban agglomeration and significantly unrelated in Lanxi urban agglomeration; education investment is significantly uncorrelated in Lanxi urban agglomeration and Yanhuang urban agglomeration.

5. Conclusion

The conclusions of this paper include the following three points. (1) Through the two-dimensional analysis of time and space, it is found that the overall urban green development in Northwest China is on a good trend, but there are great differences in the level of development between cities, and the unbalanced characteristics are prominent, and there is a path dependence and Matthew effect of “the strong is always strong, the weak is always weak.” (2) In order to

further study the core cities in Northwest China, it is proposed how to play a greater role in the efficiency of high green development. This paper analyzes the convergence and coordination of four urban agglomerations in Northwest China. It is found that there is no good linkage development model within the urban agglomerations, and their respective operations, resource redistribution, and other phenomena are obvious, which seriously hinder the spillover effect of urban agglomerations as regional growth poles. (3) To study the Northwest China, the driving factors of urban green development efficiency, combined with data characteristics, are analyzed by the Tobit model. It is found that economic development level, population density, traffic conditions, and education investment have significant positive impact on green development efficiency, industrial structure has significant negative impact on green development efficiency, and technological innovation has no significant impact. Based on the above analysis results, the following suggestions are put forward to promote the economic green development and high-quality development of cities in Northwest China.

5.1. Establish Scientific Concepts and Break Through Development Barriers Efficiently. The Northwest region is a concentrated area of traditional “high pollution and high energy consumption” industries in China. Therefore, to achieve a long-term green development mechanism, a scientific development concept must be established. First, the government must establish a green development concept and get rid of “pollution first and governance later.” The traditional development path should avoid measuring regional development only by GDP and attach importance to the coordinated development of development quality and economic system-social system-ecosystem. Secondly, it is necessary to establish a scientific and green development evaluation system that meets the characteristics of regional development and promote cities to focus on a distinctive green development path. Finally, policy support should be given to guide the people to develop a green lifestyle, establish a green consumption concept, expand the green industry market, and increase the motivation for green development. This article measures the obstacles to the green development of regional cities. Therefore, under the guidance of scientific concepts, different regions should conduct scientific assessments of existing obstacles, formulate targeted policies, and break through development constraints

in a reasonable and efficient manner. Formulate key industry development directions and economic policies based on the theory of comparative advantage, focus on breaking through the issue of green growth, and at the same time attach importance to social construction and reduce barriers to green welfare. Gansu Province, Qinghai Province, and Ningxia Autonomous Region will strengthen infrastructure construction and build more, while economic development in the Xinjiang Autonomous Region must maintain the development speed, optimize relevant policies, and improve the level of green development.

5.2. Improve Urban Green Synergy. It is found that there is a serious Matthew effect in the green development efficiency of cities in Northwest China. From the perspective of provincial level, the green development efficiency of Shaanxi Province is significantly higher than that of other four provinces. From the perspective of cities in the province, the green development efficiency of provincial capital cities is significantly higher than that of ordinary prefecture-level cities, and the spillover effect of better developed cities is not obvious. Therefore, it is necessary to improve the communication density between cities in Northwest China, and local governments must play a good role in policy guidance, promote cities with different green development efficiency to form mutual brother cities, and share the excellent experience in promoting the development of green industry, reducing pollutant emissions, accelerating the construction of green consumption market, and other aspects, so as to learn from each other and jointly promote green development. At the same time, the development of the northwest cannot be separated. To regard the northwest as the same economic area, each provincial government should set up a provincial development coordination platform, seek common ground while reserving differences, coordinate planning, and unify development, make full use of the natural resources and location advantages of the northwest, give full play to the coordination effect of node cities and important urban agglomerations, and expand the city of Guanzhong urban agglomeration led by Xi'an. The opening degree of the city, including Longdong cities such as Qingyang and Tianshui into the overall planning of Guanzhong City Cluster, fully cooperates in green industry transfer and green technology sharing, and the provincial capitals along the Yellow River, led by Yinchuan and Lanzhou, should give full play to the influence of the provincial capitals and promote the green development of Zhongwei, Baiyin, and other intermediate cities through industrial coordination and resource sharing. Xining, as a city on the Qinghai-Tibet Plateau, should increase its ties with Lanzhou in terms of resource exchange, transportation, and make full use of the opportunity of Lanxi urban agglomeration to improve the quality of economic development. The northern slope urban agglomeration of Tianshan, led by Urumqi and Karamay, should not only actively integrate into the development groups of other northwest cities but also take the Northwest cities as the economic hinterland, actively connect with Central Asia Eastern European market, give full play to the

location advantage of connecting Asian and European markets, improve the quality of development, and realize green development.

5.3. Speeding up the Adjustment of Green Industry Structure. In the study of this paper, the industrial structure factors have a significant negative impact on the green development of Northwest cities. In this paper, the proportion of the secondary industry is used to represent the industrial structure, so the growth of the secondary industry will inhibit the improvement of the green development efficiency. As the pillar industry in Northwest China, the secondary industry must speed up the pace of industrial structure adjustment. First of all, all provinces and cities must do a good job in top-level design according to their own industrial development, make full use of national think tank resources, give full play to the resource advantages of all regions to do a good job in policy guidance, and do a good job in the planning and key project preparation of industrial structure adjustment, so as to create a good platform for industrial structure adjustment; second, a backward area of China's economic development is the Northwest China's industry. In the process of structural adjustment, we should actively introduce advanced technology to the advantageous industries, realize industrial upgrading through technological transformation, promote the development of industries to low pollution, low energy consumption, and low emission, and constantly promote the growth of emerging industries. As a geothermal, solar, and wind energy rich area in China, Northwest China has energy advantages in big data, information, and other industries, so we should vigorously promote it. The implementation of relevant projects should actively introduce green high value-added industries and actively promote the development of ecological industries. Finally, a service-oriented government should be established to improve the administrative level of the government. Cities in Northwest China should pay more attention to the application of foreign capital, create a good environment for the entry of foreign capital, give full play to the leading role of foreign capital, and introduce excellent production management methods and technical level. Different foreign-funded enterprises enter the northwest, give full play to the "catfish effect," and speed up the development of green industry through market competition.

5.4. Introduce Human Capital and Accelerate Technological Transformation. People are the foundation of development, but cities in Northwest China are facing the situation of low population concentration. Therefore, first of all, cities in Northwest China should introduce human capital, increase regional population density, attract people from counties, towns, and other areas to flow to cities, establish green channels in settlement policies, simplify settlement procedures, optimize settlement policies, and vigorously develop online application and approval. The settlement system confirmed on the site will gather human capital; on this basis, we will vigorously introduce high-level talents, improve financial support, and introduce scientific research

and management talents through preferential policies such as housing, spouse, and children's work, so as to provide talent support for green development. At the same time, we should also do a good job in retaining talents and improve the population's dependence on the city by providing suitable jobs, generous treatment level, good living environment, and full emotional care. In Xi'an, Lanzhou, and other provincial capitals with sufficient human capital, we should give full play to the advantages of talent gathering, accelerate the transformation of technological achievements, make use of the advantages of many colleges and universities and scientific research institutes, vigorously develop the economy of colleges and universities, promote the combination of production, teaching, and research, encourage teachers and researchers in colleges and universities to carry out research on technological transformation, build a joint platform for the transformation of scientific and technological achievements, fully connect the intellectual resources of scientific research institutes and production resources of enterprises, promote the transformation of scientific and technological achievements through platform development, establish funds for scientific and technological transformation, encourage enterprises to upgrade production technology, provide financial support, establish a good market system, improve the enthusiasm of enterprises to upgrade technology, and fully promote from two directions of technology theory and technology application transformation of scientific and technological achievements into industrial achievements.

5.5. Strengthen Transportation and Education and Promote Balanced Development. Transportation and education are two important measures to improve the efficiency of green development. Northwest China has complex terrain, poor natural conditions, and the overall traffic situation lags behind the national average. Meanwhile, the regional economic development is slow, the economic strength is weak, and it is difficult to improve the traffic conditions in an all-round way objectively. Therefore, Northwest China must focus on the traffic construction and give full play to the market power, encourage private capital to enter the field of infrastructure construction, do a good job in road network planning, give priority to the construction of connecting roads between key counties and cities, and ensure the arterial connection of regional economy and, on this basis, carry out road construction sinking work, gradually connect counties and towns, and construct a road network for green economic development. Through this study, education investment will have a significant positive impact on the efficiency of green development. Therefore, it is an inevitable trend to continuously increase the investment in education to improve the efficiency of green development. The backward development of higher education in Northwest China is an important factor restricting the green development. Therefore, we should focus on increasing the investment in higher education. In the process of investment, we should make clear the key points, adopt the form of project application system to allocate funds, and combine the needs of regional

industrial development, scientific research advantages, and environmental governance different scientific research projects should be set up to promote colleges and universities and research institutes to apply for special research on related topics, actively guide colleges and universities in other regions to participate in competition, stimulate academic vitality, link educational investment with scientific and technological development and transformation, and form a good cycle system.

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 conflicts of interest.

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Research Article

Supply Chain Investment in Carbon Emission-Reducing Technology Based on Stochasticity and Low-Carbon Preferences

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Due to excessive greenhouse gas emissions, carbon emission-reducing measures are urgently needed. Important emission-reduction measures mainly include carbon trading and low-carbon cost subsidies. Comprehensive consideration of these two policies is a research hotspot in the field of low-carbon technology investment. Based on this background, this paper considers the impact of consumer low-carbon preferences on market demand and the impact of uncertainty in carbon emission-reduction behaviour. We construct a stochastic differential game model with upstream and downstream enterprises based on cost-sharing coordination under a cost subsidy. From a dynamic perspective, this paper researches the optimal equilibrium strategy and evolution characteristics of the joint emission-reduction mechanism in a supply chain. This paper discusses the sensitivity of the parameters and uses numerical simulation to verify the impact of each parameter on the emission-reduction decision-making activities of stakeholders after introducing the cost subsidy. The results show that a cost subsidy policy can promote carbon emission-reduction investment and supply chain profit. Thus, it is important to strengthen technical cooperation and exchange among enterprises.

1. Introduction

Low-carbon economy is an inevitable choice for the sustainable development of global economy. Developing low-carbon economy is conducive to breaking through the bottleneck constraints of resources and environment in the process of economic development and taking the new road of industrialization; it is conducive to forming a sound policy mechanism and institutional guarantee system to promote sustainable development; it is conducive to promoting industrial upgrading and technological innovation of enterprises and building the future international core competitiveness of enterprises. It provides a rare opportunity to realize the fundamental transformation of the economic mode. Under the current situation, actively developing circular economy and low-carbon economy is the best choice to achieve sustainable development. It requires us not only to change the traditional high-carbon economic development mode from

the adjustment of industrial structure and energy structure but also to seek energy-saving ways and promote energy-saving technology from all aspects of the industrial chain. As a major developing country and high-carbon-emitting country, China is actively exploring various carbon emission-reduction measures. The government actively adjusts the industrial and energy structures from a macroperspective, implements carbon emissions trading, and encourages technological innovation from a micro-perspective. With the implementation of China's carbon trading system, the carbon trading market's demand for carbon-dependent enterprises has gradually risen. Designing a carbon trading policy that encourages carbon-dependent enterprises to invest in production and carbon emission-reduction measures has become a focus of social concern. Due to the dynamic and uncertain nature of innovation, carbon emission-reduction behaviour presents high uncertainty. Therefore, it is important to study the influence of the carbon trading system on corporate

emission reduction based on the perspective of stochastic differential games.

Under the background of carbon emission trading and cost subsidies, and considering the low-carbon preferences of consumers and the randomness of the emission-reduction process, this paper uses a stochastic differential game method to analyse the game relationships between the government, manufacturers, retailers, and consumers under cost-sharing coordination from a dynamic perspective. The equilibrium strategies of government, supply chains, and consumers are obtained, and the evolutionary paths of emission reduction, manufacturer profit, and retailer profit are obtained.

The object of this paper is to (1) calculate an objective function describing carbon emission reduction, manufacturer profit, retailer profit, and cost-sharing ratio; (2) consider the low-carbon preferences of consumers and the randomness of the emission-reduction process and study the optimal equilibrium strategies of the government, supply chains, and consumers under cost subsidies and the evolutionary path of carbon emission reduction and supply chain profit; and (3) explore the sensitivity of cost subsidy rates and other stochastic factors to supply chain emission reductions via a numerical experiment.

The theoretical value of this paper lies in its in-depth exploration of supply chain enterprise cooperation mechanisms and the design of carbon emission-reduction investment paths. It provides a theoretical basis for decision-making by supply chain enterprises operating under environmental regulation. The practical significance of this paper is to analyse the optimal decision-making paths of coordinated cost-sharing decision-making under a carbon trading system and cost subsidy policies from a dynamic perspective. This provides theoretical support for technological investment and output decision-making by supply chain enterprises.

The structure of this paper is as follows. Section 2 is a literature review. Section 3 describes the problem in terms of the carbon trading system and emission-reduction technological innovation subsidies under uncertain circumstances of carbon emission-reduction behaviour. A stochastic differential game model is then constructed on this basis. Section 4 uses stochastic differential game theory to solve the Stackelberg equilibrium under a feedback strategy. Section 5 uses the stochastic differential Stackelberg game model to predict emission-reduction inputs and the evolution path of variables. Section 6 provides a parameter sensitivity analysis. Section 7 describes the numerical simulation and the final section makes the conclusions.

2. Literature Review

The essence of sustainable development is that supply chain enterprises start from the energy structure and change the traditional mode of high-carbon economy. Swiader evaluated the natural area surface for carbon fiber assimilation and provided management tools and policy tools for the sustainable development of human settlements [1]. Renwick explored the effect of practice in achieving workplace goals

of environmental sustainability [2]. Bashir discussed the relationship between environmental taxes and carbon emissions, as well as the role of environmental technology and financial development [3]. Nong put forward suggestions on energy resources, policies, and scientific research to achieve a cleaner and more sustainable economy in Vietnam [4]. Jackson studied the labor, reciprocity, and care logic needed to reduce or sequester carbon through the case of carbon agriculture to reduce carbon emissions [5]. Douglas made a theoretical and conceptual comparative analysis on the policies and measures of coal-dependent employment, determined the measures to successfully improve the social and economic well-being of coal-dependent communities, and put forward the framework to successfully achieve a just transition [6]. Amundson proposed a quantitative risk analysis method of biomass supply chain based on Bayesian belief network (BBN) [7].

The impact of microeconomic policies on enterprises' carbon emission-reduction investment behaviour began with the research of Benjaafar, who studied the impact of joint emission reductions by supply chain members on operating costs and carbon emissions [8]. Song et al. proposed a carbon footprint calculation model based on discriminant factors [9]. Elhedhli and Merrick found that the optimal allocation of a supply chain can be achieved by adjusting the cost of carbon emissions [10]. Dai and Hu proposed a double-objective network optimization model of a low-carbon closed-loop supply chain [11]. Chen et al. constructed a fuzzy programming optimization model to find the lowest total cost [12]. Lou et al. proposed a Stackelberg game emission-reduction investment model with manufacturers as the leaders and retailers as the followers [13]. Fu et al. obtained the evolutionarily stable strategy for supplier and manufacturer emission-reduction input behaviour [14]. Liu et al. studied the operational decisions of original equipment manufacturers and authorized remanufacturers under the carbon emission quota and trading rules in a two-echelon supply chain [15]. Zhao et al. analysed the joint carbon emission-reduction problem in a secondary supply chain composed of two manufacturers and a dominant retailer [16]. In addition, Yang et al. compared the effects of four low-carbon policies on supply chain coordination [17]. Xu et al. studied the decision-making and coordination of a two-level supply chain composed of manufacturers and retailers [18]. Yang and Wang compared and analysed carbon emission reduction and supply chain profit under the three situations of decentralization, concentration, and revenue-sharing contracts [19]. Xu et al. studied the game coordination of supply chain members under consignment contracts, revenue-sharing contracts, and revenue-sharing and emission-reduction cost-sharing contracts [20].

In addition, the impact of government on supply chain emission-reduction decision-making is crucial. Zhang et al. studied the optimal investment decisions of a supply chain considering a government carbon tax [21]. Kang et al. studied the behaviour of low-carbon supply chain enterprises and strategic issues related to government low-carbon policies and emerging low-carbon markets [22]. Sun et al.

analysed carbon emission transfer and reduction among enterprises in a supply chain [23]. Wang et al. studied the dynamic coordination of long-term cooperative emission reduction in supply chains under government subsidies [24]. Peng analysed the popular quantity discount contract and revenue-sharing contract in a supply chain [25]. Li et al. discussed the coordination methods of a low-carbon supply chain under different channel power structures [26]. Wang compared differences in levels of emission-reduction effort, advertising, and the present value of supply chain total profit under decentralized and cooperative decision-making modes [27]. Han et al. established a game model to study the decision-making behaviour of manufacturers in a low-carbon e-commerce supply chain that received government carbon subsidies that considered fairness [28]. Wang et al. studied the long-term dynamic cooperative emission reduction and government subsidy strategies of a two-level supply chain [29]. Wang et al. established single and joint emission-reduction models in which supply chain members could adopt one- or two-way cost-sharing contracts and analysed the optimal strategy design and appropriate sharing rate contract [30]. Wang studied the decision-making problem of a two-echelon supply chain composed of a single manufacturer and a single retailer [31]. Zhang et al. discussed the influences of emission-reduction rate, carbon tax, and unit carbon emissions on order quantity, revenue, and contract parameters [32]. Liu and Li established a differential game model of a two-level supply chain and introduced a low-carbon preference into the model. They discussed in detail the impact of low-carbon reference carbon emission reduction by a supply chain [33]. Zhu et al. compared and analysed two situations of government subsidies to low-carbon product manufacturers and consumers who purchased low-carbon products [34]. Li et al. analysed the interactive game between government subsidies and enterprises' choices of emission-reduction cooperation [35]. Zhao et al. analysed the influence coefficient of different subsidy objects on the pricing decisions and profits of channel members [36]. Wei considered dynamic changes in carbon emissions and constructed a differential game model of emission-reduction investment by a supply chain [37]. Wang et al. studied the joint emission-reduction coordination problem of a three-level supply chain with centralized and decentralized decision-making and cost-sharing collaborative decision-making [38].

The above literature mainly considers the operational cooperation of a low-carbon supply chain from a static perspective. However, enterprise operations often span multiple cycles. Therefore, it is very important to study coordination and cooperation between the upstream and downstream enterprises in a low-carbon supply chain from a dynamic perspective. Mohamad et al. analysed the selection of the best cooperation mode for supply chain management when the carbon emission limit is exceeded [39]. Ren et al. researched the influence of government subsidies on enterprise decision-making behaviour via a two-stage dynamic game [40]. Wang et al. constructed three dynamic game models involving decentralized decision-making without cost-sharing, decentralized decision-making, and

centralized decision-making under cost-sharing. They analysed the dynamic strategy of regional low-carbon technology [41]. Huang and Yuan proposed a Stackelberg differential game model of a single government and multiple enterprises in a limited period [42]. Yang et al. constructed a continuous-time dynamic model of differential inequality [43]. Giovanni studied the optimal green advertising investment and pricing strategies of manufacturers and retailers under wholesale-pricing and reverse-revenue-sharing contracts, respectively [44]. Considering a carbon trading market and the low-carbon preferences of consumers, Liu et al. obtained the low-carbon technology conditions required to achieve a win-win situation [45]. Zhao et al. studied the vertical cooperative emission-reduction dynamic optimization problem of a low-carbon supply chain [46]. Ye et al. studied supply chain dynamic optimization and the coordination of joint emission reductions with consideration of consumers' low-carbon preferences [47]. You et al. compared the long-term dynamic equilibrium strategies of a two-level supply chain under decentralized and centralized decision-making situations [48]. Xu et al. constructed and analysed three differential game models: decentralized decision-making without cost-sharing, decentralized decision-making under a cost-sharing contract, and centralized decision-making under collaborative control [49].

Existing research has mainly focused on manufacturer research and development (R&D) investment. The retailers use low-carbon publicity or promotion to follow the manufacturers. However, no research has considered that the emission reductions related to product manufacturing decline naturally over time, which affects the incentive for enterprises to reduce emissions. Therefore, this paper uses the stochastic differential game method to expand the research in this field. Considering a scenario of a carbon trading market with a cost subsidy, this paper comprehensively analyses consumers' low-carbon preferences and random factors in the process of carbon emission reduction. It obtains the optimal equilibrium strategy and evolution path for joint carbon emission reduction by manufacturers and retailers.

3. Stochastic Differential Game Model

3.1. Problem Description. Actively developing circular economy and low-carbon economy is the best choice to achieve sustainable development. To develop low-carbon economy, we should not only change the traditional development mode of high-carbon economy but also seek energy-saving ways and promote energy-saving technologies from all aspects of the supply chain. Therefore, this paper considers a carbon emission-reduction system of a simple secondary supply chain composed of a manufacturer and a retailer. Widely used low-carbon supply chain coordination mechanisms include cooperative advertising contracts, revenue-sharing contracts, wholesale price contracts, cost-sharing contracts, and two-part contracts. This paper studies the cooperation between upstream and downstream enterprises in the practice of carbon emission-reduction supply chain management. The upstream manufacturer carries out

energy and emission reductions, and the downstream retailer shares certain costs. In general, the manufacturer is the main source of emission reduction and faces more pressure than the retailer. Meanwhile, the manufacturer can transfer the cost of emission reduction downstream through market forces. Therefore, the manufacturer is the decision-maker in the differential game and the retailer follows the manufacturer to share the R&D cost of emission reduction. In China's quota-based carbon trading system, the government grants enterprises a certain carbon quota. Emissions that exceed the quota must be purchased from the society. At the same time, carbon trading is carried out in some large markets and the supply chain has no effect on the carbon price. Therefore, it is assumed that the carbon price is exogenous. In addition, this paper assumes that consumers have a low-carbon preference; i.e., they prefer products associated with lower carbon emissions.

To describe the above problems, this paper defines the parameters shown in Table 1.

This paper simplifies the complex conditions and makes the following hypotheses.

Hypothesis 1 (demand function hypothesis). Referring to the research of Laroche et al. [50] and Ouadighi [51, 52], market demand is mainly affected by price factors and nonprice factors, which affect market demand in the form of separable multiplication. The product demand function is as follows:

$$Q_E(t) = (a - bp(t))kE(t). \quad (1)$$

Hypothesis 2 (input cost hypothesis of emission-reduction technology). The manufacturer's emission-reduction cost function is an extension of the hypothesis of the innovation cost function. The function is a convex function describing emission-reduction efforts. Thus, the manufacturer's emission-reduction cost at time t is given by

$$C(Z_M(t)) = \frac{\mu_M}{2} Z_M^2(t). \quad (2)$$

Hypothesis 3 (interest intensity hypothesis). Suppose that the upstream manufacturer and downstream retailer have the same interest intensity ρ , and $\rho > 0$.

3.2. Dynamic Model of Carbon Emission-Reduction Investment. The supply chain modelled in this paper is a

simple two-level supply chain with one manufacturer and one retailer. This paper studies a model of investment in carbon emission-reduction technology based on government subsidies and consumer low-carbon preference. The decision-making process of the government, supply chain, and consumers is shown in Figure 1.

The emission-reduction process is affected by investment in emission-reduction subject, facilities maintenance, consumer environmental awareness, and various uncontrollable factors. Thus, the emission-reduction process is random.

Hypothesis 4. The stochastic process of carbon emission reduction is composed of three driving forces. One is a random factor, which can be described as a standard Wiener process $dE(t) = \delta\sqrt{E(t)}dz(t)$, in which δ is a fluctuation parameter of carbon emission reduction. The second is the carbon emission reduction resulting from R&D investment by the emission-reduction subject $dE(t) = \alpha Z_M(t)dt$, in which $Z_M(t)$ is the emission-reduction effort. The third changes in environmental awareness and equipment ageing, $dE(t) = -\sigma E(t)dt$, in which σ is the emission-reduction coefficient. The overall dynamic equation is the sum of the three parts:

$$dE(t) = (\alpha Z_M(t) - \sigma E(t))dt + \delta\sqrt{E(t)}dz(t). \quad (3)$$

3.3. Objective Function of the Manufacturer and Retailer. Carbon trading system based on a carbon quota is essentially the intensity control mode. It is assumed that the carbon quota and carbon emissions per unit product set by the government are fixed in a certain period. Thus, the function of the carbon emissions trading cost is as follows:

$$E_{MT(t)} = p_e [g_M Q_E(t) + E(t) - e_M Q_E(t)]. \quad (4)$$

In actual operations, for a carbon emission-reduction supply chain that is regulated by the government, the profit function of the manufacturers consists of sales revenue, carbon emission-reduction costs, and carbon trading income. Considering that the retailer will share part of the carbon emission-reduction cost of the manufacturer, the retailer's profit function is composed of sales revenue and carbon emission-reduction cost. In addition, the goal of the game between the manufacturer and retailer is to maximize profit. For ease of expression, t is not listed below.

Thus, the objective function of the manufacturers is as follows:

$$\begin{aligned} \max E\{J_M[\omega, Z_M, \xi]\} = \\ \max E\left\{\int_0^\infty e^{-\rho t} \left\{ (w - c)Q_E - (1 - \xi)(1 - \tau) \frac{\mu_M}{2} Z_M^2 + p_e (g_M Q_E + E - e_M Q_E) \right\} dt\right\}. \end{aligned} \quad (5)$$

TABLE 1: Description of the parameters of the model.

| Variable | Description |
|----------|---|
| p | Product retail price |
| a | Product market size |
| Q_E | Quantity demanded considering consumer low-carbon preference |
| μ_m | Abatement cost coefficient |
| α | Impact coefficient of the manufacturer's emission-reduction effort |
| g_m | Per unit product emission quota set by government regulations |
| c | Manufacturer's unit production cost |
| J_M | Profit of the manufacturer |
| k | Low-carbon sensitivity coefficient of consumers |
| τ | Cost subsidy coefficient |
| δ | Fluctuation coefficient of emission reduction |
| w | Manufacturer's wholesale price |
| b | Product marginal demand |
| Z_m | Emission-reduction effort |
| E | Carbon emission reduction |
| σ | Relative attenuation rate for the product emission-reduction function |
| e_m | Carbon emissions per unit product without emission-reduction investment |
| ρ | Discount rate |
| J_R | Profit of the retailer |
| ξ | Retailer emission-reduction cost-sharing proportion |
| p_e | Carbon trading price |

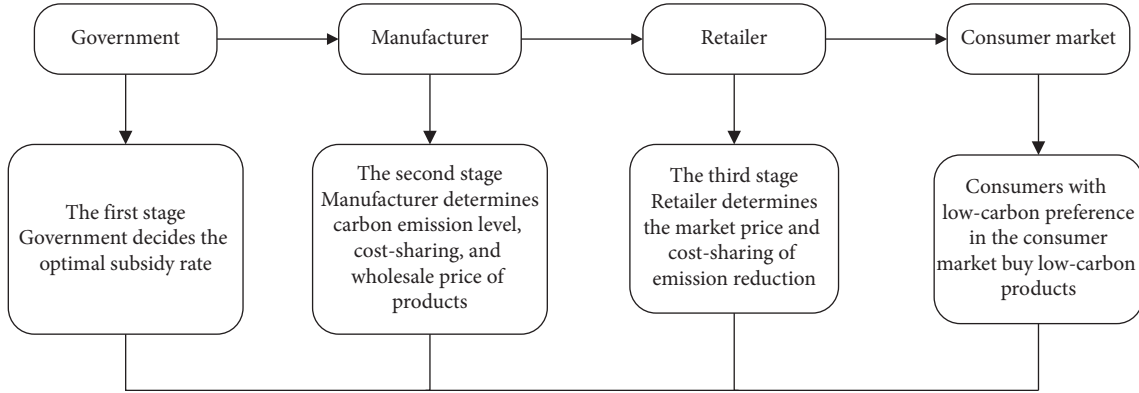


FIGURE 1: Decision diagram.

The objective function of the retailers is as follows:

$$\max E\{J_R[p, \xi]\} = \max E\left\{\int_0^\infty e^{-\rho t} \left\{ (p - w)Q_E - \xi(1 - \tau)\frac{\mu_M}{2}Z_M^2 \right\} dt\right\}. \quad (6)$$

3.4. Stochastic Differential Game Model. Assuming that the government, manufacturers, and retailers adopt a progressive Stackelberg game, the stochastic differential game model of the carbon emission system is as follows:

$$\text{s.t.} \begin{cases} \max_{\omega, Z_M, \xi} J_M(w, Z_M, \xi; p), \\ \max_{p, \xi} J_R(w, Z_M, \xi; p); \\ dE(t) = (\alpha Z_M(t) - \sigma E(t))dt + \delta \sqrt{E(t)} dz(t), \\ E(0) = E_0. \end{cases} \quad (7)$$

4. Equilibrium Strategy

Based on the stochastic differential game method, this paper discusses the game process between upstream and downstream enterprises of a supply chain and obtains the feedback equilibrium between the manufacturer and the retailer. Firstly, the manufacturer determines the wholesale price and carbon emission-reduction efforts of the products at each moment and carries out a game with the retailer to determine the cost-sharing proportion. Secondly, the retailer determines the market price of products at each moment and carries out a game with the manufacturer to determine the emission-reduction cost-sharing ratio.

Theorem 1. *The decision-making goal of upstream manufacturers and downstream retailers is to maximize their respective profits. The game equilibrium results of the manufacturer and retailer are as follows:*

$$\begin{aligned} w^* &= \frac{1}{2b} (a + bc + bp_e e_M - bp_e g_M), \\ Z_M^* &= \frac{V_M^S}{(1-\xi)(1-\tau)} \frac{\alpha}{\mu_M}, \\ p^* &= \frac{1}{4b} (3a + bc + bp_e e_M - bp_e g_M), \\ \xi &= \frac{2V_R^S - V_M^S}{2V_R^S + V_M^S}. \end{aligned} \quad (8)$$

Proof. It is assumed that the wholesale price of manufacturer $\omega(t)$ and the carbon emission-reduction effort $Z_M(t)$ are given for any time $t \in [0, \infty)$. This paper uses backward induction and continuous-time dynamic programming theory to obtain the HJB equation. The HJB equation satisfies the retailer's optimal product pricing and optimal cost-sharing ratio.

$$\rho V_R^S = \max_{p, \xi} \left\{ (p - w)(a - bp)kE - \xi \frac{\mu_M(1-\tau)}{2} Z_M^2 + V_R^S (\alpha Z_M - \sigma E) \right\} + \frac{1}{2} \delta^2 E V_R^S, \quad (9)$$

where V_R^S is the retailer's optimal value function.

Optimizing the right-hand side of the retailer's function, the product price-response strategy of the retailer can be obtained as follows:

$$p = \frac{a + bw}{2b}. \quad (10)$$

This paper uses continuous-time dynamic programming theory to obtain the HJB equation. In addition, the optimal wholesale price and carbon emission-reduction effort strategy of the manufacturer should satisfy the following HJB equation:

$$\begin{aligned} \rho V_M^S &= \max_{Z_M \geq 0} \left\{ (w - c - p_e e_M + p_e g_M)(a - bp)kE - (1 - \xi) \frac{\mu_M(1-\tau)}{2} Z_M^2 + p_e E \right. \\ &\quad \left. + V_M^S (\alpha Z_M - \sigma E) \right\} + \frac{1}{2} \delta^2 E V_M^S. \end{aligned} \quad (11)$$

The retailer's product price reflecting strategy is introduced into the above formula, which can be solved as

$$\begin{aligned} \rho V_M^S &= \max_{Z_M \geq 0} \left\{ (w - c - p_e e_M + p_e g_M) \left(\frac{a - bw}{2} \right) kE - (1 - \xi) \frac{\mu_M(1-\tau)}{2} Z_M^2 \right. \\ &\quad \left. + p_e E + V_M^S (\alpha Z_M - \sigma E) \right\} + \frac{1}{2} \delta^2 E V_M^S, \end{aligned} \quad (12)$$

where V_M^S is the optimal value function of the manufacturer.

Solving the optimization problem at the right-hand side of the equation, the manufacturer's optimal wholesale price and optimal carbon emission-reduction effort are as follows:

$$\begin{aligned} w^* &= \frac{1}{2b} (a + bc + bp_e e_M - bp_e g_M), \\ Z_M^* &= \frac{V_M^S}{(1-\xi)(1-\tau)} \frac{\alpha}{\mu_M}. \end{aligned} \quad (13)$$

Substituting the emission-reduction effort into the retailer's HJB equation, and making the first-order partial derivative equal to zero, we can obtain the following result:

$$\xi = \frac{2V_R^S - V_M^S}{2V_R^S + V_M^S}. \quad (14)$$

To obtain the strategies of the manufacturer and retailer, it is necessary to determine their optimal value functions. These are obtained by introducing the strategies of manufacturer and retailer.

$$\rho V_M^S = \max_{Z_M \geq 0} \left\{ \left[\frac{1}{8b} (a - bc - bp_e e_M + bp_e g_M)^2 k - V_M^{S'} \sigma + p_e + \frac{1}{2} \delta^2 V_M^{S''} \right] E - \frac{\alpha^2 V_M^{S'} (2V_R^{S'} + V_M^{S'})}{4\mu_M (1 - \tau)} \right\}, \quad (15)$$

$$\rho V_R^S = \max_{p, \xi} \left\{ \left[\frac{1}{16b} (a - bc - bp_e e_M + bp_e g_M)^2 k - V_R^{S'} \sigma + \frac{1}{2} \delta^2 V_R^{S''} \right] E + \frac{V_R^{S'} \alpha^2 (2V_R^{S'} + V_M^{S'})}{2\mu_M (1 - \tau)} - \frac{\alpha^2 (2V_R^{S'} - V_M^{S'}) (2V_R^{S'} + V_M^{S'})}{8\mu_M (1 - \tau)} \right\}. \quad (16)$$

Solving the differential equation system separately, the optimal value functions of the manufacturer and retailer are as follows:

$$\begin{cases} V_M^S = f_1 E^2 + f_2 E + f_3, \\ V_R^S = g_1 E^2 + g_2 E + g_3. \end{cases} \quad (17)$$

The first and second derivatives of the optimal value function of the manufacturer and the retailer are given by

$$\begin{cases} V_M^{S'} = 2f_1 E + f_2, \\ V_R^{S'} = 2g_1 E + g_2, \end{cases} \quad (18)$$

$$\begin{cases} V_M^{S''} = 2f_1, \\ V_R^{S''} = 2g_1. \end{cases} \quad (19)$$

To make the optimal value functions of the manufacturer and the retailer assumed in equation (17) is the solution of equations (15) and (16), substituting equations (17)–(19), respectively, into equations (15) and (16), which can be solved as

$$\begin{cases} \rho f_1 = \frac{\alpha^2 (2f_1 g_1 + f_1^2)}{\mu_M (1 - \tau)} - 2\sigma f_1, \\ \rho f_2 = \frac{(a - bc - bp_e e_M + bp_e g_M)^2 k + 8bp_e + 8b\delta^2 f_1 - 8b\sigma f_2}{8b} + \frac{\alpha^2 (f_1 g_2 + f_2 g_1 + f_1 f_2)}{\mu_M (1 - \tau)}, \\ \rho f_3 = \frac{\alpha^2 f_2 (2g_2 + f_2)}{4\mu_M (1 - \tau)}, \end{cases} \quad (20)$$

$$\begin{cases} \rho g_1 = \frac{\alpha^2 (4g_1 + 2f_1)^2}{8\mu_M (1 - \tau)} - 2\sigma g_1, \\ \rho g_2 = \frac{(a - bc - bp_e e_M + bp_e g_M)^2 k + 16b\delta^2 g_1 - 16b\sigma g_2}{16b} + \frac{\alpha^2 (2g_2 + f_2) (2g_1 + f_1)}{2\mu_M (1 - \tau)}, \\ \rho g_3 = \frac{\alpha^2 (2g_2 + f_2)^2}{8\mu_M (1 - \tau)}. \end{cases} \quad (21)$$

Equations (20) and (21) are valid for all possible values of carbon emission reduction, which indicates that the

coefficients and constant terms on both sides of the equation are equivalent. They can be solved as

$$\begin{cases} f_1 = \frac{2(2\sigma + \rho)\mu_M(1 - \tau)}{\alpha^2}, \\ f_2 = \frac{[(a - bc - bp_e e_M + bp_e g_M)^2 k \alpha^2 (\sigma + \rho) + 8b\alpha^2 p_e (3\sigma + 2\rho) - 8b\delta^2 (2\sigma + \rho)(8\sigma + 5\rho)\mu_M(1 - \tau)]}{4b\alpha^2 [(3\sigma + 2\rho)(8\sigma + 5\rho) - 2(2\sigma + \rho)^2]}, \\ f_3 = \frac{\alpha^2 g_2 f_2}{2\mu_M(1 - \tau)\rho} + \frac{\alpha^2 f_2^2}{4\mu_M(1 - \tau)\rho}, \end{cases} \quad (22)$$

$$\begin{cases} g_1 = \frac{(2\sigma + \rho)\mu_M(1 - \tau)}{2\alpha^2}, \\ g_2 = \frac{[(a - bc - bp_e e_M + bp_e g_M)^2 k \alpha^2 (4\sigma + 3\rho) - 16b\alpha^2 p_e (2\sigma + \rho) + 8b\delta^2 (2\sigma + \rho)(16\sigma + 9\rho)\mu_M(1 - \tau)]}{16b\alpha^2 [(3\sigma + 2\rho)(8\sigma + 5\rho) - 2(2\sigma + \rho)^2]}, \\ g_3 = \frac{\alpha^2 (4g_2^2 + f_2^2 + 4g_2 f_2)}{8\mu_M(1 - \tau)\rho}. \end{cases}$$

Firstly, we calculate the coefficient f_1 according to the given parameters and then calculate the other coefficients. Secondly, we derive the optimal value function according to formula (17). Finally, we use Theorem 1 to obtain the manufacturer's carbon emission-reduction effort and wholesale price, the retailer's retail price, and the carbon emission-reduction cost-sharing ratio. \square

5. Characteristics of Evolution in the Emission-Reduction Rate

Theorem 2. *The expectation of random carbon reduction and the expectation limit are, respectively, as follows:*

$$\begin{aligned} E_{(E)} &= e^{Mt} (E_0 + NM^{-1} - NM^{-1}e^{-Mt}), \\ \lim_{t \rightarrow \infty} E_{(E)} &= -NM^{-1}. \end{aligned} \quad (23)$$

The variance of random carbon reduction and variance limit are, respectively,

$$\begin{aligned} D_{(E)} &= e^{2Mt} (E_0 + NM^{-1} - NM^{-1}e^{-Mt})^2 - e^{2Mt} (E_0^2 + (ME_0 + N)(2N + \delta^2)M^{-2} - N(2N + \delta^2)(2M^2)^{-1}) \\ &\quad - e^{Mt} (ME_0 + N)(2N + \delta^2)M^{-2} + N(2N + \delta^2)(2M^2)^{-1}, \\ \lim_{t \rightarrow \infty} D_{(E)} &= N(2N + \delta^2)(2M^2)^{-1} - N^2M^{-2}, \end{aligned} \quad (24)$$

where $M = -(3\sigma + \rho)$ and $N = \alpha^2(2g_2 + f_2)[2\mu_M(1 - \tau)]^{-1}$.

Proof. The manufacturer's carbon emission-reduction efforts in Theorem 1 are brought into the process of carbon emission reduction, which can be solved as

$$\begin{aligned} dE(t) &= [\alpha Z_M(t) - \sigma E(t)]dt + \delta \sqrt{E(t)}dZ(t), \\ E(0) &= E_0. \end{aligned} \quad (25)$$

Integrating the two sides by using boundary conditions, it can be solved as

$$E = E_0 + \int_0^t (ME + N)dt + \int_0^t \delta \sqrt{E(t)}dZ(t). \quad (26)$$

Taking the expectations on both sides by using the zero-mean property of the Wiener process, it can be solved as

$$E_{(E)} = E_0 + \int_0^t (ME_{(E)} + N)dt. \quad (27)$$

Integrating again, it can be solved as

$$E_{(E)} = e^{Mt} (E_0 + NM^{-1} - NM^{-1}e^{-Mt}). \quad (28)$$

When $t \rightarrow \infty$, we can obtain $M < 0$, which can be solved as

$$\lim_{t \rightarrow \infty} E_{(E)} = -NM^{-1}. \quad (29)$$

TABLE 2: Parameter sensitivity analysis.

| | $E(E(t)^*)$ | Z_M^* | w^* | p^* |
|----------|--------------|--------------|---------------|---------------|
| k | \uparrow | \uparrow | \rightarrow | \rightarrow |
| μ_M | \downarrow | \downarrow | \rightarrow | \rightarrow |
| α | \uparrow | \uparrow | \rightarrow | \rightarrow |
| p_e | \uparrow | \uparrow | \downarrow | \downarrow |
| τ | \uparrow | \uparrow | \rightarrow | \rightarrow |

Based on the ITO theorem, we determine the change process of the square of carbon reduction, which can be solved as

$$\begin{aligned} dE^2 &= [2ME^2 + (2N + \delta)^2 E]dt + 2\delta E\sqrt{E(t)}dZ(t), \\ E^2(0) &= E_0^2. \end{aligned} \quad (30)$$

Integrating the two sides by using boundary conditions, we obtain

$$E^2 = E_0^2 + \int_0^t (2ME^2 + (2N + \delta)^2 E)dt + \int_0^t 2\delta E\sqrt{E(t)}dZ(t). \quad (31)$$

Taking the expectations on both sides by using the zero-mean property of the Wiener process, we can obtain

$$E_{(E^2)} = E_0^2 + \int_0^t (2ME_{(E^2)} + (2N + \delta^2)E_{(E)})dt. \quad (32)$$

By substituting the result into the above formula, we obtain

$$E_{(E^2)} = e^{2Mt} \left(E_0^2 + \frac{(ME_0 + N)(2N + \delta^2)}{M^2} - \frac{N(2N + \delta^2)}{2M^2} \right) - e^{Mt} \frac{(ME_0 + N)(2N + \delta^2)}{M^2} + \frac{N(2N + \delta^2)}{2M^2}. \quad (33)$$

We then determine the variance in carbon reduction according to the following equation:

$$D_{(E)} = E_{(E^2)} - [E_{(E)}]^2. \quad (34)$$

Considering $M < 0$, we get $\lim_{t \rightarrow \infty} E_{(E^2)} = ((N(2N + \delta^2))/(2M^2))$. Thus, the variance limit of emission reduction is $\lim_{t \rightarrow \infty} D_{(E)} = \lim_{t \rightarrow \infty} E_{(E^2)} - \lim_{t \rightarrow \infty} [E_{(E)}]^2 = ((N(2N + \delta^2))/(2M^2)) - (N^2/M^2)$. It is assumed that the process of carbon emission reduction does not produce random interference ($\delta = 0$); that is,

$$\lim_{t \rightarrow \infty} E_{(E^2)} = (N^2/M^2); \quad \text{thus, } D_{(E)} = E_{(E^2)} - [E_{(E)}]^2 = 0. \quad \square$$

6. Parameter Sensitivity Analysis

Assume that the consumer low-carbon preference coefficient is k , the emission-reduction effort influence coefficient of manufacturer is α , the emission-reduction cost coefficient is μ_M , the carbon trading price is p_e , and the cost subsidy rate is τ . We then calculate the impact of the above parameters on the optimal emission-reduction effort, wholesale price, retail

price, and emission reduction. The results are shown in Table 2.

Inference 1. Under the coordinated decision-making of cost subsidy, the increase in the consumer low-carbon preference coefficient will lead to increased carbon

emissions. The manufacturers will increase their emission-reduction efforts, and the wholesale price of the manufacturer and the retail price of the retailer will remain invariant.

Proof

$$\begin{aligned}
 \frac{\partial p^*}{\partial k} &= 0, \\
 \frac{\partial w^*}{\partial k} &= 0, \\
 \frac{\partial Z_M^*}{\partial k} &= -\frac{(2\sigma + \rho)}{\alpha} \frac{dE_{(E)}}{dk} + \frac{(a - bc - bp_e e_M + bp_e g_M)^2 \alpha (6\sigma + 5\rho)}{16b\mu_M (1 - L) [(3\sigma + 2\rho)(8\sigma + 5\rho) - 2(2\sigma + \rho)^2]} > 0, \\
 \frac{\partial M}{\partial k} &= 0.
 \end{aligned} \tag{35}$$

Inference 2. Under the coordinated decision-making of cost subsidy, with increases in the manufacturer's emission-reduction cost coefficient, the system's carbon emission reductions will decrease, the manufacturer will reduce

emission-reduction efforts, and the manufacturer's wholesale price and retailer's retail price will remain invariant.

Proof

$$\begin{aligned}
 \frac{\partial p^*}{\partial \mu_M} &= 0, \\
 \frac{\partial w^*}{\partial \mu_M} &= 0, \\
 \frac{\partial Z_M^*}{\partial \mu_M} &= -\frac{(2\sigma + \rho)}{\alpha} \frac{dE_{(E)}}{d\mu_M} - \frac{(a - bc - bp_e e_M + bp_e g_M)^2 k \alpha (6\sigma + 5\rho) + 16b\alpha p_e (\sigma + \rho)}{16b\mu_M^2 (1 - L) [(3\sigma + 2\rho)(8\sigma + 5\rho) - 2(2\sigma + \rho)^2]} < 0, \\
 \frac{\partial M}{\partial \mu_M} &= 0, \\
 \frac{\partial N}{\partial \mu_M} &= -\frac{(a - bc - bp_e e_M + bp_e g_M)^2 k \alpha^2 (6\sigma + 5\rho) + 16b\alpha^2 p_e (\sigma + \rho)}{16b\mu_M^2 (1 - L) [(3\sigma + 2\rho)(8\sigma + 5\rho) - 2(2\sigma + \rho)^2]} < 0.
 \end{aligned} \tag{36}$$

Inference 3. Under the coordinated decision-making of cost subsidy, increases in the emission-reduction cost coefficient will lead to increases in carbon emission reductions, the

manufacturers will increase carbon emission-reduction efforts, and the manufacturer's wholesale price and retailer's retail price will remain invariant.

Proof

$$\frac{\partial p^*}{\partial \alpha} = 0,$$

$$\frac{\partial w^*}{\partial \alpha} = 0,$$

$$\frac{\partial Z_M^*}{\partial \alpha} = \frac{(2\sigma + \rho)(E - \alpha(dE_{(E)}/d\alpha))}{\alpha^2} + \frac{8b\delta^2\rho(2\sigma + \rho)}{16b\alpha^2[(3\sigma + 2\rho)(8\sigma + 5\rho) - 2(2\sigma + \rho)^2]} > 0, \quad (37)$$

$$\frac{\partial M}{\partial \alpha} = 0,$$

$$\frac{\partial N}{\partial \alpha} = \frac{(a - bc - bp_e e_M + bp_e g_M)^2 k\alpha(6\sigma + 5\rho) + 16b\alpha p_e(\sigma + \rho)}{8b\mu_M(1 - L)[(3\sigma + 2\rho)(8\sigma + 5\rho) - 2(2\sigma + \rho)^2]} > 0.$$

Inference 4. Under the coordinated decision-making of cost subsidy, increases in the carbon trading price will lead to increases in carbon emission reduction, the manufacturers will reduce their emission-reduction efforts, and at the same

time, the manufacturers will reduce their wholesale price and retailers will reduce their retail price. \square

Proof

$$\frac{\partial p^*}{\partial p_e} = \frac{1}{4}(e_M - g_M) < 0,$$

$$\frac{\partial w^*}{\partial p_e} = \frac{1}{2}(e_M - g_M) < 0,$$

$$\frac{\partial Z_M^*}{\partial p_e} = -\frac{(2\sigma + \rho)}{\alpha} \frac{dE_{(E)}}{dp_e} + \frac{8\alpha(\sigma + \rho) + (a - bc - bp_e e_M + bp_e g_M)k\alpha(g_M - e_M)(6\sigma + 5\rho)}{8\mu_M(1 - L)[(3\sigma + 2\rho)(8\sigma + 5\rho) - 2(2\sigma + \rho)^2]} > 0, \quad (38)$$

$$\frac{\partial M}{\partial p_e} = 0,$$

$$\frac{\partial N}{\partial p_e} = \frac{8\alpha^2(\sigma + \rho) + (a - bc - bp_e e_M + bp_e g_M)k\alpha^2(g_M - e_M)(6\sigma + 5\rho)}{8\mu_M(1 - L)[(3\sigma + 2\rho)(8\sigma + 5\rho) - 2(2\sigma + \rho)^2]} > 0.$$

Inference 5. Under the coordinated decision-making of cost subsidy, increases in the cost subsidy rate will lead to increases in carbon emission reduction, the manufacturers will

increase their emission-reduction efforts, and the wholesale price of manufacturers and the retail price of retailers will remain invariant. \square

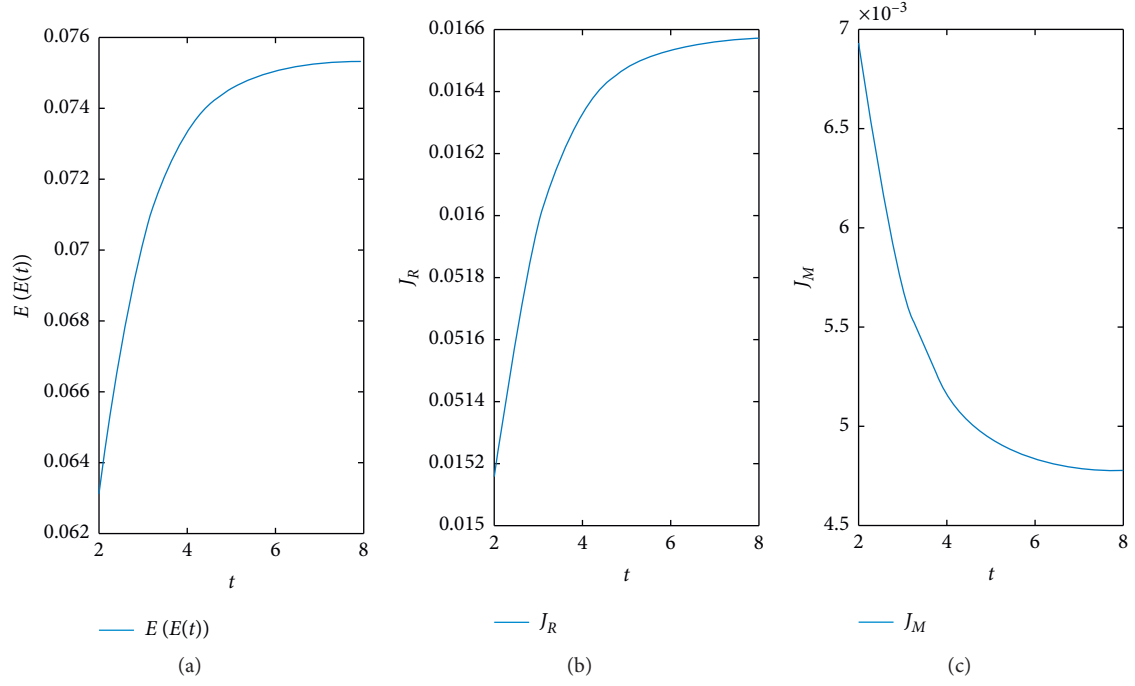


FIGURE 2: State variable trajectories under a cost-sharing and coordinated decision-making scenario.

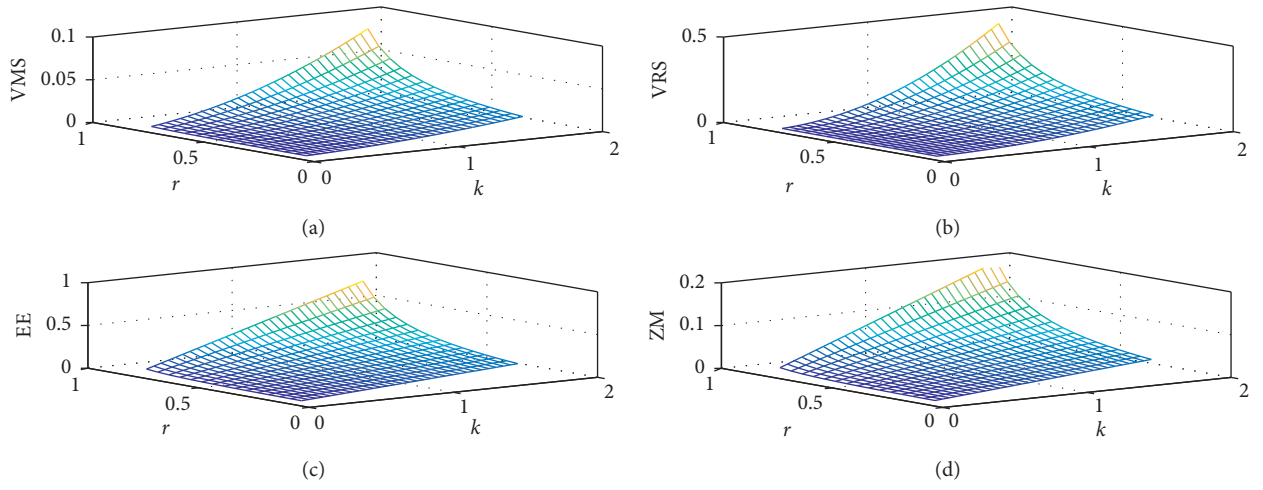


FIGURE 3: Sensitivity analysis of consumers' carbon sensitivity coefficient and cost subsidy rate.

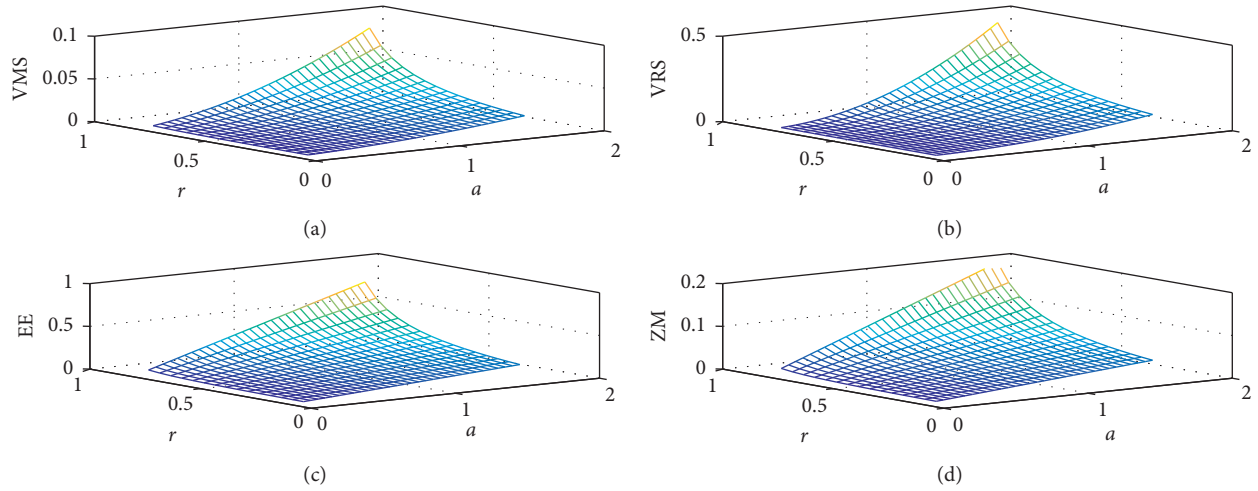


FIGURE 4: Sensitivity analysis of efforts influence coefficient and cost subsidy rate.

Proof

$$\frac{\partial p^*}{\partial \tau} = 0,$$

$$\frac{\partial w^*}{\partial \tau} = 0,$$

$$\frac{\partial M}{\partial \tau} = 0,$$

(39)

$$\frac{\partial N}{\partial \tau} = \frac{8b\delta^2\rho(2\sigma + \rho)}{16b[(3\sigma + 2\rho)(8\sigma + 5\rho) - 2(2\sigma + \rho)^2]} > 0,$$

$$\frac{\partial Z_M^*}{\partial \tau} = -\frac{(2\sigma + \rho)}{\alpha} \frac{dE_{(E)}}{d\tau} + \frac{8b\delta^2\rho(2\sigma + \rho)}{16b\alpha[(3\sigma + 2\rho)(8\sigma + 5\rho) - 2(2\sigma + \rho)^2]} > 0.$$

□

7. Numerical Example

7.1. Evolution Path Analysis. This paper intuitively analyses the supply chain's optimal strategic trajectory under cost-sharing and coordinated decision-making through parameter assignment. The parameters of this paper are set as follows: $\rho = 0.3$, $\sigma = 0.2$, $a = 4.5$, $b = 1$, $c = 3$, $\alpha = 0.8$, $p_e = 0.02$, $k = 0.6$, $\mu_M = 1$, $e_M = 0.5$, $g_M = 2$, $E(0) = 0$, $\tau = 0.15$, and $\delta = 0.01$. The trajectory of the supply chain's profit and emission reductions under cost-sharing and coordinated decision-making can be obtained, as shown in Figure 2.

In Figure 2, the carbon emission reductions and retailer profit show nonlinear upward trends with time, and the rate of increase becomes slower and slower and finally becomes

stable. The change of manufacturer's profit is opposite to that of the retailer.

7.2. Sensitivity Analysis

7.2.1. Sensitivity Analysis of τ and k . Assuming that other parameters remain unchanged, the simulation of the cost subsidy rate and consumer low-carbon sensitivity coefficient is as shown in Figure 3.

As shown in Figure 3, the manufacturer profit, retailer profit, product carbon emissions, and the emission-reduction effort of the manufacturer increase with increases in the cost subsidy rate and consumer low-carbon sensitivity coefficient. However, the impacts of the cost

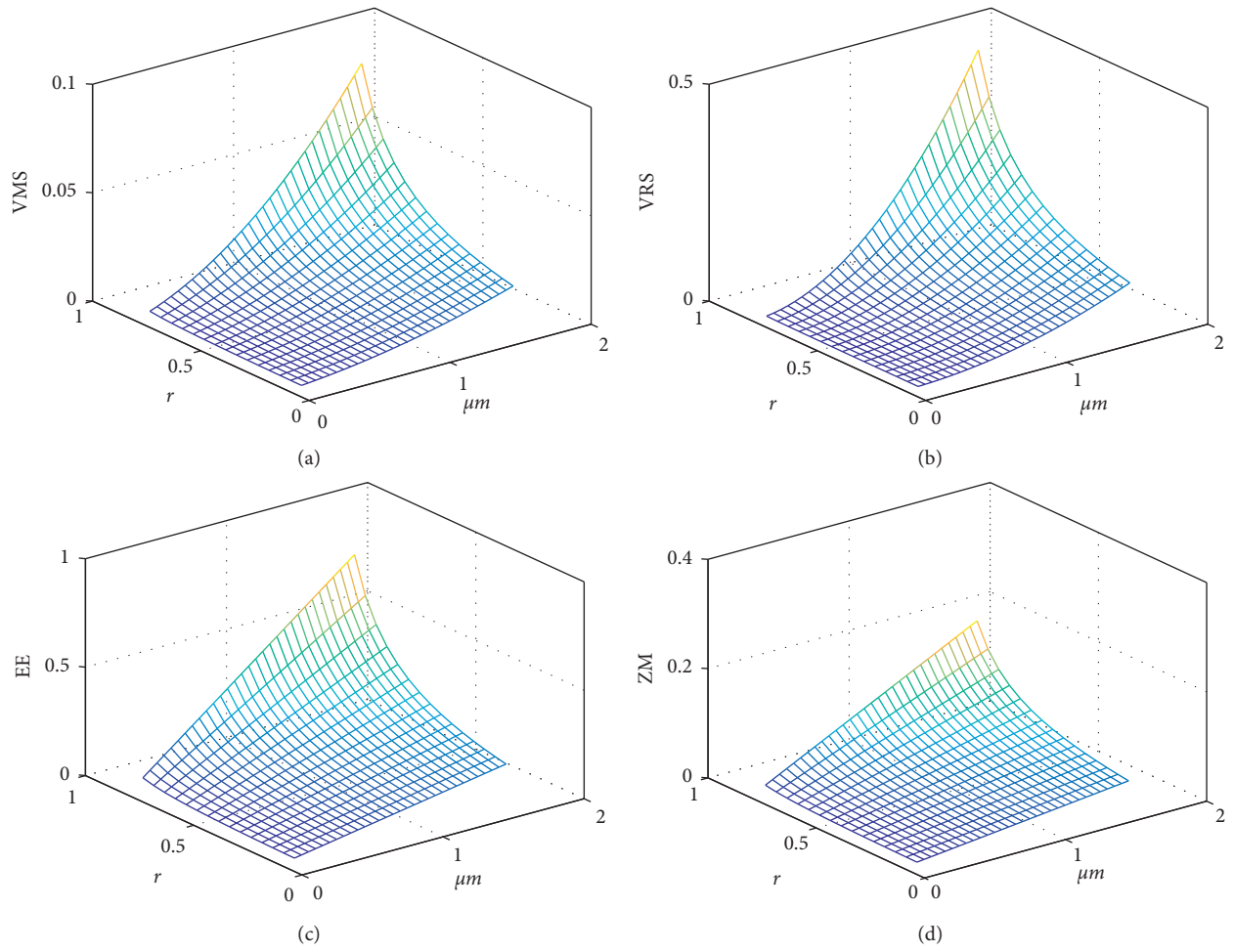


FIGURE 5: Sensitivity analysis of emission-reduction efforts, cost coefficient, and cost subsidy rate.

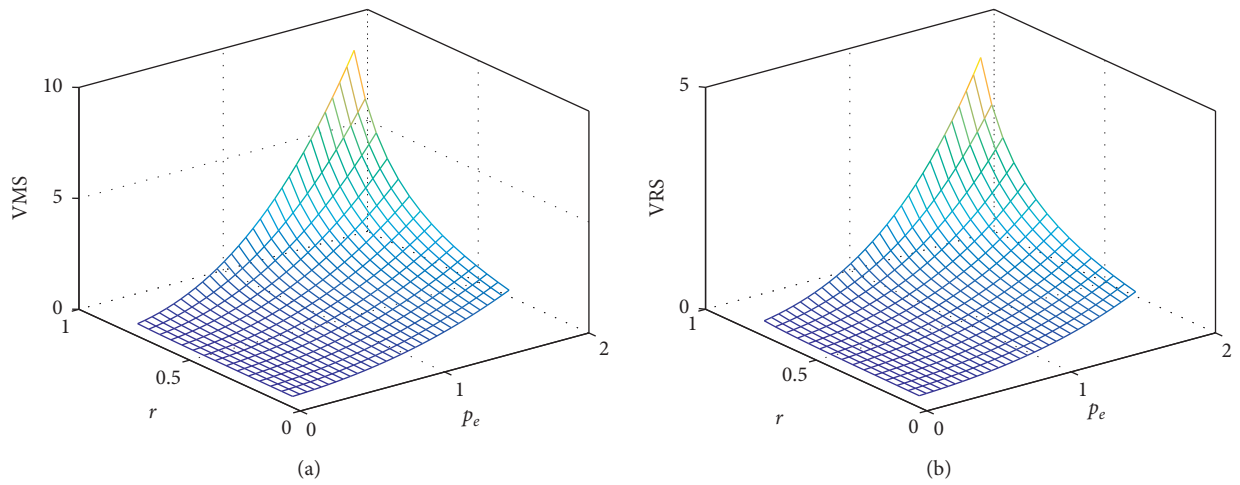


FIGURE 6: Continued.

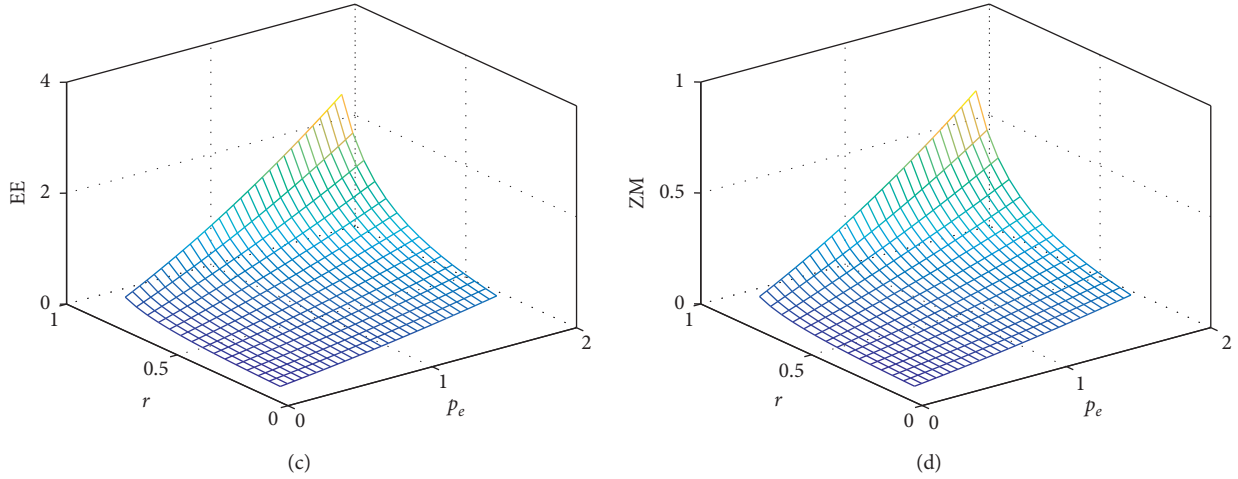


FIGURE 6: Sensitivity analysis of carbon trading price and cost subsidy rate.

subsidy rate and consumer low-carbon sensitivity coefficient on the parameters are different. When the government subsidy rate is fixed, the consumer low-carbon sensitivity coefficient positively affects product carbon emissions, the emission-reduction effort of the manufacturer, and the profits of upstream and downstream enterprises in the supply chain. At the same time, the cost subsidy rate enhances the impact of the low-carbon sensitivity coefficient on the parameters, indicating that government subsidies can incentivize enterprises to invest in carbon emission reduction.

7.2.2. Sensitivity Analysis of τ and α . When other parameters remain unchanged, the simulation results of the cost subsidy rate and impact coefficient of manufacturers' emission-reduction efforts are as shown in Figure 4.

As shown in Figure 4, the manufacturer profit, retailer profit, product carbon emissions, and manufacturer emission-reduction effort increase with increases in the cost subsidy rate and impact coefficient of manufacturers' emission-reduction efforts. However, the influences of the cost subsidy rate and manufacturer's emission-reduction effort influence coefficient on parameters are different. When the government subsidy rate is fixed, manufacturer's emission-reduction effort influence coefficient positively affects the product carbon emissions, manufacturer emission-reduction effort, and the profits of the upstream and downstream enterprises in the supply chain. Meanwhile, the introduction of government subsidies enhances the influence of the manufacturers' emission-reduction impact coefficient on the parameters, indicating that government subsidies can incentivize enterprises to invest in carbon emission reductions.

7.2.3. Sensitivity Analysis of τ and μ_m . With other parameters unchanged, the simulation results of the cost subsidy rate and cost coefficient of carbon emission reduction are as shown in Figure 5.

As shown in Figure 5, the manufacturer profit, the retailer profit, product carbon emissions, and the manufacturer emission-reduction effort increase with increases in the cost subsidy rate and cost coefficient of carbon emission reduction, but the effects of the latter two are different. When the government subsidy rate is fixed, the cost coefficient of carbon emission reduction has a negative influence on product carbon emissions, manufacturer emission-reduction efforts, and supply chain members' profits. These parameters all decrease with increases in the cost coefficient of carbon emission reduction, but the increase in government subsidy rate leads to an increase in carbon emissions, manufacturer emission-reduction effort, and the profits of the upstream and downstream enterprises in the supply chain. Moreover, the influence of the government subsidy rate on the parameters is greater than that of the emission-reduction effort cost coefficient, so these parameters show an upward trend. Thus, government subsidies can incentivize enterprises to invest in carbon emission reductions.

7.2.4. Sensitivity Analysis of τ and p_e . With other parameters unchanged, the simulation results of cost subsidy rate and carbon trading price are as shown in Figure 6.

As shown in Figure 6, manufacturer profit, retailer profit, product carbon emissions, and manufacturer emission-reduction effort increase with increases in the cost subsidy rate and carbon trading price, but the influences of the latter two are different. When the government subsidy rate is fixed, the carbon trading price positively affects the product carbon emissions, manufacturer emission-reduction effort, and the profits of the upstream and downstream enterprises in the supply chain. At the same time, the introduction of a government subsidy enhances the influence coefficient of carbon trading price on the parameters, which shows that government subsidies can incentivize enterprises to invest in carbon emission reduction.

8. Conclusions

Under the background of economic globalization, supply chain enterprises can only improve their competitiveness and achieve the goal of sustainable development by formulating specific strategies and measures based on the perspective of sustainable development. In order to achieve sustainable development, supply chain enterprises need to follow the steps of the world closely and abide by the carbon rules of the international community and international organizations. Supply chain enterprises should give consideration to both economic and ecological benefits and maximize benefits with the minimum cost and carbon emissions. Therefore, this paper comprehensively considered the influences of an efficiency-based carbon quota system and an incentive-based cost subsidy system on supply chain emission-reduction investment decisions. From a dynamic perspective, this paper considered consumer low-carbon preferences and the randomness of the emission-reduction process. We used a stochastic differential game model to determine the equilibrium strategies of the government, supply chain, and consumers, the evolution path of carbon emission reduction, and manufacturer and retailer profits.

To characterize the impact of carbon trading price, cost subsidy rate, consumer low-carbon preferences, and various uncontrollable factors on supply chain emission-reduction technology decision process, this paper used the zero-mean property of the Wiener process and the Ito theorem to describe the carbon emission-reduction decision-making process under stochastic circumstances. According to the profit structure of the manufacturer and retailer, this paper analysed the profit objective function of the manufacturer and retailer. Based on the supply chain emission-reduction technology decision process and the profit objective function of the manufacturer and retailer, this paper established a Stackelberg stochastic differential game model of a dynamic supply chain system. Using a stochastic differential game model and dynamic optimization method, we obtained the manufacturer's equilibrium wholesale price, manufacturer's equilibrium emission-reduction effort, retailer's equilibrium product price, retailer's equilibrium emission reductions, cost-sharing rate, and the optimal function of upstream and downstream enterprises' profits in the supply chain.

This paper analysed the sensitivity of each parameter to the carbon emission-reduction process in supply chain. The results show that the consumer low-carbon sensitivity coefficient, manufacturer carbon emission-reduction effort coefficient, carbon trading price, and cost subsidy rate have positive effects on carbon system emissions and supply chain profits. The cost coefficient of emission reduction has negative impacts on carbon system emissions and supply chain profits. To grasp the statistical characteristics of stochastic carbon emission reduction in the system, this paper also analysed the statistical properties of expectation and variance. Finally, this paper simulated and assigned the parameters, intuitively analysed the optimal strategy trajectory of the supply chain under cost-sharing coordination decisions, and verified the influence

of different parameter changes on carbon emission-reduction behaviour.

This paper discussed the dynamic investment decisions of carbon emission-reduction technology in an ideal secondary supply chain with one supplier and one retailer under a cost-sharing coordination decision scenario. However, the simple secondary supply chain is too idealistic and does not meet actual development needs. Future research will focus on investment decision-making related to carbon emission reductions in a multilevel supply chain.

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.

Authors' Contributions

Q. H and S. Y conceptualized the study, validated the study, and performed data curation. Q. H was responsible for methodology, software, project administration, and funding acquisition and supervised the study. S. Y performed formal analysis, investigated the data, prepared the original draft, reviewed and edited the manuscript, and visualized the study and was responsible for resources.

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Research Article

Spatiotemporal Heterogeneity and Driving Force Analysis of Innovation Output in the Yangtze River Economic Zone: The Perspective of Innovation Ecosystem

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The Yangtze River Economic Zone (YREZ) is a major corridor of national science and innovation culture, an innovation-driven region that fosters new drivers of growth and leads transformation and development, and plays an important strategic support and exemplary leading role in the overall pattern of regional development. This paper analyzes the spatiotemporal differentiation characteristics of innovation output of 110 cities of YREZ from 2008 to 2018 by using Gini coefficient, coefficient of variation (CV), geographical weighted regression, and other methods. The factors affecting innovation output are selected from the perspective of innovation ecosystem. The results show the following. (1) Innovation output showed an increasing trend, and the high-value concentration cities in downstream areas gradually became prominent, the geographical concentration degree fluctuated and declined, and the distribution of innovation output gradually became balanced. (2) The global Moran's *I* index of innovation output shows a fluctuation pattern of “M” shape and an overall upward trend. The analysis of local spatial correlation indicates that spatial distribution pattern of innovation output has not changed significantly. (3) There is obvious regional heterogeneity under different impacts of factors of innovation ecosystem on innovation output. Enterprises have the greatest impact, followed by financial resources and infrastructure environment.

1. Introduction

As a key “booster” of regional development in the era of knowledge economy [1], innovation is an essential driving force to promote regional economic growth and enhance competitiveness [2, 3], and innovation output can reflect the ability and level of regional innovation [4]. The concept of innovation was first put forward by the economist Schumpeter [5], and its connotation and research field have been constantly updated [6]. The research of innovation paradigm has gone through three stages: linear innovation model, innovation system, and innovation ecosystem. The linear innovation theory advocates independent innovation within the enterprise, but it is difficult to adapt to the rapidly changing technological development, while the innovation

system based on system theory advocates open innovation and puts forward the three-spiral theory of “politics, industry, and science” and the open innovation theory. Freeman studied the technology policy and economic performance of Japan in the 1980s and first proposed the concept of national innovation system. After the 1990s, Japan suffered an economic downturn, while Silicon Valley in the United States showed continued innovation vitality. “The Silicon Valley Edge: a habitat for innovation and entrepreneurship” proposes to understand the innovation ecosystem from an ecological perspective, arguing that the advantage of Silicon Valley lies in its dynamic, open, and powerful knowledge ecosystem. The success of Silicon Valley in the United States is largely due to the formation of a collaborative and interactive network innovation model of

multiple subjects with universities, research institutions, and enterprises as the core elements and auxiliary elements such as governments, financial institutions, and intermediary organizations. In-depth cooperation and resource integration among technological innovation subjects produce continuous innovation. [7]. At the same time, Japan also put forward that the industrial structure policy should shift from technology policy to innovation policy based on ecological concept, emphasizing that the innovation ecology should be the foundation for Japan to maintain its sustainable innovation ability in the future. At present, innovation ecosystem is widely valued and studied in China, India, and other countries.

The YREZ stretches across the eastern, central, and western regions of China, and its population size and economic aggregate exceed the “half of the country” of the country. It is one of the regions with the greatest strategic support in China. Due to the great differences in economic development, natural resources, and industrial base among cities, the YREZ is generally divided into the upper, middle, and lower reaches. Among them, the upper reaches are Guizhou, Yunnan, Sichuan, and Chongqing, the middle reaches are Hunan, Hubei, and Jiangxi, and the lower reaches are Anhui, Zhejiang, Jiangsu, and Shanghai. On November 14, 2020, Xi Jinping hosted a symposium on comprehensively promoting the development of the YREZ in Nanjing, Jiangsu Province, and emphasized that the high-quality development of the YREZ will be promoted, a new model for coordinated regional development will be created, and new advantages in innovation-driven development will be created to enable the YREZ that has become the main force leading the domestic and international dual-circulation aorta and leading the high-quality economic development. There are six independent innovation demonstration zones in the YREZ, namely, Wuhan East Lake, Shanghai Zhangjiang, Southern Jiangsu, Changzhutan, Chengdu High-Tech Zone, and Hangzhou High-Tech Zone, and Shanghai and Hefei have been approved as comprehensive national science centers successively. All these will help to build the YREZ into a “science and innovation corridor.”

As a major national development strategy, YREZ is the leading region of China’s innovation-driven development [8]. The report on innovation and development of YREZ (2018) pointed out that the provinces and cities of YREZ have different levels of innovation investment, innovation capacity, and innovation development. From the perspective of innovative enterprises and innovative output, Jiangsu has the most, while Guizhou and Yunnan have the least, and 77.43% of the product exports of innovative industrial clusters are concentrated in downstream cities. The number of R&D personnel and patent authorization quantity shows that Jiangsu and Zhejiang accounted for 47.3% of YREZ, while Jiangxi, Yunnan, and Guizhou only accounted for 7.43%, with relatively low patent authorization quantity. At present, problems such as unbalanced distribution of innovation elements, large gap of innovation capacity, and segmentation of innovation market in the region seriously hinder YREZ from becoming an innovation-driven and high-quality representative in China.

Innovation ecosystem is an open and complex system of symbiosis, competition, and dynamic evolution between various innovation subjects and innovation environment through the connection and conduction of material flow, energy flow, and information flow. Its fundamental goal is to realize the continuous emergence of innovation. Therefore, it is necessary to scientifically measure the innovation output of YREZ and reveal its spatial evolution rules. By using the economic geography model, the driving factors of regional innovation output differences are analyzed from the perspective of the innovation ecosystem. It is conducive to narrowing the gap in regional innovation and development, enhancing the capacity and level of regional innovation, enhancing the spatial allocation effect of innovation, and promoting the coordinated development and high-quality economic development of YREZ. Based on this, this paper takes the period from 2008 to 2018 as the research period, with 110 cities of YREZ as the research objects. Taking the amount of patent authorization as the index of innovation output, using Gini coefficient, coefficient of variation (CV), and exploratory spatial data analysis (ESDA) method, this paper analyzes spatio-temporal heterogeneity of innovation output in YREZ. The factors affecting innovation output were selected from the key elements of building an innovation ecosystem and analyzed by using the geographical weighted regression model so as to provide reference for the promotion of the innovation output of YREZ.

2. Literature Review

Innovation is seen as key to enhancing competitive advantage in a constantly changing environment [9, 10]. With the development of innovation theory, the research of innovation has experienced linear model of innovation, innovation system model, and innovation ecosystem model [11]. The President’s Council of Advisors on Science and Technology (PCAST) argues that the U.S. economic boom and its leadership are largely due to the innovation ecosystem [12]. Japan also emphasizes that innovation is the foundation for sustaining innovative capacity [13]. YREZ has rich innovation resources and is an important source of driving force for China’s innovation. Therefore, the key step is to find the innovation impetus from the perspective of innovation ecosystem.

2.1. Research on Innovation Output. Innovation output is an important embodiment of regional innovation level. At present, there is no unified standard for its measurement in academia [14]. The measurement index mainly includes number of papers published [15], output value of new products [16], and number of patent applications [17]. Many scholars began to study regional innovation from a spatial perspective in recent years, using indicators such as Moran Index and Gini coefficient to measure the characteristics of innovation agglomeration and differentiation and using spatial measurement methods to study the influencing factors based on geographical proximity [18–20].

2.2. Research on Influencing Factors of Innovation Output. There are two main parts in analysis of factors affecting the innovation output: the internal factors of the innovation subject [21–23] and the macro environment and policy [24–27]. To be specific, the ability of innovation subjects to absorb innovation resources [28], market-oriented R&D activities [29], breadth and depth of cooperation [30], and efficiency of researchers [31] have positive effects on innovation output. However, there is no evidence showing that increasing the size of weak firms [32] or subsidies for R&D investment [33] will boost innovation output. In addition, the effect of innovation environment on innovation output, such as regional knowledge environment [34], legal environment [35], and technological environment [36], should not be ignored. At the same time, there is no denying that the system and governance of the government strongly support the innovation output [37, 38] and even have a long-term impact [39]. However, some studies have reached the opposite view, believing that environmental regulations [40] and state control over enterprises [41] will hinder innovation output.

2.3. The Role of the Innovation Ecosystem. The innovation ecosystem is an extension of the traditional innovation cluster network and a product of the combination of ecological theory and innovation research [42–44]. At present, the academic community has not reached a consensus on the definition of its connotation [45, 46], but most of them focus on the interaction between the internal elements of the innovation ecosystem and the basic characteristics of the interaction between the innovation system itself and the external environment [47–49]. In recent years, most countries, regions, and industries have realized that the innovation ecosystem is an important foundation for promoting sustainable innovation and have begun to examine their own state of innovation from perspective of innovation ecosystem and seek ways to improve their innovation capacity [50–52]. Studies have proved that the cooperation among diverse innovation subjects [53–55] and coordination and integration of heterogeneous innovation resources in the innovation ecosystem can help to improve the innovation rate and success rate [56]. The appropriate innovation environment can guide the direction of innovation and provide guarantee for innovation activities [57]. The openness of the innovation ecosystem not only promotes the flow of innovative elements such as material, information, and knowledge but also facilitates the commercialization of technologies, products, and other innovative achievements [58, 59].

2.4. Summary: Contributions of This Paper. In general, the research on innovation output and its influencing factors and innovation ecosystem is relatively mature, which lays a solid theoretical foundation for this paper. Existing studies have gradually begun to pay attention to the spatial heterogeneity of innovation output, extensively explored the root causes of innovation differences, and realized the

important role of innovation ecosystem in improving innovation capacity. However, few studies have explored the reasons for the spatial heterogeneity in innovation output from the perspective of innovation ecosystem. Compared with existing literatures, the innovations of this paper are as follows. (1) Research perspective: in recent years, a growing number of scholars have begun to understand and study the development of urban agglomeration in China [60]. YREZ is rich in innovation resources, with one-third of the national universities and research institutions concentrated in Wuhan East Lake, Shanghai Zhangjiang, and other national independent innovation demonstration zones. It is the main battlefield of China's innovation-driven development. Therefore, it is of practical significance to find the reasons for the heterogeneity of innovation output regions in YREZ from the key components of the innovation ecosystem. (2) Research methods: first, the CV, Gini coefficient, and global Moran's I are used to measure the overall characteristics of innovation output of YREZ, and LISA cluster graph was presented. Second, the GWR model was constructed to seek ways to improve the innovation output.

3. Research Methods, Data Sources, and Index Selection

3.1. Research Methods

3.1.1. Coefficient of Variation (CV). CV is the ratio between the standard deviation and the mean of the selected samples, which can reflect the relative equilibrium degree of innovation. The formula is

$$CV = \frac{\sqrt{\sum_{i=1}^n ((y_i - \bar{y})/n)}}{\bar{y}}, \quad (1)$$

where y_i is the i -th regional innovation output; \bar{y} is the average value of innovation output in the city; and n is the number of cities. The larger the CV is, the more discrete the innovation output in the city is.

3.1.2. Gini Coefficient. Gini coefficient can reflect the degree of regional differences in development and measure the spatial agglomeration of innovation output in YREZ. The calculation formula is

$$G = \frac{1}{2n^2 \bar{x}} \sum_{i=1}^n \sum_{j=1}^n |x_i - x_j|, \quad (2)$$

where G is the Gini coefficient, \bar{x} represents the mean value of innovation output, and x_i and x_j represent innovation output of cities i and j , respectively. The value of G ranges from 0 to 1. The greater the Gini coefficient is, the greater the regional innovation output difference is and the higher the geographical agglomeration degree of innovation output is.

3.1.3. Exploratory Spatial Data Analysis (ESDA). ESDA is a common method to study the distribution characteristics of spatial data. It determines the regional adjacency

relationship based on spatial weight matrix and reflects spatial dependence or heterogeneity of geographical phenomena through the distribution characteristics of spatial data.

- (1) Global spatial autocorrelation: global spatial autocorrelation explores the overall spatial correlation and difference of innovation output in the region. Moran's I index is selected to measure the spatial correlation characteristics of innovation output in YREZ, and its spatial agglomeration trend is analyzed. The calculation formula is

$$I = \frac{\sum_{i=1}^n \sum_{j=1}^n w_{ij} (x_i - \bar{x})(x_j - \bar{x})}{S^2 \sum_{i=1}^n \sum_{j=1}^n w_{ij}}, \quad (3)$$

where I is global Moran's I , \bar{x} is $(1/n) \sum_{i=1}^n x_i$, x_i and x_j represent the innovative output in region i and region j , respectively, and w_{ij} is the spatial weight matrix. The value of Moran's I is usually between $(-1, 1)$, and a value greater than 0 indicates a positive correlation. In other words, regions with similar innovation outputs are in a state of spatial aggregation. Less than 0 means negative correlation, that is, areas with similar innovation outputs are distributed in a decentralized manner.

- (2) Local spatial autocorrelation: local spatial autocorrelation is used to measure the degree and significance of regional spatial difference of innovation output in YREZ. Local spatial autocorrelation statistics refer to local Moran's I . Generally, the rule of local spatial distribution is analyzed in combination with Moran scatter plot and LISA aggregation graph. Its formula is

$$I_i = z_i \sum_{j \neq i}^n w_{ij} z_j, \quad (4)$$

where z_i and z_j are the standardized values of innovation output in regions i and j and w_{ij} is the spatial weight matrix. Under a given significance level, positive Moran's I shows that there are similar values in a region and its adjacent area. Similar values mean the spatial agglomeration effect exists (HH: high-value cluster areas and LL: low-value cluster areas); otherwise, there are spatial outliers (HL: high-low isolated area and LH: low-high hollow area).

3.1.4. Geographically Weighted Regression. GWR is an estimation method of spatial changing coefficient, which is used to test the regression relationship among spatial variables. Local parameter estimation is used instead of global parameter estimation to better evaluate the nonstationary state of spatial data, which is conducive to the exploration of spatial variation characteristics and spatial rules. Therefore, the GWR model is used to study spatial heterogeneity of driving forces of innovation output in YREZ. The formula is as follows:

$$Y_i = \alpha_0(u_i, v_i) + \sum_{j=1}^k \alpha_j(u_i, v_i) x_{ij} + \varepsilon_i, \quad (5)$$

where Y_i is the global dependent variable, x_{ij} is the independent variable, $\alpha_0(u_i, v_i)$ is constant, (u_i, v_i) represents the spatial coordinates of the i -th region, $\alpha_j(u_i, v_i)$ is the variable parameter of the j -th explanatory variable x_{ij} in the i -th region, and ε_i is a random error term.

3.2. Indicator Selection and Data Sources

3.2.1. Index of Innovation Output. Due to the large span of YREZ and because the regional innovation and development levels are different and the technical market turnover statistics and accounting methods are different, new product certification standards are also different. Although different regions have differences in patent inclination and patent quality, patent data are an embodiment of innovation activities. Therefore, this article makes use of patent data. However, regarding the choice of patent applications or authorizations, some scholars support the number of patent applications [61], mainly considering that the time lag of patent authorization is likely to cause information distortion. Scholars who support the amount of patent authorization believe that most inventors apply for patents out of strategic motivation, rather than for the purpose of obtaining patent authorization [62]. In view of the availability, scientificity, and representativeness of the data, patent authorization is selected to measure YREZ's innovative output.

3.2.2. Index Construction of Innovation Ecosystem. According to the discussion on innovation ecosystem in the literature review, this paper constructs an innovation ecosystem composed of innovation subjects, resources, and environment (Table 1). From the perspective of innovation subjects, universities, research institutions, and enterprises are the "engines" of innovation activities [63]. Among them, universities and research institutions are the core subjects of knowledge innovation. Their strong academic atmosphere has accelerated the burst of new ideas and new understanding and promoted knowledge innovation. They mainly focus on basic research [64, 65]. Because of its own profitability, enterprises are more focused on the characteristics of applied research and promote the output of products and services through application development [66, 67]. Therefore, the number of undergraduate universities and scientific research institutions is selected as the index to measure the universities and research institutes. The number of industrial enterprises above designated size is selected as the index to measure enterprise.

From the perspective of innovation resources, human resources are an important part of the innovation ecosystem and a decisive force affecting the innovation output [68]. Researchers are the key talents of innovation, and higher education teachers are not only the contributors of innovation output but also the disseminators of innovative ideas.

TABLE 1: Index construction of innovation ecosystem.

| First class indicator | Second class indicator | Third class indicator | Fourth class indicator | Specific indicators | Unit |
|-----------------------|------------------------|--------------------------------------|--|--|--------------------|
| Innovation ecosystem | Innovative subject | Knowledge creator | Colleges and universities | Number of undergraduate schools in general institutions of higher learning | PCS |
| | | | Scientific research institutions | Number of scientific research institutions | PCS |
| | | Knowledge applicator | Enterprise | Number of industrial enterprises above designated size | PCS |
| | | | Researcher input | R&D personnel per 10,000 people | People |
| | Innovation resources | Human resources | Investment in education personnel | Number of full-time teachers in colleges and universities | People |
| | | Financial resources | Government expenditure on science and technology | The proportion of science and technology in public expenditure | % |
| | | | Research input | Internal expenditure of R&D funds | 1000 CNY |
| | | | Informationization degree | Number of Internet broadband access ports | 10,000 households |
| | | Infrastructure environment | Traffic environment | The road network density = highway mileage/total area of regional mileage | km/km ² |
| | Innovation environment | Economic environment | The level of demand | Per capita retail sales of consumer goods | CNY |
| | | | Economic level | Per capital GDP | CNY |
| | | Cultural and educational environment | Educational environment | Number of students in colleges and universities per 10,000 | People |
| | | | Cultural environment | The total number of books in the public library | 1000 volumes |

Therefore, the human resources index is measured by a number of R&D personnel and full-time teachers in universities and colleges per 10,000 people. Financial resources are the guarantee of regional sustainable innovation [69, 70]. Enterprise R&D expenditure can stimulate enterprise innovation vitality, while government expenditure on science and technology plays a leading role in the investment of social capital in innovation activities. Therefore, the proportion of science and technology expenditure in public financial expenditure and the internal expenditure of R&D expenditure in each region are selected to measure the financial resource index.

From the perspective of innovation environment, infrastructure environment is an important carrier of the flow of innovation elements. In addition to the connectivity of traditional transportation infrastructure, the improvement of urban informatization infrastructure can increase the output of innovation [71, 72]. Therefore, the road network density and the number of Internet broadband access ports are selected to measure the infrastructure environment index of each city [73]. The level of economic development shows the attractiveness of a region to innovation factors, and the improvement of market environment will stimulate the innovation vitality of enterprises, thus enhancing the regional innovation output. Therefore, the economic environment index is mainly measured from the per capita GDP and per capita retail sales of consumer goods that affect innovation output. The regional cultural environment and educational environment are fertile soil for breeding innovative knowledge and talents and provide continuous nutrition for

sustainable development of the innovation ecosystem [74, 75]. Therefore, the cultural and educational environment index is calculated by the number of students in colleges and universities and the total number of books in public libraries.

In this paper, the entropy method is used to calculate the weight of regional innovation ecological index, and the weight is used to calculate the third-layer index coefficient of each region, such as human resources, financial resources, infrastructure environment, and so on. Considering that innovation has a certain time lag from input to output, a 1-year lag period is adopted in this paper [76], that is, a dynamic panel regression model is constructed based on indicators of innovation ecosystem in 2017 and innovation output in 2018. The data are from *China urban statistical yearbook* from 2009 to 2019, *statistical yearbook* of all provinces in YREZ, *science and technology yearbook*, and *bulletin on national economic and social development* of each city.

4. Spatial Differentiation of Innovation Output

4.1. Overall Characteristics of Innovation Output Differences. According to the patent authorizations of prefecture-level cities in YREZ in 2008, 2013, and 2018, referring to classification criteria for innovation output and combining with the number of patent licenses in the YREZ [77], it is divided into four intervals of 0–5000, 5001–10000, 10001–20000, and more than 20001. The spatial agglomeration diagram of the innovative output of YREZ is drawn with ArcGIS10.2 software, and the evolution process of its spatial agglomeration is shown in Figure 1. The only city that exceeded

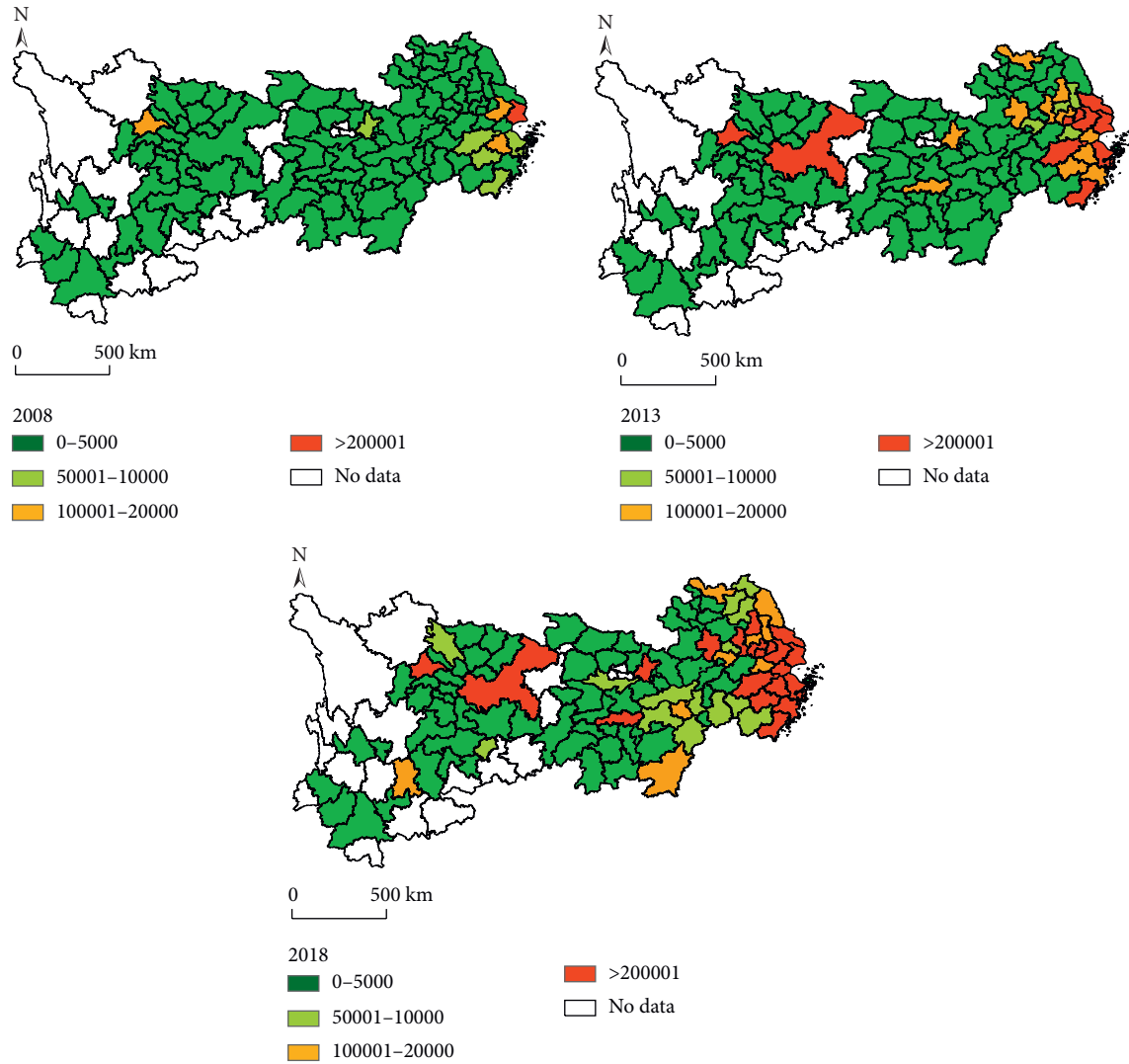


FIGURE 1: Spatial agglomeration of innovation output in YREZ in 2008, 2013, and 2018.

20,000 patents in 2008 was Shanghai. By 2018, it had increased to 19 cities, accounting for 17.27%, mostly concentrated in the coastal areas downstream of YREZ. In 2008, 101 cities with patent authorizations are below 5,000. The number fell to 86 cities by 2013 and to 68 in 2018, with the proportion falling from 91.82% to 61.82%, mainly distributed in midstream and upstream of YREZ. In general, evolution of the spatial and temporal pattern of innovation output has the following characteristics in YREZ: (1) The overall number of patent authorizations continues to increase, showing a gradual improvement; (2) The amount of patents granted in the coastal areas of the lower reaches of the YREZ shows a high-value concentration and continues to spread inland.

The article calculates the CV and Gini coefficient of urban patent authorizations from 2008 to 2018 in Figure 2 so as to show the spatial difference of urban innovation output in YREZ. The CV and the Gini coefficient showed a trend of decrease from 2008 (2.3637 and 0.5707) to 2018 (1.6179 and 0.3404), while the former has a slight fluctuation. It shows

that the urban innovation output of YREZ becomes more and more balanced, and the geographical concentration gradually decreases, showing a trend of convergence.

In order to highlight the neighboring areas of spatial relationships, we use GeoDa software construction space adjacency matrix to calculate Moran's I index value of innovation output in YREZ during 2008–2018 (see Figure 3). As can be seen from Figure 3, Moran's I index is greater than 0 from 2008 to 2018 and shows a rising trend. This shows that a positive spatial correlation exists among innovation output in the various regions of YREZ, showing a significant spatial agglomeration phenomenon, and the overall trend is rising with some fluctuations. In detail, the first trend of fluctuation of Moran's I index is in 2008–2010, which jumped from 0.3996 to 0.5366, with an average annual growth rate of 15.88%, reflecting that spatial agglomeration of innovation output in YREZ is increasing in this stage. Then, the value fell to 0.4681 in 2013, reflecting a gradually weakening spatial agglomeration. The second trend of fluctuations of Moran's I index is in 2013–2018, eventually converging to 0.4316, with

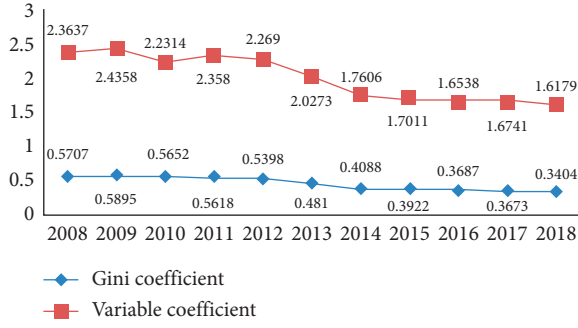


FIGURE 2: Differences and dynamic changes in innovation output of YREZ from 2008 to 2018.

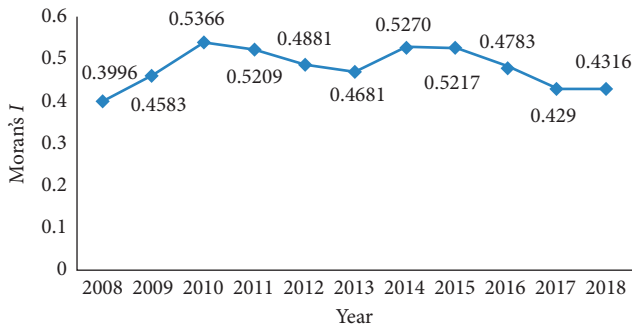


FIGURE 3: The evolution of Moran's I index from 2008 to 2018.

an average growth of 8% compared with 2008, suggesting that innovation output fluctuates and rises. It generally presents an "M" shaped wave pattern.

4.2. Local Autocorrelation Analysis of Innovation Output. Moran's I index of global spatial autocorrelation reveals the spatial dependence of YREZ during 2008–2018, while the local spatial autocorrelation LISA index reflects the correlation between the same attributes of each spatial position and the neighboring locations around them. Taking 2008, 2013, and 2018 as sample, GeoDa software was used to analyze the spatial correlation and cluster evolution of innovation output in YREZ, and LISA clustering results of innovation output are shown in Table 2.

Table 2 shows that spatial distribution pattern of innovation output in YREZ basically did not change significantly in 2008, 2013, and 2018, which indicates that innovation activities have certain spatial locking characteristics. Taizhou (Jiangsu), Nantong, Taizhou (Zhejiang), Suzhou, Shanghai, Huzhou, Jiaxing, and Shaoxing are always in high-value cluster areas (HH). The city's innovation output is high, and the average level of peripheral innovation output is also high, which reflects the obvious spatial agglomeration effect. This shows that the level of innovation output of this city and its surrounding cities is relatively stable. These cities are concentrated in the Yangtze River Delta region, which is one of the regions with the strongest innovation capacity in China. Innovation resources are shared in the region, and Shanghai, Suzhou, and other cities

have a strong driving effect, which makes the innovation output level of these cities relatively high. Compared with 2013, the low-high hollow area (LH) increased in Xuancheng in 2018, indicating that the city's innovation output is lower than that of the surrounding cities. It reflects that the growth rate of innovation output in the surrounding area is higher than that of Xuancheng. Most relatively economically backward areas (Baoshan, Lincang, Panzhihua, Liupanshui, etc.) are distributed in low-value cluster areas (LL), and innovation output in those areas and surrounding areas is low. In 2013, the number of LL cities increased by half compared with that in 2008, and it was widely distributed in midstream and upstream of YREZ. By 2018, the number of LL cities was reduced, mainly concentrated in the upper reaches, which indicated that the innovation output in the middle reaches increased, and the LL in the upper reaches was enhanced. Chongqing has always been a high-low isolated area (HL) of innovation output. The city has a marked polarization characteristic, is at the center of polarization, and has a low diffusion effect on innovation output in the surrounding areas; by 2018, Kunming becomes HL from LL, indicating that Kunming's innovation output has increased compared with surrounding cities. Compared with the surrounding cities, Chongqing and Wuhan are both national central cities with good economic strength, development level, innovation level, and innovation environment. However, due to weak spillover effect on the surrounding areas, they appear as high-low isolated areas.

5. Analysis on the Influencing Factors of Innovation Output in YREZ

5.1. Result Analysis. During the calculation of the GWR model, the core type is ADAPTIVE and the bandwidth is AICc. The results show that R^2 is 0.9620 and adjusted R^2 is 0.9570, indicating that the GWR estimation model can better simulate the effects of innovation ecosystem variables on innovation output. By sorting out the regression coefficients in the calculation results, the five statistic values were selected. It can be seen from Table 3 that each variable of the innovation ecosystem has a specific regression coefficient on the impact of each city's innovation output with large differences in the values, which shows that the impact of each variable on different cities has a large difference. From the perspective of regression coefficients and average values, knowledge applicator has a positive impact on innovation output, followed by financial resources and basic environment; knowledge creator, human resources, economic environment, and culture and educational environment shows both positive and negative effects on innovation output. In addition to the economic environment, other influencing factors are mostly positive effects, and a few regions have negative effects.

5.2. Spatial Heterogeneity Analysis of Influencing Factors

5.2.1. Innovation Subject. Innovation subjects have different effects on the innovation output of each city. Specifically, in Figure 4(a), the regression coefficient range of knowledge

TABLE 2: LISA clustering results of innovation output of YREZ based on the Moran scatterplot.

| Quadrant | 2008 | 2013 | 2018 |
|---------------------|---|--|---|
| Quadrant one (HH) | Huzhou, Jiaxing, Jinhua, Nantong, Ningbo, Shanghai, Shaoxing, Suzhou, Taizhou (Jiangsu), Taizhou (Zhejiang) | Taizhou (Jiangsu), Nantong, Taizhou (Zhejiang), Suzhou, Shanghai, Huzhou, Jiaxing, Shaoxing, Wuxi | Huzhou, Jiaxing, Jinhua, Nantong, Shanghai, Shaoxing, Suzhou, Taizhou (Jiangsu), Taizhou (Zhejiang), Wuxi, Zhenjiang, |
| Quadrant two (LH) | NA | Xuancheng | Xuancheng |
| Quadrant three (LL) | Jiujiang, Baoshan, Lincang, Panzhihua, Liupanshui, Kunming, Jingdezhen, Bengbu | Jiujiang, Baoshan, Lincang, Panzhihua, Liupanshui, Kunming, Bazhong, Zigong, Yibin, Pu'er, Ji'an, Huaihua, Nanchong, Bijie | Baoshan, Lincang, Panzhihua, Liupanshui, Bazhong, Zigong, Yibin, Pu'er |
| Quadrant four (HL) | Chongqing | Chongqing, Wuhan | Chongqing, Kunming |

TABLE 3: Calculation results of the GWR model.

| Influencing factor | Min | Lower quartile | Mean | Upper quartile | Max |
|-------------------------------------|---------|----------------|---------|----------------|--------|
| Knowledge creator | -0.0853 | 0.0946 | 0.1284 | 0.1681 | 0.2064 |
| Knowledge applicator | 0.0031 | 0.4332 | 0.5107 | 0.6032 | 0.6213 |
| Human resources | -0.0424 | 0.0131 | 0.1247 | 0.2273 | 0.7183 |
| Financial resources | 0.1917 | 0.2188 | 0.2581 | 0.2955 | 0.4182 |
| Infrastructure environment | 0.0252 | 0.0328 | 0.0380 | 0.0424 | 0.0544 |
| Economic environment | -0.0512 | -0.0398 | -0.0201 | -0.0024 | 0.0066 |
| Culture and educational environment | -0.2156 | 0.0499 | 0.0770 | 0.1221 | 0.1281 |

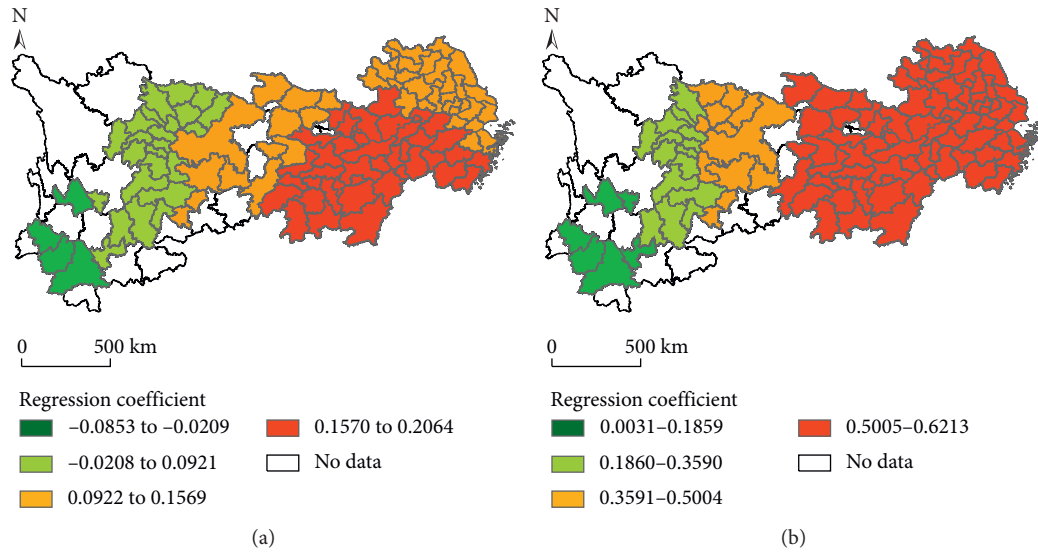


FIGURE 4: Spatial distribution of regression coefficient of innovation subject to innovation output. (a) Universities and research institutes. (b) Enterprise.

creator to innovation output is $(-0.0853, 0.2064)$. The regression coefficients of all cities are positive except Baoshan, Lincang, Lijiang, and Pu'er. In other words, 96.36% of the cities' universities and research institutions positively affected innovation output, which shows that innovation sources of innovation ecosystem provide impetus for the realization of sustainable innovation output. Among them, Baoshan, Lincang, Lijiang, and Pu'er showed relatively weak negative influence, which may be due to the relatively weak economic foundation and scientific research atmosphere,

leading to the failure of input into innovation output. Most cities in Hunan, Hubei, Jiangxi, Anhui, and Zhejiang are the most affected by universities and research institutions, while most cities in Sichuan and Yunnan are the least affected. This difference is mainly related to the following factors. On the one hand, the quantity and quality of universities and research institutions in different regions determine the efficiency and quality of innovation output. On the other hand, whether universities and research institutions can find their location in innovation ecosystem and establish cooperation

mechanism with enterprise is the key to realize the transformation of innovation achievements. For example, the number of universities and scientific research institutions in Ya'an, Bazhong, Leshan, Guangyuan, Shaotong, and other cities is small, and the lack of high-level universities and research institutions leads to a weak impact on innovation output, while Shanghai, Hangzhou, Chongqing, Nanjing, Wuhan, and other places are the concentration of double first-rate universities, providing a large number of high-quality scientific research resources for regional innovation, while the region pays attention to deep integration of industry-university-research, which can accelerate the knowledge spillover and can avoid ignoring market demand.

Figure 4(b) shows the spatial distribution of enterprises. Enterprises, as the knowledge applicant, are the most important factor influencing innovation output and show positive correlation. Ganzhou (0.6213) has the largest regression coefficient, and Baoshan (0.0031) has the smallest. This shows that in the innovation ecosystem, enterprises, as the main body of innovation, are one of the important driving forces of regional innovation development. The regression coefficients of enterprise are distributed continuously in space. Most of the high value areas are concentrated in Jiangsu, Anhui, Zhejiang, Shanghai, Jiangxi, Hunan, and Hubei, with 78 cities in total. For every 1% increase in the number of enterprises in these cities, the innovation output will increase by 0.5005%–0.6213%. The regions where innovation output is relatively less affected by enterprises are mainly in Sichuan and Yunnan. The regression coefficients of these regions are between 0.0031 and 0.1859, which shows that enterprises in this region have not fully played the role of innovation. There are two possible reasons. First, the number of enterprises is small, which cannot gather innovation resources, resulting in the increase of innovation cost and risk, so the innovation output is low. Secondly, the construction of collaborative innovation platform of industry-university-research in this region is not perfect, and the ability of enterprises to absorb and transform new knowledge is weak, which causes the deficiency of technological innovation ability and the lack of dominant position in innovation system, thus affecting the innovation output.

5.2.2. Innovation Resources. Each index of innovation resources has different effects on urban innovation output. In detail, the regression coefficient of human resources to innovation output ranges from -0.0424 to 0.7183 , as shown in Figure 5(a). Among them, the human resources of 16 cities such as Ganzhou, Fuzhou, Ji'an, Nanchang, and Pingxiang have negative effects on innovation output, and the remaining 85.45% have positive effects, which to a certain extent proves that human capital is the endogenous power of regional innovation output promotion. The gathering of scientific and technological talents helps to enhance regional knowledge absorption ability, break the knowledge barrier of technology diffusion, and enhance regional knowledge diffusion and regional innovation output. In particular,

Baoshan, Lincang, Lijiang, Pu'er, Panzhihua, Ya'an, and other cities in the upper reaches of YREZ will increase innovation output by 0.4320%–0.7183% for each 1% increase in human resources in these areas. This is because compared with the downstream areas, the human resources in upstream are relatively scarce. According to the law of diminishing marginal utility, the innovation output brought by increasing the input of human resources is higher than that of other areas with relatively rich human resources. In addition, human resources in most cities of Jiangxi have a weak negative impact on innovation output, which may be due to the implementation of relevant documents, such as "Pilot measures for encouraging innovation and entrepreneurship of scientific and technological personnel in provincial independent scientific research institutes" and "Several provisions of Jiangxi Province to encourage scientific and technological personnel to innovate." This fully arouses the initiative of innovation subjects, provides support for transformation of scientific and technological achievements, and creates more innovative output with less human resources.

Financial resources are positively influencing and promoting the innovation output, the performance of which corresponds to Figure 5(b). The maximum value of regression coefficient is Pu'er (0.4182), and the minimum value is Zhoushan (0.1917). The coefficient decreases with "upstream-middle-downstream." This confirms that R&D investment and government science and technology expenditure are important driving forces to increase innovation output. The financial input of upstream cities has a greater positive effect on innovation output than that of downstream cities, especially Baoshan, Lincang, Lijiang, Pu'er, Panzhihua, Yuxi, Ya'an, Kunming, and Qujing. This may be due to the weak economic foundation, insufficient R&D investment in the upstream, and the fact that the region is in the initial stage of regional innovation and has not yet formed a relatively complete innovation network. Therefore, increasing financial input can speed up the construction of regional innovation network, optimize the innovation environment, and improve the innovation capacity and level. At the same time, it should be noted that although the financial input of these cities promoted the innovative output to a certain extent, the gap with the innovative output brought by the input of human resources was relatively large. The reasons may be as follows: the unreasonable intensity and structure of R&D investment leads to insufficient R&D investment in some regions and fields, while R&D investment in other regions and fields has a diminishing marginal effect. In addition, government expenditure on science and technology provides financial support for regional innovation entities, but it may also interfere too much in enterprise innovation, resulting in inefficient resource allocation and affecting innovation output.

5.2.3. Innovation Environment. The indicators of the innovation environment have different effects on urban innovation output. In Figure 6(a), the infrastructure environment has a positive effect, and the economic environment, culture, and education environment have both

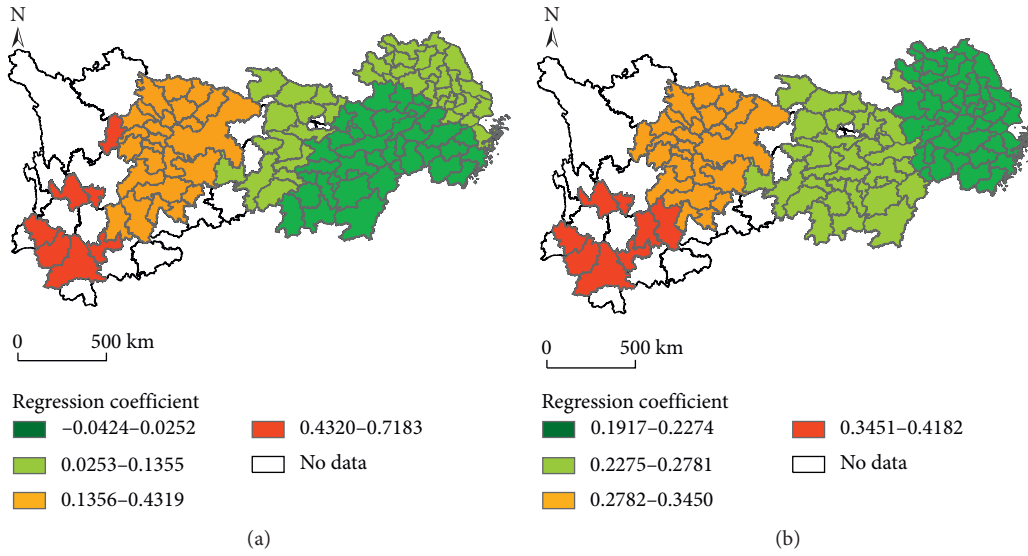


FIGURE 5: Spatial distribution of regression coefficients between innovation resources and innovation output. (a) Human resources. (b) Financial resources.

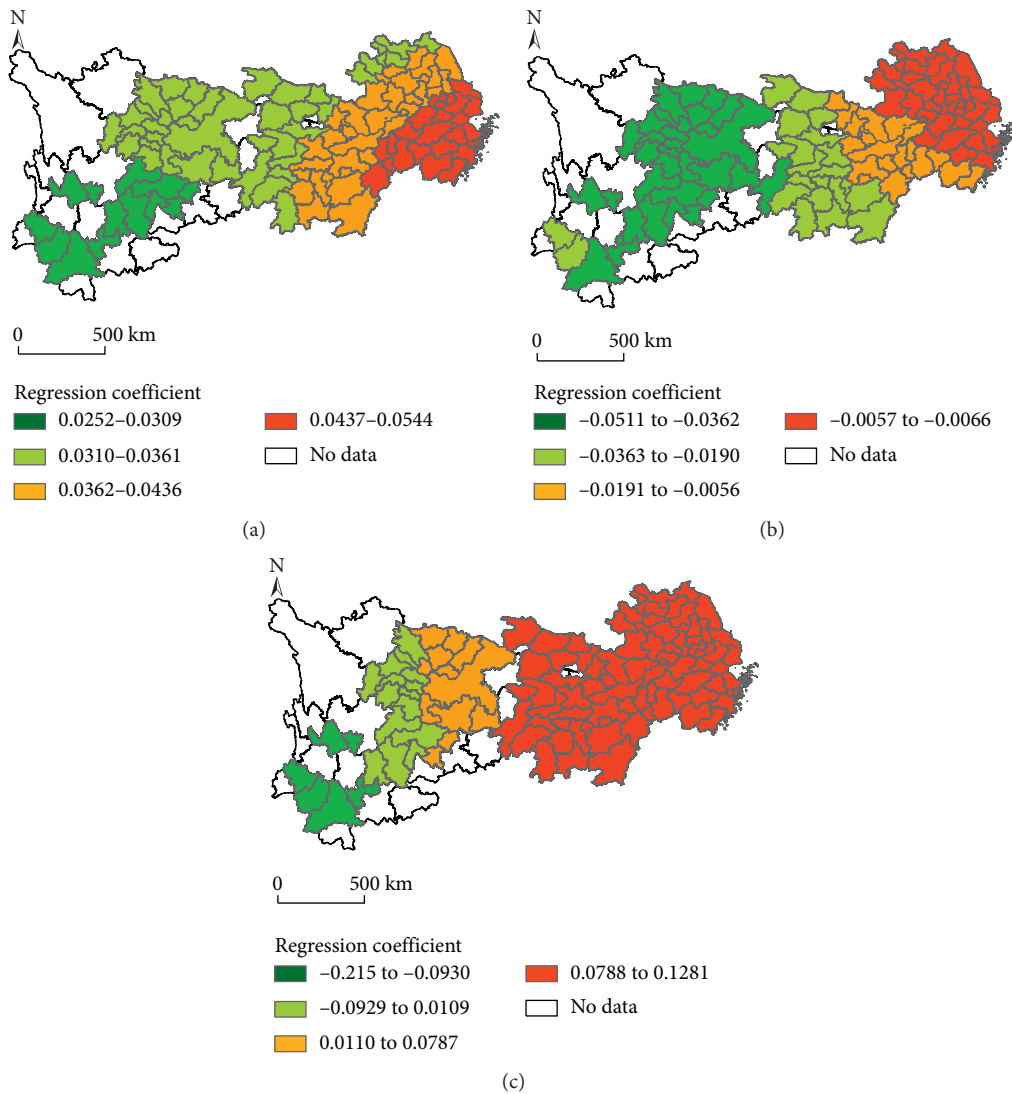


FIGURE 6: Spatial distribution of regression coefficient between innovation environment and innovation output. (a) Infrastructure environment. (b) Economic environment. (c) Cultural and educational environment.

positive and negative effects. In detail, the regression coefficients of the infrastructure environment on innovation output are all positive, and the range is 0.0252–0.0544. This may be because the improvement of the urban transportation infrastructure and the improvement of informatization can speed up the spread of technology and knowledge in the market, enhance interregional exchanges and cooperation, and facilitate the rational allocation of innovative resources, which will help increase the output of innovation. Specifically, the infrastructure environment in the upstream has the smallest impact on innovation output, and the impact level in the mid- and downstream exhibits a staircase pattern that increases from northwest to southeast. Traffic infrastructure is relatively backward in Pu'er, Yuxi, Lincang, Kunming, Qujing, and Baoshan due to the complex topography and poor geological conditions. Besides, the Internet penetration rate in those cities is below the national average level, which also hinders the flow of knowledge and information, leading to lower impact on innovation output. The regression coefficient in the Yangtze River Delta is relatively high. According to “*Digital China Construction Development Report (2018)*,” informatization development evaluation index in Jiangsu, Shanghai, and Zhejiang ranks among the top five in the country. In recent years, it has continuously promoted the development of informatization innovation and strengthened the construction of new infrastructure, gradually building a regional network information technology innovation system to provide strong support for innovation and development.

In Figure 6(b), the regression coefficient of the economic environment on innovation output ranges from −0.0512 to 0.0066, of which 92 cities have negative impact, accounting for 83.64% of the total. With characteristics of “upstream-middle-downstream,” the influence intensity gradually weakened. Among them, cities such as Liupanshui, Qujing, Anshun, Bijie, and Kunming have a strong hindrance to innovation output, while cities such as Hefei, Bengbu, Huzhou, HuaiBei, and Shaoxing have relatively smaller hindrance. The attractiveness of a region to innovative resources is related to economic development, and the market is a platform for contact between innovation supply and innovation demand. Both have an undeniable role in enhancing innovation output. However, from the regression results, the economic environment has not actively promoted innovation output of each city and even shows a slight obstruction effect, which is contrary to theoretical cognition. There are two possible reasons: first, some cities are caught in the path-dependent predicament, which makes it impossible to carry out path innovation on the original industrial chain; second, the market environment's inadequate guarantee mechanism for innovation output has resulted in insufficient innovation motivation for innovation subjects but has reduced innovation output. However, there are also some cities represented by Shanghai, Suzhou, and Nanjing whose economic environment is more optimistic about innovation output. This may be due to the rapid growth of tertiary industry and better quality of economic development in those cities. At the same time, they pay attention to creating an ecological and livable urban environment, attracting

high-tech industries and high-tech talents to settle in, creating a fair competition market environment for them, and promoting the transformation of innovation results.

In Figure 6(c), the coefficient of culture and education environment on innovation output ranges from −0.2156 to 0.1281. There are 94 cities showing positive influence, which proves to a certain extent that the ability of innovation is inseparable from the social culture and educational environment. Among them, cities such as Shanghai and Nanjing are the pioneering areas for reform and opening up. Cultural environment of encouraging innovation and tolerance for failure and high-quality educational resources provide more possibilities for innovation output. However, 14.55% of the cities in YREZ showed a negative correlation, mainly distributed in Baoshan, Lincang, Lijiang, Pu'er, Panzhihua, Yuxi, and Meishan. The reasons for the negative impact are as follows. First, the number of universities in the region is few, educational resources are scarce, the proportion of the population with higher education is low, coupled with the lagging economic development, and the brain drain is serious, resulting in low level of humanities education and innovation output. Second, it is important for the whole society to actively create an atmosphere that supports and encourages innovation. However, the innovation foundation in these regions is relatively weak, and a complete innovation system has not yet been formed. It shows that even a better cultural and educational environment cannot promptly increase innovation output.

6. Conclusion and Suggestion

6.1. Conclusion. The Gini coefficient, CV, and exploratory spatial data are used to analyze the changes and spatial correlation and cluster evolution of 110 cities' innovation output in YREZ from 2008 to 2018, and then we use the entropy method to calculate innovation ecosystem index of each city. Finally, the impact of each factor of the innovation ecosystem on innovation output is analyzed by using the GWR model. Some conclusions can be drawn as follows. First, the overall level of urban innovation output in YREZ has increased year by year, and the geographic concentration has shown a downward trend in fluctuation. From 2008 to 2018, the number of patent authorizations showed increase year by year, and the downstream high-value agglomeration areas gradually became prominent. From CV and Gini coefficient, there is a trend of decreasing volatility, the geographical concentration gradually decreases, and the distribution of innovation output has evolved from an imbalance to a state of equilibrium.

Second, the innovation output of the cities in YREZ shows a positive spatial correlation. The agglomeration distribution of cities with similar innovation output shows an overall upward trend. Moran's I index of innovation output exhibited an “M” shaped volatility pattern during 2008–2018. Local spatial correlation analysis indicates that spatial distribution pattern of innovation output has not changed significantly. The HH area is concentrated in the downstream, and the LL area is concentrated in the upstream, reflecting the obvious spatial agglomeration effect.

Chongqing and Kunming are located in the HL area, showing obvious polarization characteristics, and Xuan-cheng's innovation output level is significantly lower than that of the surrounding cities, so it is located in the LH area.

Third, the influence of each factor of the innovation ecosystem on innovation output has obvious regional differences. Overall, knowledge applicators, financial resources, and infrastructure environment positively influence innovation output, and knowledge applicators have the greatest impact; knowledge creator, human resources, economic environment, and cultural and educational environments have both positive and negative effects on innovation output; in addition to the economic environment, other influencing factors are mostly positive effects, and a few regions have negative effects and significant heterogeneity. Among them, universities and research institutes, enterprise, and the cultural and educational environment's effect on innovation output have spatially exhibited the layout characteristics of "high in the west and low in the east". The intensity of human input, financial input, and economic environment's effect on innovation output in the spatial distribution generally shows the characteristics of "high in the east and low in the west"; the degree of impact of the infrastructure environment in the middle and lower reaches shows enhanced ladder from northwest to southeast.

6.2. Policy Recommendations. First, we should break the traditional boundary of innovation subject and realize multiparty cooperation and deep integration. We should break the boundary between knowledge creators and knowledge applicators in innovation ecosystem, strengthen the endogenous power of enterprises as main institutions, stimulate the synergy of universities and scientific research institutions to support innovation, maintain dynamic balance in competitive symbiosis, avoid the phenomenon of "innovation isolated island," and realize cross-border cooperation, multiparty cooperation, and deep integration among innovation subjects. The influence of innovation subjects on innovation output is weak in the upper reaches and strong in the middle and lower reaches. Therefore, the cultivation of innovation subjects in the upper reaches should be strengthened to fully stimulate innovation vitality. Specifically, for universities and research institutions, they should, according to their own advantages, establish innovation priorities in a differentiated way. At the same time, a coordination mechanism is formed between the various innovation entities in the system, so as to realize the effective complementation and connection of innovation resources and enhance the innovation output of the region. First of all, universities and research institutions should remove the administration of academic issues and avoid the link between administrative power and scientific research resources, which leads to the lack of autonomy of scientists. At the same time, they should establish a scientific and reasonable innovation incentive mechanism to maximize the innovation vitality of researchers. Secondly, under the unified layout and coordinated guidance of the government, we should make full use of funds for scientific research projects from various

channels to increase the construction of infrastructure for scientific research institutions and support innovation of universities and research institutions in the fields of infrastructure and cutting-edge technology research. Finally, we should actively explore cooperation channels with enterprises, strengthen the positive interaction between universities, research institutions, and enterprises, set up market-oriented projects and carry out R&D, and open up a channel for patent transformation of scientific and technological achievements. For knowledge carriers, especially in upper reaches of YREZ, we should strengthen the enterprise as the main body of improving the innovation output. For knowledge users, especially the upper reaches of the Yangtze River Economic Belt, enterprises should strengthen their position as the mainstay of innovation output, guide various innovation elements to gather in enterprises, increase support for enterprise innovation, and introduce and support technological innovation. Leading enterprises play their leading role in demonstration, effectively attracting various innovative resources and elements, accelerating the improvement of the industrial chain and innovation chain, and driving the growth of a large number of small- and medium-sized enterprises, making them the backbone of improving technological innovation capabilities and increasing innovation output. Besides, the government should give full play to its "policy power" and introduce special policies to further increase subsidies and tax incentives for innovation-oriented enterprises so as to reduce their innovation costs.

Second, we should increase the investment of innovation resources reasonably and accelerate the development of scientific and technological innovation to improve quality. The influence of innovation resources is mostly positive, which is mainly manifested in the high east and low west. Therefore, the input of human resources and financial resources in the eastern region has greatly improved the innovation output of the region. Reasonable input of human and financial resources to innovation provides key support for innovation ecosystem construction and innovation output. For the human resources of innovation ecosystem, it is undeniable that human resources are the key force to enhance innovation output. First of all, deepen the reform of the education system, pay attention to basic research, and train "advanced" innovative talents. Secondly, it should give more autonomy to the researchers in scientific research institutions and universities and stimulate their creative talents and vitality to the greatest extent by giving them intellectual property rights and material incentives. Finally, by enhancing the "talent stickiness" to enhance the "innovation concentration" and constantly optimizing the innovation ecological environment, we will create a "strong magnetic field" for talents to gather, which will be transformed from attracting investment to "attracting talents and attracting talents." We will focus on introducing leading talents in key technology fields and emerging technology fields to give full play to the siphon effect and realize "attracting talents with talents." In terms of financial resources, it is an effective way to improve innovation output to reasonably increase the investment in innovation financial resources and continuously improve the utilization

efficiency of funds. On the one hand, we should encourage universities and research institutes to increase investment in R&D by establishing a diversified mechanism for government, enterprises, and financial institutions to invest in innovation and guide nongovernmental and private capital to invest in R&D so as to reduce the innovation risks of enterprises. On the other hand, each innovation subject should constantly improve the system and mechanism of science and technology fund management to maximize the utilization rate of funds. For example, we should reform the way the government funds for science and technology are used, eliminate the disadvantages of the traditional model of “project approval in advance and grant free funds,” set up special funds, and make full use of the market mechanism to leverage financial capital to invest in the science and technology industry.

Third, continuously optimize the innovation environment and fully stimulate the enthusiasm of the main body of innovation. The innovation environment affects the creation, flow, and application capacity of innovation elements such as knowledge and technology. Optimizing the environment of the innovation ecosystem helps the innovation subjects to strengthen cooperation and exchange, effectively coordinate the use of innovation resources, and accelerate the flow of innovation elements. The impact of innovation environment on innovation output is complex, so it should be optimized according to the differences of innovation environment in different regions. For the infrastructure environment, improving the infrastructure environment, especially in terms of information infrastructure, is conducive to greatly increasing innovation output. Therefore, the investment in informatization should be increased, and the funds should be appropriately inclined to the communication engineering, especially in the areas with low informatization level in upstream of the Yangtze River, so as to actively promote the informatization infrastructure construction in YREZ and give full play to the innovation-driven effect of informatization. In addition, each innovation subject should be good at using information technology to build an open and shared scientific and technological information platform, build the “Internet +,” integration of the Yangtze River Economic Belt, break through barriers that hinder the flow of knowledge and technology, and promote the flow of information and cooperation and exchanges between regions to achieve information exchange, resource sharing, and knowledge sharing which are used to improve innovation efficiency and narrow the regional innovation gap. For the economic environment, we should stand at the commanding height of future industrial development, target emerging industries such as cloud computing and artificial intelligence, and focus on fostering development so as to constantly improve the quality of economic development. In addition, for the purpose of stimulating innovation, improve the construction of the intellectual property management system, immediately promulgate laws and regulations, establish a benefit-sharing and risk-sharing benefit mechanism, form a joint force for system protection, and optimize the legal “soft environment” that promotes technological innovation. Efforts will

be made to solve the problems faced by intellectual property protection, effectively guarantee the economic benefits of innovation entities, and achieve a win-win situation for multiple entities. For the cultural and educational environment, first, we should strengthen the publicity of science and technology, fully arouse the enthusiasm of various innovation subjects, create a scientific and technological innovation atmosphere, and form a culture and social values that are conducive to innovation, tolerate failure, encourage experimentation, and advocate competition. Second, education is the basis of the social and cultural environment. In particular, institutions of higher learning in upstream of the Yangtze River must grasp the social changes, enhance the quality of education and pay attention to the improvement of students’ innovative consciousness and ability, and optimize the population structure.

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.

Acknowledgments

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Research Article

Relationship between Team Conflict and Performance in Green Enterprises: A Cross-Level Model Moderated by Leaders' Political Skills

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It is evident that, being a member of the organization, the team has to cue the influx of the green management concepts. This study focuses on the aspect of team management in green enterprises. Applying leadership theory to sample green enterprises, this paper proposes that political skills of team leadership have moderating effects on the relationship between team conflict (relationship conflict and task conflict) and performance at both the individual and team levels. Empirical data were collected from 85 dyads of leaders and team members in 36 green enterprises in China. It was found that the leaders' political skills weakened the negative effects of relationship conflict on individual performance and team performance. Further, leaders' political skills strengthened the positive effects of task conflict on individual and team performance. The results of this study deepen the cognition of two types of team conflict in theory and provide theoretical guidance for green enterprises in carrying out effective team conflict management and practical political skills training for leaders.

1. Introduction

Green enterprises are part of a contemporary trend toward sustainable development in modern enterprise development. Innovation systems are necessary for green enterprises to promote an organic integration and coordinated development of marketization, knowledge, and ecology [1, 2]. The development of green enterprises must extend the characteristics of ecological processes to enterprises. Green enterprises should bear ecology and economics in mind, controlling pollution and husbanding resources in all aspects of business operation, which often involves complex decision-making [3, 4]. For example, green enterprises must balance efficiency and fairness, economic benefit and environmental protection, and corporate interests and social evaluation. Some members are more motivated to perform environmental tasks, where it pays to be green, but others

may be more motivated to perform economic tasks [5]. Thus, more conflicts may arise within teams in green enterprises relative to other conventional enterprises, especially in terms of green decision-making or the execution of green strategies. Conflict management thus plays an important role in green enterprises.

Here, team conflict refers to team members' perceptions of disharmony or contradiction between each other [6]. In green enterprises, the contradiction between economic benefits and environmental benefits is most likely to lead to team conflicts. The team in the green enterprise is often responsible for analyzing, planning, implementing, controlling, and coordinating the enterprise action and making it conform to the environmental strategy of the enterprise. Therefore, it is a common phenomenon that teams in green enterprises suffer from the ideological conflicts about economic efficiency and green decision-making. On the one

hand, teams in green enterprises are burdened with the responsibility and obligation of formulating environmental business strategies and improving the environmental processes in organizations [7]. Consequently, there may be much conflict of attitudes and green decisions in teams. On the other hand, team in green enterprises usually uses recombinant ability to adopt explorative behaviors and combines previous knowledge to establish green strategies [8]. In the processes of team recombinant, different ideas or solutions may come into being and may induce team conflict [9]. More importantly, green technologies play an important role in green enterprises' green strategies, and Orsatti and Pezzoni [8] have verified that green technologies were almost generated by creative teams. Therefore, teams in green enterprise not only undertake the important task of enterprise development, but also accumulate the risk of fierce team conflict. For example, some recent studies have suggested that team resilience helps a lot for a green enterprises' green sustainable development [7]. The above aspects all highlight the necessity and importance of team conflict management in green enterprises.

Team conflict in green enterprises includes task and relationship conflict. Task conflict refers to disputes among team members about the choice of task completion scheme, while relationship conflict comes from interpersonal friction among team members that has no direct relationship with team function or goals [10]. The traditional view holds that conflict is an obstacle to team development, but close study of human relationships has indicated that it is inevitable, and team conflict may have positive effects. Empirical studies have shown that team conflict can have a negative impact on output, but no clear relationship between team task conflict and performance has been determined. It is commonly thought that team task conflict has positive effects on team performance and team innovation through the development of improved efficiency in information processing, team creativity, and team problem-solving [6, 11]. However, it has also been suggested that team task conflict may enhance team relationship conflict, which might adversely affect team performance by reducing the efficiency of information-processing mechanisms among team members [12].

The inconsistency of the results of prior research indicates that situational variables strengthen or inhibit the impact of team task conflict and relationship conflict on performance. Conflict is a common and inevitable phenomenon in team work, especially in green enterprises. Thus, it is of great importance to explore the links between team task/relationship conflict and performance, including the boundaries of these links. Few studies have examined how the positive effects of task conflict could be enhanced and the negative effects of relationship conflict could be reduced. In recent years, scholars have begun to pay attention to moderating factors between team conflict and team output in different aspects, such as the interactions between team members, team management, team members' emotions, and other aspects [13]. In practice, the leadership and coordination ability of team leaders are very important to the management of team conflict in green enterprises due to their particularity. According to the leadership theory,

leaders can effectively take their advantages to influence subordinates' attitudes and behaviors by using abilities, skills, talents, or professional knowledge that their subordinates have recognized, so as to achieve excellent performance of the organization or team [14]. A large number of scholars have discussed the important role of leadership in organization and team management from the theoretical perspectives of leadership traits, leadership behaviors, and leadership contingency [13]. With the increasing uncertainty in organizations especially in green enterprises, political behavior plays an increasingly important role, and leaders' political skills become important skills to effectively manage organizations and teams [7]. The political skills of leaders are indispensable for coordinating inconsistent goals, tasks, needs, and interests of teams in green enterprises. Team leaders have an important influence on all aspects of team activities, and their political skills can help resolve team conflicts, especially in team conflict management for green enterprises to formulate a sustainable business strategy [7]. However, discussion of the role of leaders' political skills is still lacking. Therefore, this paper uses leaders' political skills as a moderator to investigate its effect on team conflict management.

Task conflict is related to cognitive differences between team members due to inconsistency in views, and relationship conflict is related to emotional differences caused by interpersonal discussions of weariness or dislike [15]. Therefore, task conflict and relationship conflict can affect both team and individual performance. However, existing studies pay greater attention to the impact of conflict on team performance, ignoring the effects of conflicts on individual performance. Team members respond differently to team situations, so team performance cannot be equated with individual performance. In fact, high-performance members can inhibit overall team performance in certain cases [16]. To properly assess the role of team task conflict and relationship conflict in performance, it is necessary to distinguish the effects of team and individual performance at both the team and individual levels. From the literature aforementioned, we found that the existing studies on team conflict focus on traditional performance with few studies on green performance especially in green enterprises. For green enterprises, performance not only includes the traditional understanding of performance, but also cares about the interactions between the environmental dimension and business [17]. In addition to achieving the demanding profit rate or income growth rate in traditional performance appraisal, the implementation of greenification and sustainable development is also an important part of green enterprise performance. The performance appraisal of green enterprises often presents characteristics such as high production cost, green quality assurance, high requirement of R&D capability, and requirements of green supply chain. This paper therefore constructs a cross-level model of the effects of leadership political skills on team conflict and green enterprises' performance at both the team and individual levels. This paper is thus able to enrich the study of team conflict management from a leadership perspective. The results extend team-individual cross-level conflict theory

and provide specific guidance on how to promote the positive role of team conflict and to restrain its negative effects in the practice of green enterprise management.

2. Background and Hypotheses

2.1. Relationship between Team Task Conflict, Individual Performance, and Team Performance. The individual performance of team members describes how individual members are evaluated by their team leaders and peers and the degree to which individual production records meet or exceed team or organizational standards [18]. Individual performance is positively influenced by team task conflict. Authoritative studies (such as Wanous and Youtz [19]) have found that inconsistency in opinions among team members can stimulate them to produce novel plans or engage in creative thinking and other cognitive activities. Task conflict can create novel inspiration and lead to valuable decisions that promote individual performance [20]. Putnam reported that team task conflict helps members identify and better understand issues related to task completion and encourages them to develop new ideas and methods, thus improving the quality of their decision-making [21]. Fiol suggested that when team members differ in their understanding of task-related matters, their ability to learn and accurately assess the situation will be improved [22]. Differing views and perspectives for team task conflict can encourage team members to obtain additional information, think more deeply about different viewpoints and perspectives, and put forward more unique ideas [23]. However, for teams with low amounts of task conflict, team members become more committed to maintaining consistency with others, ignoring differences in views between members, making it difficult to improve the quality and quantity of team decisions, and limiting the ability to obtain the most efficient individual performance [24].

Hypothesis 1. Team task conflict is positively correlated with team members' individual performance.

Team performance describes the ability of a team's production output to meet or satisfy established performance standards [25] including the needs of environment development [7]. To meet team performance standards, team members must evaluate the status quo, understand their tasks, and propose solutions based on their own and their teammates' knowledge, views, and abilities, with the ultimate goal of solving problems [26]. Team task conflict promotes the critical evaluation of problem-solving by team members and reduces the team's collective thinking by increasing thoughtful thinking and improving alternatives [27]. Team task conflict allows team members to identify and discuss different perspectives and to improve their understanding of their tasks, which allows them to develop more thorough assessments of the performance standards that the team needs to achieve, thereby producing high-quality decisions and improving team members' acceptance of collective decisions, which in turn promote improved team performance [28]. Team task conflict also gives team members a greater opportunity to express their views and

propose solutions, encourages them to comprehensively evaluate all alternatives, and respects their positions and views, enabling an enhancement of team members' commitment to their tasks [29]. Task commitment helps intensify team members' initiative for participating in team work and has a stimulant effect on team performance.

Hypothesis 2. Team task conflict is positively related to team performance.

2.2. Relationship between Team Relationship Conflict, Individual Performance, and Team Performance. Team relationship conflict negatively affects team members' individual performance. First, increased team relationship conflict is usually accompanied by negative communication and expression, unwillingness to cooperate, and negative psychological emotions of anger, distrust, fear, and depression [18]. These negative emotions seriously affect team members' individual efficiency and working enthusiasm, reducing their individual performance. The content involved in team relationship conflict is not related to team tasks. It is easy to cause negative emotions among team members and seriously threaten their self-identity and their sense of self-worth [30]. According to threat stiffness theory, when people feel threats from the outside world, they tend to stagnate, reduce, or withdraw input [31]. Therefore, in conditions of high relationship conflict, team members tend to adopt passive sabotage behaviors that lead to lower individual performance. Second, following the theory of limited attention resources, team members' attention resources in the team are allocated between work-related and unrelated transactions [32]. When tension, friction, and emotional disharmony are common among team members, each team member allocates additional resources to deal with these non-work-related matters and can only devote a small amount of resources to discuss problem solutions. Therefore, team relationship conflict reduces individual performance by diverting work attention.

Hypothesis 3. Team relationship conflict is negatively correlated with individual performance.

Team relationship conflict hinders positive interaction among team members. With the increase of the relationship conflict, team members tend to attribute differences in views and problem solutions to their interpersonal relationship friction, and they adopt a hostile attitude to others' suggestions, especially critical ones [33]. This makes them unwilling to accept the opinions of others or to draw inspiration from them, which limits the improvement of team performance. Second, team relationship conflict can easily cause negative emotions among team members. Guided by their negative emotions, team members can become narrow-minded and critical. They may not only ignore the information and resources that can impact team performance, but also find it difficult to integrate resources and information into the team effectively, often prohibiting them from making the optimal decision [34], and they may even make the wrong decisions, which can affect improved team

performance. Third, team relationship conflict limits the team's ability to process information, and team members are driven to spend additional time and energy in dealing with their relationships and to neglect the development of solutions to team problems [35]. Fourth, team relationship conflict enhances stress and anxiety among team members and hinders their cognitive ability, making it difficult to put forward better solutions to achieve team goals and objectively reducing team performance.

Hypothesis 4. Team relationship conflict is negatively correlated with team performance.

2.3. Moderating Effects of Team Leader Political Skills on the Relationship between Task Conflict and Performance. Ferris described political skills as the means by which individuals can understand others effectively at work and use this understanding to influence others and enable them to support themselves to achieve individual and organizational goals [35]. Political skills are actualized in the interaction and mutual influence between individuals and other individuals, groups, or organizations, and they are an organic combination of individual social effectiveness and interpersonal interaction capabilities. Following previous studies, Treadway proposed that leaders' political skills are key to improving team and organizational performance [36] and presented three characteristics that leaders with high political skills possess: first, they use suggestive behavior flexibly, and they identify and classify other people's motivations in a timely and accurate manner through observation; second, they are good at influencing others and adjusting their attitudes and behaviors to changing environments; and third, they are good at strengthening their social capital and employing scarce resources through the establishment and management of interpersonal networks [37]. Team leaders' political skills involve their social acumen, interpersonal influence, network operations, and sincere performance, which affect team members, formulate work plans, and effectively manage teams. Team leaders with high-level political skills can flexibly adjust their team management strategies according to the dynamics of the given team environment and the interactions among team members [38].

The political skills of team leaders can effectively support the management of task conflicts. Social impact theory indicates that team leaders with high levels of political skills can get along well with team members and help them save face in team interactions. They can gain the trust and higher evaluation of team members more easily and achieve effective management by influencing team members [39]. Team leaders' political skills have an important impact on the effective management of team conflict. Studies have shown that too many task conflicts can increase the cognitive load of team members, distract them, and even cause team relationship conflicts, which are bad for both team and individual performance [40]. Team leaders with high political skills can actively adjust the team atmosphere in relation to the state of the interactions and the degree of

conflict between team members. First, they can influence and control the attitudes and behaviors of team members and maintain a reasonable level of task conflict to promote its positive impact on individual and team performance. Second, when faced with excessive team task conflicts, team leaders with high political skills can persuade their team members to regard differing views and ideas as opportunities to learn, using social sensitivity, interpersonal influence, and sincerity. This can help guide team members to integrate a range of information and provide better feedback. In addition, team leaders that have high political skills can also enable the establishment of an atmosphere of trust in a team because they can prevent the team from mistakenly attributing task conflicts to interpersonal threats and team task conflicts from becoming team relationship conflicts that can harm team performance [41]. Additionally, the political skills of team leaders have not only a positive impact on the trust of team members but also a negative impact on their cynicism [37]. Team leaders with high political skills can understand the work motivation of team members in relation to their different characteristics. On this basis, leaders can classify team members according to the differences in their characteristics and adopt appropriate communication styles and strategies to specifically increase their trust in their leaders [42], encourage them to adopt a positive attitude toward team task conflicts as the effort of team members to achieve compatible goals, promote the application of individual effort to team and individual goals [43], and reinforce the positive impact of team task conflict on individual and team performance.

Hypothesis 5. Team leaders' political skills moderate the positive impact of team task conflict on individual performance: the stronger the political skills, the stronger the positive impact of team task conflict on individual performance.

Hypothesis 6. Team leaders' political skills moderate the positive impact of team task conflict on team performance: the stronger the political skills, the stronger the positive impact of team task conflict on team performance.

2.4. Moderating Effects of Team Leader Political Skills on the Relationship between Relationship Conflict and Performance. Employment of an effective conflict management strategy or reduction of the relationship between team relationship conflict and the negative emotions of team members can limit the negative impact of team relationship conflict on individual and team performance [6]. Studies have shown that leaders play an important role in choosing effective methods of managing conflict and weakening the negative side of relationship conflicts [13]. As noted, leaders with high political skills are adept in the flexible use of suggestive behaviors and can recognize and classify others' motivations in a timely and accurate fashion through observation. They can influence others and adjust their own attitudes and behaviors in terms of dynamic environments: team leaders with high political skills can shore up their social capital and

resources through the effective establishment and management of interpersonal networks [37]. The above characteristics indicate that team leaders with high political skills can play an important role in suppressing the negative effects of team relationship conflict on individual and team performance.

At the individual level, leaders with high levels of political skills can get along well with team members and help save face in team interactions. They can gain the trust of team members more easily [44]. First, where team leaders have high political skills, team members are more willing to communicate with them and vent their negative feelings, which is conducive to their work. Leaders with high political skills are good at observing members' behaviors and emotions and are able to adopt effective means of relieving the negative emotions, such as anger, distrust, fear, and depression that are caused by relationship conflicts among members with different characteristics [44]. Leaders with high levels of political skills can help team members find ways to relieve or eliminate negative feelings to improve their individual efficiency, enthusiasm for work, and individual performance. Leaders with high political skills can reduce the negative impact of relationship conflicts on team members' individual performance. Second, when the self-identity and self-worth of team members are threatened, leaders with high political skills can help members restore their self-esteem by making use of their interpersonal influence, which also aids in the restoration of their enthusiasm for work [43]. Leaders with high political skills can adopt appropriate communication styles in response to members' different personalities to enhance their perception of the political skills of leadership, increase their trust in leadership, aid them to respond to team relationship conflict with a positive attitude and regard it as a simple misunderstanding encountered while achieving compatible goals, and enable them to shift their attention from dealing with interpersonal conflicts to work tasks [45]. Thus, the negative impact of team relationship conflict on individual performance is reduced.

At the team level, leaders with high political skills have a high sense of social acuity, and they both recognize the negative feelings of team members and hostile relationships among them and take timely and effective communication and facilitation measures to minimize the impact on team performance [7, 13]. First, leaders with high political skills exert a strong interpersonal influence, leading their teams to correctly appraise their different opinions, which can help them approach these opinions rationally and guide them to accepting others' opinions to bring inspiration and new thought that improves team performance. Second, leaders with high political skills have strong abilities in network operation [45]. They make use of their influence and resources to focus the attention of team members on team tasks, guide team members to avoid narrow mindedness, attach importance to information and resources that can impact team performance, and effectively integrate resources and information to make optimal decisions that can solve team problems [46]. Third, leaders with high political skills can build an atmosphere of trust and harmony, reduce

tension and pressure caused by relationship conflict among team members, and enable team members to use their cognitive ability effectively to contribute to team decision-making. Team leaders with high political skills can also unblock communication channels within teams [47] to promote the effective circulation of information and resources among different members and guide people to seek new information resources from existing ones, help their team reach the best solution to their problems, and promote team performance [48]. Accordingly, we propose the following research hypotheses.

Hypothesis 7. Team leaders' political skills moderate the negative impact of relationship conflict on individual performance: the stronger the political skills, the weaker the negative impact of team relationship conflict on individual performance.

Hypothesis 8. Team leader political skills moderate the negative impact of team relationship conflict on team performance: the stronger the political skills, the weaker the negative impact of team relationship conflict on team performance.

The theoretical model of this research is presented in Figure 1.

3. Materials and Methods

3.1. Sample and Procedure. Using a multisource, multilevel survey design, we collected data from 500 members of 120 work teams in 36 green enterprises in four types of businesses in China, including enterprises making food, electronic technology, motor vehicles, and chemical products. We invited attendee companies at a green economy forum at a major research institution in the south of China, to participate in the study. Once they had agreed, the companies identified teams that were available to complete the survey. The authors distributed and collected paper copies of the questionnaires either on-site or over network communications during working hours. The responses were voluntary, and the confidentiality of the participants was assured. The members of the participating work groups were in customer service, marketing, R&D, and top management. To minimize potential common method bias, we collected perception data (e.g., team tasks and friendship conflicts and leaders' political skills) from team members and data on team and individual performance from the team leaders' performance files. Team members described their perceptions of their leaders' political skills, task relationships, and relationship conflicts. Unless otherwise indicated, all continuous variables were measured on a 5-point Likert scale (1 = strongly disagree; 5 = strongly agree).

We distributed surveys to 120 teams, of which 105 (87.50%) provided responses, including 454 team members. Team size ranged from 3 to 10 people, with an average of about 6. Excluding teams with fewer than three responses and eliminating questionnaires with incomplete information resulted in a valid team response rate of 71.00%. This represented 85 team leaders and 414 members. These teams

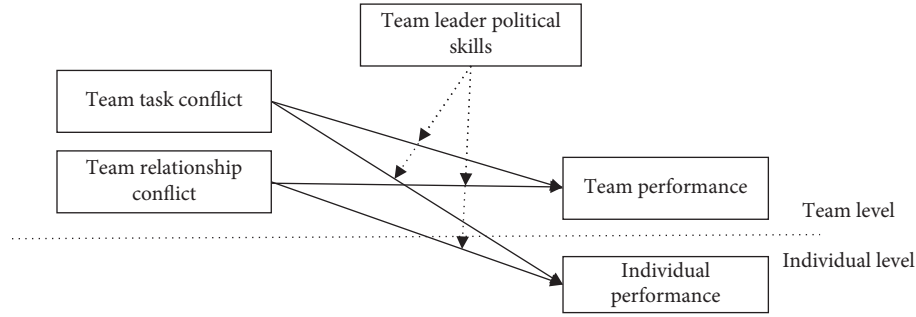


FIGURE 1: Cross-level model of interactions between team conflict and performance.

were from several regions of China (Beijing, Guangdong, Shanghai, Zhejiang, Hubei, Jiangxi, and Hunan), and 32.94% of the sample was from food enterprises, 28.24% was from electronic technology enterprises, 21.18% was from motor vehicle enterprises, and 17.64% was from daily chemical products enterprises.

3.2. Measures. Using the back-translation procedure [49], we first translated all English-language measures into Chinese and then independently translated them into English to guarantee equivalency of meaning. We recruited 30 MBA students and 6 PhD students to ensure the content validity of our questionnaires. The survey was revised in response to their feedback and suggestions.

- (i) Team task conflict: a four-item scale developed by Jehn was used to measure team task conflict [50]. Team task conflict is a team-level variable, so it was completed by team members to describe their own perceptions, and the responses were aggregated at the team level in the analysis.
- (ii) Team relationship conflict: a four-item scale developed by Jehn was used to measure team relationship conflict [18]. After the confirmatory factor analysis, we found that a single-factor model had good fit, $\chi^2/df = 1.965$, GFI = 0.942, SRMR = 0.050, RMSEA = 0.071, TLI = 0.929, and CFI = 0.950. This indicates that the team relationship conflict scale had good construct validity. Team relationship conflict was also assessed at the team level. The scale was completed by team members to describe their own perceptions, and the responses were aggregated at the team level in the analysis.
- (iii) Leader political skills: a scale of political skills developed by Ferris et al., including the four dimensions of social acuity, interpersonal influence, interpersonal network ability, and performance sincerity [51], was used. Confirmatory factor analysis shows that the single-factor model had a good fit, $\chi^2/df = 2.23$, GFI = 0.942, SRMR = 0.049, RMSEA = 0.063, TLI = 0.936, and CFI = 0.963. To ensure objectivity, the 18-item scale was completed by team members to describe their own perceptions.
- (iv) Team performance and individual performance: we used time lag objective data to measure team and

individual performance including incubators of green business and environment concerns. Three months after the team members had completed the political skills and relationship conflicts questionnaires, we collected objective data on team and individual performance from team performance files. To facilitate uniformity in the data analysis, we averaged performance data for multiple teams in each company and for multiple members of each team. Then we coded team (individual) performance within the range 1–5 according to differences in team (individual) mean (1, three standard deviations below the mean; 2, one standard deviation below the mean; 3, equal to the mean; 4, one standard deviation above the mean; and 5, three standard deviations above the mean).

- (v) Control variables: following the previous research, in addition to measuring these key variables, we also controlled variables that affect team and individual performance at both the individual and team levels. Control variables at the individual level were gender, tenure, and education; at the team level, they were team size and team type. To ensure study validity, this paper controls the role of task conflict in testing the effects of relationship conflict on performance, and it controls the role of relationship conflict for testing the effects of task conflict on performance.

3.3. Data Aggregation. Task conflict and relationship conflict were measured based on the perceptions of team members. This enabled us to collect data at the individual level. This entails the necessity of analyzing the consistency of team members' perceptions before the data analysis to determine whether individual-level data could be aggregated to the team level. We adopted the method developed by James et al. to calculate pairs of variables from the members of each team [52]. The median of $R_{wg(j)}$ index for team task conflict and team relationship conflict was 0.91 and 0.89, so the variables exhibit good internal consistency and can be aggregated at the team level [53].

4. Results

4.1. Descriptive Statistics and Correlation Analysis. Table 1 shows the means, standard deviations, and correlation coefficients for all variables. Results at the team level

TABLE 1: Means, standard deviations, and correlations.

| Variables | Mean | SE | Max | Min | 1 | 2 | 3 | 4 |
|------------------------------------|------|------|------|------|--------|---------|-------|---|
| Team level | | | | | | | | |
| Task conflict | 3.22 | 0.64 | 1.56 | 5.00 | 1 | | | |
| Relationship conflict | 2.49 | 0.75 | 1.20 | 4.00 | -0.21* | 1 | | |
| Team performance | 3.59 | 0.71 | 1.00 | 5.00 | 0.30* | -0.33** | 1 | |
| Leader political skills | 3.65 | 0.90 | 1.00 | 5.00 | 0.37** | -0.66** | 0.38* | 1 |
| Individual level | | | | | | | | |
| Individual performance | 4.42 | 0.54 | 1.80 | 5.00 | 1 | | | |
| Leader political skills perception | 3.96 | 0.73 | 1.00 | 5.00 | 0.53** | 1 | | |

$N=85$ and $n=414$. * $p < 0.05$ and ** $p < 0.01$.

indicated that team task conflict was positively correlated with team performance ($r=0.30$, $p < 0.05$), but team relationship conflict was negatively correlated ($r=-0.21$, $p < 0.05$). Leaders' political skills were positively correlated with team task conflict ($r=0.37$, $p < 0.01$) and team performance ($r=0.38$, $p < 0.05$) but negatively correlated with team relationship conflict ($r=-0.66$, $p < 0.01$). Furthermore, team task conflict was negatively correlated with team relationship conflict ($r=0.21$, $p < 0.05$). At the individual level, team members' perceptions of their leaders' political skills were positively correlated with team members' individual performance ($r=0.53$, $p < 0.01$).

4.2. Data Analysis and Hypothesis Testing

4.2.1. Team-Individual Cross-Level Hypothesis Testing. Because team members are nested within teams, individual performance is naturally influenced by team-level variables like task or relationship conflicts, and leaders' political skills. We used a multilayer linear model (hierarchical linear modeling, HLM) to test hypotheses 1, 3, 5, and 7.

HLM software was used to test the moderating effects of team leader political skills on the relationship between team task conflict (relationship conflict) and individual performance. First, a zero model was constructed with individual performance as the result variable to verify nesting in the model. Then, team task conflict (relationship conflict) and leaders' political skills were placed into the model for main effect analyses. The third step was to verify moderating effects by inserting interactions between team task conflict and leaders' political skills. All variables were centered before they were put into the model.

Team task conflict had a significant positive effect ($\beta=0.28$, $p < 0.05$) on individual performance, as shown in Model 3-1 in Table 2, where pseudo- R^2 was 0.40, and the change was significant, so Hypothesis 1 was supported. Model 4-1 shows that the interaction between team task conflict and leadership political skills significantly enhanced individual performance ($\beta=0.18$, $p < 0.05$). Pseudo- R^2 was 0.33, and the change was significant. Therefore, leaders' political skills enhanced the positive effects of team task conflict on individual performance, and Hypothesis 5 was supported. Model 3-2 shows that team relationship conflicts had a significant negative impact on individual performance ($\beta=-0.14$, $p < 0.001$). Pseudo- R^2 was 0.23. The change was significant, so Hypothesis 3 was supported. Model 4-2

showed that the interaction between team relationship conflict and leader political skills had a significant effect on individual performance ($\beta=0.06$, $p < 0.05$). Pseudo- R^2 was 0.23, and the change was significant. Therefore, leaders' political skills inhibited the negative effects of team relationship conflict on individual performance, and Hypothesis 7 was supported.

4.2.2. Hypothesis Testing at the Team Level. Hypotheses at the team level were tested using hierarchical regression analysis, as shown in Models 3 to 5 in Table 3. Team performance was taken as the explained variable; the control variables and team relationship conflicts at team level were put into the regression model first, and then team task conflict and team leader political skills were put into the regression model with a stepwise approach to investigate the effects of interaction items on team performance. We found that team task conflict positively affected team performance ($\beta=0.42$, $p < 0.001$), so Hypothesis 2 was supported.

The interaction between team task conflict and team leader political skills was significant ($\beta=0.15$, $p < 0.05$), and leaders' political skills enhanced the positive correlation between team task conflict and team performance: the higher the leaders' political skills, the stronger the positive impact of team task conflict on team performance. Hypothesis 6 was thus supported.

As shown in Models 4 to 6 in Table 3, we first put team-level control variables and team task conflicts into the regression model. Following this, we placed team relationship conflict and team leader political skills into the regression model, followed by the interaction items of team relationship conflict and team leader political skills through a step-by-step approach to investigate the effects of interaction items on team performance. We found that team relationship conflict negatively affected team performance ($\beta=-0.61$, $p < 0.001$), so Hypothesis 4 was supported, and the interaction between team relationship conflict and leaders' political skills was significant ($\beta=0.11$, $p < 0.05$). The stronger the political skills, the weaker the negative impact of team relationship conflict on performance. Hypothesis 8 was thus supported.

To more simply reflect the role of team leaders' political skills in moderating the relationship between team task or relationship conflict and team performance, a moderating effect map was drawn (Figures 2 and 3). We categorized average value of leaders' political skills at plus one and minus

TABLE 2: Effects of leader political skills on the relationship between team conflict and individual performance.

| Variables | Individual performance | | | | | | |
|-------------------------|------------------------|------------------------------|------------------------|-------------------------------|------------------------------|------------------------|-------------------------------|
| | Model 1: zero model | Model 2-1: control variables | Model 3-1: main effect | Model 4-1: interaction effect | Model 2-2: control variables | Model 3-2: main effect | Model 4-2: interaction effect |
| Intercept γ_{00} | 3.80*** | 3.81*** | 3.81*** | 3.81*** | 3.81*** | 3.81*** | 3.81*** |
| Individual level | | | | | | | |
| Gender | | -0.02 | -0.02 | -0.02 | -0.02 | -0.02 | -0.02 |
| Tenure | | 0.04 | 0.04 | -0.04 | 0.04 | 0.04 | -0.04 |
| Education | | 0.10* | 0.10* | 0.10* | 0.10* | 0.10* | 0.10* |
| Team level | | | | | | | |
| Team size | | -0.02 | -0.01 | -0.00 | -0.02 | -0.01 | -0.00 |
| Team type | | -0.07 | -0.06 | -0.07 | -0.07 | -0.06 | -0.07 |
| TRC | | -1.85* | | | | -0.14*** | -0.38** |
| TTC | | | 0.28*** | 1.08** | 0.27*** | | |
| LPS | | | 0.20*** | 0.93** | | 0.12*** | -0.05 |
| TTC*LPS | | | | 0.18* | | | |
| TRC*LPS | | | | | | | 0.06* |
| σ^2 | 0.34 | 0.26 | 0.22 | 0.25 | 0.06 | 0.06 | 0.06 |
| T | 0.40*** | 0.22*** | 0.24*** | 0.27** | 0.13*** | 0.17*** | 0.16*** |
| $\chi^2(df)$ | 920.72(82) | 1055.16(82) | 1021.93(82) | 1041.96(82) | 920.72(82) | 1075.11(82) | 1041.96(82) |
| Pseudo- R^2 | | 0.45 | 0.40 | 0.33 | 0.41 | 0.23 | 0.27 |

Notes. $N=85$ and $n=414$, * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$. TRC: team relationship conflict; TTC: team task conflict; LPS: leader political skills.

TABLE 3: Effect of leader political skills on relationship between team conflict and team performance.

| Variables | Team performance | | | | | | |
|----------------|------------------|----------|----------|----------------|---------|----------|----------|
| | Model 1 | Model 2 | Model 3 | Variables | Model 4 | Model 5 | Model 6 |
| Team size | -0.35** | 0.07 | 0.67 | Team size | -0.35** | 0.07 | 0.67 |
| Team type | -0.11 | -0.05 | -0.23 | Team type | -0.11 | -0.05 | -0.23 |
| TRC | -0.33** | | | TTC | 0.30** | | |
| TTC | | 0.42*** | 0.43*** | TRC | | -0.61*** | -0.55*** |
| LPS | | -0.49*** | -0.31*** | LPS | | -0.61*** | -0.58*** |
| TTC * LPS | | | 0.15* | TRC * LPS | | | 0.11* |
| Adjusted R^2 | 0.10 | 0.71 | 0.73 | Adjusted R^2 | 0.11 | 0.53 | 0.55 |
| F value | 4.91** | 72.20*** | 5.05* | F value | 6.35*** | 37.44*** | 4.27* |
| ΔR^2 | 0.13 | 0.60 | 0.02 | ΔR^2 | 0.13 | 0.42 | 0.02 |

Notes. $N=85$ and $n=414$. * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$. TRC: team relationship conflict; TTC: team task conflict; LPS: leader political skills.

one standard deviation as high political skills and low political skills, respectively. Team leaders with higher political skills (solid lines) show a steeper slope of team task conflict and team performance than that of team leaders with lower political skills (dashed lines). The slope for team relationship conflict and team performance is flat compared with that of leaders with lower political skills (dashed lines), indicating that higher political skills produce a more positive impact of team task conflict on team performance and a less negative impact of team relationship conflict on team performance. Team leaders' political skills enhanced the positive impact of team task conflict on team performance and weakened the negative impact of team relationship conflict on team performance. Hypotheses 6 and 8 were thus supported.

5. Discussion

This paper adopted a leader-member paired questionnaire and objective performance data from the team performance

appraisal archives in green enterprises from 85 teams and corresponding 414 members to test the effects of team task conflict and relationship conflict on team and individual performance. Using leadership theory, this paper discusses the role of leaders' political skills in green enterprises in moderating the relationship between team conflict (task conflict and relationship conflict) and performance. First, we found a significant positive correlation between team task conflict and individual and team performance. This supports the results of previous research on the positive effects of task conflict on team performance [19] and expands the study of task conflict on individual performance, enriching the cross-layer theory of team task conflict, which further supports the suggestion that team-level interactions may impact members' individual processes and outputs [54]. Second, a significant negative correlation was found between team relationship conflict and individual and team performance. This was consistent with the conclusion of previous studies that team relationship conflict has a negative effect at the team level [55, 56]. It was also consistent with the

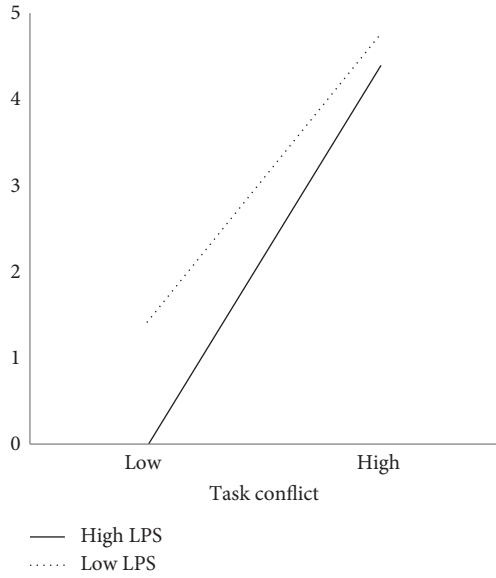


FIGURE 2: Moderating Effects of Team Leadership Political Skills on Task Conflict and Performance.

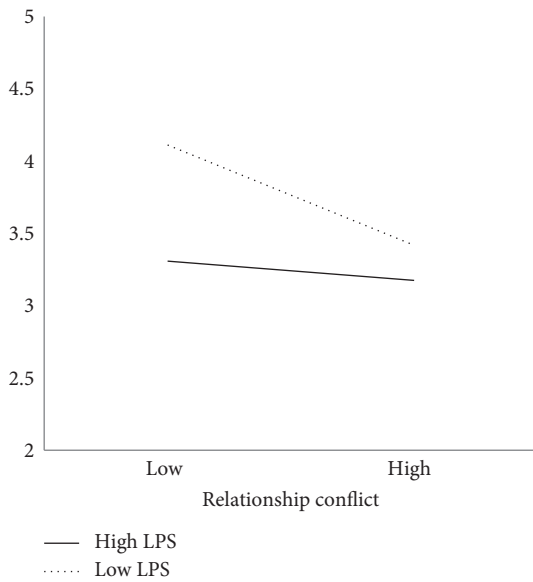


FIGURE 3: Moderating Effects of Team Leadership Political Skills on Relationship Conflict and Performance.

suggestions of Jehn and Chadwick [57] that team-level relationship conflict has a deep impact on individual-level affective and informational states, expanding the research field for relationship conflict and conducting to the expansion and deepening of cross-layer team theory [58]. Third, team leader political skills moderated the relationship between task and relationship conflict and performance at both the individual and team levels. For high leaders' political skills, the negative effect of relationship conflict on individual and team performance was significantly suppressed, and the positive effect of task conflict on individual and team performance was significantly enhanced. This result supported the conclusions of Shi and Chen [59], namely, that political skills are positively related to proactive personality and in-role performance, and it also extended

the application of political skills to the team and leadership perspective, which is conducive to understanding the effectiveness of political skills more thoroughly.

The results were also in accord with a basic contention of conflict management, which proposes that a leader has an important influence on the outcomes of team conflict, such as in the leader's conflict management style and its correlation to innovation performance [13] and the relationship between teams' reactions to conflict and teams' task and social outcomes, which is moderated by transformational and emotional leadership [60]. This empirical study from green enterprises also implicated the importance of effective conflict management and the very important role of team leaders' political skills which suggested that environment leadership was positively correlated to environment culture and performance [61]. Besides, the results were consistent with the suggestions that green team resilience helped a lot in achieving environmental sustainability through green transformational leadership policy [7].

5.1. Theoretical Contributions. Overall, this study made the following theoretical contributions. First, it enriches the theory of team conflict management. Previous studies are generally limited to exploring team conflict management from situational perspectives, ignoring the leadership perspective. This study used leadership theory to study the effects of team conflict on team and individual performance, enriching team conflict theory. Second, research on team conflict has paid closer attention to its influence on team processes, and little research has been devoted to its impact on team members. In relation to the important role of team members in the implementation of green strategy, this study enriched multilevel team theory in green enterprises by discussing the boundaries of team conflict. It deepened the understanding of two types of team conflict in theory while also providing theoretical guidance for team conflict management and practical leaders' political skills training. Third, this study proposed effective ways for green enterprises to improve performance from the microerspective of internal team conflict management based on leadership theory, which expands and enriches the research on green enterprises performance. The previous studies on green enterprise performance were almost based on theories like institutional innovation and ecological civilization from the macro-perspectives. However, the lack of research on the microlevel of the organization is obviously not appropriate because the individual in the enterprise and the team composed of individuals are the ultimate value source of green enterprises.

5.2. Managerial Contributions. Team conflict management in green enterprises requires further attention. To promote the internal systems innovation and sustainable development in green enterprises, team conflict must be reduced to its lowest possible level. Improving the effectiveness of team conflict management plays an important role in the optimization of team processes and team performance improvement. However, not all team conflicts have a negative impact on team management, nor are all of the consequences of team conflicts directly related. It is possible that

team conflicts are only a phenomenon whose real cause must be seriously investigated. Therefore, the management of team conflict by team managers should go beyond distinguishing different types of team conflict and exploring the deep reasons behind the conflict to improve the effectiveness of team conflict management. Green development has become the theme of the times. The green transformation of the entire green enterprises indicates that team conflict can be an inevitable problem. Organization and team conflict management in green enterprises should be highly valued by managers in green enterprise, and they should try their best to reduce the negative effects of team conflict and take advantage of its positive effects. Green enterprises should realize the benign interaction in organizations and teams, achieve the unity of short-term interests and long-term development, and realize the sustainable development of green enterprises.

Green enterprises should look rationally at team conflicts. The development of such enterprises incorporates the promotion of green production, the provision of green products, the implementation of green marketing strategies, the shaping of green culture, and other tasks. It is a complex unit, composed of many stakeholders. It is possible that this is not the best conflict management scheme for reducing relationship conflict and increasing task conflict. In some cases, managers may consider upgrading conflict management by upgrading team leaders' political skills. Effective leadership practices help minimize the negative role of relationship conflict and maximize the positive role of task conflict.

Finally, attention should be paid to the training of political skills in team leadership. The implementation and development of green strategies in green enterprises require strong leadership. Team leaders play an important role in promoting orderly team management, alleviating negative team conflicts, creating a positive team work atmosphere, and improving team performance. To improve the level of team conflict management and team performance, the political skills training of team leaders must be strengthened.

5.3. Limitations and Opportunities for Future Research. There were some limitations in this study. First, the theoretical model and empirical testing were applied only at two levels, those of the team and individual. However, a team is a multilayer nesting system whose organization may play an important role in team conflict management and performance improvement. Studying the mechanism and effects of team conflict management using a three-level model will be of great significance. Second, the sample of this paper was concentrated on green enterprises, so the conclusions may have had some limitations in terms of its universality and generalizability. In future research, we hope to investigate other industries to improve the external validity of the results and create management suggestions that are more practical and instructive. Third, due to the limitations of the research goal and the length of the paper, the relationships among the multiple variables involved in the theoretical model of this study were not examined. For example, team

task conflict may have had a certain impact on team relationship conflict, which should be investigated in future research. This factor would likely not fundamentally alter the findings in the current study; it should be incorporated in future research to improve the accuracy of the findings.

Data Availability

Empirical data were collected from 85 dyads of leaders and team members in 36 green enterprises in China. The questionnaire data used to support the findings of this study are included within the supplementary information files. Anyone who wants to get the data can contact the corresponding author at e-mail: eric_zhang@hnu.edu.cn.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Supplementary Materials

The supplementary files consist of data at two different levels in the same green enterprises. Data at team level is composed of four main variables and two control variables. TRC means team relationship conflict and TTC means team task conflict, which are the independent variables at team level; LPS means leader political skills and TP means team performance, which denote the moderating variable and dependent variable at team level, respectively. Team type and team size are both control variables at team level. Data at individual level is composed of one main variable and three control variables. IP means individual performance, which denotes the dependent variable at individual level. Gender, tenure, and education are all control variables at individual level. In order to establish a one-to-one relationship, we put a number on each team and individual. (*Supplementary Materials*)

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Research Article

The Evolution and Determinants of Interorganizational Coinvention Networks in New Energy Vehicles: Evidence from Shenzhen, China

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With the increasing attention to climate change, air pollution, and related public health issues, China's new energy vehicles (NEVs) industry has developed rapidly. However, few studies investigated the evolution of interorganizational collaborative innovation networks in the sector domain of NEVs and the influence of different drivers on the establishment of innovation relationships. In this context, this paper uses the joint invention patent of Shenzhen, a low-carbon pilot city of China, to investigate the dynamics of network influencing factors. The social network analysis shows that the scale of coinvention network of NEVs is constantly increasing, which is featured with diversified cooperative entities, and collaboration depth (i.e., the intensity of the interactions with these partners) is also expanding. The empirical results from the Exponential Random Graph Model (ERGM) demonstrate that, with the deepening of collaborative innovation, technological upgrading caused by knowledge exchange makes organizations in the network more inclined to cognitive proximity and less dependent on geographical proximity. In addition, organizational proximity and triadic closure contribute positively to the collaborative network, with their relevance remaining nearly the same, while the impeding effect of cultural/language difference is slightly decreasing with time.

1. Introduction

The promotion and development of new energy vehicles (NEVs) is not only a strategic choice to reduce emissions containing atmospheric pollutants, but also an inevitable need for the development of a low-carbon economy [1–3]. Many countries have released preferable policies to support their application such as free vehicle plates, governmental subsidies, rapid development of charging stations, and cheaper insurance fees [4]. The development of China's NEVs industry began in the early twenty-first century. Since the launch of the “863” major electric vehicle project in 2001, the national and local governments have constantly introduced relevant policies to promote the development of NEVs. In 2010, the NEVs industry was listed in China's

seven strategic emerging industries. In the “13th five-year plan for the development of strategic emerging industries” issued by the State Council in 2016, it pointed out to cultivate green and low-carbon industries such as NEVs into pillar industries. A series of policies reveal that China's NEVs industry is facing unprecedented opportunities.

As a representative of the emerging industry, NEVs adopt emerging technologies and the core of their industrial competitiveness depends on technological innovation [5, 6]. Due to the complexity of technology and the high cost and uncertainty of innovation, innovation subjects are gradually shifting from independent research and development (R&D) to cooperative innovation, so as to realize the sharing of innovation resources, cost reduction, and risk diversification [7]. As the main carrier of the transformation of scientific

and technological achievements in the process of cooperative innovation, patent application, to a large extent, represents the innovation ability of a firm's R&D capacity. A large amount of literature has explored patent cooperation in the high-tech industry. Lei et al. [8] studied the overall situation of patent cooperation of Taiener battery by elaborating three different types of cooperation, and the changing trend of cooperation mode. Omelianenko [9] analyzed the necessity of establishing diplomatic relations and mutual relations between clusters and further proposed that international partnership development between clusters is the most appropriate form for developing cooperation between high-tech sectors.

With the acceleration of network research, the collaborative innovation network of high technology has attracted extensive attention. Choe et al. [10] studied the structure and characteristics of knowledge flow among countries, institutions, and technologies in the field of organic photovoltaic cells. Zheng et al. [11] analyzed the development of international cooperation in nanotechnology by using a patent network. Sun and Liu [12] established a multilayer network model of intraregional and interregional joint patent research and applied the model to China context. De Paulo et al. [13] studied photovoltaic technology patents and cooperation according to the structure and interaction among national clusters. Generally, studies on the outline of these collaborative research networks, especially at the interorganizational level, remain few and far between.

With regard to the development of the electric vehicle industry, several studies focus on patents and technological innovation for NEVs. For instance, taking Japan as an example, Ahman [14] discussed the relationship of government policy and the development path of the electric vehicle. Based on a comparative analysis of the entire invention patents and joint patents, Wang and Zhu [15] examined patents development in China's NEVs industry from the perspective of industry-university-institute cooperation. Christensen [16] argued that sharing components of power transmission systems, such as battery power systems, hybrid power, and fuel systems, is of great help to implement the modular strategy. However, most of the existing research on patents of NEVs industry address the technology development trend [17] and the driving forces of industrial development [18, 19]. Notable exceptions in this respect included and the studies of Sun et al. [20] studied the characteristics of patent cooperation network based on the top 38 organizations with the most NEV-related patents as research objects, and the study of Cao et al. [21] established technological cooperation innovation network and analyzed the invincibility and optimization process of the network. The role of proximity in favoring the transmission of knowledge in innovation and interorganizational networks has also received increasing attention recently [22–27]. Despite this, existing studies find little evidence about the evolution of geographical or nongeographical factors in the formation of such networks [28].

The aim of this study is to investigate the impact of the different relationships between partners for the establishment of innovation linkages in Shenzhen's NEVs industry.

This paper expands the existing literature on two aspects. First, it explores the evolutionary path of topological structure and spatial patterns of interorganizational innovative collaboration in NEVs industry. Second, in contrast to most literature on a static or certain type of influential factors [29, 30], the paper provides an explanation for the evolutionary mechanism of interorganizational innovative networks. For this purpose, we analyze the determining factors employing the Exponential Random Graph Model (ERGM) which can combine the endogenous structures and the exogenous factors [31]. Hence, we could distinguish between different types of determinants to confirm how the significance and magnitude of the influential factors change.

In particular, Shenzhen is chosen as the study area to inspect and analyze interorganizational coinvention network of NEVs. In an attempt to promote the implementation of China's greenhouse gas emissions control target, Shenzhen was offered as the pilot low-carbon city in 2010 and has reduced carbon emissions by more than 200,000 tones annually due to the implementation of low-carbon transportation and construction projects [32]. In addition, the local government has set up a special fund for the development of NEVs industry since low-carbon city construction, making the focal area an archetypal location for interorganizational coinvention network of NEVs research.

The remainder of the paper is structured as follows: Section 2 discusses the theoretical foundation of potential determinants of interorganizational knowledge collaboration and formulates several hypotheses. Section 3 describes the data collection followed by introducing the theoretical network model. Network characteristic evolution based on respective network indicators is presented in Section 4, while, in Section 5, we report and interpret the empirical results; and the final section concludes the paper.

2. Research Hypotheses

In this work, we mainly focus on four commonly identified types of geographical and nongeographical proximity in the development of NEVs networks, including geographical, cognitive, organizational, and cultural factors.

Geographical proximity indicates the degree of proximity of spatial distance between enterprises, and it is regarded as a prerequisite for enterprises in a cluster to pursue knowledge externality [33]. On the one hand, geographical proximity reduces the cost of transportation and communication between enterprises, thereby facilitating the transfer and learning of tacit knowledge. On the other hand, it provides opportunities for frequent face-to-face communication among enterprises and helps to enhance mutual trust and understanding among enterprises, especially for highly skilled workers [34]. However, despite the tendency for spatial agglomeration of innovation activities, the number of interregional R&D collaborations has increased markedly as well [35, 36]. They believe that permanent colocation within a cluster is not necessary, and the excessive proximity of partners will bring certain negative effects such as lock-in, a situation in which inventors successively create

technologies of the same type, industrial structures [37]. In the early stage of the development of NEVs coinvention network, companies benefit from geographical proximity in space and conduct extensive short-distance collaborations [38]. With the continuous development of technology and industry, cooperation between companies is not limited to proximity in space. Long-distance collaboration is often more valuable and involves the exchange of knowledge in high-level technological fields. Therefore, we test the following hypothesis.

Hypothesis 1. Geographical distances impede upon research collaboration between Shenzhen and other cities, and the effect is diminishing over time in importance.

Cognitive proximity is a particularly important element for promoting innovation. Coinvention requires an appropriate capacity to absorb new knowledge, which requires the establishment of a homogeneous cognitive basis [39]. Neither very small nor large cognitive distances result in good outputs and learning effects in the interactions [40]. On the one hand, the development of new technology is more and more based on the combination of remote technological fields [41], as it helps generate new knowledge and radical innovations and avoid cognitive lock-in. On the other hand, the amount of knowledge grows exponentially. Even with intensive and interdisciplinary education, the proportion of everyone in the overall knowledge is declining, so it is necessary to work with collaborators who have minor cognitive distance [42]. In the embryonic development period of NEVs industry, most enterprises are making exploratory attempts. Firms and other organizations primarily form ties with other actors that share the same knowledge base and competencies since establishing relations between different knowledge bases are more difficult. For these reasons, we assume the increased specialization outweighs the increased interdisciplinarity in the innovative collaboration of NEVs and state.

Hypothesis 2. The positive relationship of cognitive proximity, with the probability of a coinvention link between two organizations, remains stable over time.

Organizational proximity refers to rules and procedures that connect enterprises to the same organizational framework, reflecting the degree of sharing of relationships within and between organizations [31]. Similar rules and incentive mechanisms among enterprises help to manage knowledge exchange and reduce transaction costs. In addition, organizations need strong control mechanisms to ensure their ownership of new technologies and adequate returns. However, excessive organizational proximity may also limit interactive learning and flexibility between organizations. Based on the constraints of the same organizational framework, the possibility of establishing cooperative relations between parent corporations and subsidiaries is much higher than that of general enterprises. Therefore, we will test the following hypothesis.

Hypothesis 3. Organizational proximity plays an important role in the establishment of innovative collaborations

between organizations, and its importance remains stable over time.

Apart from the above proximity affecting coinvention activities, the transmission of knowledge is easier when individuals and companies share a common language and similar cultural and religious values [39]. Regarded as informal institutional proximity, cultural/linguistic proximity can increase trust and lower transactions costs, assisting in the generation and diffusion of collaborative ideas.

In China, regional dialects are quite prevailing in their respective areas and act as an important factor of cultural identity [43, 44]. The complexity of Chinese dialects is parallel in many respects with the Roman family in Europe [45]. Different linguistic areas are therefore supposed to intensify the fragmentation of the research networks between Shenzhen and other cities. However, as both the Chinese central government and the local government in Shenzhen have promulgated a set of policies aiming to strengthen the position of Shenzhen as a national scientific center and knowledge linkages to the globe, Shenzhen has established branches of many renowned URIs at the national and global scale, such as Peking University, Harbin Institute of Technology, and Moscow State University. In addition, it has launched its “Peacock Plan” in 2011 to attract overseas talent to work in the city. We assume that these projects could facilitate cultural proximity in the long run. Hence, we will test the following hypothesis.

Hypothesis 4. The negative relationship of cultural/linguistic differences with the probability of a coinvention link between two organizations decreases over time.

3. Data and Methodology

3.1. Data. Through the patent information inquiry system of China National Intellectual Property Administration, the paper takes the applicant’s address and the new energy vehicle keywords as the screening conditions and uses custom *Python* scripts designed to crawl the specific coinvention patent data whose at least one of the coinventors is located at Shenzhen from 2006 to 2017. The new energy vehicle keywords include electric vehicles, new energy, new energy vehicles, charging piles, hybrid, intelligent vehicles, new energy batteries, electronic controls, automobile motors, and automobile safety. The paper has extracted 1351 NEVs coinvention patent data involving 2 or more inventors in the study period.

3.2. Methods

3.2.1. Network Index

(1) *Network Density.* Network density reflects the overall connectivity level by dividing the number of actual ties by the number of maximum possible ties. A higher network density means a higher degree of connectivity between node cities in the network. Using V_1 to denote the number of

actual ties in the network with N cities, network density D_N can be expressed as

$$D_N = \frac{V_1}{(N \times (N - 1)/2)}. \quad (1)$$

(2) *Centrality*. Centrality measures the importance of a node city in the network. Although there are as many as thirty centrality indicators, the degree of centrality is considered to be the indicator that most directly reflects the location of the node network by focusing on the number of ties an organization has [46, 47]. In equation (2), C_i denote the degree centrality of organization i and l_{ij} denote the ties from organization i to organization j :

$$C_i = \frac{\sum_{j=1, j \neq i}^N l_{ij}}{(N - 1)}. \quad (2)$$

Eigenvector centrality is to find the node with the most central position on the basis of the overall network structure. Its basic principle is to identify the dimension of the distance between network nodes. Each node has a position on each dimension, which is an eigenvalue, and all eigenvalue sets are eigenvectors.

3.2.2. The ERGM Specification. ERGM is a statistical model to analyze the factors affecting network formation [48]. By abstracting and modeling social networks, ERGM can express the influence of network links and character attributes on social networks. The main advantage of ERGM lies in its capacity to analyze the dependence among nodes on the formation of a network [49].

The specification of ERGM can be set as

$$\Pr(Y = y) = \left(\frac{1}{k}\right) \exp \left\{ \sum_A \eta_A g_A(y) \right\}, \quad (3)$$

where A denotes all possible network configurations and η_A is its corresponding parameter; $g_A(y) = \prod_{(i,j) \in A} y_{ij}$ represents the network statistic corresponding configuration which obtains a value of 1 when it is observed in y . k is a normalizing constant which ensures the distribution of equation (3).

Another advantage of ERGM is that it can simultaneously consider structural network level factors, as well as node and dyad level factors, which correspond to the three parts of the network configuration [50]. The general form of ERGM that includes the three kinds of factors can be specified as follows:

$$\Pr(Y = y) = \left(\frac{1}{k}\right) \exp \{ \eta_\alpha g_\alpha(y) + \eta_\beta g_\beta(y) + \eta_\gamma g_\gamma(y) \}. \quad (4)$$

The parameters (α, β, γ) signify the significance and importance of selected factors. The estimation of the parameters is done with the Markov Chain Monte Carlo method using R software.

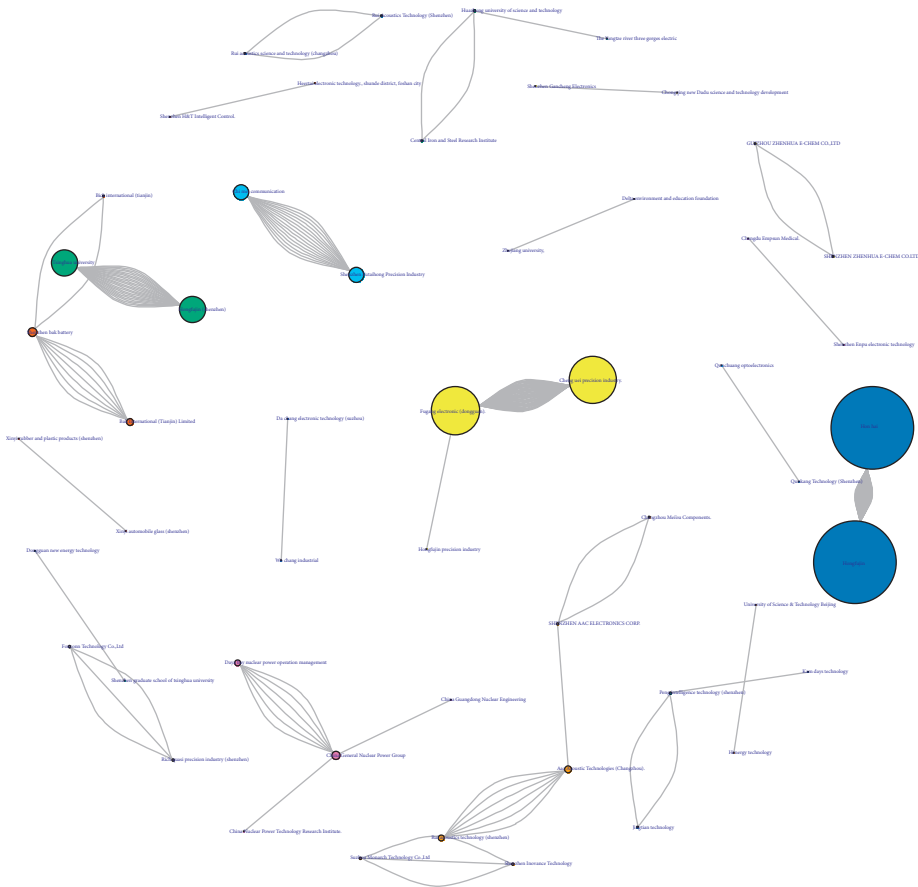
4. The Network Characteristic and Evolutionary Pattern

4.1. Structural Evolution Analysis. To illustrate the dynamics of the collaborative network, we divide the sample into three periods of roughly equal length: 2006–2009, 2010–2013, and 2014–2017. In addition, R software is used to draw the topology evolution diagram of the collaboration network. As shown in Figure 1, the connection line represents the cooperative relationship between the patent applicants in the coinvention network of NEVs. The larger node suggests the more collaborators it has, and the thicker the connection line, the more frequent cooperation between the nodes.

In the first period, from 2006 to 2009, the network is in the initial stage of formation and the amount of patent cooperation is relatively small. With the development of NEVs industry, universities and enterprises begin to exchange knowledge, technology, and resources and gradually develop a cooperative relationship with each other. At this stage, patent cooperation mainly occurs between enterprises. For example, Hongfujin Precision Industry (Shenzhen) Co., Ltd. establishes a stable partnership with HonHi Precision Industry. Fugang Electronic (Dongguan) Co., Ltd. and Cheng Uei Precision Industry Co., Ltd. are also frequent collaborators.

The cooperative network develops into the expansion stage during the period of 2010–2013, reflecting an increasing number of organizations carrying out collaborative innovation activities carry out innovative activities. It is notable that cooperation between universities and enterprises is on the rise, which entails the frequent flow of knowledge, technology, and other resources in the network. For instance, Tsinghua University and Hongfujin Precision Industry (Shenzhen) Co., Ltd. establishes a close cooperative relationship and conducts exchanges, which weakens the limitation of spatial distance on knowledge transmission. In addition, Tsinghua University occupies a relatively central position in the cooperative network. This shows that universities represented by Tsinghua University possess critical knowledge resources, which plays an important role in promoting the evolution of the coinvention network for NEVs.

In the first two stages, the networks are relatively sparse. From the third period, however, the network begins to develop towards multipolarization. In the meanwhile, the partnerships between the nodes of the cooperative network have also been established substantially. Among the nodes, Dongguan Tafel New Energy Technology Co., Ltd. and Shenzhen Tafel New Energy Technology Co., Ltd. have established a constant and close relationship with each other and also maintain cooperation with multiple nodes. Moreover, Tsinghua University is still in the dominant position of the network for the diffusion of R&D related resources. It signifies that Shenzhen has reinforced the exchange of knowledge between different geographical regions.



(a)

FIGURE 1: Continued

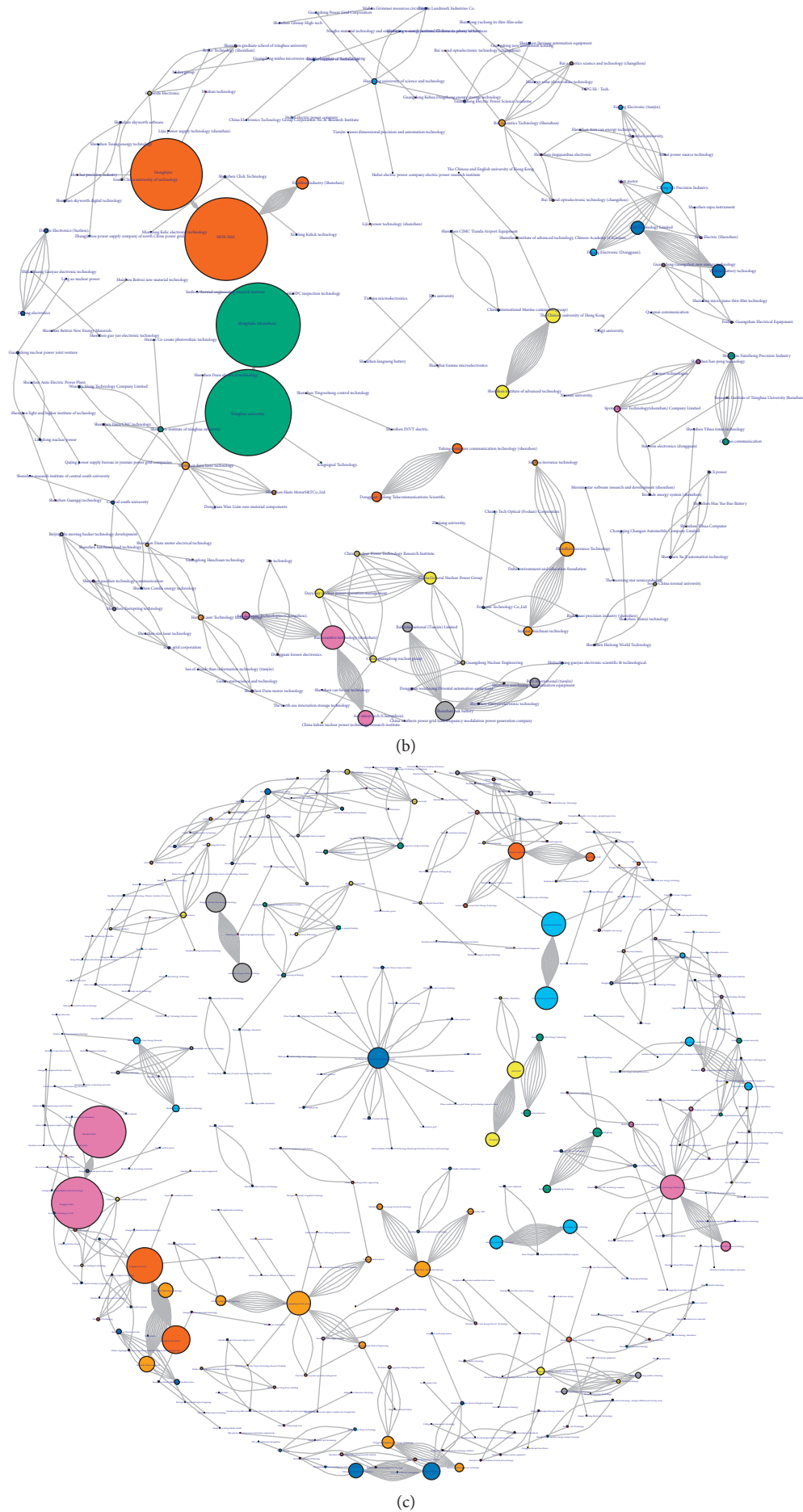


FIGURE 1: Topological evolution of NEVs coinvention network. (a) 2006–2009, (b) 2010–2013, (c) 2014–2017.

4.2. Network Structure Analysis. We show the evolutionary process of the interorganizational coinvention network of NEVs by calculating multiple network indicators to illustrate the structural characteristics of the overall network, which is depicted in Table 1.

Network size means the number of organizations participating in the interorganizational network. As shown in Table 1, with the gradual development of NEVs coinvention activities, the network scale is expanding enormously. The number of nodes in the network increases from 52 in period 2006–2009 to 285 in period 2014–2017, and the network scale expands nearly 5 times. Network edges refer to the total number of relationships generated by the cooperation between nodes. As depicted in the above table, similar to network size, the number of network edges increases substantially, suggesting a continuously growing trend of the establishment of cooperative relationship in the network.

Network density reflects the overall connectivity level by dividing the number of actual ties by the number of maximum possible ties. A higher network density means a higher degree of connectivity between node cities in the network. As shown in Table 1, the increase speed of the network edge number is less than the expansion speed of the network scale, resulting in the decline of the network density from 0.0128 in the first stage to 0.0024 in the third stage. This reveals that the relationship between innovation entities is not particularly close.

Network diameter is the length of the largest geodesic path in the network. The smaller network diameter indicates that the cooperative network has higher transmission performance and efficiency. The average path length is the average value of the geodesic path length between any pair of nodes in the network. It can be observed that the cooperative network has a small average path length, and this indicator fluctuates between 1.1 and 1.3 over these three stages, indicating that cooperation and interaction between innovative organizations of the NEVs coinvention network are relatively frequent.

Average weighting is the average weighted value of all nodes. The value of this indicator is declining constantly over the whole period. The network's average clustering coefficient is the average of the clustering coefficients for all of the nodes. The small value of this indicator means that there are still some obstacles to establish cooperative relations between adjacent nodes. The common evaluation standard for the quality of community detection is the maximization of a benefit function called network modularity Q ; when Q approaches 1, the community connectivity of a given network is strong. Remarkably, modularity increases from 0.713 in the first stage to 0.965, and the value is continuously increasing in the past decade. This shows that Shenzhen's NEVs coinvention network is becoming more advanced and complex.

In order to further analyze the evolution of key nodes in Shenzhen's NEVs coinvention network, we use degree centrality and eigenvector centrality to reflect the importance of nodes in the network structure. The results are listed in Table 2.

It can be seen from Table 2 that, in the first stage, enterprises occupy the core position of Shenzhen's NEVs coinvention network. Hongfujin Precision Industry (Shenzhen) Co., Ltd. has the highest degree of degree centrality and eigenvector centrality. It signifies that Hongfujin Precision Industry (Shenzhen) Co., Ltd. has the most patent cooperation with other nodes in the NEVs field and is the center of knowledge diffusion in the network.

In the second stage, the degree centrality and eigenvector centrality of Tsinghua University is increasing, which indicates that it has become another important node in the network. In addition, Hongfujin Precision Industry (Shenzhen) Co., Ltd. is still a key node in the cooperative network with strong control ability. It has the largest number of partners and some nodes connected with it are also important nodes in the network, which means that there are more resources such as knowledge and information at its disposal.

For the 2006–2017 period, Tsinghua University is in a relatively central position, whereas Hongfujin Precision Industry (Shenzhen) Co., Ltd.'s position in the coinvention network is declining. In addition, it can be observed that in the third stage, Dongguan Tafel New Energy Technology Co., Ltd. and Shenzhen Tafel New Energy Technology Co., Ltd. also occupy the core positions. They have established close cooperative relations and carried out patent collaborations frequently. It signifies that Shenzhen has strengthened its geographical proximity with organizations within and beyond the city.

5. Evolution of Determinants of Coinvention Network

5.1. ERGM Specification. Links(dependent variable) is given by the absolute number of connections in the node. This variable is constructed from the total number of collaborations between institutions a and b during the process of technological production, in which the patent application has more than one inventor.

In order to verify the four hypotheses proposed in this paper about how coinvention networks evolve, the following variables are given as follows:

- (1) Geographical distance is measured as the logarithm of the physical distance between two organizations. This variable is introduced to test Hypothesis 1.
- (2) Cognitive proximity is computed based on institutions' technology profiles. Each firm and organization's technology profile has been classified based on its IPC codes. The cognitive proximity between two institutions is obtained by calculating Pearson's correlation coefficients between their technology vectors, after which the values are min–max scaled. Two institutions with the highest similarity in technology profiles have a value equal to 1, while the two institutions with the most different technology profiles have a value equal to 0. This estimate is applied to test Hypothesis 2.

TABLE 1: Topological structure indicators of NEVs coinvention network.

| Periods | Network size | Number of edges | Network density | Network diameter | Average path length | Average weighting degree | Average clustering coefficient | Modularity |
|-----------|--------------|-----------------|-----------------|------------------|---------------------|--------------------------|--------------------------------|------------|
| 2006–2009 | 52 | 215 | 0.0128 | 2 | 1.15 | 8.27 | 0 | 0.7130 |
| 2010–2013 | 154 | 470 | 0.0045 | 3 | 1.24 | 6.10 | 0 | 0.8140 |
| 2014–2017 | 285 | 657 | 0.0024 | 3 | 1.16 | 4.61 | 0.0396 | 0.9655 |

TABLE 2: Key nodes of the NEVs coinvention network.

| Periods | The name of the node | |
|-------------------------|---|---|
| | Sorted by degree centrality | Sorted by eigenvector centrality |
| Phase one (2006–2009) | Hongfujin Precision Industry (Shenzhen) Co., Ltd. | Hongfujin Precision Industry (Shenzhen) Co., Ltd. |
| | Hon Hi Precision Industry Co., Ltd. | Hon hi Precision Industry Co., Ltd. |
| | Cheng Uei Precision Industry Co., Ltd. | Tsinghua University |
| | Fugang Electronic (Dongguan) Co., Ltd. | Cheng Uei Precision Industry Co., Ltd. |
| | Tsinghua University | Chi Mei Communication Co., Ltd. |
| Phase two (2010–2013) | Hongfujin Precision Industry (Shenzhen) Co., Ltd. | Hongfujin Precision Industry (Shenzhen) Co., Ltd. |
| | Tsinghua University | Tsinghua University |
| | Hon Hi Precision Industry Co., Ltd. | Hon Hi Precision Industry Co., Ltd. |
| | Rui Acoustics Technology (Shenzhen) Co., Ltd. | Futaihua Industry (Shenzhen) Co., Ltd. |
| | Rui Aoustics Science and Technology (Changzhou) Co., Ltd. | Huahan Technology Co., Ltd. |
| Phase three (2014–2017) | Dongguan Tafel New Energy Technology Co., Ltd. | Dongguan Tafel New Energy Technology Co., Ltd. |
| | Shenzhen Tafel New Energy Technology Co., Ltd. | Shenzhen Tafel New Energy Technology Co., Ltd. |
| | Hongfujin Precision Industry (Shenzhen) Co., Ltd. | Hongfujin Precision Industry (Shenzhen) Co., Ltd. |
| | Tsinghua University | Tsinghua University |
| | Han's Laser Technology Industry Group Co., Ltd. | Han's Laser Technology Industry Group Co., Ltd. |

(3) Organizational proximity is usually measured by two methods. The first one is whether enterprises belong to the same group company or parent company, that is, constrained by organizational structure and hierarchy [29]. The second measurement is by the degree of similar routine and incentive mechanism among enterprises [51]. Considering the limited number of cooperation between scientific research institutes in the NEVs industry and the amount number of cooperation between the parent company and its subsidiaries, head office, and branch company, we use the first method to construct the organizational proximity matrix. If two organizations belong to the parent-subsidiary relationship or are between the head office and the branch company, the value is 1; otherwise, it is 0. This variable is introduced to test Hypothesis 3.

(4) Linguistic difference is set up to measure the cultural differences. This variable for cultural/linguistic difference is set to 1 when two institutions are located in different dialect areas. The partition of dialect areas of China is indexed from the 2010 Atlas of Chinese Dialects [52].

Other variables are also included in the ERGM analysis. Firmscale represents the size of firms, which is measured by the organizations' number of employees. Larger firms may be more likely to be tied to other organizations. Uniscale represents the size of universities, which is measured by the number of students in the school.

The above variables are categorized into three types following ERGM specification: Firmscale and Uniscale are node covariates. Geographical distance, Cognitive proximity, Linguistic difference, and organizational proximity are exogenous relational covariates. Mutual and Edges are an endogenous structure.

5.2. ERGM Results. The results of ERGM from 2006 to 2017 are presented in Table 3. Geographical distance is found to exhibit statistically negative impacts over the whole period and shows a decreasing effect. These results corroborate Hypothesis 1, signifying that geographical proximity plays an increasingly weaker role in the evolution of the collaborative network. In the meantime, with the deepening of collaborative innovation, the technological upgrading caused by knowledge exchange makes the organizations in the network more inclined to cognitive proximity and less dependent on geographical proximity. A possible explanation is that due to the construction of high-speed railways and airports since 2010, Shenzhen has strengthened its geographical proximity with cities within and beyond Guangdong province. Figure 1 also shows, in the second and third stage of the innovation network, that Rui Acoustics Technology (Shenzhen) Co., Ltd. has carried out extensive cooperation with Aac Microtech (Changzhou). Big companies such as Hongfujin Precision Industry (Shenzhen) Co., Ltd. have also established partnerships with Tsinghua University.

Concerning cognitive proximity, we find a positive overall trend, suggesting that closer cognitive base and

TABLE 3: Cross-sectional ERGM results for interorganization coinvention network from 2006 to 2017.

| | Dependent variable | | |
|--------------------------------|----------------------|----------------------|----------------------|
| | 2006–2009 (1) | 2010–2013 (2) | 2014–2017 (3) |
| Edges | −1.820*** (0.045) | −3.098*** (0.068) | −3.269*** (0.098) |
| Mutual | 4.773*** (0.084) | 4.503*** (0.065) | 5.369*** (0.075) |
| Firmscale | 0.001*** (0.0003) | 0.011*** (0.001) | 0.005** (0.002) |
| Uniscale | 0.018*** (0.005) | 0.028*** (0.006) | 0.036*** (0.004) |
| Cognitive proximity | 0.082*** (0.002) | 0.091*** (0.001) | 0.109*** (0.001) |
| Geographical distance | −0.182*** (0.005) | −0.090*** (0.004) | −0.061*** (0.005) |
| Organizational proximity | 0.086*** (0.020) | 0.146*** (0.025) | 0.100*** (0.031) |
| Cultural/linguistic difference | −0.050*** (0.008) | −0.025*** (0.007) | −0.023*** (0.008) |
| Akaike Inf. Crit. | 34,743.710 | 46,832.720 | 40,778.240 |
| Bayesian Inf. Crit. | 34,891.500 | 46,980.520 | 40,926.030 |

***, **, and * represent significance at the levels of 1%, 5%, and 10%, respectively.

values generate more links among the inventors of different organizations. In other words, it appears that increasing specialization outweighs interdisciplinarity, confirming Hypothesis 2. It demonstrates that the trend goes rather towards specialization in the NEVs coinvention activities in Shenzhen. This result is consistent with Broekel and Boschma's [23] investigation in the Dutch aviation industry and also corroborates the majority of literature that they do not find a change in the negative impact of cognitive distance over time on a global or national scale [42]. It is worth noting that, in recent years, as a result of the construction of high-speed railways and airports, as well as the establishment of cross-city branches of many renowned universities and research institutes (URIs), the strengthening of geographical proximity of Shenzhen with other cities has also facilitated cognitive proximity, such as knowledge interactions between researchers from different URIs.

With regard to organizational proximity, it is positively associated with the intensity of interorganizational scientific collaboration, indicating that there are many collaborations between parent and subsidiary companies or subsidiaries in NEVs coinvention network, such as Shenzhen Tafel New Energy Technology Co., Ltd. and Dongguan Tafel New Energy Technology Co., Ltd. This result corroborates Broekel and Boschma's [23] empirical result that organizational proximity is a driver behind the formation of knowledge network relationships. Therefore, Hypothesis 3 is supported.

In terms of dialect, similar to geographical distance, the impeding effect of cultural/linguistic difference is statistically significant and loses slight importance over time, providing evidence for Hypothesis 4. On the one hand, long-distance collaboration is often more valuable and involves the exchange of knowledge in high-level technological fields. Teixeira et al.'s [53] research demonstrated that projects that are more technologically advanced are geographically

distant and culturally diversified, while those close to each other are inherently low tech. On the other hand, cultural difference is to some extent complemented by the increasing number of overseas returnees who have gained their degrees in foreign universities.

For node-level variables, the coefficients of *Firmscale* and *Uniscale* stay positive and significant over time, meaning that firms with larger size are prone to have more links as anticipated. The same applies to big universities. Besides, the significant coefficients of *Edge* and *Mutual* at the level of structural networks empirically confirm the correlation at this level. The negative coefficient of *Edges* is a common feature of social processes established networks, indicating that such networks exhibit less density than exponential random networks. Besides, the coefficient of *Mutual* is also positive and significant. It means that organizations tend to form connections with patterners that have similar degree centrality values. The result also indicates that triadic closure is a driving force in promoting the evolution of the inter-organization coinvention networks.

6. Conclusion and Discussion

In order to study the structure and evolution of interorganizational scientific collaborations in the NEVs, this paper uses the coinvention data of Shenzhen, China, to construct the coinvention network of NEVs. The evolution pattern of coinvention activities from 2006 to 2017 is analyzed by using social network analysis. Then, we test our proposed evolutionary hypothesis with ERGM to investigate the dynamics of network influencing factors. The main conclusions of this paper are as follows.

First, the scale of coinvention network keeps expanding, and the cooperation depth between nodes has remarkably improved, which is featured with diversified cooperative entities. In addition, geographical distance shows a

statistically negative but diminishing effect over the whole period. The ERGM results confirm our hypothesis that geographic proximity plays a weaker role in the evolution of cooperative networks. In the meanwhile, with regard to cognitive proximity, it presents a positive overall trend, indicating that closer cognitive bases and values generate more connections between inventors in different organizations. It demonstrates that, with the deepening of collaborative innovation, technological upgrading caused by knowledge exchange makes organizations in the network more inclined to cognitive proximity and less dependent on geographical proximity, which is consistent with most of the existing studies. Due to the construction of high-speed railways and airports, as well as the establishment of cross-city branches of many famous universities and research institutions (URIs), the reduction of Shenzhen's travel time to other cities also promotes cognitive proximity.

Secondly, in terms of organizational proximity, it is positively correlated with the intensity of interorganizational scientific cooperation. As far as dialects are concerned, similar to geographical distances, the impeding effect of cultural/linguistic differences is statistically significant and has declined slightly in importance over time. Moreover, cultural differences are to some extent complemented by a growing number of returnees from overseas who have earned degrees at foreign universities. In addition, the result indicates that triadic closure is a driving force in promoting the evolution of the interorganizational coinvention networks.

For policy implications, firstly, the potential cooperation between innovation organizations in the field of NEVs needs to be fully explored. The establishment of a technology information sharing platform and the design of a cooperation innovation incentive mechanism would effectively shorten the technological distance and improve the efficiency of information transmission. Secondly, infrastructures that facilitate the flow of people and information, such as transportation and telecommunications, should be improved to facilitate the dissemination of technological information and the exchange of innovative talents, which would help expand the industrial clusters of cross-regional coinvention activities in Shenzhen's NEVs, especially for the industry-university-research collaborations. Thirdly, as the market share of NEVs continues to expand, the government should support technology opening and patent sharing, so as to further stimulate joint innovation vitality.

In terms of extension work, analysis on the level of individuals would help answer mechanisms behind the organizational-level network patterns. Nevertheless, our research provides a valuable explanation of the evolutionary mechanisms of knowledge cooperation activities among organizations in new energy technologies. The study of Shenzhen would also be of great interest in developing international comparisons within the same industry to be able to generalize more results of the work.

Data Availability

The data will be made available upon request to the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Jia liu and Zhaohui Chong's contributions include the study design, data analysis and writing. Shijian Lu participated in the revision of the article.

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Research Article

Theory and Realization of Secondary Task Assignment for Multi-UAV Pickup Based on Green Scheduling

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The development of artificial intelligence technology has brought changes to various industries. Under the concept of green sustainable development, how to use the progress of science and technology to implement low-carbon strategies is a problem that every enterprise should consider. Aiming at the problem of picking up goods in logistics industry, this paper proposed a secondary task assignment theory for multiple unmanned aerial vehicle (Multi-UAV) based on green scheduling. The theory greatly improves the utilization rate of unmanned aerial vehicle (UAV) and reduces the energy consumption. We analyzed the advantages and disadvantages of local optimal algorithm and global optimal algorithm in time and energy consumption. Through repeated experiments in different ranges, we have well verified the high efficiency and general applicability of this theory, which can provide theoretical and practical implications for logistics enterprises using UAV to achieve low-carbon sustainable development in the future.

1. Introduction

While the rapid economic development has brought convenience to the world, the environmental problems are becoming increasingly serious. In the past century, the frequency of major natural disasters and diseases has increased from 0.263 times per year from 1920 to 1999 to 1.2 times per year from 2000 to 2020 [1]. Severe environmental problems have posed challenges for the survival and development of mankind. In 2015, the United Nations Sustainable Development Summit was held in New York. Seventeen sustainable development goals were set to solve the problems between social development, economic growth, and the environment.

A feasible solution to the environmental challenge is to realize low-carbon sustainable development. The low-carbon development strategies of enterprises are the key link to achieve green sustainable development. This requires enterprises to have green supply chain management [2]. With the rapid development of the Internet, e-commerce is gradually replacing the traditional entity business model, which also

drives the rapid development of the logistics industry. At the same time, the development of artificial intelligence technology has also brought changes to various fields. Due to the advantages of low cost and high efficiency, more and more unmanned equipment is used to complete various tasks instead of human beings. In the military field, unmanned aerial vehicle (UAV) is widely used in security patrol [3], area detection [4], target strike [5], etc. In the manufacturing industry, intelligent machines realize the automatic production of factories [6]. In the medical field, intelligent machines are used for some high-precision operations [7]. In the logistics industry, intelligent machines are mainly used to replace the traditional manned transportation mode [8]. Especially in the context of the outbreak of Novel Coronavirus this year, the use of intelligent machines to achieve contactless pickup is even more important.

Due to the complexity of ground environmental factors, it is a hot spot to use UAV to pick up goods instead of truck or in a combined way [9]. Compared with the complex constraints of ground operations, there are relatively fewer restrictions in the air. So UAV can complete the

transportation task with less time, closer distance, and lower energy consumption.

In the actual transportation, UAV group and goods constitute a huge information system. The collaborative control of UAV group is an extremely complex process. This is mainly reflected in the following:

- (i) Diversity of UAV: due to the differences in the size of each pickup location, homogeneous UAV system has great limitations in task assignment, and different types of heterogeneous UAV system make the task assignment more complex.
- (ii) Complexity of constraints: each UAV has the maximum loading weight and volume. The weight and volume of the goods at each pickup location are also different, so the correspondence between UAV and goods is a complex optimization problem.
- (iii) Computational complexity: with the increase of the number of UAV and goods, the amount of calculation for searching the optimal solution increases exponentially.
- (iv) Environmental complexity: complex terrain and bad weather will have a great impact in UAV transportation.
- (v) Complexity of communication: with the increase of the number of pickup locations and UAV and the expansion of transportation range, the burden of communication among the UAV group will also increase.

Under the influence of the above factors, the realization of multiple unmanned aerial vehicle (Multi-UAV) cooperative transportation is a very complex subject, which has also caused extensive research at home and abroad.

In order to solve the problem of limited capacity of UAV, a receding horizon task assignment heuristic algorithm [10] was proposed to achieve persistent UAV delivery schedules. Ren et al. [11] proposed four transport modes of vehicle cooperating with UAV. Reference [12] integrated the scalable K -means algorithm and genetic algorithm to realize a UAV scheduling strategy including reverse logistics. Reference [13] proposed a mixed-integer (0-1 linear) green routing model to reduce transportation cost and carbon dioxide emission.

At present, using UAV to pickup and delivery is still in an initial experimental stage, and there are not many relevant theories of task assignment. In addition, most references about the cooperative of Multi-UAV are based on one-time task assignment. In terms of the difficulty of secondary assignment, the objective function and constraints of the first and second task assignment models are different. As we need to redistribute the UAV which still has the ability to perform tasks after the first assignment, the constraints and logical relationship of the second assignment model are more complex, and the design and realization of the algorithm are more difficult. So there are a few studies on secondary assignment which is exactly the key point of this paper. The redistribution of UAV can make full use of its loading capacity, reduce energy consumption, and realize low-carbon operation.

We established a complete set of Multi-UAV pickup theory. According to the total weight and volume of the goods, we determine the initial minimum number of UAV. The first task assignment order is determined according to the fitness between the pickup location and UAV. For unassigned locations, we proposed two algorithms based on local optimal and global optimal, respectively, and compared the advantages and disadvantages in distance and time. Through a large number of experiments in five different task area radiuses, we verified the general applicability of the theory.

We organize the paper as follows. Section 2 introduces the concept of UAV mission planning, centralized control structure and corresponding algorithm, green scheduling theory, and secondary assignment theory. The first assignment theory based on fitness and the second assignment theory based on local optimal and global optimal are proposed in Section 3. Then, Section 4 shows the calculated results of different algorithms and the analysis. Finally, we summarize the research content of this paper and put forward some suggestions and prospects for future researches in Section 5.

2. Basic Theory

UAV task planning is to plan path or assign target for UAV according to the types of tasks, the characteristics of UAV, or the resources carried by UAV. The core is to maximize the total revenue of the UAV group, minimize the task time, or minimize the energy consumption under all kinds of constraints. With the increasing complexity of tasks, we often need to weight multiple objective functions to make the task optimal as a whole [14].

In the logistics system, UAV task planning can be divided into pickup tasks and delivery tasks according to the types of tasks. With the improvement of intelligent system, UAV may need to pick up and deliver goods at the same time in future transportation. According to the real-time performance of UAV tasks, task planning can be divided into dynamic planning and static planning. Dynamic planning [15] needs to consider the real-time changes of information and makes adjustments in time to ensure that the task planning is optimal within a certain time. Static planning is to make the optimal transportation scheme according to the information of current nodes. It is usually used in the case of stable environment and less influence of uncertain factors. According to the control structure of UAV group, it can be divided into centralized control structure and distributed control structure. In different task systems, the optimal control type should be selected according to the characteristics of the task. The Multi-UAV pickup theory that we proposed in this paper adopted centralized control structure.

2.1. Centralized Control Structure. Centralized control structure means that there is only one central controller. Each UAV only inputs and outputs data, so the cost of UAV is relatively low. After analysis and calculation, the central controller sends the decision to each UAV for execution, as

shown in Figure 1. Centralized control structure solves the problem from a global perspective, which can produce a global optimal solution. Different from the distributed control structure, which needs to solve the problem of data consistency, the centralized control structure does not need to consider the coordination problem between nodes. However, as the scale of transportation increases, the computational load increases significantly. As it has only a single central controller, when it breaks down, the entire system will be paralyzed.

Commonly used centralized task assignment models include Multiple Traveling Salesman Problem [16], Vehicle Routing Problems [17], and Mixed-Integer Linear Programming [18]. The algorithms used for solving these models mainly include genetic algorithm and particle swarm algorithm.

2.1.1. Traditional Algorithm. Genetic algorithm is a random search algorithm proposed by Holland [19], which is evolved from the evolutionary rules of nature. Because of its intelligence, parallelism, and good global search ability, it is widely used in optimization and combination, machine learning, and other fields. Many improved genetic algorithms have been proposed to overcome the shortcomings of local convergence or nonconvergence of genetic algorithm. Reference [20, 21] solved the multiobjective task assignment of UAV through improved genetic algorithm.

Inspired by the behavior of bird swarm, Eberhart and Kennedy [22] proposed particle swarm optimization (PSO). It is similar to genetic algorithm, which also seeks the optimal solution through iteration. But PSO does not need crossover or variation; it obtains the optimal solution through the self-adjustment of particles to the optimal solution. Compared with genetic algorithm, PSO is simpler and more likely to converge to the optimal solution faster. The flow chart of PSO is shown in Figure 2.

2.1.2. The Proposed Algorithm. In this paper, the algorithm that we used to solve the secondary task assignment of Multi-UAV is based on some ideas of PSO. We considered every UAV as a particle. By calculating the fitness between UAV and pickup locations, the optimal assignment scheme under the current state was determined. Then, we updated the UAV status information and fitness to determine the next task until all pickup locations were assigned. Different from PSO, the calculation of the optimal solution of our algorithm is the superposition of the optimal solution of each subtask.

2.2. Green Scheduling. Green scheduling is a kind of green and low-carbon task assignment theory under the background of green logistics policy [23], aiming to reduce the harm to the environment as much as possible under the premise of completing the transportation task. It improves transportation efficiency and reduces cost and energy consumption by making full use of carrying capacity, assigning task objectives reasonably, optimizing task path

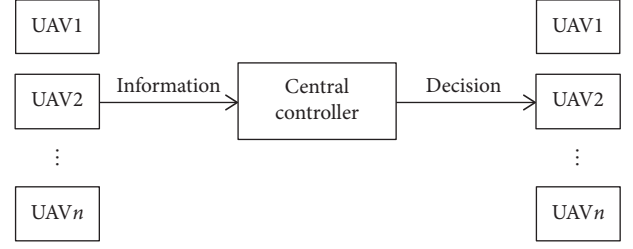


FIGURE 1: Centralized control structure.

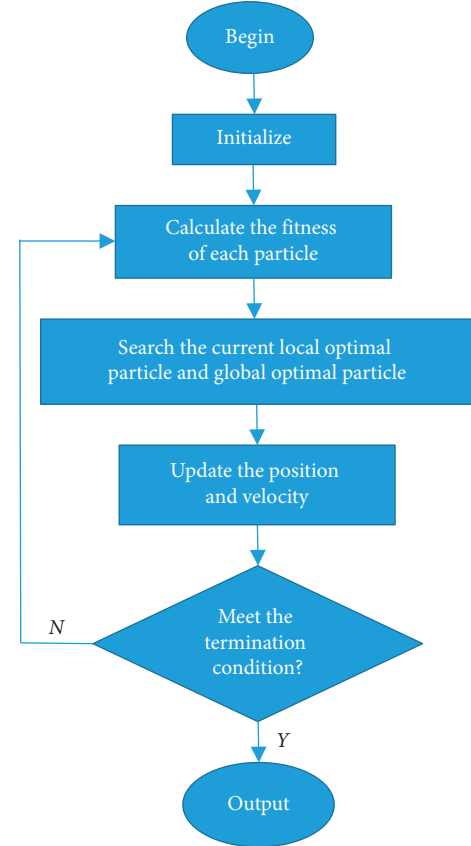


FIGURE 2: Flow chart of PSO.

[24], and many other methods. A good UAV assignment model can assign tasks more reasonably and reduce the flight time and distance of UAV. Using secondary assignment can make full use of the carrying capacity of each UAV and reduce the total number of UAVs, finally achieving low-carbon sustainable development.

2.3. Secondary Assignment Theory. In the UAV task assignment system, when the number of UAV is more than the total number of tasks, all tasks can be assigned only once. This will lead to excess performance, that the capability of each UAV is not fully utilized. In the actual task, the number of UAV dispatched is often less than the number of task targets. In this case, we need to select UAV that has completed the first mission and meet the constraints for secondary task assignment. Through redistribution, we can

reduce the total number of UAV, maximize the utilization of each UAV, and achieve green task assignment.

3. Multi-UAV Pickup Theory Based on Green Scheduling

This paper mainly studies the application of green scheduling theory in the pickup problem of transportation system. In the UAV pickup system, the fewer the UAV completing the pickup task in a shorter path, the less the energy consumption and exhaust emission. Suppose that there are s pickup locations. The j th location has a_j goods, and each piece of goods has weight w_{jn} and volume v_{jn} , $n = 1, 2, \dots, a_j$. We send homogeneous UAV from the warehouse to pick up the goods. Set w_{\max} as the maximum loading weight and v_{\max} as the maximum loading volume.

The Multi-UAV pickup theory proposed in this paper combines the idea of green scheduling and the theory of secondary task assignment, aiming to dispatch the least UAV to complete the pickup task. In the process of secondary assignment, we use both local optimal algorithm and global optimal algorithm to explore the shortest time and shortest distance of task execution.

3.1. Determine the Initial Number of UAV. By calculating the total weight and volume of the goods at each pickup location, we obtain the goods information matrix X . Set u as the initial number of UAV. It should make the total weight and volume of the UAV group exceed the total weight and volume of all goods. It can be expressed as the following mathematical model:

$$\begin{aligned} & \min u, \\ & \text{s.t.} \begin{cases} uw_{\max} \geq \sum_{j=1}^s X_{1j}, uv_{\max} \geq \sum_{j=1}^s X_{2j}, \end{cases} \end{aligned} \quad (1)$$

where u is an integer and X_{1j} and X_{2j} represent the total weight and volume of all goods at the j^{th} pickup point, respectively.

3.2. The First Task Assignment. Formula (1) only gives the minimum number of UAV that can complete the pickup task in theory. As the UAV will not be fully loaded in the actual situation, the initial u UAVs cannot be spread over s pickup locations at the same time. Set f as the fitness between the pickup location and UAV. It is calculated by the proportion of the goods in the UAV's maximum carrying capacity, including weight fitness f_w and volume fitness f_v . We assign tasks from large to small according to f .

Set $\varepsilon_w, \varepsilon_v$ as the minimum weight proportion and the minimum volume proportion of the goods in the UAV's carrying capacity. When the remaining capacity of UAV is less than this ratio, we say that the utilization rate of UAV has reached the upper limit. In order to minimize the secondary assignment of UAV, we give priority to the pickup location with the highest utilization rate of UAV, which means

$$f_w > 1 - \varepsilon_w, \quad (2)$$

or

$$f_v > 1 - \varepsilon_v. \quad (3)$$

The remaining pickup locations will be assigned according to f , if there are still UAVs available. The flow chart of the first task assignment is shown in Figure 3 and the pseudo-code is shown in Algorithm 1.

This assignment mode can maximize the utilization rate of UAV in the first task, reduce the number of times of UAV picking up goods at different locations, and reduce the energy consumption of UAV flying between each location.

3.3. The Second Task Assignment. When the number of locations is more than the number of UAVs, one-time assignment cannot meet the whole task. In this case, we need to make a secondary assignment for the remaining locations according to f . In order to improve the utilization rate of UAV, we redistributed the UAV that still had the ability to perform other tasks after the first assignment. For a specific task, we would give priority to the UAV that has been dispatched. When more than one UAV can complete the task, we choose the optimal assignment scheme by comparing the time and distance. A new UAV will be dispatched from the warehouse only when there is no UAV available.

In the first task assignment, all UAVs are located in the warehouse, so the distance from the pickup location is the same. We only need to consider the size of f of each pickup location. After the first assignment, the position of each UAV will be different, which makes the distance between UAV and the unassigned location different. In this case, if we only consider the size of f , it may appear that the task will be assigned to the UAV far away from the task location. This will reduce the efficiency of the whole UAV group. Therefore, we need to select the UAV with the shortest flight distance from all the UAVs that can complete the pickup task.

3.3.1. Local Optimal Algorithm. For the unassigned pickup location k , we set R_k as its quantity of goods. The remaining carrying capacity of UAV i after the first task assignment is set as I_i . If

$$I_i \geq R_k, \quad (4)$$

we say that UAV i can complete the pickup task of location k . For all the UAVs that can complete the pickup task, we calculate the distance between each UAV and location k and then select the shortest path to assign the task. When no UAV is available or needs to be called from two or more locations, we directly assign a new UAV q from the warehouse to perform the task and add its remaining carrying capacity I_q to the total UAV information list I . The flow chart of the second task assignment based on the local optimal algorithm is shown in Figure 4 and the pseudo-code is shown in Algorithm 2.

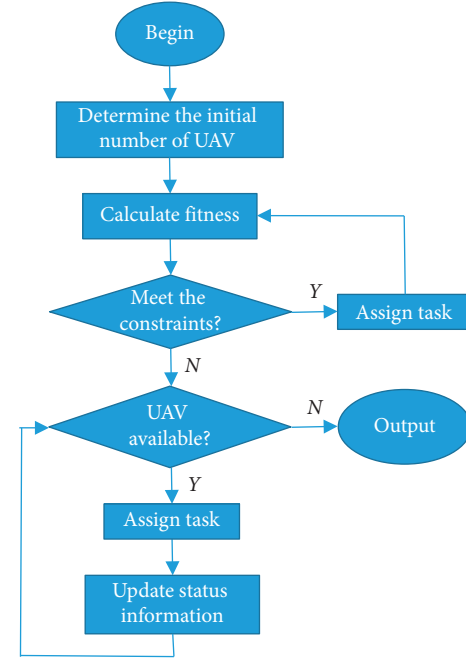


FIGURE 3: Flow chart of the first task assignment.

Input: Goods information matrix X , maximum loading weight w_{\max} , maximum loading volume v_{\max} .

- (1) Initialize u_1, b, j ,
- (2) Calculate initial number of UAV u , fitness matrix f , minimum weight proportion ε_w , minimum volume proportion ε_v , UAV for each location A ;
- (3) $u_1 = u$;
- (4) **for** $j = 1$ to s
- (5) **if** $f_{1j} \geq 1 - \varepsilon_w \parallel f_{2j} \geq 1 - \varepsilon_v$
- (6) Send UAV to location j ;
- (7) Update u_1 and f ;
- (8) **end**
- (9) **end**
- (10) **while** $u_1 \sim = 0$
- (11) Finding the column c where the largest element is located in f ;
- (12) **if** $u_1 > A_c$
- (13) Send UAV to location c ;
- (14) Update u_1 and f ;
- (15) $b = b + 1$;
- (16) **end**
- (17) **if** $b \geq s$
- (18) **break**
- (19) **end**
- (20) **end**

Output: The first assignment matrix L .

ALGORITHM 1: The pseudo-code of the first task assignment.

3.3.2. Global Optimal Algorithm. The distance obtained by the above algorithm is optimal only in the process of secondary task assignment; it may not reach the global optimization in the whole UAV pickup task. This is because the unassigned pickup location may be around the return route of UAV. If selected from these UAVs to carry out the pickup task, although it may increase the time for the entire UAV

group to complete the task, it will shorten the total flight distance of the UAV group. The global optimal algorithm not only considers the distance between UAV and unassigned location but also considers the impact on other UAVs in path planning when the task is assigned to a UAV. The global optimal algorithm selects the UAV which makes the total distance of the UAV group the shortest.

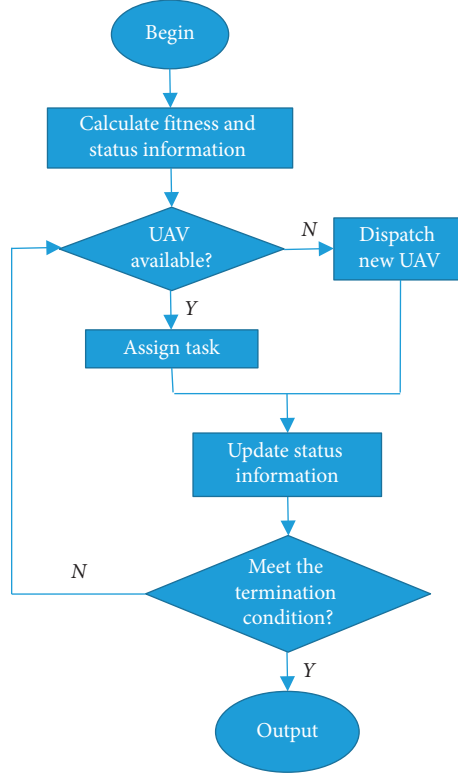


FIGURE 4: Flow chart of the second task assignment.

Input: Fitness matrix f , goods surplus $X1$, UAV payload surplus $X2$, number of locations s , location coordinate matrix P .

- (1) **while** $f \sim = 0$
 - (2) Finding the column c where the largest element is located in f ;
 - (3) $f_{1c} = f_{2c} = 0$;
 - (4) **for** $j = 1$ to s
 - (5) **if** $X1_{1j} \geq X1_{1c} \& X2_{2j} \geq X2_{2c}$
 - (6) Calculate the assignment matrix D ;
 - (7) **end**
 - (8) **end**
 - (9) **if** column c of D is not all zero
 - (10) Finding the column d where the minimum element is located in D , $D1_{dc} = 1$;
 - (11) **else**
 - (12) Dispatch new UAV;
 - (13) **end**
 - (14) **end**
- Output:** Secondary assignment matrix $D1$.

ALGORITHM 2: The pseudo-code of the second task assignment.

4. Experiments and Analysis

The experiment consists of three parts. Firstly, determine the initial number of UAV according to the total quantity of goods. Secondly, carry out the first task assignment according to the size of f . Finally, use the local optimal algorithm and global optimal algorithm, respectively, to carry out the second task assignment for the unassigned locations.

Set the warehouse as the center of a circle. We consider homogeneous UAV to pick up at 8 locations randomly

generated in the circle with radius $R = 1$ km. Set $w_{\max} = 10$ kg, $v_{\max} = 60$ dm³. The parameters of all goods at each pickup location are shown in Table 1. According to Table 1, we can calculate the total amount of goods of each pickup location, as shown in Table 2.

From formula (1), we get $u = 7$. It can be calculated from Table 2 that $\varepsilon_w = 0.0730$, $\varepsilon_v = 0.0567$. The fitness matrix f of each pickup location is shown in Table 3.

We can see from Table 3 that locations 1, 4, and 6 satisfy the constraints of formula (2) or (3). The number of UAVs

TABLE 1: The parameters of all goods.

| Location | Goods | | | | | | | |
|----------|-------|-------|-------|-------|------|-------|-------|------|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1 | 4.01 | 0.75 | 12.39 | 1.57 | 0.99 | — | — | — |
| | 3.22 | 2.67 | 33.81 | 9.22 | 6.17 | — | — | — |
| 2 | 1.02 | 1.32 | 0.3 | 1.1 | 0.46 | 0.35 | 1.56 | — |
| | 12.11 | 7.57 | 2.57 | 5.63 | 3.78 | 4.51 | 2.69 | — |
| 3 | 0.78 | 0.91 | 0.32 | 0.4 | 0.58 | — | — | — |
| | 4.48 | 7.61 | 16.48 | 1.58 | 1.15 | — | — | — |
| 4 | 1.74 | 2.25 | 0.41 | 1.15 | — | — | — | — |
| | 16.69 | 17.69 | 8.34 | 15.66 | — | — | — | — |
| 5 | 2.54 | 0.88 | 1.43 | — | — | — | — | — |
| | 25.73 | 5.57 | 1.38 | — | — | — | — | — |
| 6 | 2.39 | 1.06 | 3.78 | 3.76 | 1.97 | 0.54 | 3.09 | 0.74 |
| | 17.23 | 18.12 | 10.29 | 7.23 | 9.89 | 13.14 | 35.55 | 3.69 |
| 7 | 0.64 | 0.82 | 1.01 | 0.31 | 0.43 | 0.44 | — | — |
| | 2.46 | 3.67 | 4.72 | 2.34 | 0.83 | 7.05 | — | — |
| 8 | 2.22 | 3.51 | 1.13 | — | — | — | — | — |
| | 3.5 | 13.76 | 7.63 | — | — | — | — | — |

Note: for every location, the first row represents the weight and the second row represents the volume.

TABLE 2: The total amount of goods of each pickup location.

| | Location | | | | | | | |
|---------------------------|----------|-------|-------|-------|-------|--------|-------|-------|
| Number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Weight (kg) | 19.71 | 6.11 | 2.99 | 5.55 | 4.85 | 17.33 | 3.65 | 6.86 |
| Volume (dm ³) | 55.09 | 38.86 | 31.30 | 58.38 | 32.68 | 115.14 | 21.07 | 24.89 |

TABLE 3: Fitness matrix f .

| | Location | | | | | | | |
|--------|----------|--------|--------|--------|--------|--------|--------|--------|
| Number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| f_w | 0.9855 | 0.6110 | 0.2990 | 0.5550 | 0.4850 | 0.8665 | 0.3650 | 0.6860 |
| f_v | 0.9182 | 0.6477 | 0.5217 | 0.9730 | 0.5447 | 0.9595 | 0.3512 | 0.4148 |

that they needed is 2, 1, and 2, respectively. For the remaining two UAVs, we will assign them according to the size of f . That is, we assign location 8 first for its proportion of weight which is 0.6860 and then assign location 2 for its proportion of volume which is 0.6477. The first assignment matrix L is shown in Table 4. Seven UAVs are sent to locations 1, 2, 4, 6, and 8. The specific effect of the first task assignment is shown in Figure 5.

For secondary assignment, we calculate the goods surplus R_j ($j = 1, 2, \dots, s$) at each location and the payload surplus I_i ($i = 1, 2, \dots, s$) of each UAV, respectively, as shown in Tables 5 and 6. According to Table 3, the order of secondary task assignment is $5 \rightarrow 3 \rightarrow 7$.

For location 5, the remaining UAV carrying capacity cannot meet its demand, so we directly dispatch a new UAV 8 from the warehouse and add its remaining carrying capacity I_m to the total information list I so that the UAV can continue to participate in the subsequent task assignment. For locations 3 and 7, we select the UAV with the shortest distance from all the UAVs that satisfy the constraints. Based on the generated coordinates of 8 locations above, we use the global optimal algorithm to calculate the total time and total

TABLE 4: The first assignment matrix L .

| | Location | | | | | | | |
|--------|----------|---|---|---|---|---|---|---|
| Number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| UAV | 2 | 1 | 0 | 1 | 0 | 2 | 0 | 1 |

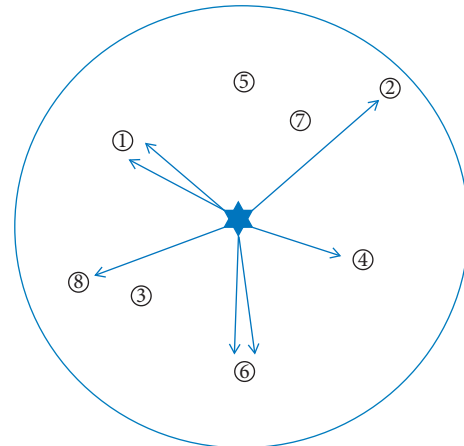


FIGURE 5: The effect of the first task assignment.

TABLE 5: Goods surplus.

| | Location | | | | | | | |
|---------------------------|----------|---|-------|---|-------|---|-------|---|
| Number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Weight (kg) | 0 | 0 | 2.99 | 0 | 4.85 | 0 | 3.65 | 0 |
| Volume (dm ³) | 0 | 0 | 31.30 | 0 | 32.68 | 0 | 21.07 | 0 |

TABLE 6: UAV payload surplus.

| | Location | | | | | | | |
|---------------------------|----------|-------|---|------|---|------|---|-------|
| Number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Weight (kg) | 0.29 | 3.89 | 0 | 4.45 | 0 | 2.67 | 0 | 3.14 |
| Volume (dm ³) | 64.91 | 21.14 | 0 | 1.62 | 0 | 4.86 | 0 | 35.11 |

TABLE 7: Comparison of two algorithms.

| | Local optimal algorithm | Global optimal algorithm |
|---------------|-------------------------|--------------------------|
| Time (min) | 4.5049 | 6.2503 |
| Distance (km) | 10.5244 | 10.4409 |

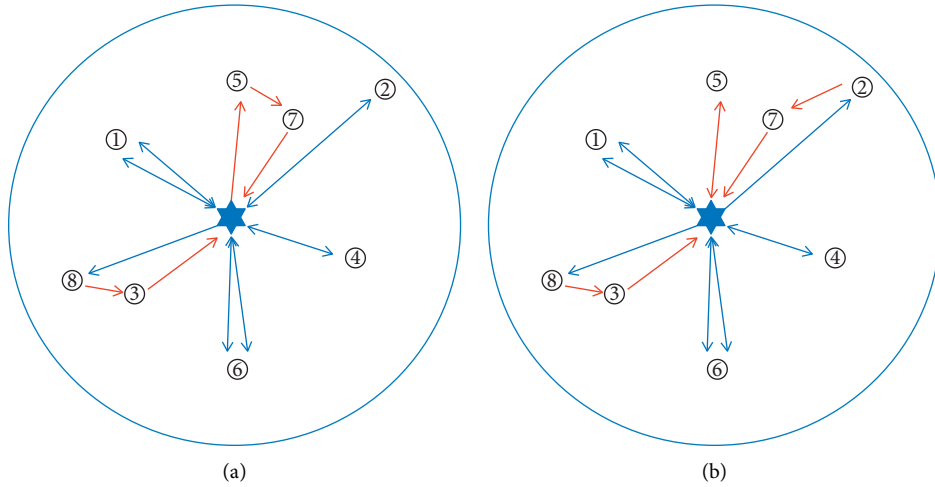


FIGURE 6: The effect of two algorithms: (a) local optimal algorithm and (b) global optimal algorithm.

distance of the UAV group. The comparison with the local optimal algorithm is shown in Table 7 and Figure 6.

Due to the randomness of the coordinate of each pickup location, we repeat the above experiment 100 times to compare the advantages and disadvantages of the local optimal algorithm and the global optimal algorithm under more general conditions, as shown in Figure 7. We can see that the local optimal algorithm focuses on minimizing the task time of the UAV group, while the global optimal algorithm focuses on minimizing the total flight distance of the UAV group. This is because the local optimal algorithm considers the shortest flight path of a single UAV. The total time of UAV group depends on the UAV with the longest task time, in other words, the UAV with the longest flight path. The local optimal algorithm is optimizing from the perspective of a single UAV, which can shorten the longest

path of one UAV and increase the total distance of the whole UAV group. On the contrary, the global optimal algorithm is optimizing from the perspective of the whole UAV group. The distance of a single UAV may increase, but the flight distance of the whole UAV group will decrease.

In order to verify the universal applicability of the algorithm, we also simulate in a larger circle with $R = 2, 3, 4, 5$ km, respectively. The results are shown in Figures 8–11. We marked the maximum effect of the optimization and calculated the average values of different algorithms, as shown in Table 8.

We can see clearly that, in a variety of different ranges, the local optimal algorithm can always get the minimum task time and the global optimal algorithm gets the shortest flight distance. And with the increase of the range, the advantages of each algorithm become more and more obvious.

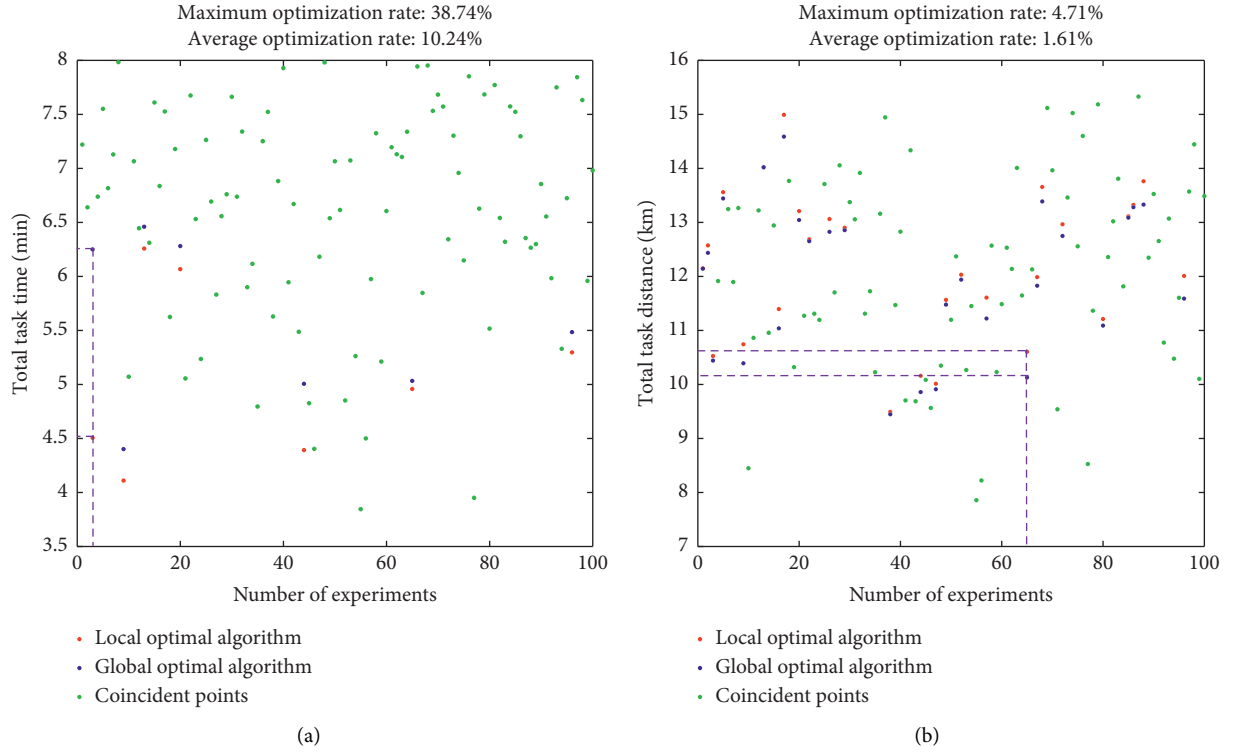


FIGURE 7: The results of two algorithms when $R = 1$ km: (a) total task time of two algorithms; (b) total task distance of two algorithms. Maximum optimization rate: 38.74%; maximum optimization rate: 4.71%.

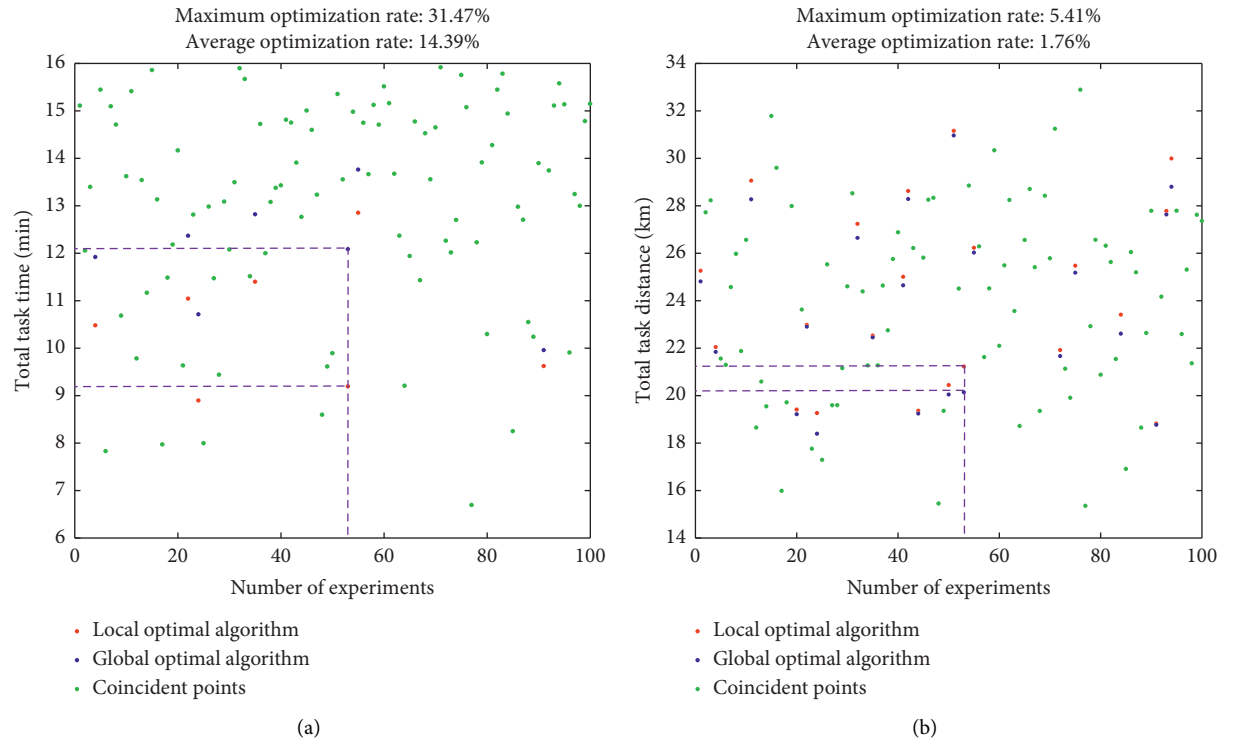


FIGURE 8: The results of two algorithms when $R = 2$ km: (a) total task time of two algorithms; (b) total task distance of two algorithms. Maximum optimization rate: 31.47%; maximum optimization rate: 5.41%.

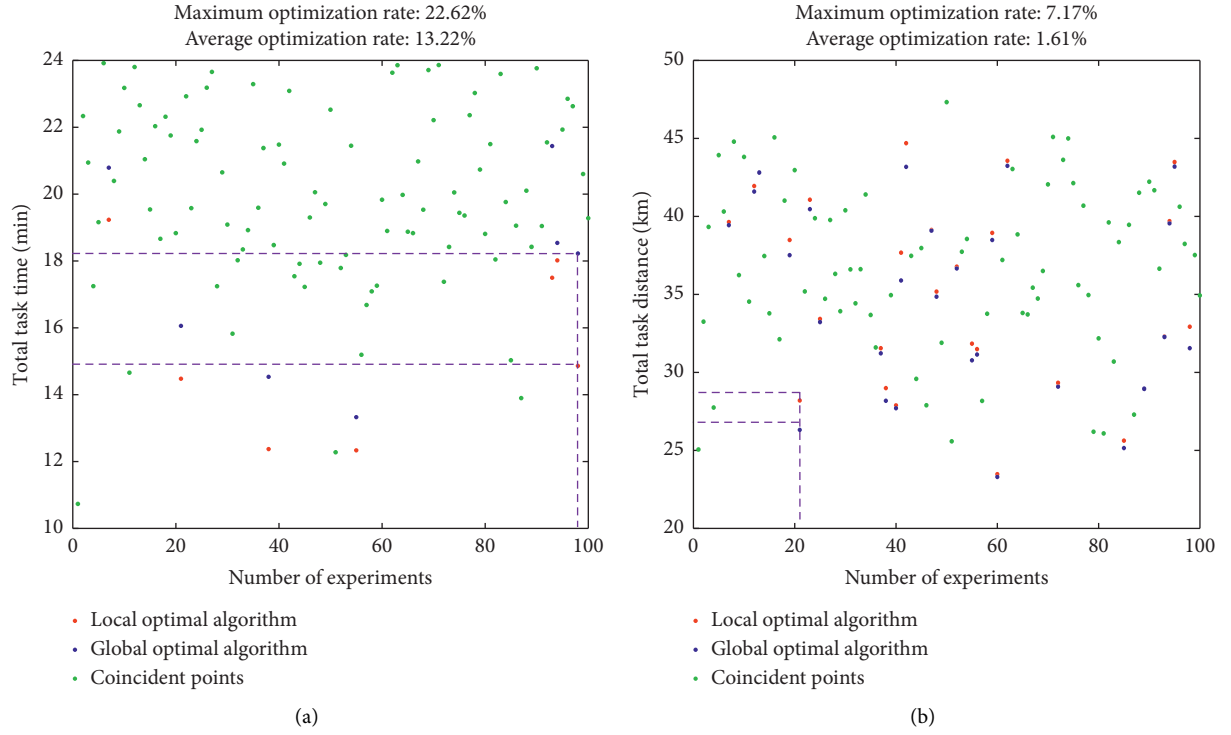


FIGURE 9: The results of two algorithms when $R = 3$ km: (a) total task time of two algorithms; (b) total task distance of two algorithms. Maximum optimization rate: 22.62%; maximum optimization rate: 7.17%

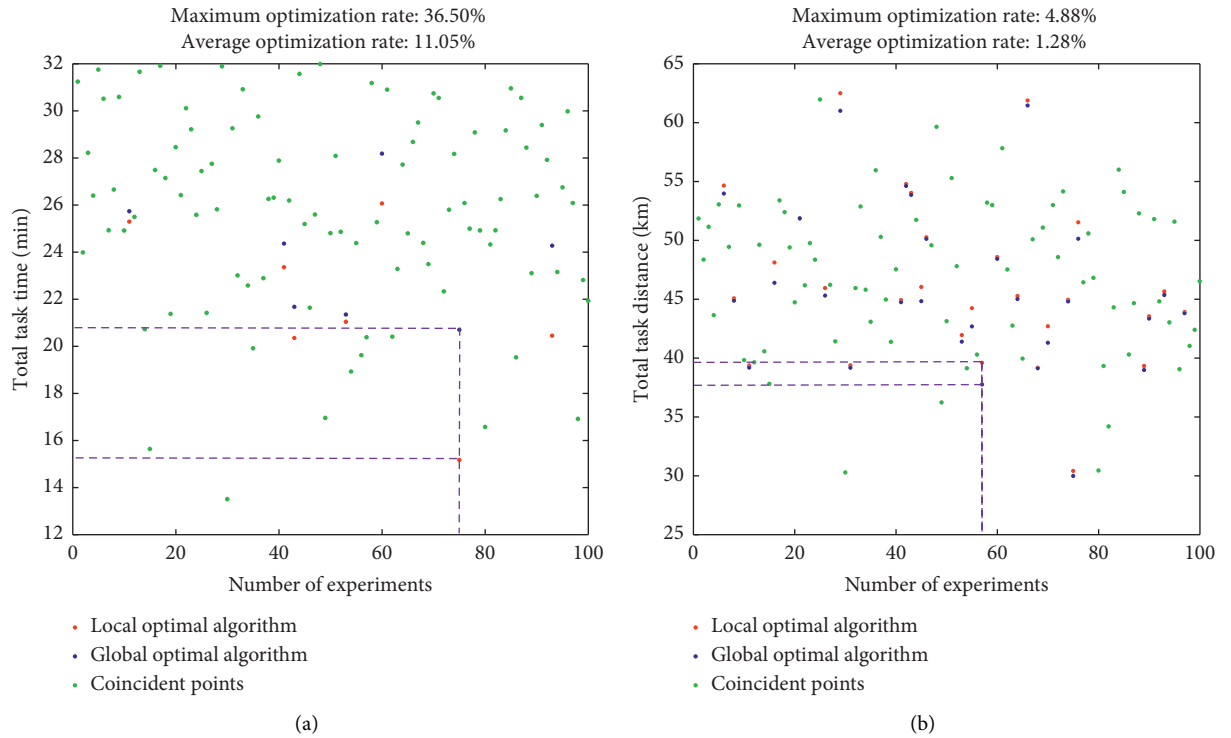


FIGURE 10: The results of two algorithms when $R = 4$ km: (a) total task time of two algorithms; (b) total task distance of two algorithms. Maximum optimization rate: 36.50%; maximum optimization rate: 4.88%.

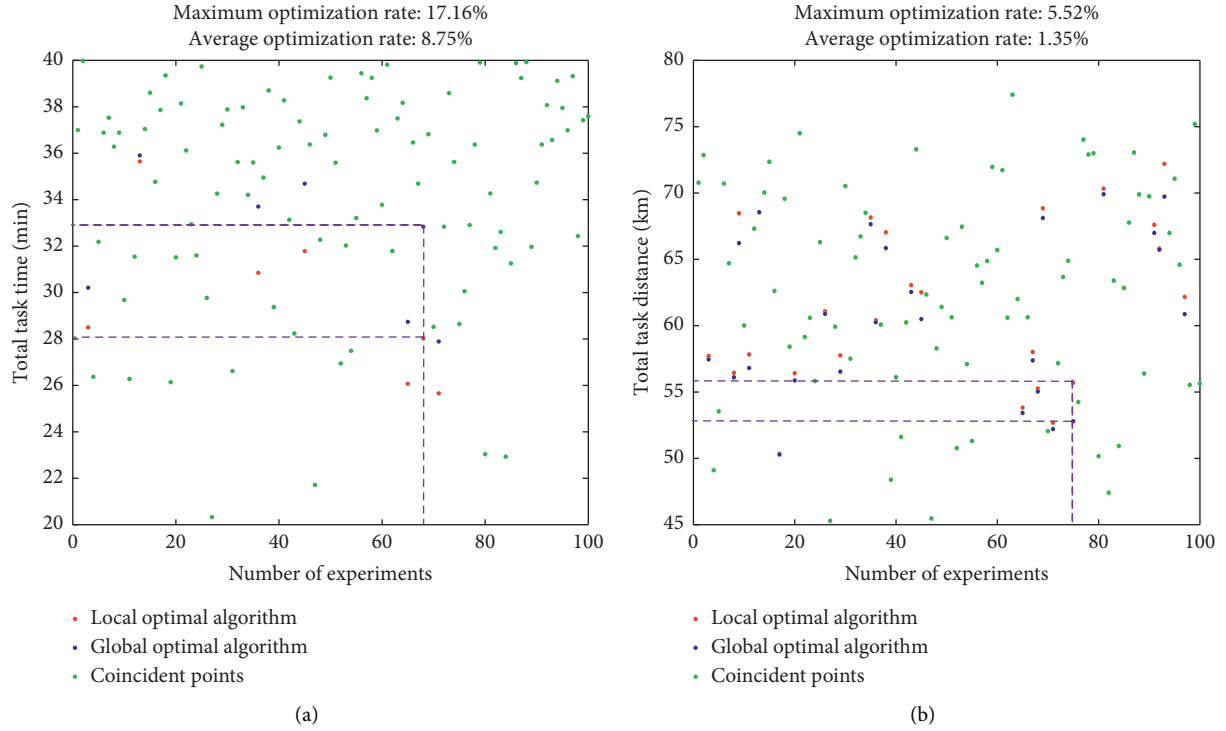


FIGURE 11: The results of two algorithms when $R = 5$ km: (a) total task time of two algorithms; (b) total task distance of two algorithms. Maximum optimization rate: 17.16%; maximum optimization rate: 5.52%.

TABLE 8: The average of the results of the two algorithms.

| | $R = 1$ km | | $R = 2$ km | | $R = 3$ km | | $R = 4$ km | | $R = 5$ km | |
|--------|---------------|------------|---------------|------------|---------------|------------|---------------|------------|---------------|------------|
| | Distance (km) | Time (min) | Distance (km) | Time (min) | Distance (km) | Time (min) | Distance (km) | Time (min) | Distance (km) | Time (min) |
| Local | 12.1281 | 6.5031 | 24.0385 | 12.8648 | 36.3274 | 19.6593 | 46.8312 | 25.5667 | 62.3682 | 34.0831 |
| Global | 12.0771 | 6.5364 | 23.9490 | 12.9662 | 36.1841 | 19.8004 | 46.6705 | 25.7123 | 62.1633 | 34.2576 |

5. Conclusion and Prospect

This paper proposed a set of secondary task assignment theory based on the idea of low-carbon and sustainability under the background of Multi-UAV pickup. By minimizing the number of UAV and minimizing the task time and the total distance, the energy consumption can be reduced as much as possible to achieve green scheduling.

The feasibility and universal applicability of the theory were well verified by a large number of simulations in many different situations. We compared the local optimal algorithm and the global optimal algorithm in detail and verified their advantages in time and distance, respectively. In the actual task assignment, managers can choose a more appropriate algorithm according to their own needs.

At present, the use of UAV for transportation is still in the stage of continuous exploration and improvement. Our theory of Multi-UAV secondary assignment has realized the green scheduling to a certain extent, but there are still the following main deficiencies:

- The UAV group is homogeneous. When there is a large difference in the quantity of goods among pickup locations, the homogeneous UAV group may not be able to meet the needs of the task.
- With the increase of the number of pickup locations and the amount of goods, whether the theory proposed in this paper can get good task assignment effect needs to be further verified.

Therefore, in the following research work, we plan to set up more pickup locations to verify the feasibility of this theory. We also consider a heterogeneous UAV system. Through the reasonable collocation of UAVs of different specifications, the utilization rate of the UAV group is further improved, the resource consumption is reduced, and the goal of low-carbon sustainable development is achieved.

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 with respect to the research and publication of this article.

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Research Article

New Models for Home Health Care under Uncertainty with Consideration of the Coordinated Development of Economy and Environment

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With the aggravation of population aging, home health care (HHC) services are paid more and more attention by the elderly. Previous studies aim at improving service quality and reducing cost, ignoring the coordinated and sustainable development of the economy and environment. From the perspective of sustainable development, this paper first establishes a linear optimization (LO) model considering transportation, time, and carbon emission costs. However, the uncertainty of service demand is a very difficult problem for HHC research. Most of the previous studies only consider the deterministic model, which has difficulty dealing with the uncertain situation. Therefore, a robust optimization (RO) model is proposed to resist uncertain disturbances by introducing a robust uncertain set response. The experimental results show that the increase of low-carbon transition cost only increases the total cost of the LO model but has a significant positive impact on the RO model. With the increase of uncertainty, the robust model will pay the cost of robustness, but it can obtain a higher service level (93.20% to 93.38%). In addition, when the carbon tax increases, the total transportation cost does not increase but decreases, thus obtaining environmental benefits. When the carbon tax increases by 25%, the average total cost of using the RO model is reduced by 8.274%. The research results of this paper can provide enlightenment and reference for the low-carbon transformation of HHC enterprises.

1. Introduction

The aging of the population has become a major problem restricting the development of the 21st century. As a new type of service, home health care is quietly changing people's lives. In the past, researches only focused on how to improve social welfare but ignored the coordinated development of environmental ecology. The concept of HHC first appeared in 1945 [1]. Later, with the passing of the times and the progress of technology, it gradually entered the life of ordinary residents [2]. HHC provides door-to-door services such as health care for people who are dependent and implements different types of care according to the needs of specific people [3]. Fikar and Hirsch (2017) divide the HHC

service into three steps, which are collecting information, formulating resource allocation, and path planning [4]. In the context of the two eras, the increasing aging of the population, and the substantial improvement in material life, the demand for HHC services is rapidly increasing. In recent years, the healthcare industry has become one of the largest economic sectors in Europe and North America [5]. Cho et al. (2018) found that the effective implementation of HHC work is of great help to improve the quality of people's life [6]. At present, HHC can be regarded as a supplementary form of public health under the auspices of the government. Through the door-to-door service, allowing the demanders to receive treatment at home can alleviate the resource shortage caused by the limited public health resources [7].

While people enjoy the convenient services brought by HHC, the increasing energy consumption and environmental pollution problems are becoming increasingly prominent. In recent years, environmental problems have become increasingly prominent, and greenhouse gas emissions have become more stringent. In the path planning problem, we must not only consider economic costs, but environmental costs are also an important factor that affects path selection. How to find a balance between economy and environment is worth exploring. At the strategic level, Wang et al. (2018) found that cooperative strategies can minimize carbon emissions and achieve green vehicle path planning [8]. Yu et al. (2019) proposed an improved branching and pricing algorithm to solve the routing problem of heterogeneous green fleet vehicles with time windows [9]. Bettinelli et al. (2019) studied the problem of urban double-layer logistics path planning and found that it is of positive significance to coordinate the arrival of facility vehicles and nursing staff with corresponding time constraints [10]. At the same time, HHC is also facing general problems and emerging challenges today. The most important goal of an HHC service company is to meet the needs of the demanders in a timely manner. During this process, two main operational problems are often encountered. One is the delay in service to the demanding personnel, and the other is the travel of the medical team routing problem. Of these two, the issue of time delay is particularly important, which not only punishes service providers but also may lead to more serious consequences for improper treatment of demanders. Therefore, while the operating platform is pursuing profits, how to effectively plan limited resources is the primary factor that needs to be considered for HHC [11]. It can be seen that the path planning of family medical and nursing services has become a key issue for service providers to reduce operating costs and improve service quality. In a fiercely competitive market environment, HHC companies of the traditional chain will face a severe impact from Internet informatization, especially today, with the growing development of technology and big data. HHC companies that operate on network platforms may become the main subject of industry [12, 13].

For the HHC service path planning problem, many scholars have used different theoretical methods to study operation options of nursing station selection and vehicle route allocation. In general, those two well-known operation options play a key role [14]. Shore (1999) explored a new world of health care by creating a health policy implementation plan [15]. Matteo (2000) constructed an empirical model of mixed determinants based on data from Canada's total health expenditure during the 1975–1996 decade and the usage of hospitals, doctors, and drugs [16].

Current research results on path planning can be divided into the following two categories, deterministic path planning models and uncertain path planning models. Moussavi et al. (2017) outlined how to carry out planning activities in the HHC structure, especially the route and arrangement of nursing staff, and pointed out that patients are the core of the decision-making system [14]. In terms of reality, at the same time, it is considered that the route and arrangement of

nursing staff are the basic problems in transportation planning during the path planning process. In the path planning stage, under normal circumstances, decision makers tend to consider relevant parameters as deterministic values [17]. Some scholars have conducted in-depth research on green logistics [18, 19]. However, in the actual market operating environment, even with the support of advanced network technologies such as big data and the Internet, some parameters are still unpredictable, such as specific demand, key parameters such as the customer's waiting time; uncontrollable factors, such as road conditions, weather conditions, and even emergency emergencies. Therefore, the deterministic path optimization model has difficulty in dealing with these unknown factors. The application of robust optimization can be used to deal with uncertainty [20, 21]. Since the robust optimization method does not depend on the characteristics of the probability distribution of data, it has unique advantages in solving uncertain problems [22]. In the path planning problem, scholars use robust optimization proposed by Ben-Tal et al. (2002) to deal with uncertainty [23]. In the research field of uncertain decision-making problems, compared with stochastic programming, the robust optimization model is more flexible. The principle of robust optimization is that the uncertainty of parameters is irregular, which is the biggest difference between robust optimization and stochastic programming. For robust optimization, there is no need to restrict the membership rules of parameters, which avoids the controversy. Thus, the robust optimization is more general in describing randomness, and the model is more compatible. In general, robust optimization can adjust the size of the fluctuation range space of parameters to meet the needs of different decision makers for different risk attitudes.

Robust optimization focuses on constructing uncertain sets and describing uncertain problems, such as Box sets, Ellipsoids, or Polyhedron, and measuring the risk through changes in uncertain sets [24, 25]. One advantage of robust optimization is that as long as the appropriate uncertainty set is designed, the consistency between the robust correspondence model and the original problem model can be guaranteed [26]. The research of robust optimization was further developed. Montemanni (2005) proposed a branch and bound algorithm for the robust spanning tree problem [27]. Sarac et al. (2006) invented a branch-price algorithm to solve and optimize the problem of abnormal airline routes [28]. Subsequently, Zhang et al. (2007) established a multi-granular robust routing model in a mesh network and proposed a load balancing robust routing scheme [29]. Huang and Wang (2009) used the optimized genetic algorithm to solve the robust optimal network solution of multiobjective optimization and proved the convergence of the algorithm through numerical experiments [30]. Some scholars have studied the home health care routing problem through an intelligent algorithm and verified the feasibility of the paper model through practical cases [31–34]. In addition, some scholars have studied uncertain decision-making problems and multicriteria decision-making problems through robust optimization [35–38]. Therefore, based on the above characteristics, the robust optimization method

has extensive research value in the theoretical and practical fields. To the best of our knowledge, very few scholars currently apply robust optimization theories and methods to the path planning of HHC, and this article is to supplement this, so it has considerable research value. The main contributions of this article are as follows:

- (i) Taking carbon emission cost as an important reference factor for path planning
- (ii) According to the actual situation, build a LO model of HHC services
- (iii) Introduce uncertain parameters to further expand the LO model into three RO models and construct different security level models through three uncertain sets
- (iv) In the case of numerical case analysis, use real case data for analysis and provide routing planning solutions for path planning decisions of actual HHC services companies

It can be seen that the innovation of robust optimization theory is of great significance and the application field is extremely broad. At present, most HHC related studies only consider deterministic models and less uncertainty. Therefore, the decisions given in these solutions have limited applicability in practical situations [39, 40]. In addition, even though there are some researches on uncertainties in family medical services, they have not intervened from the perspective of robust optimization. Therefore, from the perspective of robust optimization, this paper studies the path planning of HHC under uncertain parameters. According to the literature review, this article will be one of the first important studies to apply robust optimization theory to HHC path planning. Although the literature has elaborated on the application of robust optimization theory, the model is basically a single set of uncertain sets. As an improvement, this paper will propose and construct a robust optimization under multiple sets of uncertain sets, so the model has a deeper and richer research level.

The rest of this article is organized as follows. Section 2 is the basic model. Section 3 describes the HHC path problem and constructs the LO model to solve the two-level path planning problem. Section 4 transforms the LO model into three RO models. Section 5 conducts numerical experiments and analyzes the results. Section 5 summarizes the research work of this article and summarizes and proposes future research directions.

2. Basic Model

This paper studies the problem of two-level routing planning for the HHC problem under uncertain environment (Figure 1). In this problem, two types of sites are considered: home care and nursing stations and demand communities. On the one hand, the home care station deals with the order demand from the demand community. The number of nursing stations needs to be considered comprehensively to minimize operation and management costs. On the other hand, considering the cost minimization and demand

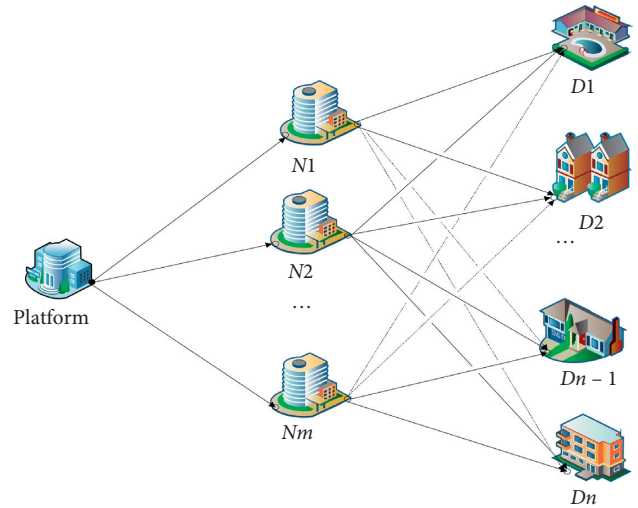


FIGURE 1: Schematic diagram of routing planning for HHC.

responsiveness, optimize the driving routing of service personnel. On the basis of meeting the community needs to the maximum extent, the driving cost of vehicles can be reduced through reasonable planning routing. In our study, cost types are considered including fixed cost, vehicle cost, time cost, and transportation cost [41]. This paper studies the optimal routing planning of M HHC stations and N demand communities and establishes an optimization model of HHC. The purpose is to meet the needs of customers to the maximum extent and minimize the total cost under the constraints of nursing station, time, and road condition.

2.1. Symbolic Variable Description. The parameters and variables used in this model are described in Table 1.

2.2. Basic Assumptions. The following assumptions for the above routing planning problems are presented:

- (i) The problem of routing planning is to provide medical and nursing services from one platform nursing station to multiple communities in need
- (ii) The needs of all communities must be met
- (iii) At least one nursing station provides nursing services at each demand point
- (iv) The vehicles used are of the same model with the same fuel consumption and load capacity
- (v) Both the time window for the geographic location and needs of the community are known
- (vi) The average speed of vehicles in different regions is different, which depends on the road conditions and time period in the region

2.3. Cost Analysis. This study reflects the actual situation of the medical care routing planning process under the operation of a sharing platform. The specific cost includes the fixed cost of the medical care station, transportation cost, vehicle carbon emission cost, and time cost.

TABLE 1: Parameters and variables.

| Type | Symbol | Description |
|-----------------------|--------------------|---|
| Decision variables | x_i | $x_i \in [0, 1]$, continuous variable. If $x_i \neq 0$, select i |
| | y_{ij} | $y_{ij} \in [0, 1]$, continuous variable. If $y_{ij} \neq 0$, select ij |
| | D_j | The demand of HHC services |
| | c_f | Fixed cost of nursing station |
| | H_i^{Max} | Maximum resource allocation of nursing station i |
| Basic parameters | h_v | Maximum load of HHC vehicle |
| | c_v | Unit vehicle transportation fuel consumption cost |
| | E_c | Unit fuel consumption of nursing vehicles |
| | c_t | Penalty cost per unit delay |
| | c_e | Carbon tax |
| | d_{ij} | Distance between demand community and nursing station |
| | \bar{v}_i | Average speed of the area where nursing station i is located |
| | t | Arrival time of benchmark service personnel |
| | T_t^{Max} | Maximum arrival time |
| | I | Nursing station set, consisting of i |
| Indicating parameters | J | Demand community aggregation, consisting of j |

2.3.1. Fixed Cost. Considering the fixed cost, the fixed cost is the infrastructure investment cost, including the loss cost of office equipment, the basic water and electricity cost of the nursing station, and the salary of management. The fixed cost of agricultural sharing platform operation is calculated as follows:

$$C_f = \sum_{i=1}^m c_f [x_i], \quad x_i \in [0, 1], \quad (1)$$

where, $[x_i]$ means to round up the value, for example, if $x_i = 0.1$, then round up to 1; $x_i = 1.1$ round up to 2. The actual meaning is that once the warehouse is selected, the fixed cost will exist.

2.3.2. Vehicle Transportation Cost. In order to ensure the accurate arrival of home care personnel, the transportation cost is as follows:

$$C_v = c_v \sum_{i=1}^m \sum_{j=1}^n \left(\frac{D_j}{h_v} \right) y_{ij} d_{ij}. \quad (2)$$

2.3.3. Cost of Waiting Time. The cost of waiting time is the reward (or punishment) brought by the advance (or delay) of time, and the specific form is as follows:

$$C_t = c_t \sum_{i=1}^m \sum_{j=1}^n [y_{ij}] \left(\frac{d_{ij}}{\bar{v}_i} - t \right), \quad (3)$$

among them, c_t is the unit reward (or punishment) cost related to time, which is the time for a basic nursing home visit, \bar{v} the average speed of vehicles in the area of home care station [42].

2.3.4. Vehicle Carbon Cost. Due to the government's environmental protection requirements, a certain amount of carbon emission tax should be levied on motor vehicles [5]. The specific costs are as follows:

$$C_c = c_c \sum_{i=1}^m \sum_{j=1}^n e d_{ij} E_c D_j y_{ij}. \quad (4)$$

2.4. Basic Low-Carbon Linear Optimization Model. To sum up, this paper constructs a low-carbon linear optimization (LO) model [43], which aims to minimize the total cost on the basis of meeting customer needs in the maximum extent. The specific model is as follows:

(Low-carbon LO model)

$$\min C_f + C_v + C_t + C_c, \quad (5)$$

$$\text{s.t. } \sum_{i=1}^m y_{ij} = 1, \quad \forall j \in J, \quad (6)$$

$$\sum_{j=1}^n D_j y_{ij} \leq H_i^{\text{Max}}, \quad \forall i \in I, \quad (7)$$

$$[y_{ij}] \cdot \left(\frac{d_{ij}}{\bar{v}_j} \right) \leq T_t^{\text{Max}}, \quad \forall i \in I, \forall j \in J, \quad (8)$$

$$C_c(x_i, D_j) \leq E_c^{\text{Max}}, \quad \forall i \in I, \forall j \in J, \quad (9)$$

$$0 \leq y_{ij} \leq 1, \quad \forall i \in I, \forall j \in J, \quad (10)$$

$$0 \leq x_i \leq 1, \quad \forall i \in I. \quad (11)$$

The specific objective functions and constraints of the basic LO model are as follows. The objective (5) is the synthesis of the above cost analysis, including fixed cost, transportation cost, vehicle carbon emission cost, and time cost. Constraint (6) represents that all HHC services under the platform of the region are provided by the nursing station, without any other external diversion, and the needs of any community under the platform must be met. Constraint (7) the ability of nursing service provided by nursing

station was less than its maximum ability and constraint (8) is a time constraint, that is, the time consumed by any routing is less than its maximum travel period. Constraint (9) is that the cumulative carbon emission is less than the maximum limit. Constraint (10) means that the resource allocation proportion on any routing is not less than 0 and not more than 1; when $y_{ij} = 0$, it means that this line is not selected; when $y_{ij} = 1$, it means that all the needs of the community are supplied by i . Constraint 11) indicates that the resource allocation variable of the nursing station is a continuous fractional variable.

3. RO Models

In reality, due to the complexity of the external market environment, it is very difficult to obtain the accurate value or probability distribution of key parameters, especially for demand [44]. This leads to the low feasibility or even nonexistence of the ideal model in the real society; that is to say, the robustness of the routing planning scheme of the basic model is low under the uncertain conditions. Therefore, the research of robust optimization theory is more attractive. In this section, using the theory of robust optimization, the above-mentioned deterministic model is transformed into a robust optimization model, so that the uncertain parameters change in an uncertain set, so that the probability distribution can also be carried out to the research of routing planning with the independence of the model. Robust optimization is one of the main methods to achieve the goals [45]. The greater the volatility of customer demand, the greater the uncontrollability. Therefore, it is defined as a random demand parameter $\tilde{D}_j = D_j^0 + \hat{D}_j$, D_j^0 as nominal demand, $\hat{D}_j = \varepsilon D_j^0$ as demand fluctuation, and ε as disturbance proportion. On this basis, the RO models of Box, Polyhedron, and Ellipsoid set are established [43]. In order to facilitate the description, this paper divides the cost into two, one is nominal deterministic item $C_D(D_j^0) = C_v(D_j^0) + C_t(D_j^0) + C_c(D_j^0)$, the other is $C_S(\hat{D}_j) = C_v(\hat{D}_j) + C_t(\hat{D}_j) + C_c(\hat{D}_j)$, which is affected by uncertain parameters.

3.1. Box-RO Model. In the Box-RO model, the uncertainty requirement is \tilde{D}_j , and the uncertainty set is Box [46]. According to the robust optimization theory, the robust equivalent model is (12), $U^B = U_\infty = \{\varepsilon: \|\varepsilon\|_\infty \leq \Psi\} = \{\varepsilon: |\varepsilon_j| \leq \Psi\}$ and Ψ is the uncertain level parameter (i.e., safety parameter, SP). SP represents that at most Ψ parameters deviate from nominal value.

Theorem 1. According to the relevant theory of robust optimization, the equivalent robust correspondence of $\{\max c^T x | Ax \leq B, l \leq x \leq u\}$ is $\sum_j a_{ij} x_j + \max_{\xi \in U} \sum_j \hat{a}_{ij} x_j \xi_{ij} \leq B$. The resulting Box-RO model is as follows:

(Box-RO model)

$$\min Z_B$$

$$C_f + C_D(D_j^0) + \psi [C_S(\hat{D}_j)] \leq Z_B$$

$$\sum_{i=1}^m y_{ij} = 1, \quad \forall j \in J$$

$$\sum_{j=1}^n D_j^0 y_{ij} + \psi \sum_{j=1}^n \hat{D}_j y_{ij} \leq H_i^{\text{Max}}, \quad \forall i \in I$$

s.t.

$$\lceil y_{ij} \rceil \cdot \left(\frac{d_{ij}}{v_j} \right) \leq T_t^{\text{Max}}, \quad \forall i \in I, \forall j \in J$$

$$C_v(x_i, D_j) + \psi [C'_S(\hat{D}_j)] \leq E_e^{\text{Max}}, \quad \forall i \in I, \forall j \in J$$

$$0 \leq y_{ij} \leq 1, \quad \forall i \in I, \forall j \in J$$

$$0 \leq x_i \leq 1, \quad \forall i \in I.$$

(12)

Proof. General Linear Programming (LP) problem is $\{\max c^T x | Ax \leq B, l \leq x \leq u\}$. Under uncertain conditions, the uncertain Linear Programming (LP) problem can be expressed as follows:

$$\left\{ \min_x \{c^T x + d: Ax \leq B\} \right\}_{(c,d,A,B) \in U}. \quad (13)$$

Among them, the cost function is $c^T x + d$, the basic constraint is $Ax \leq B$, and the support set is U . Considering i^{th} row of matrix A , assume that element \hat{a}_{ij} in A is uncertain, then define that $\tilde{a}_{ij} = a_{ij} + \hat{a}_{ij} \xi_{ij}$, where \tilde{a}_{ij} is true value of parameter, a_{ij} is nominal value while \hat{a}_{ij} is fluctuation of parameter, ξ_{ij} is factor ($\xi \in U$, U is the uncertainty set), ξ can take any possible value in U . So, (5) can be represented as (6). Then, uncertain sets and their corresponding robust equivalences are as follows:

$$\sum_j a_{ij} x_j + \max_{\xi \in U} \sum_j \hat{a}_{ij} x_j \xi_{ij} \leq B. \quad (14)$$

And (6) is equivalent to $\sum_j a_{ij} x_j + \Psi \sum_j \hat{a}_{ij} |x_j| \leq B$. Set $\mathbb{P}_\infty = [\mathcal{J}_{L \times L}; \mathbb{O}_{1 \times L}]$, $\mathcal{P}_\infty = [\mathcal{O}_{L \times 1}; \Psi] \dots_\infty = \{[\theta_{L \times 1}; t]: \|\theta\|_\infty = t\}$, where L is the number of uncertain parameters. Therefore, the inner layer maximization in (6) can be rephrased as $\max_{\xi \in U^B} \{\sum_j \hat{a}_{ij} x_j \xi_{ij}: \mathbb{P}_\infty \xi + \mathcal{P}_\infty \in \mathbb{K}_\infty \Psi\}$. Define the dual variable as w_i, λ_i , according to dual cone theory $\mathbb{K}_\infty^* = \{[\theta_{L \times 1}; t]: \|\theta\|_1 \leq t\}$, then, $\min_{w, \lambda} \{\Psi \lambda_i: w_{ij} = \hat{a}_{ij}$

$x_j, \forall j, \sum_{\mathcal{J}} |w_{ij}| \leq \lambda_i$, and $\min_{w, \lambda} \{\Psi \sum_{\mathcal{J}} |w_{ij}|: w_{ij} \leq \hat{a}_{ij} x_j, \forall j\}$ are equal. Thus, it can be reformed as $\Psi \sum_{\mathcal{J}} \hat{a}_{ij} x_j$. So, Theorem 1 is proved.

3.2. Polyhedron-RO Model. If the uncertainty set of each node is Polyhedron, and the Polyhedron set is defined by l_1 norm: $U^P = U_1 = \{\zeta: \|\zeta\|_1 \leq \Gamma\} = \{\varepsilon \cdot \sum |\varepsilon_j| \leq \Gamma_j\}$, where Γ is the uncertain horizontal parameter. The Polyhedron-RO model is given in the following theorem, where Γ represents the SP of uncertain demand [47–50].

Theorem 2. *The equivalent robust correspondence of $\{\max c^T x | Ax \leq B, l \leq x \leq u\}$ is $\sum_j a_{ij} x_j + \Gamma_i p_i \leq B_i, p_i \geq \hat{a}_{ij} |x_j|$. The resulting Polyhedron-RO model is as follows: (Polyhedron-RO model)*

$$\begin{aligned}
 & \min Z_p \\
 & C_f + C_D(D_j^0) + \Gamma[C_S(\hat{D}_j)] \leq Z_p \\
 & \sum_{i=1}^m y_{ij} = 1, \quad \forall j \in J \\
 & \sum_{j=1}^n D_j^0 y_{ij} + \Gamma' C_S(\hat{D}_j) \leq H_i^w, \quad \forall i \in I \\
 & \text{s.t.} \\
 & [y_{ij}] \cdot \left(\frac{d_{ij}}{\bar{v}_j} \right) \leq T_t^{\text{Max}}, \quad \forall i \in I, \forall j \in J \\
 & C_v(x_i, D_j) + \Gamma'[C_S'(\hat{D}_j)] \leq E_e^{\text{Max}}, \quad \forall i \in I, \forall j \in J \\
 & 0 \leq y_{ij} \leq 1, \quad \forall i \in I, \forall j \in J \\
 & 0 \leq x_i \leq 1, \quad \forall i \in I.
 \end{aligned} \tag{15}$$

Proof. Constraint (16) is equivalent to constraint (14).

$$\sum_j a_{ij} x_j + \Gamma_i p_i \leq B_i, \quad p_i \geq \hat{a}_{ij} |x_j|. \tag{16}$$

Defining that $\mathbb{P}_1 = [\mathcal{J}_{L \times L}; \mathbb{O}_{1 \times L}]$, $\mathcal{P}_1 = [\mathcal{O}_{L \times 1}; \Gamma] \cdot \dots \cdot 1 = \{[\theta_{L \times 1}; t]: \|\theta\|_1 = t\}$, where L is the number of uncertain parameters. Therefore, the problem of inner layer maximization in (14) can be rephrased as $\max_{\xi \in U^P} \{\sum_{\mathcal{J}} \hat{a}_{ij} x_j \xi_{ij}: \mathbb{P}_1 \xi + \mathcal{P}_1 \in \mathbb{K}_1 \Gamma\}$. Define the dual variable as w_i, λ_i , according to dual cone theory $\mathbb{K}_1^* = \{[\theta_{L \times 1}; \mathcal{T}]: \|\theta\|_1 \leq \mathcal{T}\}$.

$$\begin{aligned}
 & \max_{\xi \in U^P} \left\{ \sum_{\mathcal{J}} \hat{a}_{ij} x_j \xi_{ij}: \mathbb{P}_1 \xi + \mathcal{P}_1 \in K_1 \right\} \\
 & = \min_{w, \lambda} \{ \Gamma \lambda_i: w_{ij} = \hat{a}_{ij} x_j \|w_i\|_{\infty} \leq \lambda_i \} \\
 & = \min_w \left\{ \Gamma \max_{\mathcal{J}} |w_{ij}|: w_i = \hat{a}_{ij} x_j \right\} \\
 & = \Gamma \mathcal{P}_i, \quad \mathcal{P}_i \geq \hat{a}_{ij} |x_j|.
 \end{aligned} \tag{17}$$

In summary, Theorem 2 can be proved.

3.3. Ellipsoid-RO Model. In the Ellipsoid-RO model, the uncertain parameters are defined according to l_2 norms, $U^E = U_2 = \{\zeta: \|\zeta\|_2 \leq \Omega\} = \{\varepsilon \sqrt{\sum_j \varepsilon_j^2} \leq \Omega\}$, where Ω is the adjustable uncertain parameter (safety parameter) and the ball diameter of the uncertain set. The Ellipsoid uncertainty set of \tilde{D}_j is $U^E = \{\tilde{D} \in R, \sum_{j=1}^n [(\tilde{D}_j - D_j^0)/\hat{D}_j]^2 \leq \Omega^2\}$. Since the model is a nonlinear constraint problem, set U^E is equivalent to the following form: $U^E = \{\tilde{D} \in R, (\tilde{D}_j - D_j)^T C^{-1} (\tilde{D}_j - D_j) \leq \Omega^2\}$, where C is an n -order diagonal matrix with element (nonzero) of \hat{D}_j^2 , then $C_{11} + C_D(D_j^0) + \Omega_1 \sqrt{\sum_{j=1}^n \hat{D}_j^2 (\sum_{i=1}^m \sum_{j=1}^n y_{ij} c_e)^2} \leq Z_E$. Let $r_i = \sum_{i=1}^m \sum_{j=1}^n y_{ij} c_e$, $P = \sqrt{\sum_{j=1}^n \hat{D}_j^2 r_{ij}^2}$, then the above formula is transformed to $C_{11} + C_D(D_j^0) + \Omega_1 P \leq Z_E$. Since the goal is to minimize the total cost, then add relaxation constraint $P \geq \sqrt{\sum_{j=1}^n \hat{D}_j^2 r_{ij}^2}, r_i \geq \sum_{i=1}^m \sum_{j=1}^n y_{ij} c_e$.

Theorem 3. *The equivalent robust correspondence of $\{\max c^T x | Ax \leq B, l \leq x \leq u\}$ is $a_i^T X + \Omega_i \sqrt{\hat{a}_i^2 X^2} \leq B_i$. The resulting Ellipsoid-RO model is as follows: (Ellipsoid-RO model)*

$$\begin{aligned}
 & \min Z_e \\
 & C_f + C_D(D_j^0) + \Omega P \leq Z_e \\
 & P \geq \sqrt{\sum_{j=1}^n \hat{D}_j^2 r_{ij}^2}, \quad \forall i \in I, \forall j \in J \\
 & r_i \geq \sum_{i=1}^m \sum_{j=1}^n y_{ij} c_e \\
 & \sum_{i=1}^m y_{ij} = 1, \quad \forall j \in J \\
 & \text{s.t.} \\
 & \sum_{j=1}^n D_j^0 y_{ij} + \Omega P \leq H_i^w, \quad \forall i \in I \\
 & [y_{ij}] \cdot \left(\frac{d_{ij}}{\bar{v}_j} \right) \leq T_t^{\text{Max}}, \quad \forall i \in I, \forall j \in J \\
 & C_v(x_i, D_j) + \Omega' P \leq E_e^{\text{Max}}, \quad \forall i \in I, \forall j \in J \\
 & 0 \leq y_{ij} \leq 1, \quad \forall i \in I, \forall j \in J \\
 & 0 \leq x_i \leq 1, \quad \forall i \in I.
 \end{aligned} \tag{18}$$

Proof. Constraint (19) is equivalent to constraint (14).

$$a_i^T X + \Omega_i \sqrt{\hat{a}_i^2 X^2} \leq B_i. \tag{19}$$

The uncertainty ellipsoid uncertainty set is defined as follows:

$$U^E = \{a_i \in R^n: (a_i - \bar{a}_i)^T \Sigma^{-1} (a_i - \bar{a}_i) \leq \Omega^2\}. \quad (20)$$

Among them \bar{a}_i is nominal value, Σ is positive definite matrix, Ω is SP. It can be converted to a sphere with radius of Ω .

$$U^E = \{a_i \in R^n: a_i = \bar{a}_i + \Delta\xi, \xi \leq \Omega\}. \quad (21)$$

And, where $\Delta = \Sigma^{1/2}$, the constraints $\max a_i^T X \leq B$ of (6) can be translated.

$$\max\{a_i^T X: (a_i - \bar{a}_i)^T \Sigma^{-1} (a_i - \bar{a}_i) \in \Omega^2\}. \quad (22)$$

As for Σ being positive, $\max\{a_i^T X: (a_i - \bar{a}_i)^T \Sigma^{-1} (a_i - \bar{a}_i) \in \Omega^2\}$ is a convex problem. Therefore, LP can be solved by Karush–Kuhn–Tucker (KKT) condition. Set a_i^* is an optimal solution, u^* is Lagrange multiplier, and z^* is an optimal value, then,

$$\begin{aligned} \min \mathcal{F}(a_i^*) &= -a_i^{*T} X \\ \text{s.t. } g(a_i^*) &= (a_i^* - \bar{a}_i)^T \Sigma^{-1} (a_i^* - \bar{a}_i) - \Omega^2 \leq 0. \end{aligned} \quad (23)$$

According to KKT condition,

$$\begin{aligned} L(a_i^*, u_i^*) &= f(a_i^*) + u_i^* g(a_i^*), \\ \text{s.t. } \frac{dL(a_i^*, u_i^*)}{da_i^*} &= 0; \quad a(a_i^*) = 0; \quad u^* \geq 0, \\ L(a_i^*, u_i^*) &= -a_i^{*T} X + u^* [(a_i^* - \bar{a}_i)^T \Sigma^{-1} (a_i^* - \bar{a}_i) - \Omega^2], \\ \text{s.t. } -X + 2u^* \Sigma^{-1} (a_i^* - \bar{a}_i) &= 0, \\ u^* [(a_i^* - \bar{a}_i)^T \Sigma^{-1} (a_i^* - \bar{a}_i) - \Omega^2] &= 0, \\ u^* &\geq 0. \end{aligned} \quad (24)$$

So,

$$\begin{aligned} a_i^* - \bar{a}_i &= \frac{\Sigma X}{2u^*}, \\ \left[\left(\frac{\Sigma X}{2u^*} \right)^T \Sigma^{-1} \left(\frac{\Sigma X}{2u^*} \right) \right] &= \Omega^2. \end{aligned} \quad (25)$$

Then,

$$\begin{aligned} \left[\left(\frac{\Sigma X}{2u^*} \right)^T \Sigma^{-1} \left(\frac{\Sigma X}{2u^*} \right) \right] &= \Omega^2 \\ \Rightarrow \frac{1}{2u^*} X^T \Sigma^T \Sigma^{-1} \frac{1}{2u^*} \Sigma X &= \Omega^2 \\ \Rightarrow \frac{1}{(2u^*)^2} X^T \Sigma X &= \Omega^2 \\ \Rightarrow \frac{1}{(2u^*)^2} &= \frac{\Omega^2}{X^T \Sigma X} \\ \Rightarrow \frac{1}{2u^*} &= \frac{\Omega}{\sqrt{(X/2)^T \Sigma (X/2)}} \end{aligned} \quad (26)$$

From (25) and (26), we get the following:

$$a_i^* = \bar{a}_i + \frac{\Omega}{2\sqrt{(X/2)^T \Sigma (X/2)}} \Sigma X = \bar{a}_i + \frac{\Omega}{\sqrt{X^T \Sigma X}} \Sigma X. \quad (27)$$

Therefore,

$$\begin{aligned} z^* &= X^T a_i^* + X^T \frac{\Omega}{\sqrt{X^T \Sigma X}} \Sigma X, \\ z^* &= X^T a_i^* + \Omega \sqrt{X^T \Sigma X}. \end{aligned} \quad (28)$$

Since Σ_i is a diagonal matrix of elements \hat{a}_i^2 , then,

$$\begin{aligned} a_i^T X + \Omega_i \sqrt{X^T \Sigma_i X} &\leq B_i \\ \Rightarrow a_i^T X + \Omega_i \sqrt{\hat{a}_i^2 X^2} &\leq B_i. \end{aligned} \quad (29)$$

Above all, Theorem 3 can be proved.

4. Case Analysis

In this section, an example is given to verify the effectiveness of the robust optimization method in solving the routing planning problem of HHC. In this paper, the HHC enterprise in Tangshan (China) is selected as a sample (Figures 2 and 3). The company is engaged in HHC and nursing assistance services to provide services for some communities in Tangshan city. The company is faced with double-level planning problems in the operation process.

The first level of planning is to determine the location of the nursing station. On the basis of comprehensive consideration of various location factors, the HHC and nursing service company selected the following 6 nodes as alternative nursing stations, namely, Concord nursing station, Fengnan nursing station, workers' nursing station, affinity source nursing station, Fule nursing station, and Kaiping nursing station, which are represented by N_1, N_2, \dots, N_6 in the following article. So, the first level of planning is to determine the choice of these nursing stations.

The second level is routing planning. In this medical nursing system, there are 6 alternative nursing stations, 8 demand communities, and 48 alternative routings corresponding to different operating costs. The eight demand communities are Luanxing community, Hongda community, Fulianyuan, Shengtai manor, Tianheyuan community, Jiarun Rainbow City, Guzhen new town, and Yuehua new building, which are expressed in D_1, D_2, \dots, D_8 later. The setting of transportation cost is based on the comprehensive calculation of the real-time oil price in Tangshan, the actual distance between the demand community and the nursing station. It even involves factors such as traffic congestion and time limit. Therefore, the choice of routing is second level planning based on the comprehensive consideration of relevant costs.

4.1. Related Data. The basic data information includes the nominal demand of the demand community, the maximum service supply of the medical care and nursing station, the

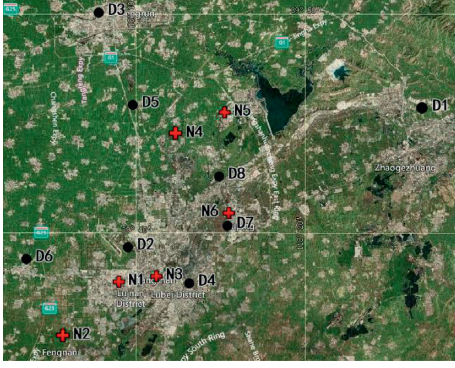


FIGURE 2: Actual map location.

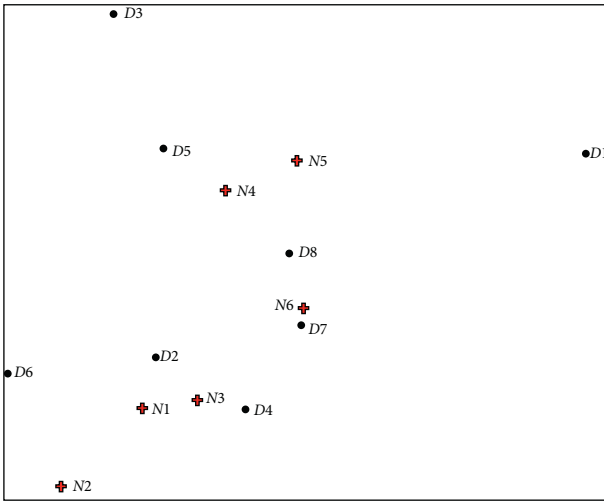


FIGURE 3: Relative location.

traffic conditions of the area, and the fixed operating costs, as shown in Table 2.

The actual distance between nodes obtained directly through Google map is shown in Table 3. Other parameters of the model are as follows: the benchmark door-to-door service time is 20 mins, the time delay cost is 10 CNY/hour, and the maximum delay time is 60 mins. If it is overdue, the demand community will cancel the demand service order. The carbon tax is 2.1 CNY/kg, and the fuel consumption per unit distance vehicle is 8.33 L/100 km. In addition, the CO₂ emission coefficient is 0.16 L/h * t, and the CO₂ emission factor is 2.51 kg/L [42].

4.2. Optimal Solution. In this section, we use MATLAB as the programming platform, use Gurobi (9.0.2) programming to solve the above model and compare LO with three RO models.

4.2.1. Algorithm and Optimal Result of Models. The specific calculation process is shown in Table 4:

Through the above algorithm, the optimal solution of the LO model is $7.2665 E + 03$ CNY, time consuming 4.535591 s. The routing planning scheme of the LO model is shown in

TABLE 2: Basic parameters.

| Communities | D_1 | D_2 | D_3 | D_4 | D_5 | D_6 | D_7 | D_8 |
|-----------------|-------|-------|-------|-------|-------|-------|-------|-------|
| Nominal demand | 125 | 95 | 140 | 135 | 160 | 155 | 175 | 130 |
| HHC station | N_1 | N_2 | N_3 | N_4 | N_5 | N_6 | — | — |
| Maximum service | 225 | 260 | 240 | 235 | 180 | 225 | — | — |
| Average speed | 45 | 40 | 50 | 65 | 35 | 40 | — | — |
| Fixed costs | 750 | 650 | 550 | 450 | 420 | 480 | — | — |

TABLE 3: Distance between nodes.

| d_{ij} | D_1 | D_2 | D_3 | D_4 | D_5 | D_6 | D_7 | D_8 |
|----------|-------|-------|-------|-------|-------|-------|-------|-------|
| N_1 | 35.40 | 5.40 | 2.40 | 8.10 | 17.90 | 11.60 | 14.70 | 16.90 |
| N_2 | 36.80 | 13.30 | 8.50 | 15.50 | 29.10 | 10.80 | 23.90 | 24.90 |
| N_3 | 33.10 | 5.90 | 6.50 | 4.50 | 17.70 | 14.00 | 10.80 | 18.20 |
| N_4 | 26.90 | 14.60 | 22.10 | 15.10 | 6.10 | 22.00 | 12.30 | 7.30 |
| N_5 | 19.80 | 23.80 | 29.10 | 22.10 | 12.50 | 34.80 | 15.10 | 9.70 |
| N_6 | 24.10 | 12.20 | 15.70 | 10.40 | 17.20 | 26.00 | 4.20 | 5.50 |

TABLE 4: Algorithm steps of LO model.

| | |
|--------|--|
| Step 1 | Input initial value and relevant parameters; |
| Step 2 | Input parameter variable constraints, carbon emission constraints, time window constraints, and other constraints; |
| Step 3 | Set the solution environment and solve it through the solver Gurobi; |
| Step 4 | If step 2 is satisfied, terminate, no, execute step 1; |
| Step 5 | Output the optimal solution and running time. |

Figure 4. The wider the routing line width is, the larger the proportion of this routing is. As can be seen from Figure 4, in the second level of routing planning, HHC and nursing stations are the main ones, accounting for 38.3% and 32.5% of the total demand, respectively, and they are responsible for the supply of main service personnel. Although this can ensure the stable supply, there is a certain space for improvement in the routing planning, such as over long-distance service, which increases the transportation cost in a large amount that is not conducive to the operation of the company, so it is necessary to optimize the distribution routing.

The algorithm is shown in Table 5. And the results of the models are shown in Table 6.

4.2.2. Box-RO Model. In the Box-RO model, the influence of Ψ on the lowest total cost is constantly changing. The calculation results of the Box-RO model are shown in Table 6. The total cost of the HHC care planning network raises with the trend of increase. When $\Psi = 0$, the model is equivalent to the LO model, and the total cost is $7.6213E + 03$ CNY. As shown in Figure 5, the Box-RO model is similar to the LO model: (i) In the selection of nursing sites, the first level planning needs to add two nodes, from 4 nursing stations to 6 nursing stations. (ii) In the second layer of routing planning, the number of routings increases from 16 to 19. The routing planning is more complex, and its total cost also increases. As a whole, there are many long-distance transmission lines.

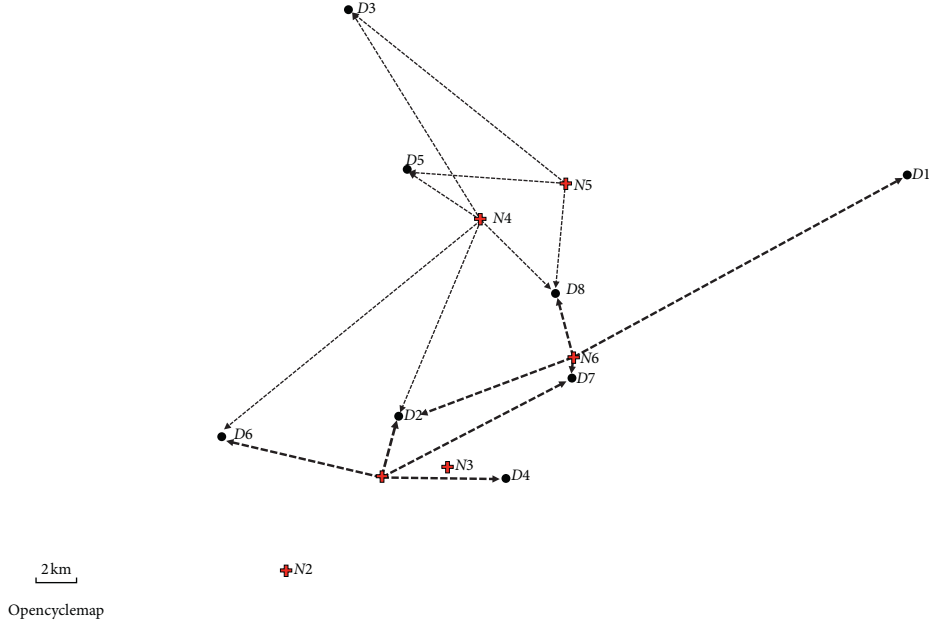


FIGURE 4: Distribution routing in LO model.

TABLE 5: Algorithm steps of RO model.

| | |
|--------|--|
| Step 1 | Input initial value, given the parameters: $U^B = \{\varepsilon: \ \varepsilon\ _\infty \leq \Psi\} = \{\varepsilon: \varepsilon_j \leq \Psi\}; U^P = \{\varsigma: \ \varepsilon\ _1 \leq \Gamma\} = \{\varepsilon: \sum \varepsilon_j \leq \Gamma_j\}; U^E = \{\varsigma: \ \varepsilon\ _2 \leq \Omega\} = \{\varepsilon: \sqrt{\sum \varepsilon_j^2} \leq \Omega\};$ |
| Step 2 | If the random number satisfies the condition, step 3; otherwise, return step 1; Input parameter and constraints; |
| Step 3 | #1 Box-RO and Polyhedron-RO model direct input constraints; #2 Ellipsoid-RO after the model further relax the parameter constraints; |
| Step 4 | If meets step 3, terminate; else, execute step 1; |
| Step 5 | Set the solution environment and solve it through the solver Gurobi; |
| Step 6 | Output the optimal solution and running time. |

TABLE 6: Operation results of RO models.

| SP | Box-RO model | | Polyhedron-RO model | | Ellipsoid-RO model | |
|----|--------------|----------|---------------------|----------|--------------------|----------|
| | Total cost | Time | Cost | Time | Cost | Time |
| 0 | 7.2665E+03 | 4.747611 | 7.2665E+03 | 4.688161 | 7.2665E+03 | 4.493691 |
| 1 | 7.8087E+03 | 4.297063 | 7.6183E+03 | 4.454975 | 7.4332E+03 | 4.348147 |
| 2 | 7.8420E+03 | 4.471258 | 7.6719E+03 | 4.528155 | 7.4520E+03 | 5.021394 |
| 3 | 7.9285E+03 | 4.146447 | 7.8808E+03 | 4.411533 | 7.5019E+03 | 4.091843 |
| 4 | 7.9541E+03 | 4.098501 | 7.9590E+03 | 4.387638 | 7.5282E+03 | 4.187512 |
| 5 | 8.0119E+03 | 4.602096 | 8.1480E+03 | 4.467358 | 7.6244E+03 | 4.949629 |
| 6 | 8.1215E+03 | 4.465805 | 8.4583E+03 | 4.248660 | 7.7855E+03 | 4.498152 |
| 7 | 8.1620E+03 | 4.049612 | 8.5868E+03 | 4.267902 | 7.9260E+03 | 4.522854 |
| 8 | 8.2755E+03 | 4.012588 | 9.0733E+03 | 4.258624 | 8.1003E+03 | 4.320861 |

4.2.3. Polyhedron-RO Model. In the Polyhedron-RO model, the impact of Γ on the total cost is constantly changing. The calculation results of the Polyhedron-RO model are shown in Table 6. The total cost of the HHC care planning network raises with the trend of increase Γ . When $\Gamma = 0$, Polyhedron-RO model is equivalent to the LO model. As shown in Figure 6, the Polyhedron-RO model compares the Box-RO model with the LO model:

(i) In the first level planning, there are two more nursing stations than the LO model. (ii) In the second layer of planning, the number of routings is increased to 21 compared with the Box-RO model. In terms of the proportion of each routing, the proportion of long-distance line transportation is reduced and the proportion of short-distance transportation is increased, which has a positive role in promoting the routing optimization.

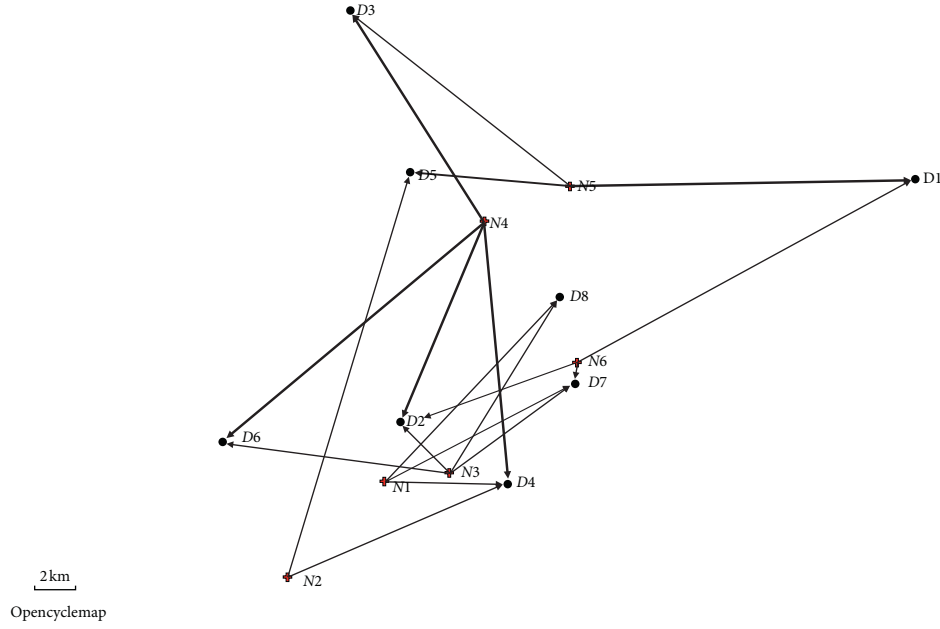


FIGURE 5: Routing planning of Box-RO model.

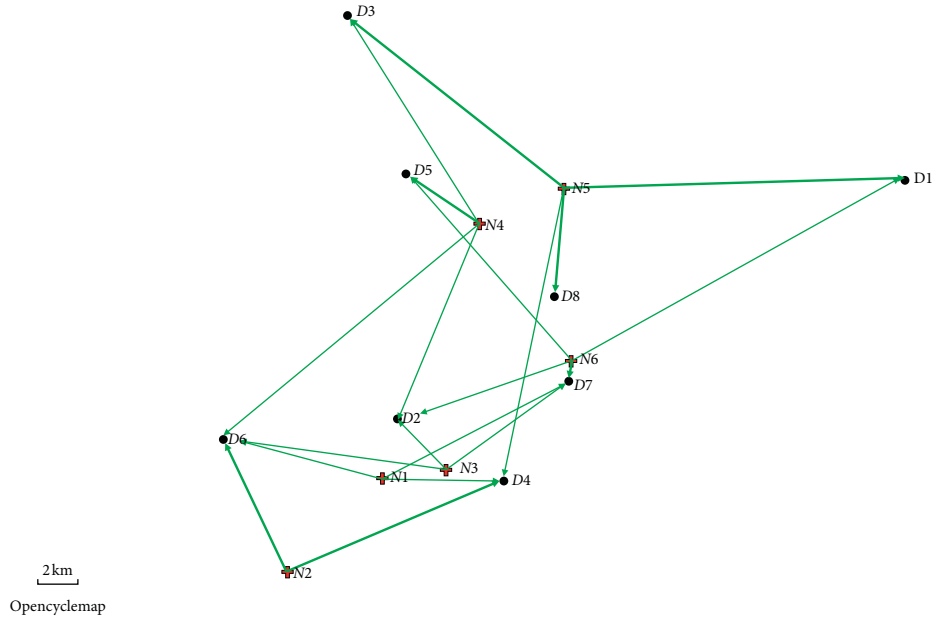


FIGURE 6: Routing of Polyhedron-RO model.

4.2.4. Ellipsoid-RO Model. In the Ellipsoid-RO model, the effect of the security parameter Ω on the lowest total cost is changing. The calculation results of the Ellipsoid-RO model are shown in Table 6. Similarly, the total cost of the HHC care planning network increases with the increase of Ω . At that time, $\Omega = 0$, the Ellipsoid-RO model was equivalent to the LO model, with the same total cost. The difference between the Ellipsoid-RO model, Box, and Polyhedron-RO model is as follows.

The Ellipsoid-RO model's route planning plan is shown in Figure 7. In the first stage $\text{planningBox} = 6 \Leftrightarrow \text{Polyhedron}$

$= 6 > \text{Ellipsoid} = 5 > \text{MILP} = 4$, and 5 nursing stations are selected for the Ellipsoid-RO model. By comparison, it is found that in the RO model, the performance is the best, next to the LO model. In the second level planning, the number of routings is reduced to 18. The proportion of service in each routing shows a trend of transferring to short-distance routing, and the proportion of HHC service supply undertaken by short-distance routing increases. Therefore, the first stage of vehicle mileage efficiency is higher; the second stage of the distribution route is more accurate, showing better optimization performance.

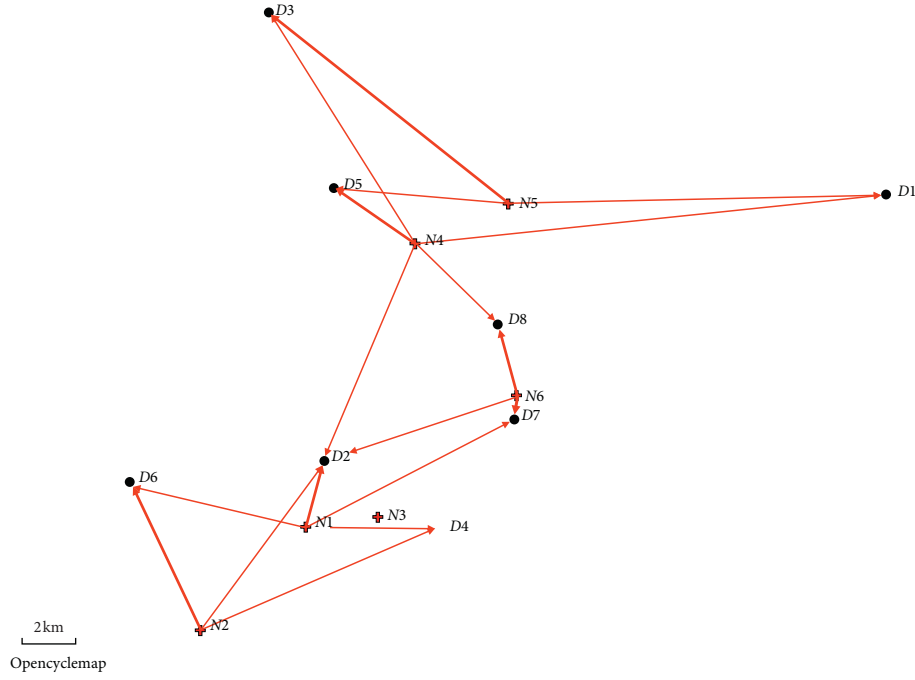


FIGURE 7: Routing scheme of Ellipsoid-RO model.

4.3. Sensitivity Analysis. This section compares the performance of each model, including efficiency, uncertainty, and the degree of demand fluctuation.

4.3.1. Efficiency Comparison. This section analyzes the operation efficiency of the four models. In order to take comparison conveniently, run the model in the same computer environment at the same time, we set the safety parameter as the only variable, and then observe the running time of the model.

Figure 8 shows the operational efficiency of the four robust optimization models. Among them, the Box-RO model has the highest operation efficiency and the fastest convergence speed (lower than the LO model as a whole: 4.535591 s). The Polyhedron-RO model is the most stable with little fluctuation (the peak value is 4.688161 s, the low value is 4.24866 s). The operation fluctuation degree of the robust optimization model of Ellipsoid is the largest (the peak is five-point zero two one three nine four s. The low value is 4.091843 s) maximum amplitude is 0.9296 s. Due to the small scale, there is little difference in the calculation time. However, when the constraints and variables in the model increase to tens of thousands or even tens of thousands, the operation efficiency will be significantly different.

4.3.2. Impact of Carbon Emission Restrictions. Through the above comparative analysis, it is found that the performance of the Ellipsoid-RO model is superior. Therefore, under the Ellipsoid-RO model, the impact of carbon emissions on the total cost is analyzed. Under the same parameters ($\varepsilon = 0.10, \Omega = 4$), with the change of carbon tax as the only variable, the calculation results are shown in Table 7. When

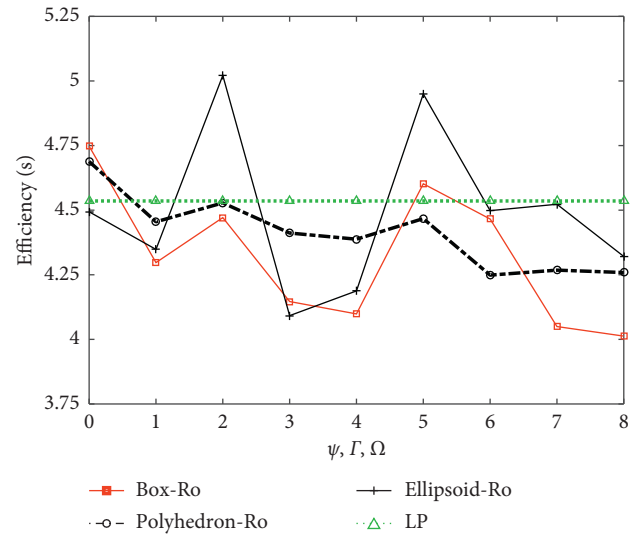


FIGURE 8: Comparison of model efficiency.

the carbon tax increases by 25% (2.0–2.50), the cost of using robust optimization model decreases by 8.274%.

With the increase of carbon emission tax, the HHC enterprises have to change their own routing distribution scheme and change the focus of resource allocation from N_2, N_5 to N_4, N_6 . The main reason is that the carbon emission cost of N_4, N_6 vehicles driving in the relatively close distance to the demand community can be significantly reduced. Fortunately, the total cost of distribution also shows a downward trend when we choose a closer route. In this way, we can not only save the cost of product distribution and transportation but also get better environmental benefits, which is conducive to the sustainable development of the ecological environment.

TABLE 7: The impact of carbon emission.

| Carbon tax | Cost | N_1 | N_2 | N_4 | N_5 | N_6 |
|------------|------------|--------|--------|--------|--------|--------|
| 2.00 | 7.5282E+03 | 25.89% | 22.03% | 18.35% | 15.34% | 18.39% |
| 2.05 | 7.6461E+03 | 27.13% | 21.78% | 18.45% | 14.09% | 18.55% |
| 2.10 | 7.6522E+03 | 28.56% | 21.45% | 18.69% | 13.18% | 18.12% |
| 2.15 | 7.6816E+03 | 29.75% | 21.16% | 19.04% | 12.45% | 17.60% |
| 2.20 | 7.4781E+03 | 30.08% | 20.57% | 19.08% | 11.12% | 19.15% |
| 2.25 | 7.4197E+03 | 30.79% | 19.34% | 20.13% | 10.13% | 19.61% |
| 2.30 | 7.2870E+03 | 31.09% | 18.94% | 21.76% | 9.45% | 18.76% |
| 2.35 | 7.2014E+03 | 31.25% | 18.21% | 22.48% | 8.07% | 19.99% |
| 2.40 | 7.1650E+03 | 31.76% | 17.09% | 23.93% | 7.96% | 19.26% |
| 2.45 | 6.9652E+03 | 32.26% | 16.72% | 24.17% | 7.13% | 19.72% |
| 2.50 | 6.9053E+03 | 32.97% | 16.18% | 24.46% | 6.23% | 20.16% |

4.3.3. Impact of Demand Fluctuation and SP. In this section, the impact of demand fluctuation on total cost in three RO models is compared and analyzed. Under the condition of fixed safety parameter ($\psi = \Gamma = \Omega = 4$), the impact of fluctuation on cost is explored. The calculation results are shown in Figure 9. Although the total cost of the RO model is higher than that of the deterministic LO model, even in the worst situation, the routing planning scheme can still be given. In addition, the increasing trend and proportion are quite different. Among them, the Polyhedron-RO model and Box-RO model have greater randomness, and the Ellipsoid-RO model has strong ability to resist uncertainty. Careful observation shows that the growth rate is slightly different. The cost of the Polyhedron-RO model increases sharply, while that of the Ellipsoid-RO model increases slowly.

Figure 10 analyzes the impact of the change of safety parameters on the total cost, and it can be seen that with the increase in SP, the overall logistics distribution cost shows an upward trend. Different RO models have different rising rates of cost, and the LO model is not affected by the safety parameters and maintains a low level; Polyhedron-RO model has the highest increasing rate of cost, and the most robust cost is paid for improving the safety level; Box-RO model is in the middle, and Ellipsoid model is the most stable, and lowest robust cost is paid for increasing SP.

4.3.4. Service Level and Responsiveness of Routing Planning.

In this section, three robust optimization models are analyzed by the level of service (SL). Due to the high requirements for the arrival time of service personnel in the process of HHC care, this section compares the service quality level of the model through the time difference and analyzes the advantages and disadvantages of different models. The calculation of service level is as follows:

$$S = \frac{\sum_{I,J} (1 - (y_{ij} \tilde{D}_j d_{ij} / \bar{v}_i - t) / t)}{(I + J) \sum_j \tilde{D}_j} \times 100\%, \quad (30)$$

where I, J represents the number of arcs in the model. The computer simulation results under different parameters are shown in Figures 11 and 12.

Figure 11 shows the influence of random demand fluctuation on the model under the condition of fixed safety

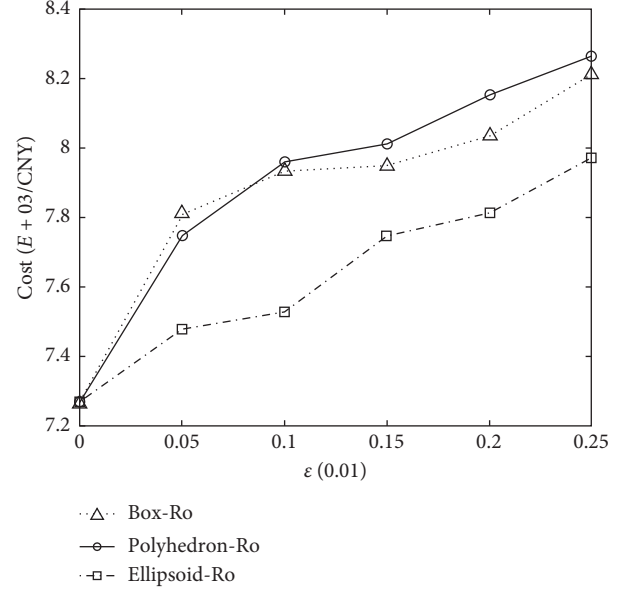


FIGURE 9: The influence of fluctuation.

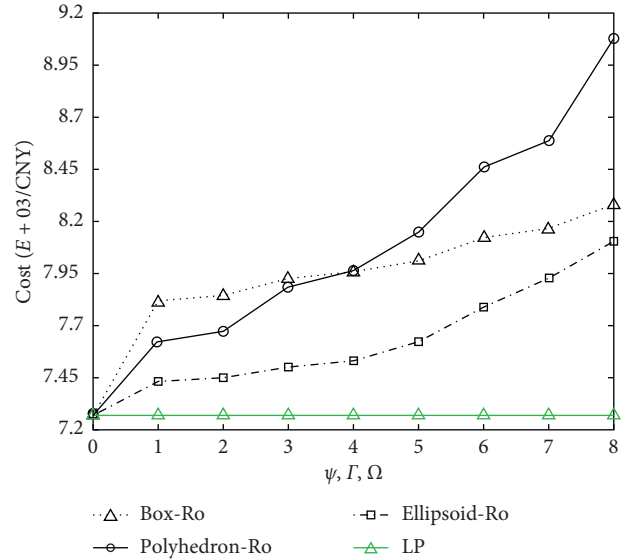


FIGURE 10: Influence of SP.

parameters ($\Psi = \Gamma = \Omega = 3$), and the following conclusions can be obtained: (i) The service level of the LO model is not affected by random parameters, and of course, it cannot solve the routing planning problem under uncertainty. However, as the data are all determined, the service level is also the highest ($SL = 93.38\%$). (ii) The service level of the three RO models shows a downward trend with the increase of random demand volatility. The larger the amplitude of random parameter fluctuation, the lower the service level. (iii) Different RO models are also affected by uncertain parameters. The relative ratio shows that the Ellipsoid-RO model has strong robustness, the Polyhedron-RO model is in the middle, the Box-RO model is the most affected by volatility, which means that Box-RO model has the weakest

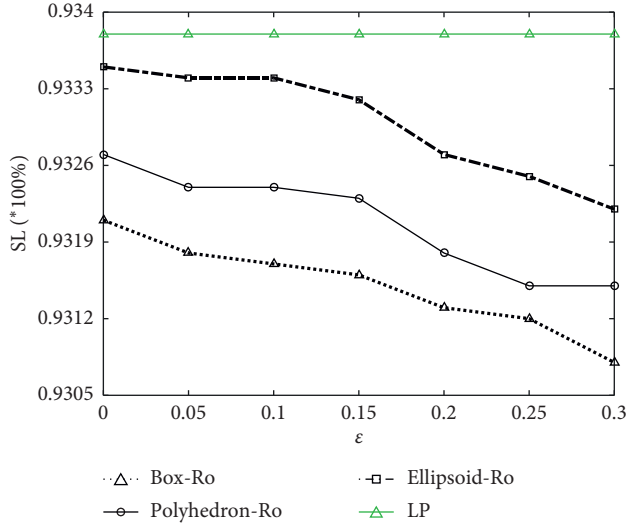


FIGURE 11: SL affected by demand volatility.

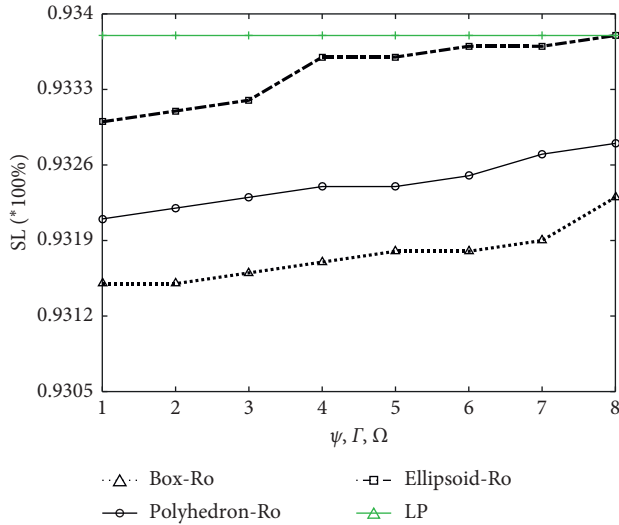


FIGURE 12: SL affected by safety parameters.

ability to resist changes in market environment, while the Ellipsoid-RO model has the best performance.

Figure 12 is an analysis of the impact of security parameters on the service level of the model under the condition of fixed random demand volatility ($\varepsilon = 0.15$). Fortunately, with the increase of security parameter level, service level shows an increasing trend. To a certain extent, it can make up for the robust cost (total cost increase) caused by uncertainty and also alleviate the loss of service level caused by stochastic demand volatility. Through careful comparison, it is found that the Ellipsoid-RO model still has strong robustness. When the security parameters increase from 1 to 8, the logistics service level increases from 93.30% to 93.38%, which is the same as the LO model. Therefore, in the actual market application, the decision maker of routing planning can determine the corresponding safety parameter level according to the preset expected service level. These studies have important reference significance for decision-making.

The following main conclusions can be drawn: (1) The basic LO model is idealized due to the market environment. In comparison, it can give the lowest total cost and the highest service level, but because the ideal data set is extremely difficult to obtain, or even unavailable, so the practical feasibility of the LO model is not high. (2) On the whole, three RO models will pay a certain robust price due to the impact of random demand fluctuations, such as increased costs, reduced service levels, and increased computational complexity, but they can solve the problem of uncertainties. The problem of path planning has a certain degree of robustness. (3) In terms of details, different RO models are also affected by uncertain demand parameters. In comparison, the Ellipsoid-RO model has strong robustness, the Polyhedron-RO model is centered, and the Box-RO model is most affected by volatility. This means that the Box-RO model has the weakest ability to resist changes in the market environment, while the Ellipsoid-RO model performs best. (4) Considering the large environmental background of the sustainable development of the economic environment, the carbon tax is studied as a cost, and it is found that when the carbon emission tax amount is increased, the company is also forced to choose a better distribution path, which not only benefits the company to save the cost but also can obtain certain environmental benefits. This discovery can provide some inspiration and reference for the low-carbon transformation and development of HHC enterprises.

5. Conclusion

Nowadays, China's economic development level is constantly improving, and the application of science and technology is constantly being updated. Especially under the severe situation that the proportion of the elderly population is constantly rising at present, the demand of all residents for community HHC is increasing accordingly. In addition, under the background of internationalization and globalization of the coordinated and sustainable development of the economic environment, the low-carbon economic model has also become an emerging development keyword for the HHC service industry. Therefore, from the perspective of a low-carbon economy, this study comprehensively considers fixed costs, transportation costs, time delay penalty costs, and carbon emission costs to explore path optimization management.

First, this paper establishes a basic linear optimization model. Under relatively ideal data, the programming algorithm is programmed through the MATLAB platform and finally solved by Gurobi with the feasible path planning scheme given. In order to prevent the alienation effect of uncertain demand parameters on the results, this article further splits random demand into nominal demand and random demand, and constructs corresponding uncertain sets, transforming linear optimization model into three robust optimization models, respectively, and then apply them to the path optimization problem of home health care service enterprise in Tangshan city. Through the case analysis of this paper, some valuable research results are

obtained, which can provide some enlightenment and reference for the low-carbon transformation and development of family health care enterprises.

Although this study considers various major factors, there are still some shortcomings, for example, the application of information technology, Internet of technology, and 5G technology in the path planning of home health care services. In the future, our research will deeply discuss the application model of science and technology. It is foreseeable that the informatization and intelligence of the HHC service industry is the development trend in the future.

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

Two-Stage Pricing Decision for Low-Carbon Products Based on Consumer Strategic Behaviour

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The development of information technology has changed the pricing strategy of retailers, and consumers have also made strategic consumption behaviours accordingly. At the same time, changes in the environment have caused changes in the retailer's products and raised consumers' environmental awareness. This paper uses a two-stage pricing model to study the low-carbon product pricing decisions of retailers based on strategic consumers with low-carbon preferences in two situations. Through the analysis of low-carbon and ordinary products in two situations, the following conclusions can be drawn: (1) In a market where retailers only sell low-carbon products, product prices and profits increase as consumers' green preference θ increases. (2) In the low-carbon product and ordinary product markets, the price and profit of low-carbon products increase with regard to consumers' green preference θ . (3) In the second stage, when consumers' intertemporal discount factor β for ordinary products is larger than that of low-carbon products, the retailer's total profit is smaller. The research conclusion comprehensively analyses the impact of customer strategic behaviour on the two-stage pricing decision of green differentiated products, which provides a very important reference for retailers to make pricing optimization decisions.

1. Introduction

With global warming and various environmental problems emerging in an endless stream [1, 2], the country has issued various related laws and policies to guide consumers and enterprises to conduct low-carbon environmental protection behaviours. In response to the national call for energy conservation and emission reduction, enterprises have developed energy-saving products. For consumers with low-carbon awareness, they are more inclined to buy low-carbon products [3]. Studies by Laroche et al. show that more consumers are willing to support higher prices for green products [4]. According to the report of the current situation of China's public green consumption (2019 Edition), 83.34% of the respondents expressed support for green consumption behaviour [5]. But for ordinary consumers, the functions of low-carbon products are the same as those of ordinary products [6], but the price is higher, so some consumers may not choose low-carbon products because of the slightly higher prices.

On the other hand, the construction and improvement of various information platforms enable consumers to learn about product attributes and price changes through various channels. Therefore, consumers choose to purchase products based on their own utility maximization, which reflects the nature of consumers' strategies [7, 8]. However, this behaviour will make retailers face the pressure of inventory and product updates. In order to alleviate the pressure, retailers will adopt measures such as price cuts and promotions, and customers will make strategic decisions based on the behaviour of the business. Therefore, retailers must take into account the strategic behaviour of consumers when making decisions to achieve their own maximum profits.

Previous research mainly focused on the coordinated pricing of a single low-carbon product supply chain. It did not consider the pricing of a single retailer in the case of product differences, and did not consider the impact of consumers' strategic behaviour on pricing. In the previous literature on the pricing of differentiated products, they generally focused on manufacturing and remanufacturing products and did not

discuss the differential pricing of low-carbon and ordinary products. In addition, consumers' low-carbon preferences will also have an important impact on retailers' pricing. When retailers set prices for low-carbon and ordinary products, they will be affected by consumer strategic behaviour and consumers' low-carbon preferences. The result will affect the retailer's profit and sales, and its pricing cannot well guide consumers to choose the products the retailer wants to sell.

Therefore, based on the green differentiated products, this paper analyses the retailer's pricing decisions under the low-carbon preference and strategic behaviour of customers. Retailers make different price decisions according to the different needs of customers, in order to reduce the backlog of inventory or make the best order quantity.

2. Literature Review

2.1. Product Pricing Decisions in Low-Carbon Supply Chain.

There are many literature studies on low-carbon products at home and abroad; most of them analyse the pricing of enterprises or supply chain from the aspects of low-carbon policy and carbon emission reduction. Guo et al. analysed the impact of the carbon tax rate and consumer carbon sensitivity factor on product pricing and designed a coordinated supply chain of carbon emission reduction cost-benefit sharing contract [9]. And mostly from a supply chain perspective, Su et al. have constructed a green supply chain pricing decision-making model with different power structures and different forms of subsidies under the context of consumer green preferences [10]. The existing literatures only make pricing decisions from the perspective of low-carbon product supply chains. However, there are not only low-carbon products but also ordinary products in the market. There are no literatures to analyze pricing decisions for green differentiated products [11, 12]. Consumers' strategic behaviour also has an important impact on product pricing. Hu and Dai studied consumer behaviour under different low-carbon product pricing strategies. It is found that incumbent manufacturers choose to produce low-carbon products and retailers choose to sell low-carbon products at high prices are the equilibrium strategy of the game between all parties [13]. Zhang et al. focus on the impacts of consumer environmental awareness (CEA) and retailer's fairness concerns on environmental quality, wholesale price, and retail price of the green product in one manufacturer and one-retailer supply chain [14, 15]. Xu et al. analyse the renewable energy from the political, technical, economic, and social perspectives [16, 17]. In order to improve the utilization rate of resources, a fuzzy resource optimal allocation model for multistage stochastic logistics tasks was proposed [18].

2.2. Pricing Decisions of Differentiated Products. There are also many literature studies on the pricing of differentiated products. Because low-carbon products have the same functions as ordinary products [19]. But low-carbon products are priced much higher than ordinary products [20]. Yang et al. studied the differential pricing decision of remanufacturing closed-loop supply chains [21]. Zhou et al. explored the influence of network externalities on the pricing strategy of quality differentiated

products [22]. Kalnins studied price changes in the dual-channel supply chain and found that price-based brand externalities have a significant impact on the choice of different quality brand sales channels [23]. Liu and Liu in an environment where low-carbon products and ordinary products co-exist, they consider that consumers have differences. Qualitative willingness to pay and consumption utility, research the supply chain's ability to price products and supply chain coordination issues [24]. When one manufacturer produces the two kinds of products, its profit will increase with the increase in carbon trading price through alliance strategy [25]. Luo et al. have studied the location and pricing of products with the same but different sales functions based on the Hotelling model [26]. Li et al. established a secondary supply chain Stackelberg game model consisting of two manufacturers (ordinary product manufacturers and low-carbon product manufacturers) and one retailer to make supply chain decisions [27].

2.3. Pricing Decisions Based on Strategic Consumers.

There are also many literature studies that examine corporate pricing decisions based on strategic consumers. Both Nair [28] and Li et al. [29] provided empirical evidence for strategic consumers and their purchasing behaviour. Whether in reality or in academia, the impact of consumers' strategic waiting and buying behaviour on business operations cannot be underestimated and ignoring consumers' tactics will bring huge economic losses to the business [30, 31]. Du et al. found that the behaviour of strategic consumers would have adverse effects on enterprises [32]. Wu et al. considered a retailer's markdown pricing and inventory decisions in multiple seasons where consumers can learn from reference prices to decide when to purchase [33]. Dong and Wu discussed the two-period pricing problem and concluded that when market demand is evenly distributed, strategic consumers may bring more benefits to manufacturers [34, 35]. But the above research ignores the low-carbon preference factors of strategic consumers. Xinmin Liu et al. distinguished three types of strategic customers according to their different preferences to analyse the optimal pricing and greenness strategies in the sustainable supply chain in strategic customer scenarios [36]. Feng et al. analysed consumer buying habits and constructed a two-stage game model between strategic consumers and retailers [37, 38]. Peng established a retailer optimization model facing homogeneous strategic consumers and used the stochastic optimal response equilibrium model to describe the limited rational behaviour of strategic consumers [39].

The above-mentioned literature analyses the pricing decisions of enterprises and retailers from the aspects of supply chain coordination, differentiated products, consumer strategy, and consumer low-carbon preference. However, there is no specific analysis on the pricing decisions of retailers selling green differentiated products under the low-carbon preference of strategic consumers. Therefore, this article takes into account the practical significance and provides decision support for retailers to determine the optimal product sales price and obtain the maximum sales profit when facing strategic consumers with low-carbon preferences. Based on the above-mentioned literature, this

article analyses the impact of retailer pricing under the consumer's low-carbon preference strategy behaviour in several aspects. One is the cost. The cost of low-carbon products is much higher than that of ordinary products; the other is consumer demand. Strategic consumers will take into account product cost, patience, and preference for low-carbon products, which will affect consumers' purchasing behaviour, which in turn affects retailers' pricing decisions.

3. Model Symbols and Assumptions

This article considers two situations. In the first model, the retailer only sells low-carbon products. After a certain period of time, some products will not be sold. The retailer will carry out certain price discount activities according to the market to stimulate consumers to consume. This will reduce the overall utility of consumers, and some consumers will wait for the timing of this price adjustment to make a purchase, which is the degree of customer strategy β .

In the second model, retailers will sell low-carbon products and ordinary products at the same time. In the second stage of the sales period, retailers will adjust the prices of different products, thereby forming a price discount coefficient, which is the degree of consumer strategy. Consumer utility is affected by the price discount coefficient, and consumers' utility for ordinary products is lower than that of low-carbon products. At the same time, which product the consumers choose is also based on consumers' green preferences.

Figure 1 shows the game sequence of retailers in different markets. Faced with two situations, the retailer pursues how to adjust prices reasonably under the influence of the above factors, and better cater to consumers' expectations, so as to maximize profits. So, this article will use the method of rational expectation equilibrium. Construct consumers' purchasing decision and retailer's pricing decision model so that retailers and customers form a game equilibrium.

In order to facilitate the analysis of the model, without loss of generality, this article is based on the following assumptions:

Assumption 1. A monopolistic retailer sells two alternative products L (low-carbon products) and N (ordinary products) with different configurations. One order is placed at the beginning of the period. The goods are sold in two stages. The first stage is full price sales, and the second stage is discount promotion. Assuming that the total number of consumers in the market is a certain value N , they are all strategic consumers, and each person can only purchase 1 product at most.

Assumption 2. p_{ij} ($i = 1, 2$, respectively, indicates the first and second sales period and $j = L, N$ indicates low-carbon products and ordinary products, respectively) is the price of the products. c_L and c_N represent the unit generation costs of low-carbon and ordinary products, respectively. q_{ij} indicates product sales.

Assumption 3. The consumer's willingness to pay is v . It obeys the uniform distribution on the interval $[0, 1]$, low-

carbon preference attributes θ , $\theta \in (0, 1)$, and $(1 + \theta)v$ represents consumers' preference for low-carbon products, which means that consumers with low-carbon preference are more inclined to choose low-carbon products.

Assumption 4. Similar to the consumer strategy degree of Zhang [40] and Ma et al. [41] in the literature is β , $\beta \in [0, 1]$. β can represent the consumer's degree of strategy; the larger the β , the greater the consumer's degree of strategy, and $\beta = 0$ means the consumer will buy the product immediately. It can also be expressed as an inter-period discount factor. In the model where low-carbon products are sold at the same time as ordinary products, consumers' psychological strategies for ordinary products in the second stage are lower than those of low-carbon products. Assuming that the degree of strategy is $k\beta$, satisfying $0 < k < 1$.

The symbols and meanings of the parameter variables involved in the article are shown in Table 1.

4. Model

4.1. The Situation Where Retailers Only Sell Low-Carbon Products (Model I). Considering that there is only one low-carbon product in the market, the price of the product changes over time, and the utility of consumers will also change as the price changes. The following uses reverse induction to analyse.

The consumer's utility function is

$$\begin{aligned} U_{1L} &= (1 + \theta)v - p_{1L}, \\ U_{2L} &= \beta(1 + \theta)v - \beta p_{2L}. \end{aligned} \quad (1)$$

In the case where the market only sells low-carbon products, consumers' purchasing decisions will be affected by their own wishes, product green preference, and strategy. When $U_{1L} > 0$ and $U_{1L} > U_{2L}$, that is $(p_{1L} - \beta p_{2L}) / (1 - \beta) < v < 1$, consumers will choose to purchase the product in the first stage. When $U_{2L} > 0$ and $U_{2L} > U_{1L}$, that is $(p_{2L} / (1 + \theta)) < v < (p_{1L} - \beta p_{2L}) / (1 - \beta) (1 + \theta)$, consumers will wait and see for a period of time and choose to buy in the second stage product.

Therefore, the demand function of low-carbon products in the first and second stages is

$$\begin{aligned} q_{1L} &= N \int_{(p_{1L} - \beta p_{2L}) / (1 - \beta) (1 + \theta)}^1 dv = N \left(1 - \frac{p_{1L} - \beta p_{2L}}{(1 - \beta) (1 + \theta)} \right), \\ q_{2L} &= N \int_{(p_{2L} / (1 + \theta))}^{(p_{1L} - \beta p_{2L}) / (1 - \beta) (1 + \theta)} dv = N \left(\frac{p_{1L} - \beta p_{2L}}{(1 - \beta) (1 + \theta)} - \frac{p_{2L}}{1 + \theta} \right). \end{aligned} \quad (2)$$

Therefore, the total sales profit of the first and second stages is

$$\Pi = (p_{1L} - c_L)q_{1L} + (p_{2L} - c_N)q_{2L}. \quad (3)$$

Find the first-order partial derivative with respect to p_{1L} and p_{2L} from equation (3) as follows:

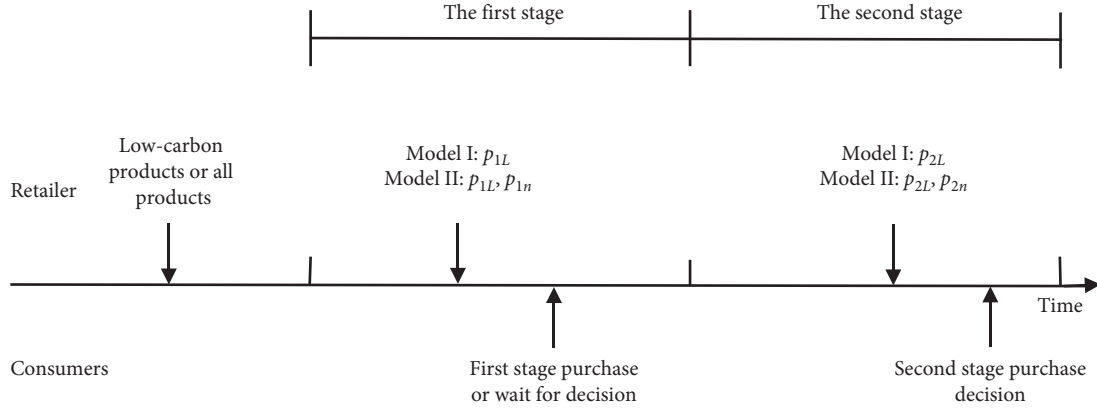


FIGURE 1: Game sequence diagram.

TABLE 1: Main parameters and parameter description.

| Parameters | Definition |
|------------|--|
| v | Consumer willingness to pay |
| θ | Consumer low-carbon preference attributes |
| β | Consumer strategy |
| N | Number of consumers |
| c_L | Cost of low-carbon products |
| p_{1L} | First stage's price of low-carbon products |
| p_{2L} | Second stage's price of low-carbon products |
| q_{1L} | First stage's demand of low-carbon products |
| q_{2L} | Second stage's demand of low-carbon products |
| γ | The proportion of products purchased by consumers in the first stage |
| c_N | Cost of ordinary products |
| p_{1N} | First stage's price of ordinary products |
| p_{2N} | Second stage's price of ordinary products |
| q_{1N} | First stage's demand of ordinary products |
| q_{2N} | Second stage's demand of ordinary products |
| Π | Total profit |

$$\frac{\partial \Pi_L}{\partial p_{1L}} = N + \frac{Np_{2L}(1+\beta) - 2Np_{1L}}{(1-\beta)(1+\theta)} = 0, \quad (4)$$

$$\frac{\partial \Pi_L}{\partial p_{2L}} = \frac{Np_{1L}(1+\beta) - 2Np_{2L}}{(1-\beta)(1+\theta)} + \frac{Nc_L - 2Np_{2L}}{1+\theta} = 0. \quad (5)$$

Find the second-order partial derivative of Π_L with respect to p_{1L} and p_{2L} as follows:

$$\frac{\partial^2 \Pi_L}{\partial p_{1L}^2} = -\frac{2N}{(1-\beta)(1+\theta)}, \quad \frac{\partial^2 \Pi_L}{\partial p_{1L} \partial p_{2L}} = \frac{N\beta + N}{(1-\beta)(1+\theta)}, \quad (6)$$

$$\frac{\partial^2 \Pi_L}{\partial p_{2L}^2} = -\frac{2N}{(1-\beta)(1+\theta)}, \quad \frac{\partial^2 \Pi_L}{\partial p_{2L} \partial p_{1L}} = \frac{N\beta + N}{(1-\beta)(1+\theta)}.$$

Through the above formula, the Hesse matrix of the second-order partial derivatives of p_{1L} and p_{2L} can be obtained as follows:

$$H(p_{1L}, p_{2L}) = \begin{bmatrix} -\frac{2N}{(1-\beta)(1+\theta)} & \frac{N\beta + N}{(1-\beta)(1+\theta)} \\ \frac{N\beta + N}{(1-\beta)(1+\theta)} & -\frac{2N}{(1-\beta)(1+\theta)} \end{bmatrix},$$

$$|H_1(p_{1L}, p_{2L})| = -\frac{2N}{(1-\beta)(1+\theta)},$$

$$|H_2(p_{1L}, p_{2L})| = \frac{N^2(3+\beta)}{(1-\beta)(1+\theta)^2}. \quad (7)$$

From formula (7), it can be seen that $H_1 < 0$ and $H_2 > 0$. The Hesse matrix is negative definite, which proves that this point is a maximum point.

Let formulas (4) and (5) are equal to 0; the two-stage retail prices of low-carbon products are

$$p_{1L}^* = \frac{2(1+\theta) + (1+\beta)c_L}{3+\beta}, \quad (8)$$

$$p_{2L}^* = \frac{(1+\theta)(1+\beta) - 2c_L}{3+\beta}. \quad (9)$$

According to formulas (8) and (9), the two-stage optimal sales volume of low-carbon products are

$$\begin{aligned} q_{1L}^* &= N \left(\frac{1+\theta - c_L}{(1+\theta)(3+\beta)} \right), \\ q_{2L}^* &= N \left(\frac{1+\theta - c_L}{(1+\theta)(3+\beta)} \right). \end{aligned} \quad (10)$$

According to formulas (8) and (9), the optimal profit of low-carbon products in a single product market is

$$\text{MAX}\Pi = N \left(\frac{1+\theta - c_L}{(1+\theta)(3+\beta)} \right) \left(\frac{(1+\theta)(3+\beta) - (7+\beta)c_L}{(3+\beta)} \right). \quad (11)$$

Proposition 1

- (1) In the first stage, the retail price p_{1L}^* of low-carbon products decreases with the increase of consumer strategy β , and the retail price p_{2L}^* of low-carbon products in the second stage decreases with the increase in consumer strategy β .
- (2) The retail price of low-carbon products in the first stage p_{1L}^* increases with consumers' green preference θ , and the retail price of low-carbon products in the second stage p_{2L}^* increases with consumers' green preference.
- (3) The optimal sales of low-carbon products in the two stages are all about β diminishing.

Proof

- (1) Calculate the derivative of p_{1L} with respect to β from formula (8), and obtain $(dp_{1L}^*/d\beta) = (2c_L - 2\theta - 2/(3+\beta)^2) < 0$, so low-carbon products are in The retail price p_{1L}^* in the first stage decreases with the increase of consumer strategy β . Calculate the derivative of p_{2L} with respect to β in formula (9), and obtain $(dp_{2L}^*/d\beta) = (2c_L - 2\theta + 2/(3+\beta)^2) > 0$, low-carbon products in the second stage. The retail price p_{2L}^* increases with the increase in consumer strategy β .
- (2) Calculate the derivative of p_{1L} with respect to θ in formula (8), and obtain $(dp_{1L}^*/d\theta) = (2/3 + \beta) > 0$, and calculate the derivative of p_{2L} with respect to θ in formula (9), and obtain $(dp_{2L}^*/d\theta) = (1 + \beta/3 + \beta) > 0$, so the prices of low-carbon products in both stages will increase with the increase in consumers' low-carbon preference θ .
- (3) Since $q_{1L}^* = q_{2L}^*$, $(dq_{1L}^*/d\beta) = (dq_{2L}^*/d\beta) = -(N(1+\theta)(1+\theta - c_L)/(\beta + \theta\beta + 3 + 3\theta)^2) < 0$, so the optimal

sales of low-carbon products in the two stages are all about β decreasing. \square

4.2. The Situation Where a Retailer Sells Low-Carbon Products and Ordinary Products at the Same Time (Model II). In the case of low-carbon preference consumers, considering that there are both low-carbon products and ordinary products on the market, the two have formed a situation of mutual competition and substitution. Assuming that consumers have a preference for low-carbon products θ , ($0 < \theta < 1$), and consumers' preference for ordinary products is less than their preference for low-carbon products; the utility function of the first stage of consumers is:

$$\begin{aligned} U_{1L} &= (1+\theta)v - p_{1L}, \\ U_{1N} &= v - p_{1N}. \end{aligned} \quad (12)$$

In the first stage, when the market sells both low-carbon products and ordinary products, consumers' purchasing decisions will be affected by their own wishes and preference for green products. Through graph analysis, when consumers' preference for low-carbon products is within the range of $\theta \in (0, 1)$, when $U_{1L} > 0$ and $U_{1L} > U_{1N}$, consumers' willingness to pay for low-carbon products is $\max\{(p_{1L}/1 + \theta) < v < (p_{1L} - p_{1N}/\theta)\} < v < 1$, when $(p_{1L}/1 + \theta) < (p_{1L} - p_{1N}/\theta)$, that is $(p_{1L} - p_{1N}/\theta) < v < 1$, consumers will choose to buy low-carbon products. When $U_{1N} > 0$ and $U_{1N} > U_{1L}$, that is $p_{1N} < v < (p_{1L} - p_{1N}/\theta)$, consumers will choose to buy ordinary products. Figure 2 is an analysis using the consumer utility function graph.

According to the consumer utility function, the market demand function is

$$q_{1L} = \gamma N \int_{(p_{1L} - p_{1N}/\theta)}^1 f(v) dv = \gamma N \left(1 - \frac{p_{1L} - p_{1N}}{\theta} \right), \quad (13)$$

$$q_{1N} = \gamma N \int_{p_{1N}}^{(p_{1L} - p_{1N}/\theta)} f(v) dv = \gamma N \left(\frac{p_{1L} - p_{1N}}{\theta} - p_{1N} \right), \quad (14)$$

γ represents the proportion of consumers who bought the product in the first stage. The profit functions of retailers selling low-carbon products and ordinary products in the first stage are

$$\Pi_{1L} = (p_{1L} - c_L)q_{1L} = \gamma N (p_{1L} - c_L) \left(1 - \frac{p_{1L} - p_{1N}}{\theta} \right), \quad (15)$$

$$\Pi_{1N} = (p_{1L} - c_N)q_{1N} = \gamma N (p_{1L} - c_N) \left(\frac{p_{1L} - p_{1N}}{\theta} - p_{1N} \right). \quad (16)$$

If $(p_{1L}/1 + \theta) > (p_{1L} - p_{1N}/\theta)$, that is, $(p_{1L}/1 + \theta) < v < 1$, in this case, the consumer utility of low-carbon products is always higher than that of ordinary products.

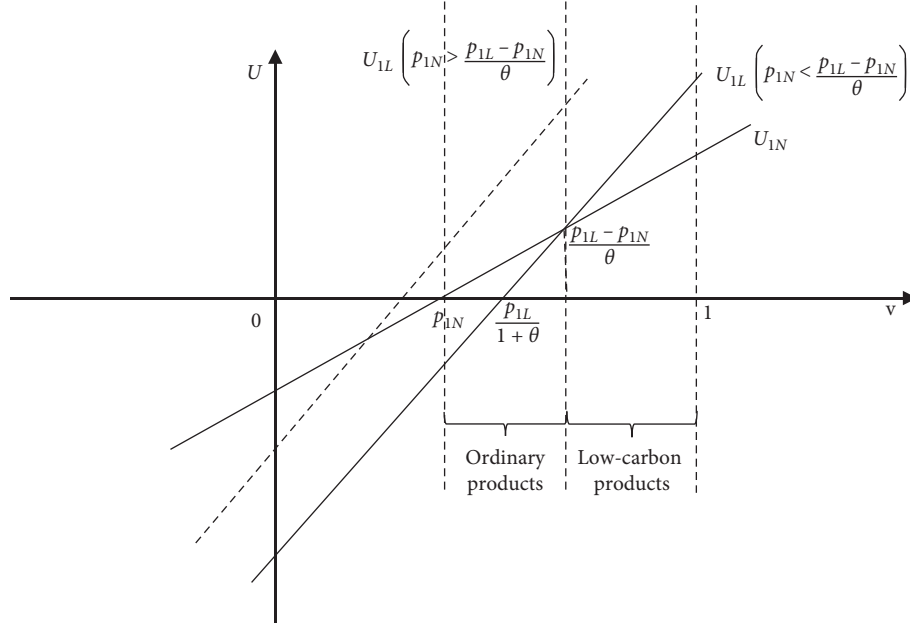


FIGURE 2: Relationship between consumer willingness and utility.

Effectiveness: consumers will definitely choose to buy low-carbon products, but this kind of situation does not match the actual sales situation, so we will not discuss it.

In the second stage, after a certain period of time sales, consumers will reduce their enthusiasm for the product and make more rational decisions. Strategic consumers will make strategic purchases. At the same time, strategic consumers will be affected by their patience, and their low-carbon levels are different for different products. Thus, the utility function expression

$$\begin{aligned} U_{2L} &= \beta(1 + \theta)v - \beta p_{2L}, \\ U_{2N} &= k(\beta v - \beta p_{2N}). \end{aligned} \quad (17)$$

When consumers' preference for low-carbon products is within the range of $\theta \in (0, 1)$, when $U_{2L} > 0$ and $U_{2L} > U_{2N}$, $\max\{(p_{2L}/1 + \theta), (p_{2L} - kp_{2N}/1 + \theta - k)\} < v < 1$; similar to the first stage, we do not consider the case of $(p_{2L}/1 + \theta) > (p_{2L} - kp_{2N}/1 + \theta - k)$. When $(p_{2L}/1 + \theta) < (p_{2L} - kp_{2N}/1 + \theta - k)$, that is $(p_{2L} - kp_{2N}/1 + \theta - k) < v < 1$, consumers will choose to buy low-carbon products; when $U_{2N} > 0$ and $U_{2N} > U_{2L}$ that is $p_{2N} < v < (p_{2L} - kp_{2N}/1 + \theta - k)$, consumers will choose to buy ordinary products in the second stage.

Therefore, the consumer demand function is

$$q_{2L} = (1 - \gamma)N \int_{(p_{2L} - kp_{2N}/1 + \theta - k)}^1 f(v)dv = (1 - \gamma)N \left(1 - \frac{p_{2L} - kp_{2N}}{1 + \theta - k}\right), \quad (18)$$

$$q_{2N} = (1 - \gamma)N \int_{(p_{2L} - kp_{2N}/1 + \theta - k)}^1 f(v)dv = (1 - \gamma)N \left(\frac{p_{2L} - kp_{2N}}{1 + \theta - k} - p_{2N}\right). \quad (19)$$

The retailer profit function is

$$\Pi_{2L} = (p_{2L} - c_L)q_{2L} = (1 - \gamma)N(p_{2L} - c_L) \left(1 - \frac{p_{2L} - kp_{2N}}{1 + \theta - k}\right), \quad (20)$$

$$\Pi_{2N} = (p_{2N} - c_N)q_{2N} = (1 - \gamma)N(p_{2N} - c_N) \left(\frac{p_{2L} - kp_{2N}}{1 + \theta - k} - p_{2N}\right). \quad (21)$$

Combining formulas (15), (16), (20), and (21), the total sales profit of low-carbon products and ordinary products in the first and second stages is

$$\Pi = \Pi_{1L} + \Pi_{1N} + \Pi_{2L} + \Pi_{2N}. \quad (22)$$

In order to maximize the profit, find the first-order partial derivatives of p_{1L} , p_{1N} , p_{2L} , and p_{2N} for equation (22) as follows:

$$\begin{aligned}
\frac{\partial \Pi_L}{\partial p_{1L}} &= \frac{\gamma N (\theta - 2p_{1L} + c_L + 2p_{1N})}{\theta}, \\
\frac{\partial \Pi_L}{\partial p_{1N}} &= \frac{\gamma N (2p_{1L} - c_L - 2p_{1N} - 2\theta p_{1N} + \theta c_N + c_N)}{\theta}, \\
\frac{\partial \Pi_L}{\partial p_{2L}} &= \frac{(1-\gamma)N(1+\theta-k-2p_{2L}+c_L+kp_{2N}+p_{2N}-c_N)}{1+\theta-k}, \\
\frac{\partial \Pi_L}{\partial p_{2N}} &= \frac{(1-\gamma)N(kp_{2L}-kc_L+p_{2L}-2p_{2N}-2\theta p_{2N}+c_N+\theta c_N)}{1+\theta-k}.
\end{aligned} \tag{23}$$

The two-stage optimal retail prices of the two products obtained by the first-order partial derivative are

$$p_{1L}^* = \frac{1+\theta+c_L}{2}, \tag{24}$$

$$p_{1N}^* = \frac{1+c_N}{2}, \tag{25}$$

$$p_{2L}^* = \frac{(-k^2-k+2+2\theta)c_L+(k+k\theta-1-\theta)c_N-2k+2\theta^2-2\theta k+2+4\theta}{3+4\theta-k^2-2k}, \tag{26}$$

$$p_{2N}^* = \frac{(1-k)c_L+(1+2\theta-k)c_N-k^2+\theta k+1+\theta}{3+4\theta-k^2-2k}. \tag{27}$$

Take the above formula into (13), (14), (18), and (19) to get the optimal sales volume as follows:

$$q_{1L}^* = \gamma N \left(1 - \frac{\theta + c_L - c_N}{2\theta} \right), \tag{28}$$

$$q_{1N}^* = \gamma N \left(\frac{c_L - c_N - \theta c_N}{2\theta} \right), \tag{29}$$

$$\begin{aligned}
q_{2L}^* &= (1-\gamma)N \left(1 - \frac{(2+2\theta-2k)c_L + (k^2 - \theta k - 1 - \theta)c_N}{(3+4\theta-k^2-2k)(1+\theta-k)} \right. \\
&\quad \left. - \frac{-3k+2\theta^2-3\theta k+2+4\theta+k^3-\theta k^2}{(3+4\theta-k^2-2k)(1+\theta-k)} \right),
\end{aligned} \tag{30}$$

$$\begin{aligned}
q_{2N}^* &= (1-\gamma)N \left(\frac{(2+2\theta-2k)c_L + (k^2 - \theta k - 1 - \theta)c_N}{(3+4\theta-k^2-2k)(1+\theta-k)} \right. \\
&\quad + \frac{-3k+2\theta^2-3\theta k+2+4\theta+k^3-\theta k^2}{(3+4\theta-k^2-2k)(1+\theta-k)} \\
&\quad \left. - \frac{(1-k)c_L + (1+2\theta-k)c_N - k^2 + \theta k + 1 + \theta}{3+4\theta-k^2-2k} \right).
\end{aligned} \tag{31}$$

Substituting equations (24)–(31) into equation (22), the total profit of low-carbon products and ordinary products in the two stages is

$$\begin{aligned}
 \Pi^* = & \gamma N \left(1 - \frac{\theta + c_L - c_N}{2\theta} \right) \left(\frac{1 + \theta + c_L}{2} - c_L \right) + \gamma N \left(\frac{c_L - c_N - \theta c_N}{2\theta} \right) \left(\frac{1 + c_N}{2} - c_N \right) \\
 & + (1 - \gamma) N \left(\frac{(-k^2 - k + 2 + 2\theta)c_L + (k + k\theta - 1 - \theta)c_N - 2k + 2\theta^2 - 2\theta k + 2 + 4\theta}{3 + 4\theta - k^2 - 2k} - c_L \right) \\
 & \cdot \left(1 - \frac{(2 + 2\theta - 2k)c_L + (k^2 - \theta k - 1 - \theta)c_N}{(3 + 4\theta - k^2 - 2k)(1 + \theta - k)} - \frac{-3k + 2\theta^2 - 3\theta k + 2 + 4\theta + k^3 - \theta k^2}{(3 + 4\theta - k^2 - 2k)(1 + \theta - k)} \right) \\
 & + (1 - \gamma) N \frac{(2 + 2\theta - 2k)c_L + (k^2 - \theta k - 1 - \theta)c_N}{(3 + 4\theta - k^2 - 2k)(1 + \theta - k)} + \frac{-3k + 2\theta^2 - 3\theta k + 2 + 4\theta + k^3 - \theta k^2}{(3 + 4\theta - k^2 - 2k)(1 + \theta - k)} \\
 & - \frac{(1 - k)c_L + (1 + 2\theta - k)c_N - k^2 + \theta k + 1 + \theta}{3 + 4\theta - k^2 - 2k} \left(\frac{(1 - k)c_L + (1 + 2\theta - k)c_N - k^2 + \theta k + 1 + \theta}{3 + 4\theta - k^2 - 2k} - c_N \right).
 \end{aligned} \tag{32}$$

Analysing the optimal solution in this situation, we can get

Proposition 2

- (1) In the first stage, the retail price p_{1N} of ordinary products has nothing to do with the customer's greenness θ of low-carbon products, while the retail price p_{1L} of low-carbon products increases with the increase in θ . In the second stage, p_{2L} increases with the increase in θ . p_{2N} decreases as θ increases.
- (2) In the first stage, the sales volume of low-carbon products q_{1L}^* increases as θ increases. The sales volume of ordinary products q_{1N}^* decreases with the increase in θ . In the second stage, the sales volume of low-carbon products increases with the increase in θ , and the sales volume of ordinary products decreases with the increase in θ .

Proof

- (1) From equation (25), p_{1N} has nothing to do with θ . Calculating the derivative of p_{1L}^* with respect to θ in equation (24) is $(dp_{1L}/d\theta) = (1/2) > 0$, so p_{1L} increases as θ increases. Calculating the derivative of p_{2L}^* with respect to θ in equation (26) is $(dp_{2L}/d\theta) = -((c_N - 2)k^3 + (4\theta + c_N - 2c_L)k^2 + (8\theta^2 + 4)k - 8\theta^2 - 8\theta - 2c_N + 4c_L/k^4 + 4k^3 - 8\theta k^2 + (-16\theta^2 - 8)k + 16\theta^2 + 16\theta + 4) > 0$; find p_{2L}^* for equation (27). The derivative of θ is $(dp_{2N}/d\theta) < 0$; so in the second stage, p_{2L} increases with the increase in θ . p_{2N} decreases as θ increases.
- (2) Calculating the derivative of q_{1L}^* with respect to θ from equation (28) is $(dq_{1L}^*/d\theta) = (\gamma N (c_L - c_N)/2\theta^2) > 0$. Therefore, the sales volume of low-carbon products in the first stage increases with the increase in customers' green preference.

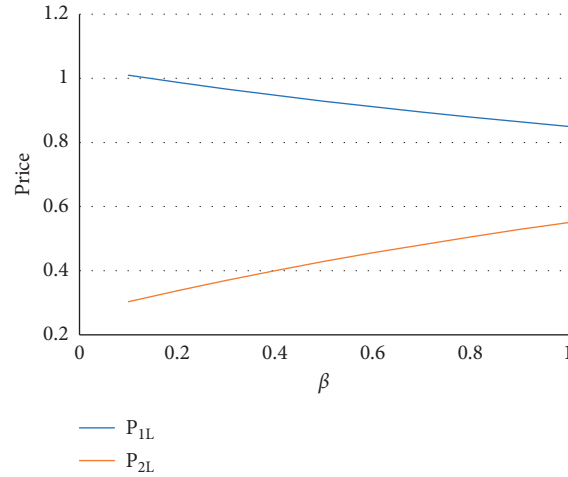
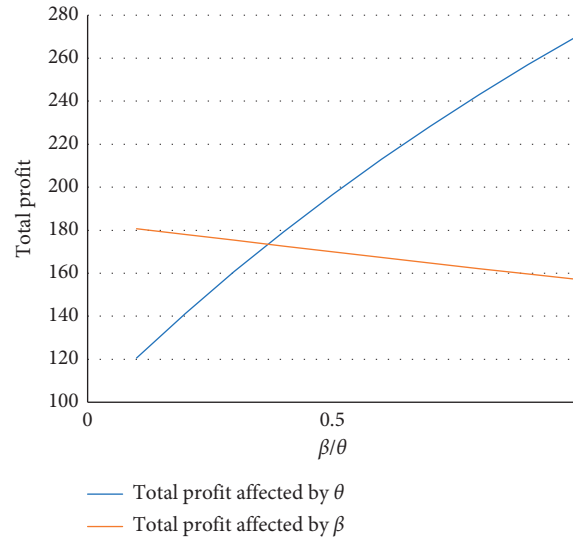
$(dq_{1N}^*/d\theta) = (\gamma N (c_N - c_L)/2\theta^2) < 0$, so, the sales volume of ordinary products in the first stage decreases with the increase in customers' green preference. In the second stage, the sales volume of low-carbon products decreases with the increase in θ , and the proposition that the sales volume of ordinary products increases with the increase in θ will be verified in the numerical analysis in Chapter 5. \square

5. Numerical Analysis

5.1. Model I

5.1.1. The Influence of Parameter β on Product Price. Assuming $c_L = 0.3$, $\beta \in (0, 1)$, $\theta \in (0, 1)$, $N = 1000$, and $c_N = 0.2$, study the influence of parameter β on the price of low-carbon products. From Figure 3, it is found that given a value of θ , the price of low-carbon products decreases with the increase in β in the first stage, and increases with the increase in β in the second stage. It shows that in the first stage, the greater the degree of customer strategy, the lower the price. In the second stage, the greater the degree of customer strategy, the greater the price. And the second stage is more affected by θ than the first stage.

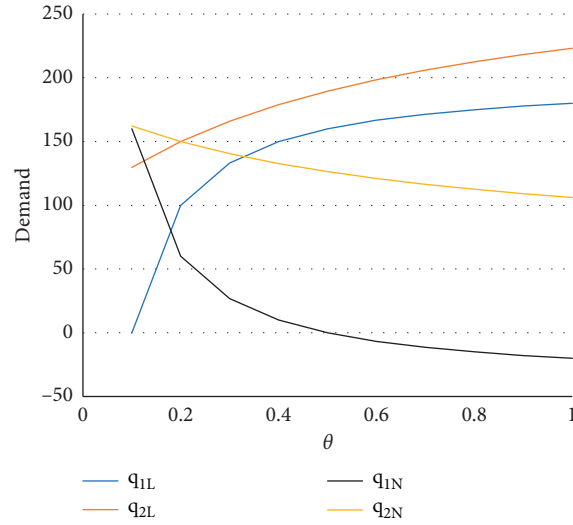
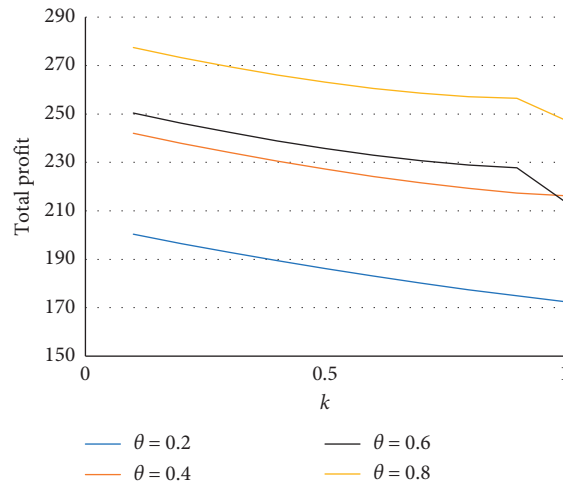
5.1.2. The Influence of Parameters β and θ on Total Profit. In the Figure 4, given the value of β , study the effect of θ on total profit. It is found that the influence of customers' low-carbon preference on profit is positive, and the total profit will increase with the increase in θ . Given the value of θ , study the effect of β on total profit and found that the impact of customer strategy on total profit is negative. The greater the customer strategy, the lower the total profit. This is because customers choose the time to purchase based on their own utility maximization. For retailers at this time, the price is lower and may cause a certain inventory cost.

FIGURE 3: The influence of parameter β on product price.FIGURE 4: The influence of parameters β and θ on total profit.

5.2. *Model II.* Assuming $c_L = 0.3$, $\beta \in (0, 1)$, $\theta \in (0, 1)$, $N = 1000$, and $c_N = 0.2$, $\gamma = 0.4$. As the Figure 5 shows that given a β value and a k value to studies the influence of the price of each stage of parameter θ . It was found that consumers' low-carbon preference has a positive effect on low-carbon products' demand and has a slight negative effect on ordinary products' demand. In the first stage, consumers' low-carbon preferences have a more significant impact on demand, while the second stage is relatively flat.

Consider $\theta = 0.2, 0.4, 0.6$, and 0.8 to study the influence of parameter k on the total profit of the two stages. As the Figure 6 shows that given the values of β and θ , the total profits of the two stages will increase as the difference in discount strength between the two products increases. When the value of k is larger, the retailer's total profit is

smaller, and the two products are negatively correlated. That is, when the intertemporal discount coefficient of consumers in the second stage of ordinary products is larger, the retailer's total profit is smaller. Therefore, for retailers, only two products with similar discount strength can increase total profit. When we give the value of k , we find that the retailer's total profit increases as consumers' low-carbon preference increases. In other words, the greater the customer's green preference, the more beneficial to the retailer. Consumers' green preference means that consumers are more willing to buy low-carbon products. In the first stage, the price of ordinary products has nothing to do with green preference, while the price of low-carbon products increases with the increase in θ , which leads to increased profits for retailers.

FIGURE 5: The influence of parameters θ on demand.FIGURE 6: The influence of parameters k on total profit.

6. Conclusions and Discussion

This paper studies the two-stage pricing model of green differentiated products based on customer strategic behaviour. First, it analyses the two-stage sales market where there is only one low-carbon product and finds the optimal pricing decision and the optimal sales volume at each stage. The study found

- (1) The price of low-carbon products in the first stage decreases as the customer's strategy degree increases, and the price of low-carbon products in the second stage increases as the customer's strategy degree increases.
- (2) The sales volume of low-carbon products in the two phases is the same and decreases with the increase in customer strategy.
- (3) The total profit of two-stage sales of low-carbon products also decreases with the increase in customer strategy.

Secondly, the two-stage pricing model with low-carbon and ordinary products is studied. The study found

- (1) The retail price of ordinary products in the first stage has nothing to do with customers' green preference θ , while the retail price of low-carbon products increases with respect to θ . In the second stage, the retail prices of low-carbon and ordinary products are all θ increasing.
- (2) The demand for low-carbon products in both stages increases with the increase in consumers' low-carbon preference, while the demand for ordinary products is the opposite.

- (3) The total profit of the two stages increases with the increase in θ , and the greater the intertemporal discount factor β of consumers for ordinary products in the second stage compared with low-carbon products, the smaller the retailer's total profit.

Therefore, there are the following inspirations for retailers:

In Model I, consumers' low-carbon preference is positively correlated with retailers' prices and profits, and the degree of consumer strategy has a greater impact on retailers. The higher the degree of consumer strategy, that is to say, the greater the retailer's discount, the more consumers prefer to buy in the second stage. In order to maintain the retailer's overall profit, the retailer's price should be maintained at an appropriate level, and consumers should be encouraged to buy products in the first stage through advertising and other means. Secondly, do not discount or make the discount too large; because if the discount is too strong, the consumer's strategy level will increase, which will reduce the retailer's profit.

In Model II, consumers' green preference has a huge impact on retailers' profits. Retailers can improve consumers' low-carbon preference through the following points. First, increase publicity and promote low-carbon knowledge through posters, advertisements, and publicity boards. Second, mark the carbon footprint of a product for consumers to understand and choose. Third, implement green packaging for products. Fourth, promote a low-carbon economic model.

The greater the difference in discount strength between the two products, the smaller the retailer's profit. Therefore, retailers should reduce the discount difference between low-carbon and ordinary products, and the greater the green preference of consumers, the greater the total profit. When retailers are selling two products, they can promote consumers' green preferences through advertising and so on, so as to encourage consumers to buy more low-carbon products.

The research of this article can be expanded from the following aspects. This article studies the retailer's pricing decision under the low-carbon preference consumer strategy, but does not involve the perspective of the supply chain. The subsequent research can start from the coordination of the entire supply chain.

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 Impact of Different Government Subsidy Methods on Low-Carbon Emission Reduction Strategies in Dual-Channel Supply Chain

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With the implementation of national carbon emission reduction policies and the development of online shopping, manufacturers are making low-carbon efforts and selling products through dual channels. This paper constructs a dual-channel supply chain decision-making model composed of low-carbon emission reduction manufacturers and retailers and studies the optimal decision-making problem of the supply chain under subsidies by the government based on emission reduction R&D and per unit product emission reduction. The research results show the following: (1) when the government subsidizes emission reduction R&D, the emission reduction will have an impact on retailers' optimal prices, manufacturers' optimal wholesale prices, and optimal direct sales channel sales prices. The profit of the manufacturer increases with the increase in carbon emissions, and the profit of the manufacturer increases to a certain level and then appears to decline. (2) When the government adopts a subsidy method based on the emission reduction per unit product, the manufacturer's wholesale price and the selling price of direct sales channels, as well as the retailer's own optimal price, will increase with the increase in emission reductions. Retailers' profits will increase linearly with the increase in carbon emissions. Manufacturers' profits will first increase in a straight line and then increase in a curve.

1. Introduction

Nowadays, China is facing environmental pollution problems, and lots of Chinese cities have encountered smog pollution and extreme high PM_{2.5} [1]. China proposed in 2016 that carbon dioxide emissions per unit of GDP will be reduced by 60%–65% by 2030 compared to 2005 [2]. In order to curb the growth of carbon emissions and complete the energy development strategy action plan, the Chinese government has promulgated many policies to increase the enthusiasm of enterprises to reduce carbon emissions, such as subsidies, tax incentives, and government priority procurement. Among them, government subsidies are considered to be generally effective policies [3].

These measures indicate the necessity for enterprises to change the traditional economic development model, and low-carbon development model is the future economic

development trend. Under this environmental and policy background, companies are under external pressure to carry out green and low-carbon activities and invest in low-carbon R&D in the production process to improve production technology and reduce carbon emissions in the production process [4]. Some large companies actively take new actions and even reduce carbon emissions through innovative research and development to show their social responsibility and enhance their public image and reputation.

Furthermore, in the context of the rapid development of e-commerce and mobile Internet, consumer shopping behavior is shifting to online shopping, prompting manufacturers to maintain traditional retail channels while opening up online sales channels and directly obtain market information to occupy more market shares. Manufacturers provide the same low-carbon products for retail channels and online sales channels in the dual-channel supply chain.

Due to factors such as product pricing and shopping convenience, the online sales channels opened by manufacturers will inevitably cause conflicts and competition between channels. They will cause problems that damage the profits of retailers or reduce the low-carbon efforts of manufacturers and change the cooperative relationship between upstream and downstream enterprises in the supply chain [5].

Nevertheless, due to different subsidy methods, the effects of subsidies are different. Based on the above situation, this paper will consider the dual-channel supply chain of low-carbon emission reduction under different government subsidies and try to explore how to make different emission reduction decisions under different government subsidies for manufacturers to obtain greater benefits and different energy conservation and emission reduction effects produced by different government subsidies.

2. Literature Review

The research related to this paper mainly focuses on three aspects: government subsidies, low-carbon supply chain, and dual-channel supply chain. Therefore, this section will summarize the above three parts.

2.1. Low-Carbon Supply Chain. In recent years, there are many literature studies about low-carbon supply chain. In terms of product pricing strategy and profit, Huang et al. found that fairness preferences changed retail prices, wholesale prices, greenness levels, and scrap recycling rates, and it affects the profit and utility of manufacturers and distributors as well as the total profit of supply chain [6, 7]. In addition, Madani and Rasti-Barzoki also analyzed the pricing and emission reduction strategies of the supply chain. They developed a competitive mathematical model of government as the leader and two competitive green and nongreen supply chains as the followers [8]. In terms of supply chain coordination, Liu and Yi discussed the coordination and cooperation mechanism between manufacturers and retailers when demand is affected by product greenness [9]. Zhang et al., Basiri, and Heydari analyzed the impact of consumer environmental awareness and product greenness on supply chain coordination [10, 11]. In terms of emission reduction strategies, by constructing a cooperative emission reduction income distribution plan, Wang et al. gave the emission reduction income distribution coefficient in the region and initial income distribution matrix of every subject, in order to improve various entities' cooperation to reduce emissions [12]. Wang et al. investigated a fresh food supply chain comprising a large-scale supplier and multiple small-scale retailers. They researched retailers' joint replenishment and supply chain members' carbon trading behavior [13]. Under the secondary supply chain consisting of a risk-averse manufacturer and a risk-averse retailer, Bai et al. have established a retail-led and manufacturer-led supply chain model under the constraints of low-carbon emission reduction [14]. Chen et al. considered the dual-information asymmetry of the enterprise's emission

reduction technology level and emission reduction capital investment and study the design of enterprise emission reduction incentive contracts [15]. Xu et al. proposed a multiobjective optimization model to solve the dynamic vehicle routing problem with limited supply in oil distribution and found that the variable neighborhood dynamic vehicle planning model is superior to other comparable schemes in terms of cost saving and satisfaction improvement [16, 17]. Xu et al. proposed a model which can effectively utilize the fuzzy resources in collaborative logistics network and avoid the resource shortage problem caused by excessive occupation of local resources [18, 19].

2.2. Dual-Channel Supply Chain. Channel coordination can make the operation of the supply chain more efficient, and channel members can benefit from it. As a result, scholars have carried out a lot of research on the coordination of dual-channel supply chain. Li et al. studied the coordination strategies of different supply chain entities in a supply chain composed of recyclers, remanufacturers, and two distributors and discussed four different coordination strategies and performed optimal decisions on different models [20]. Pu et al. found that consumers' free riding has a certain impact on the sales effect of dual-channel supply chain and proposed a cost sharing contract to achieve the coordination between them [21]. Xu et al. considered carbon allowances, carbon trading system, and consumer channel preferences, studied the impact of channel substitution on pricing and carbon emission reduction strategies, and encouraged retailers to share their revenue and cost by cutting the wholesale price so as to realize supply chain coordination [22]. Zhou considered the initial demand of physical channels and online channels and studied the supply chain channel structure selection strategy based on the relative rate of customer channel preference between manufacturers and physical retailers as decision makers [23]. Based on the differences in the game power of supply-chain members, Sun et al. constructed two types of Stackelberg games where the manufacturer dominated or the retailer dominated and the Nash game model where both parties have equal power and analyzed the impact of the three game power structures on supply chain members [24]. Wang et al. solved the optimal decision-making problem of the manufacturer and retailer under wholesale price contract and revenue sharing contract by constructing a two-channel supply chain game model [25]. Liang and Wei established a dual-channel supply chain decision-making model consisting of manufacturers and retailers with input innovation and studied the influence of government's simultaneous use of R&D subsidies and production subsidies on supply chain innovation, pricing, and profit [26].

2.3. Government Subsidies. Another closely related literature stream is government subsidies. Maria et al. pointed out that government R&D subsidies can promote enterprise R&D investment [27]. Michalsen found that when the downstream market is highly concentrated, the government provides the best R&D subsidy strategy. In other cases,

providing tax incentives is the optimal strategy [28]. Tong and Li found that both green manufacturers and retailers can benefit from government subsidies and green cost sharing contracts, but they are related to R&D cost coefficients, green sensitivity coefficients, and price sensitivity coefficients [29, 30]. Nielsen et al. found that when manufacturers set a green degree, compared with the government's incentive policies for R&D, supply chain members will obtain higher profits at lower sales prices, higher consumer surplus, and improved environment [31, 32]. He et al. considered the two scenarios of manufacturers' independent research and development of emission reduction and outsourcing emission reduction tasks and studied the optimal decision-making problem of the supply chain under the government subsidies based on emission reduction research and development and unit product emission reduction [33, 34]. Based on the two recycling modes, Xia and Zhu constructed the game model of recyclers and processors under different government subsidy strategies, compared and analyzed the influence of government subsidies on the decision variables, recycling quantity, and revenue of recycling channels, and determined the boundary conditions of the optimal recycling model [35, 36]. Zu et al. analyzed the impact of consumers' environmental awareness on profits and decision-making in different situations. Their research results showed that under centralized decision-making, an increase in the carbon tax rate will increase the low-carbon level of products and reduce the present value of profits in the supply chain. In order to mobilize the enthusiasm of enterprises to reduce emissions, the government can take into account the environmental objectives and the interests of enterprises to formulate a reasonable carbon tax policy [37, 38].

By reviewing the above literature, we can find that scholars have lots of studies on low-carbon supply chains and obtained many research results. We can see that the existing research on low-carbon supply chain is mostly from the perspective of product pricing, supplier cooperation, and corporate emission reduction strategies. For the dual-channel supply chain generated under the background of the Internet, the existing research mostly starts from the perspectives of supplier optimal decision-making, supplier power structure, and supplier cooperation in reducing emissions. In addition, in order to promote enterprises to actively participate in emission reduction activities, the Chinese government has introduced many subsidy policies in recent years. Existing studies on government subsidies are mostly based on the impact of subsidy policies on enterprises' participation in emission reduction and the game relationship between the government and enterprises. However, the research on dual-channel supply chain is still in its infancy. The existing literature rarely combines dual-channel supply chains with government subsidies, and there are fewer studies considering the differences in government subsidies. On the basis of the existing research and different from the literature above, we try to construct a dual-channel supply chain decision-making model composed of low-carbon emission reduction manufacturers and retailers and analyze the impact of different government subsidies on manufacturers and retailers in the dual-channel supply chain.

3. Problem Description and Model Hypotheses

So as to research the emission reduction strategies of the manufacturer's dual-channel supply chain under different government subsidies, this paper establishes a dual-channel supply chain model which is shown in Figure 1 consisting of a retailer and a manufacturer. The government can decide to subsidize manufacturers based on two different subsidy methods: emission reduction per unit product or emission reduction R&D investment. At the same time, manufacturers wholesale products to retailers through traditional channels on the one hand and sell products directly to the market through online channels, forming a dual-channel supply chain.

Assumption 1. Because market demand is negatively correlated with sales price and positively correlated with product low-carbon attributes and there is a price competition between channels, this paper refers to the channel demand function established by Li et al. [39] to set the demand function of traditional retail channels and online sales channels.

They are

$$D_r = \theta A - p_i^r + \beta p_i^m + k e_i, \quad (1)$$

$$D_m = (1 - \theta)A - p_i^m + \beta p_i^r + k e_i, \quad (2)$$

where D_r represents the demand of traditional retail channels, D_m represents the demand of online direct sales channels, A is the potential market size, θ ($0 \leq \theta \leq 1$) is the market share occupied by traditional channels, $1 - \theta$ is the market occupied by direct sales channels share, p_i^r is the product price in the traditional retail channel under the i -subsidy method, p_i^m is the product price in the i -subsidy network direct sales channel, β represents the cross-price elasticity coefficient of the traditional channel and the direct sales channel ($0 < \beta < 1$), k represents the level of consumer environmental awareness ($0 < k < 1$), and e_i represents the emission reduction per unit product under the i -subsidy method.

Assumption 2. The manufacturer's unit manufacturing cost remains unchanged, and the raw material procurement cost is the main factor. Other costs such as equipment and manpower are not considered for the time being. When increasing investment in emission reduction R&D, the cost of carbon emission reduction R&D investment and emission reduction are quadratic [40]. The manufacturer's carbon emission reduction R&D cost is $(1/2)Ie_i^2$, where I represents the manufacturer's emission reduction R&D cost coefficient.

Assumption 3. In order to promote manufacturers to reduce carbon emissions, the government will give manufacturers certain financial subsidies. Assume that the government subsidizes manufacturers in two forms [41]: firstly, subsidies are based on the manufacturer's emission reduction per unit product. The government's subsidy expenditure for emission reduction per unit product is λe_i , where λ is the emission

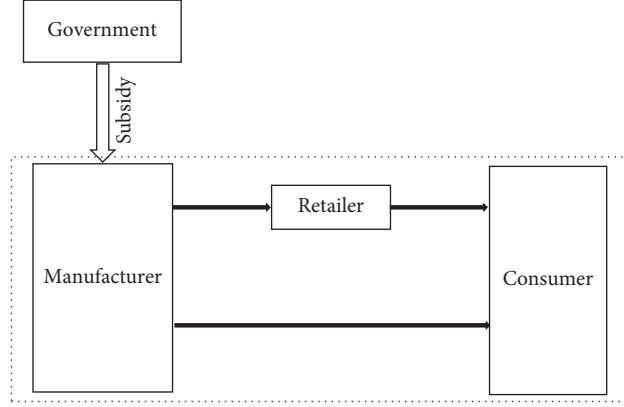


FIGURE 1: Dual-channel supply chain.

reduction subsidy coefficient per unit product; secondly, some subsidies are given according to the manufacturers' R&D investment. According to the expression of carbon emission reduction R&D investment, the total government R&D investment subsidy expenditure is te_2^2 , where t is the R&D subsidy coefficient of emission reduction.

Assumption 4. In the supply chain game model of this paper, the game sequence is that the government first determines the subsidy method, then the manufacturer determines the emission reduction e_i , the wholesale price w_i , and the direct sales price p_i^m , and finally the retailer determines the traditional channel sales price p_i^r , as shown in Figure 2.

All the parameters and their definitions involved in this paper are summarized in Table 1.

4. Model Analysis

4.1. Situation 1: under the Subsidy Method of Emission Reduction per Unit Product. In this situation, government subsidizes emission reductions per unit product and manufacturers choose to independently research and develop emission reductions. The profits of the manufacturer (π_1^m) and the retailer (π_1^r) are

$$\pi_1^m = w_1 D_r + p_1^m D_m + \lambda e_1 (D_r + D_m) - \frac{1}{2} I e_1^2, \quad (3)$$

$$\pi_1^r = (p_1^r - w_1) D_r, \quad (4)$$

where w_1 is the wholesale and retail price set by the manufacturer under the government's subsidy per unit of product emission reduction. After substituting equations (1) and (2) into equations (3) and (4), the decision model for both parties is

$$\begin{aligned} \max_{e_1, w_1, p_1^m} \pi_1^m &= w_1 \theta A - p_1^r + \beta p_1^m + k e_1 \\ &\quad + p_1^m [(1 - \theta) A - p_1^m + \beta p_1^r + k e_1], \\ \max_{p_1^r} \pi_1^r &= (p_1^r - w_1) (\theta A - p_1^r + \beta p_1^m + k e_1). \end{aligned} \quad (5)$$

It is solved by the inverse induction method: first, $N\pi_1^r$ finds the second derivative with respect to p_1^r and get $(\partial^2 N\pi_1^r / \partial p_1^{r2}) = -2 < 0$. So, there is an optimal solution for the strict concave function of p_1^r , and then by finding the first derivative of π_1^r with respect to p_1^r and making it equal to 0, we get p_1^r with respect to e_1 , the optimal response function of w_1 and p_1^m :

$$\frac{\partial \pi_1^r}{\partial p_1^r} = \theta A - 2p_1^r + \beta p_1^m + k e_1 + w_1, \quad (6)$$

$$p_1^r(e_1, w_1, p_1^m) = \frac{\theta A + \beta p_1^m + k e_1 + w_1}{2}.$$

Property 1. Under the subsidy mode of emission reduction per unit product, the retailer's optimal price response function is an increasing function of e_1 , w_1 and p_1^m .

This property indicates that in this case, manufacturers' increasing emission reductions and increasing product wholesale prices or direct sales channel prices will all cause retailers to increase traditional channel sales prices, thereby increasing the marginal revenue per unit product.

Then, substitute (6) into (5) to obtain

$$\begin{aligned} \frac{\partial^2 \pi_1^m}{\partial w_1^2} &= -1, \\ \frac{\partial^2 \pi_1^m}{\partial p_1^{m2}} &= \beta^2 - 2, \end{aligned} \quad (7)$$

$$\frac{\partial^2 \pi_1^m}{\partial w_1 \partial p_1^m} = \beta,$$

$$\frac{\partial^2 \pi_1^m}{\partial p_1^m \partial w_1} = \beta.$$

From this, the Hessian matrix of the manufacturer's profit function with respect to w_1 and p_1^m is as follows:

$$H(\pi_1^m) = \begin{bmatrix} -1 & \beta \\ \beta & \beta^2 - 2 \end{bmatrix}. \quad (8)$$

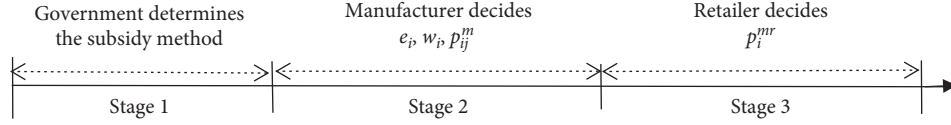


FIGURE 2: Decision sequence diagram.

TABLE 1: Notations.

| Parameters | Definition |
|------------|--|
| D_r | Demand of traditional retail channels |
| D_m | Demand of online sales channels |
| A | Market scale |
| θ | Market share of traditional retail channels |
| p_i^r | Product price of traditional retail channels |
| p_i^m | Product price of online sales channels |
| β | Cross-price elasticity factor |
| k | Consumer environmental awareness level |
| e_i | Emission reduction |
| I | Manufacturer's emission reduction R&D cost coefficient |
| λ | Subsidy coefficient of emission reduction per unit product |
| t | Subsidy coefficient of R&D for emission reduction |
| w_i | Wholesale prices |

The first-order principal subformula in this matrix is negative, $|H(\pi_1^m)| = 2(1 - \beta^2) > 0$, so the manufacturer's profit function is a strictly joint concave function of w_1 and p_{11}^m , the objective function. There is an optimal solution. Take the manufacturer's profit function (5) to derive w_1 and p_{11}^m and set them equal to 0. After the combination, the optimal inverse function of e_1 can be obtained:

$$\frac{\partial \pi_1^m}{\partial w_1} = \frac{1}{2}\theta A + \frac{ke_1}{2} - w_1 + \beta p_1^m + \frac{(\beta - 1)\lambda e_1}{2},$$

$$\frac{\partial \pi_1^m}{\partial p_1^m} = \beta w_1 + \left(1 - \theta + \frac{\beta\theta}{2}\right)A + (\beta^2 - 2)p_1^m$$

$$+ \frac{k\beta + 2k + \lambda\beta^2 + \lambda\beta - 2\lambda}{2}e_1, \quad (9)$$

$$w_1^*(e_1) = \frac{k\beta + k - \lambda + \lambda\beta^2}{2 - 2\beta^2}e_1 + \frac{\theta A}{2} + \frac{A\beta(1 - \theta + \beta\theta)}{2 - 2\beta^2}, \quad (10)$$

$$p_1^{m*}(e_1) = \frac{k\beta + k - \lambda + \lambda\beta^2}{2 - 2\beta^2}e_1 + \frac{(1 - \theta + \beta\theta)A}{2 - 2\beta^2}. \quad (11)$$

Substitute (10) and (11) into (6) to obtain the optimal response function of p_{11}^r with respect to e_1 :

$$p_1^{r*}(e_1) = \frac{\beta q_1 + k + q_1}{2}e_1 + \frac{3}{4}\theta A + \beta q_2,$$

$$q_2 = \frac{A(1 - \theta + \beta\theta)}{2 - 2\beta^2}. \quad (12)$$

In order to judge the linear relationship between p_1^{m*} , w_1^* , p_1^{r*} , and e_1 , we further sort out (10), (11), and (12) to obtain the following equations for e_1 :

$$w_1^*(e_1) = \frac{k + \lambda(\beta - 1)}{2(1 - \beta)}e_1 + \frac{\theta A}{2} + \frac{A\beta(1 - \theta + \beta\theta)}{2 - 2\beta^2}, \quad (13)$$

$$p_1^{m*}(e_1) = \frac{k + \lambda(\beta - 1)}{2(1 - \beta)}e_1 + \frac{(1 - \theta + \beta\theta)A}{2 - 2\beta^2}, \quad (14)$$

$$p_1^{r*} = \frac{(-\beta^3 - \beta^2 + \beta + 1)\lambda + (3\beta^2 + 2\beta - 1)k}{4\beta^2 - 4}e_1$$

$$+ \frac{(\beta^2\theta + 2\beta\theta - 3\theta - 2\beta)A}{4\beta^2 - 4}. \quad (15)$$

The coefficients of $w_1^*(e_1)$, $p_1^{m*}(e_1)$ are $(k + \lambda(\beta - 1)/2(1 - \beta))$, because $0 < \beta < 1$, so we cannot judge directly whether the function is increasing or decreasing, and the impact of emission reductions on wholesale prices and direct sales channel sales prices will vary with the changes of k , β , and λ .

Property 2. Under the subsidy method of emission reduction per unit product, e_1 has an impact on the retailer's optimal price p_1^{r*} , the optimal wholesale price w_1^* , and the optimal direct sales channel sales price p_1^m , and changes with the level of consumer environmental awareness, the cross-price elasticity coefficient of the dual channel, and the emission reduction subsidy coefficient per unit product.

4.2. Situation 2: under the Mode of R&D Subsidy for Emission Reduction. When the government adopts the subsidy mode of emission reduction research and development, the manufacturer (π_2^m) and retailers (π_2^r) are as follows:

$$\max_{e_2, w_2, p_2^m} \pi_2^m = w_2\theta A - p_2^r + \beta p_2^m + ke_2$$

$$+ p_2^m[(1 - \theta)A - p_2^m + \beta p_2^r + ke_2] \quad (16)$$

$$+ te_2^2 - \frac{1}{2}Ie_2^2,$$

$$\max_{p_2^r} \pi_2^r = (p_2^r - w_2)(\theta A - p_2^r + \beta p_2^m + ke_2). \quad (17)$$

The inverse induction method is used to solve the problem, and first of all, $N\pi_2^r$ calculates the second derivative of p_2^r and obtains $(\partial^2 N\pi_2^r / \partial p_2^{r2}) = -2 < 0$. So, $N\pi_2^r$ is about

p_2^r which is a strictly concave function, and there is an optimal solution. And then by finding π_2^r about p_2^r , the first derivative is equal to 0, and then we get the optimal response function of p_2^r about e_2, w_2, p_2^m :

$$\begin{aligned} \frac{\partial \pi_2^r}{\partial p_2^r} &= \theta A - 2p_2^r + \beta p_2^m + k e_2 + w_2, \\ p_2^r(e_2, w_2, p_2^m) &= \frac{\theta A + \beta p_2^m + k e_2 + w_2}{2}. \end{aligned} \quad (18)$$

Property 3. Under the R&D subsidy, the retailer's optimal price response function is about e_2, w_2, p_2^m , the increasing function.

This property shows that in this case, the manufacturer's increase of emission reduction and the increase of wholesale price or direct channel price will make the retailer increase the price of traditional channel, thus increasing the marginal revenue of unit product.

Then, equation (15) is substituted into equation (13) to obtain

$$\begin{aligned} \frac{\partial^2 \pi_2^m}{\partial w_2^2} &= -1, \\ \frac{\partial^2 \pi_2^m}{\partial p_2^{m2}} &= \beta^2 - 2, \\ \frac{\partial^2 \pi_2^m}{\partial w_2 \partial p_2^m} &= \beta, \\ \frac{\partial^2 \pi_2^m}{\partial p_2^m \partial w_2} &= \beta. \end{aligned} \quad (19)$$

Thus, regarding the profit function of the manufacturer with respect to w_{11}, p_{11}^m , the Hessian matrix is

$$H(\pi_2^m) = \begin{bmatrix} -1 & \beta \\ \beta & \beta^2 - 2 \end{bmatrix}. \quad (20)$$

In this matrix, the first principal subexpression is negative, $|H(\pi_2^m)| = 2(1 - \beta^2) > 0$, so the manufacturer's profit function is about w_2 and p_2^m . In this paper, the manufacturer's profit function formula (5) is applied to p_2^m and w_2 and makes it equal to 0; then, the optimal inverse function of e_2 can be obtained:

$$\begin{aligned} \frac{\partial \pi_2^m}{\partial w_2} &= \frac{1}{2} \theta A + \frac{k e_2}{2} - w_2 + \beta p_2^m, \\ \frac{\partial \pi_2^m}{\partial p_2^m} &= \beta w_2 + \left(1 - \theta + \frac{\beta \theta}{2}\right) A + (\beta^2 - 2) p_2^m + \frac{k \beta + 2k}{2} e_2, \end{aligned} \quad (21)$$

$$w_2^*(e_2) = \frac{k}{2 - 2\beta} e_2 + \frac{A(\theta + \beta - \beta \theta)}{2 - 2\beta^2}, \quad (22)$$

$$p_2^{m*}(e_2) = \frac{k}{2 - 2\beta} e_2 + \frac{(1 - \theta + \beta \theta) A}{2 - 2\beta^2}. \quad (23)$$

Substituting (16) and (17) into (15) yields p_2^r about e_2 , and the optimal response function is

$$p_2^{r*}(e_2) = \frac{k(3 - \beta)}{4 - 4\beta} e_2 + \frac{A(\theta - 4\theta\beta + 2\beta + \theta\beta^2)}{4 - 4\beta^2}. \quad (24)$$

Further judgment $p_2^{m*}, w_2^*, p_2^{r*}$, and e_2 , that is, to judge the positive and negative of $(k/2 - 2\beta)$, because $0 < \beta < 1$, $0 < k < 1$, and the following property can be assumed.

Property 4. Under the R&D subsidy, the retailer's optimal price response function, w_2, p_2^m are the increasing functions of e_2 .

This property shows that when the government determines the subsidy mode of R&D according to emission reduction, the manufacturer's wholesale price for traditional channels and sales price for direct sales channel, as well as the retailer's optimal price, will increase with the increase of emission reduction.

5. Numerical Simulation

In the following, numerical simulation will be used to simulate the impact of emission reductions per unit of product on manufacturers' wholesale prices, profits, sales prices of the dual channel, and retailers' profits under different government subsidies. Refer to previous related papers [42–44], and set the corresponding parameter value:

$$\begin{aligned} k &= 0.5, \\ \beta &= 0.5, \\ \lambda &= [4, 8], \\ \theta &= 0.6, \\ A &= 1500, \\ I &= 900, \\ t &= [200, 400]. \end{aligned} \quad (25)$$

5.1. The Impact of Emission Reduction on Wholesale Price under Different Subsidies. In the two cases of government subsidies based on R&D and unit quantity, the optimal wholesale price, that is, formulas (13) and (22), is numerically simulated, as shown in Figure 3. It is verified once again that under the two subsidy methods, the optimal wholesale price of manufacturers to retailers will increase with the increase of carbon emissions.

5.2. The Impact of Emission Reductions under Different Subsidy Methods on the Sales Prices of the Dual Channel. In the two cases of government subsidies based on R&D and unit quantity, the obtained optimal direct selling price and the optimal traditional retail wholesale price are calculated

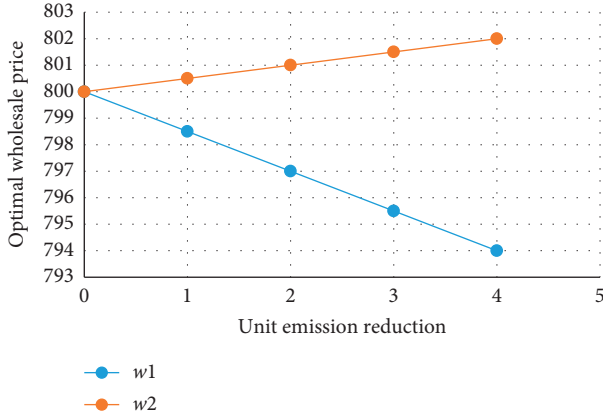


FIGURE 3: Wholesale price comparison chart.

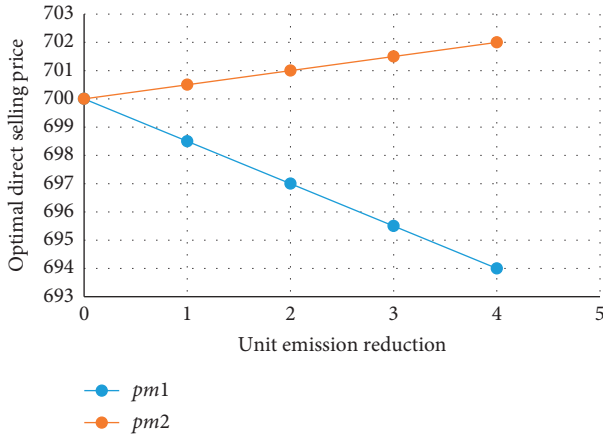


FIGURE 4: Direct selling price comparison chart.

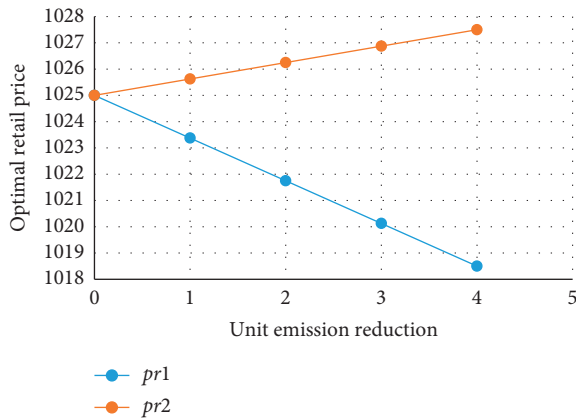


FIGURE 5: Retailer price comparison chart.

by formulas (14), (15), (23), and (24). The simulation is shown in Figures 4 and 5.

5.3. The Impact of Emission Reductions on the Profits of the Dual Channel under Different Subsidies. In the two cases of

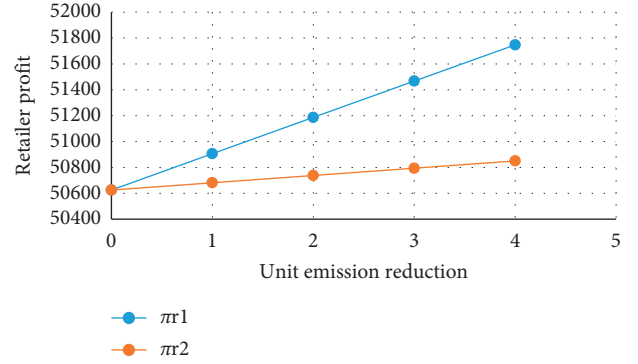


FIGURE 6: Manufacturer's profit comparison chart.

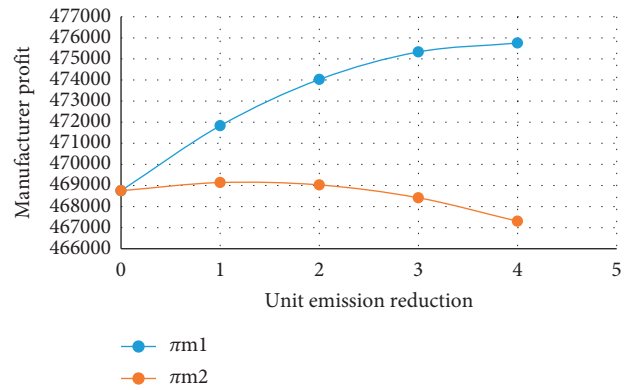


FIGURE 7: Retailer profit comparison chart.

government subsidies based on R&D and unit quantity, the obtained optimal direct selling price and the optimal traditional retail wholesale price, namely, formulas (14), (15), (23), and (24), are calculated simulation, as shown in Figures 6 and 7.

6. Conclusions and Discussion

In this paper, we consider two different ways of government emission reduction, R&D subsidies and subsidies per unit volume, establish a game model of green supply chain decision-making under different government subsidies, and analyze the impact of different subsidies on manufacturers and retailers.

The results show the following: (1) when the government subsidizes emission reduction research and development subsidies, emission reduction has an impact on the retailer's optimal price, the manufacturer's optimal wholesale price, and the optimal direct channel sales price, and changes with the consumer's environmental awareness level, the cross-price elasticity coefficient of the dual channel, and the emission reduction subsidy coefficient of unit product. (2) When the government adopts the subsidy method based on the emission reduction per unit product, after the manufacturer determines the emission reduction, the wholesale price of the manufacturer to the traditional channel and the sales price of the direct channel, and the optimal price of the

retailer itself will increase with the increase of the emission reduction. (3) When the government subsidizes the emission reduction based on the research and development of emission reduction, the retailer's optimal price will increase with the increase of emission reduction. The profit increases with the increase of carbon emission, and the profit of manufacturers decreases after it increases to a certain extent. (4) When the government adopts the subsidy based on the emission reduction per unit product, under the optimal decision, the retailer's profit increases linearly with the increase of carbon emission, and the manufacturer's profit first increases linearly and then increases curvilinearly. The research results have important reference significance for the government to choose the subsidy mode for the manufacturer-led green supply chain and for the supply chain manufacturers to make emission reduction decisions in the face of government subsidies.

Therefore, the following management implications are put forward.

For the government, low-carbon emission reduction subsidies mobilize the enthusiasm of enterprises to participate in low-carbon sustainable development, and different subsidies have different effects on enterprises. In the face of different types and sizes of enterprises, enterprises should choose different ways of subsidies. For mature large enterprises, they can be encouraged to develop more low-carbon emission reduction technologies, and small-scale enterprises can adopt the method of per unit emission reduction. In addition, we should cooperate with publicity and education to enhance consumers' awareness of environmental protection, guide consumers to buy low-carbon products, and increase the sales of green products in the whole market, so as to improve the profits of emission reduction enterprises and increase the overall social welfare.

For manufacturers, the emission reduction subsidies carried out by the government can effectively improve the overall profit of the supply chain and also promote the emission reduction level of enterprises. When the government grants R&D subsidies for emission reduction, enterprises can choose to independently develop emission reduction technologies, which is conducive to the development of enterprises in the long run, but also need to consider their own business situation. For different types of enterprises, the measures should be different. In addition, we should pay attention to the decision-making of carbon emissions, which may affect the company's profits when the carbon emissions reach a certain level. Under the influence of low-carbon emission reduction, the dual-channel sales mode has a certain income risk, which needs to be further weighed.

There are several limitations in this research. Firstly, this paper does not consider that the manufacturers can choose their own R&D and outsourcing R&D to reduce emissions, because many enterprises have begun to hand over the low-carbon emission reduction work to professional companies, and the cost and profit generated by this situation will be different from their own R&D emission reduction technologies, and the corresponding emission reduction strategies will be different; secondly, in the process of the game,

this paper does not consider retailers, and future research can explore how to achieve win-win cooperation between manufacturers and retailers under government subsidies.

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

Institutional Environment and Green Economic Growth in China

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As the answer to sustainability concerns, green economic growth has gradually attracted considerable attention. Notably, the optimization of the institutional environment contributes to green economic growth from the perspective of new institutional economics. However, few studies have systematically explained the connection between the institutional environment and green growth. In this study, the institutional environment was divided into three dimensions: governmental, legal, and cultural subenvironments. We adopted econometric models with the effect of every dimension on green growth and empirically analyzed with the generalized method of moments, based on Chinese provincial panel data from the years 2000–2016. The results indicated that there was an inverted U-shaped relationship between China's institutional environment and its green growth. That is, the institutional environment can initially promote China's green growth but, if it is not changed, will eventually inhibit it. In addition, the analysis on the three dimensions of the institutional environment highlighted that the role of the cultural sub-environment in green growth is greater than those of the governmental and legal subenvironments.

1. Introduction

Under the pressure of environmental pollution and the energy crisis, as well as through the pursuit of a high-quality life for citizens, China has modified its environmental policies to allow for a transition from a brown economy of high consumption and emission to a green economy that is environmentally friendly. Green economy aims to change production and consumption by improving resource efficiency and reducing pollution emissions and hence promote harmony between the environment and the economy. Notably, China's total energy consumption reached 4.86 billion tons of standard coal in 2019, accounting for 24.3% of the world's total energy consumption. In particular, coal accounts for 57.7% of China's total energy consumption [1]. As China's economic growth slows down, it is trying to implement a green economic development model and fulfill international commitments, such as the Paris Agreement. China has suggested developing a green economy to release both energy and environmental pressures and has presented a series of policies to promote green economy

transformation. For example, in 2016, The 13th Five-Year Plan for Economic and Social Development of the People's Republic of China introduced the green concept into the guidelines on building a moderately prosperous society in an all-round way. In 2017, the green economy concept became an important focus of China's national strategic plan. Finally, in 2018, the National Development and Reform Commission established the Green Industry Guide Directory. The new institutional economy proposes that “the institution is a new growth point of economy.” From the perspective of this new institutional economy, the promotion of institutional quality can be beneficial for economic growth. In the context of this economic transformation, it is necessary to assess the effects of institutions on China's green economy.

In the past ten years, green economy, also known as green growth, has become a buzzword and has attracted great attention from the government, enterprises, researchers, and other stakeholders [2, 3]. Some studies have focused on the quality and measurement of green economy [4–7]. Furthermore, other studies have assessed the factors that affect green growth and have suggested that foreign

direct investment (FDI), environmental regulations, financialization, and clean energy technologies are the most important ones [7–9].

The development of a new institutional economy has boosted research on institutional quality and institutional reform. For instance, a growing number of articles have suggested and constructed more effective indexes and methods to evaluate institutional quality. In addition, some articles have discussed the paths and characteristics of institutional evolution [10, 11]. Nonetheless, over the last decade, researchers rarely have considered the factors that affect the institutional environment, such as capital flows, financial development, green innovation, and energy efficiency [12–14]. As for the relationship between institutional quality and economic growth, some studies have suggested it is robust and positive [15]. However, few studies have considered the multidimensional institutional environment and examined the effect of the institutional environment on green economy.

The present study examined the relationship between the multidimensional institutional environment and green economy. We empirically examined Chinese provincial data from the years 2000 to 2016. We divided the institutional environment into governmental, legal, and cultural subenvironments (GSE, LSE, and CSE, respectively) and estimated the specific effects of these subenvironments on the green growth in China. The results indicated an inverted “U-shaped” nonlinear relationship between the institutional environment and green growth, and the cultural subenvironment was more important than both the governmental and legal subenvironments.

Our study presents two main innovations. First, as the impact of the institutional environment on green growth is often ignored by developing countries, we utilized China as an example to conduct the investigation, which presents a new perspective for research that focuses on the institutional environment and green growth in developing countries. Second, the relative importance of the Chinese institutional environment and its subindicators for green growth was analyzed, which provides a reference for improving the institutional environment and promoting green growth in other countries.

Hereafter, we present a literature review and hypotheses (Section 2), describe the modeling process and data selection (Section 3), present and discuss regression results (Section 4), and provide recommendations for policymaking and future research (Section 5).

2. Literature Review

2.1. Green Growth. As a “triple-win” solution to sustainable development, green growth, which positively affects the economy, environment, and energy, attracts the attention of many researchers from different fields. Green growth, also referred to as green economy, has multiple definitions but, tracing back to its origins, green growth encompasses the concept of environmentally sustainable economic growth [3, 16, 17]. The World Bank describes green growth as “one that is efficient in its use of natural resources, clean in that it

minimizes pollution and environmental impacts, and resilient in that it accounts for natural hazards” [18].

The measurement of green growth is divided into two categories: the indirect approach—such as the use of integrated indexes with weighting and aggregating techniques, as well as screening and comprehensive green economy indicators—and the direct approach, such as the application of the global Malmquist-Luenberger productivity index and super-efficiency DEA models [4, 5, 7]. However, researchers have gradually recognized methods based on more factors and comprehensive comparisons. Likewise, in the present study, we constructed a green productivity index with a super-efficiency DEA model to evaluate the development of green economy.

Multiple factors affect green growth, among which environmental regulations, fiscal expenditure, financialization, clean energy transition, economic openness, and research and development (R&D) investment have been discussed in recent years [7, 9, 19, 20]. To date, a few studies have also investigated the relationship between institutional quality and economic growth [21, 22]. Salman et al. [22] have suggested that the quality of institutions is a factor that promotes economic growth, but Abdulahi et al. [21] have treated institutions as a threshold variable because institutional quality has a dynamic effect on economic growth. However, hardly any studies have focused on the effects of institutional quality on green economy, and the effects of governmental subenvironments on green economic growth have seldom been discussed. Therefore, the institutional environment and green growth were assessed in the present study.

2.2. Institutional Environment. Among the studies that discuss institutional quality and economic growth, many are indirect research. That is, the authors adopted an institutional environment as a control variable to analyze the effects of many variables, such as international aid, FDI, economic openness, resource endowment, and resource rents, on economic growth with different institutional qualities [21, 23–26]. Overall, these studies agree that a country with a good institutional environment is advantageous for economic subjects to absorb and use foreign aid, FDI, resource factors, and so on. Furthermore, improving institutional quality is advantageous to avoid resource curse [26] and promotes economic growth by affecting other factors [27].

Some studies have adopted institutional quality as a mediator and have analyzed its effects on economic growth. For example, Dong and Zhang [28] have argued that historically accumulated social capital promotes institutional quality and improves economic growth. Additionally, Berdiev et al. [29] have introduced an important institutional factor, namely, corruption, as a mediator to analyze the negative effects of racial inequality on economic growth. They have suggested that corruption induces about two-thirds of the negative effects of racial inequality on economic growth.

By comprehensively reviewing previous literature, we discovered that empirical research on institutional quality has mainly concentrated on international comparisons and

analyzed the effects of the institutional quality of a country on international capital and factor mobility, among others, on the economic growth of that country. In contrast, researchers rarely have empirically investigated institutional quality at the subnational level because of a lack of data. Therefore, in this article, it was meaningful to organize the path for the institutional environment that affects economic growth and evaluate the direct effects of institutional quality on economic growth within different dimensions.

2.3. Multidimensional Institutional Environment and Green Growth. According to the logistics of the new institutional economy, institutional quality has a direct effect on the strategies of investors and enterprises [30]. Furthermore, the investment directions and production decisions of firms directly affect green economy transformation. Only when the investment directions and production decisions become cleaner will green industries develop further and, in turn, transform faster into a green economy. In line with the statements in Section 2.1, we hereby discuss the effects of multidimensional institutional environments on green growth.

Regarding the relationship between the GSE and green growth, researchers have commonly suggested that the optimization of the institutional environment decreases transaction costs, promotes factor mobility to optimize resource allocations, reduces space for corruption and rent-seeking, provides a fairer setting with a new significance for entrepreneurs, which inspires innovation, and further promotes development in different industries [31]. Whether the optimization of the GSE promotes green transformation also relies on the relative speed and weight of the development of green industries. In the context of “Chinese style decentralization,” the development trends of local governments affect the impact of the GSE on green economic growth, to some extent. Under Chinese fiscal decentralization, the competition between local governments has been mentioned in many studies on political or institutional impacts [32, 33]. The role of a local government as “an economic politician” prompts its motivation to develop the local economy and realize economic accumulation quickly. Notably, government behavior affects the governmental subenvironment to a great extent. If a local government is short-sighted and eager to realize economic catch-ups, the optimization of the institutional environment will provide a convenient and favorable development space for extensive industries but will restrict the development of green industries, all of which is not beneficial for the transformation to a green economy. However, if the local government fully realizes that the need for green economy transformations is urgent when targeting sustainable development, its GSE will tend to serve green industries, which is beneficial for green economic growth.

Considering the impacts of the LSE, a good legal environment leads to good investment expectations and, hence, attracts more investments to fuel local economic growth. Furthermore, the promotion of the rule of law is beneficial for protecting intellectual property rights,

promoting the enthusiasm of entrepreneurs for innovation, increasing enterprise performance [32], and, finally, providing the possibility of developing a green economy. Moreover, a good legal environment provides a stable social environment for economic development, increases the cost of breaking contracts, allows more human resources to enter into social production, and promotes factor utilization. However, the impact of government behavior also needs to be considered when analyzing the impacts of the LSE owing to its lawmaking authority. That is, if the government behavior supports green transformations, then the legal environment will become conducive as well. If the government chooses a wild and unsustainable way to realize capital accumulations, the optimization of the legal environment will support the development of highly polluting industries. Therefore, the effect of the LSE on green growth is uncertain and influenced by the behavior of the local government.

Economists have suggested that informal regulations, such as culture, are significant determinants of economic performance [28]. For instance, a positive culture of business may be a major impetus for economic growth. Likewise, a positive culture of business for environmental protection may format the driving force behind green economy transformations. As a soft power, regional entrepreneurial spirit of innovation plays a positive leading role and generates an internal motivation for economic development. Overall, the use of soft power is sometimes better than that of coercion [34]. However, if entrepreneurs focus on making nongreen innovations in a relatively mature market to make quick profits, their behaviors may not be beneficial for the transformation to a green economy. Therefore, forming an environment that protects culture is a precondition for the positive impact of the CSE on green economy transformation.

Based on Figure 1, the following hypotheses were proposed.

Hypothesis 1. The optimization of the institutional environment has a positive effect on the transformation to a green economy.

Hypothesis 2. The subindicators of the institutional environment, such as the governmental, legal, and cultural subenvironments, have an impact on green growth.

To verify these hypotheses, we used Chinese data from the years 2000 to 2016 to analyze the impact of the institutional environment and its subindicators on green growth by establishing regression models.

3. Model and Data

3.1. Model. According to the analyses in the previous sections and considering the temporal spillover effect of development and technological progress [24, 35], we adopted a model with the lag term of green total factor productivity (GTFP) to estimate the spillover effect of FDI on GTFP through the generalized method of moments (GMM). To do so, the following formula was used:

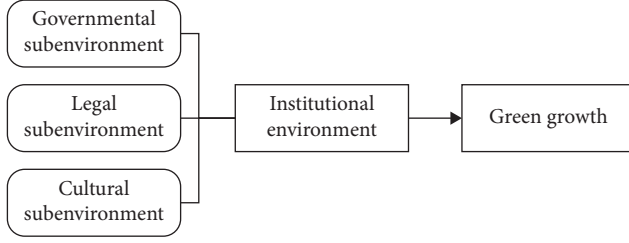


FIGURE 1: Framework of the concepts.

$$\text{GTFP}_{it} = \alpha + \sigma \text{GTFP}_{i,t-1} + \beta \text{Insti}_{it} + \delta_j \text{Control}_{it} + \text{region}_i + \text{year}_t + \varepsilon_{it}, \quad (1)$$

where Insti_{it} is the FDI inflow of region i in the year t , Control_{it} represents control variables, region_i and year_t

represent the individual effects and time effects, respectively, and ε_{it} is the standard error.

According to the previous theoretical analysis, institutional improvement may be affected by government behaviors. Considering its role as an “economic politician” and the time variance of its behaviors, a government dominates its competitive strategy with local resource endowment and a foreign competitive environment to form behavior trends in different orientations. Although the results of institutional improvement inevitably induce dynamic effects, it is difficult to weight government behaviors. In this study, we analyzed the nonlinear effects of institutional factors on green economic growth by modeling variables, including the institutional environment, in a quadratic term. Based on this, we constructed the following quadratic model:

$$\text{GTFP}_{it} = \alpha + \sigma \text{GTFP}_{i,t-1} + \beta \text{Insti}_{it} + \gamma \text{Insti}_{it}^2 + \delta_j \text{Control}_{it} + \text{region}_i + \text{year}_t + \varepsilon_{it}. \quad (2)$$

To further analyze the impacts of institutional subenvironments of different dimensions on green growth, we

introduced three institutional subenvironments into the models and constructed a basic model:

$$\text{GTFP}_{it} = \alpha + \sigma \text{GTFP}_{i,t-1} + \beta_1 \text{GSE}_{it} + \beta_2 \text{LSE}_{it} + \beta_3 \text{CSE}_{it} + \delta_j \text{Control}_{it} + \text{region}_i + \text{year}_t + \varepsilon_{it}, \quad (3)$$

where GSE_{it} , LSE_{it} , and CSE_{it} denote the governmental, legal, and cultural subenvironments, respectively.

Finally, we introduced the quadratic term of the three institutional subenvironments to identify the possible

nonlinear relationships between these institutional subenvironments and green growth:

$$\text{GTFP}_{it} = \alpha + \sigma \text{GTFP}_{i,t-1} + \beta_1 \text{GSE}_{it} + \beta_2 \text{LSE}_{it} + \beta_3 \text{CSE}_{it} + \gamma_1 \text{GSE}_{it}^2 + \gamma_2 \text{LSE}_{it}^2 + \gamma_3 \text{CSE}_{it}^2 + \delta_j \text{Control}_{it} + \text{region}_i + \text{year}_t + \varepsilon_{it}. \quad (4)$$

3.2. Data. According to the green growth statement of the World Bank and following [36], we included the GTFP, which was estimated with a super-efficiency DEA model, as an indicator of green growth. Herein, the detailed description of the DEA model has been omitted.

As the main explanatory variable, the institutional environment was measured based on the approach of [37]. Correspondingly, we assessed the GSE with five factors, including government domination, government interruption, tax on enterprises, and efficiency of administrative approval, evaluated the LSE with four factors, namely, anticorruption, social stability, patent protection, and labor protection, and identified the CSE mainly based on the entrepreneurial spirit of innovation. The description of these basic indexes is provided in Table 1. Due to insufficient data, the indexes of the institutional environments obtained in the present study differed slightly from the basic indexes proposed in [37]. Herein, details on the method have been omitted.

Based on previous studies, FDI, the level of education, and industrial structure and openness were selected as the control variables in the regressions described in Section 4 [20, 38]. All the regression variables and their corresponding indexes are described in Table 2.

We employed the panel data of 30 provinces in mainland China from the years 2000–2016. Data were derived from multiple databases, including the China Statistical Yearbooks, China Population and Employment Statistics Yearbook, Procuratorial Yearbook of China, China Intellectual Property Yearbook, Yearbook of Industry and Commerce Administration of China, and China Labour Statistical Yearbook. The statistics for all related variables are summarized in Table 2. We evaluated the variance inflation factor (VIF) of each regression model, and the obtained VIF values were below 5. Therefore, it can be considered that there was no multicollinearity. In addition, according to the Ramsey regression equation specification error test, the

TABLE 1: Indexes of institutional environment quality.

| Variable | Basic index | Description | Direction |
|-----------------------------|---|---|-----------|
| Institutional quality | A comprehensive index constituted through the entropy weight method, based on three subindexes—government, law, and culture | | + |
| | Government domination | Public finance expenditure/GDP | — |
| | Government interruption | Local financial revenue/local financial expenditure | — |
| Governmental subenvironment | Scale of government | Number of employees in public management and social organizations at the end of the year/total population | — |
| | Tax on enterprises | Industrial enterprise tax/operating revenue | — |
| | Efficiency of administrative approval | Administrative examination and approval procedures' concise situation enterprise sampling rating | + |
| | Corruption | Number of graft cases/total population | — |
| Legal subenvironment | Social stability | Logarithm of the number of criminal offenses per 10,000 people | — |
| | Patent protection | Cumulative settlement of patents/cumulative number of filed patents | + |
| | Labor protection | Labor dispute cases/total population | — |
| Cultural subenvironment | Innovation entrepreneurship | Logarithm of (patent grants/total employed population \times 10,000) | + |

Note. “+” means that the variable theoretically has a positive effect on the institutional quality, while “-” implies a negative one.

TABLE 2: Summary statistics.

| Variable | Description | Obs | Mean | Std. dev. | Min | Max |
|----------|--|-----|--------|-----------|--------|---------|
| GTFP | Green economic growth: total factor productivity | 510 | 0.4872 | 0.2214 | 0.1283 | 1.0000 |
| INSTIL | Institutional quality | 510 | 5.9995 | 0.6528 | 4.2149 | 7.8347 |
| GSE | Governmental subenvironment | 510 | 7.0041 | 0.7808 | 4.5242 | 8.4932 |
| LSE | Legal subenvironment | 510 | 6.1017 | 0.5943 | 3.4581 | 8.5107 |
| CSE | Cultural subenvironment | 510 | 4.8927 | 1.9576 | 0.0000 | 10.0000 |
| FDI | Foreign direct investment: total utilized FDI/GDP | 510 | 0.0270 | 0.0295 | 0.0000 | 0.2074 |
| EDU | Education: weighted average valuation of classified and assigned different levels of education | 510 | 8.4035 | 1.0559 | 5.4383 | 12.3891 |
| MARKET | Marketization: marketization level | 510 | 6.0102 | 1.8294 | 2.3700 | 10.9200 |
| OPEN | Openness: total volume of foreign trade/GDP | 510 | 0.3415 | 0.4399 | 0.0133 | 1.8910 |
| RD | The proportion of research and development expenditure in GDP | 510 | 0.0127 | 0.0104 | 0.0015 | 0.0628 |
| URBAN | The proportion of urban population in total population | 510 | 0.4838 | 0.1538 | 0.1389 | 0.8961 |
| IS | Industrial structure: the value of secondary industry output/GDP | 510 | 0.9386 | 0.4643 | 0.4945 | 4.1656 |

quadratic term was reasonable. For variables involving prices, the base period was the year 2000. Furthermore, indicators involving exchange rates (e.g., FDI) were calculated according to the average exchange rate of each year.

4. Regressions and Discussion

Based on the aforementioned theoretical analysis, we constructed econometric models and selected the two-step estimation of the system GMM for regressions to deal with endogeneity problems. The estimation results of these models are shown in Table 3. Notably, we used a generalized least squares regression for Model 1 and did not incorporate the GTFP lag term into the model. We used a fixed effect regression for Model 2 and a GMM regression for Model 3. Finally, Models 4 and 5 included the quadratic term of institutional quality (INSTIL) to check the nonlinear relationship between INSTIL and GTFP. According to the results of the Sargan and AR tests, it was suitable to apply the GMM to estimate the relationship between institutional environment and economic growth. The following sections (i.e., Sections 4.1–4.3) explain and analyze the five models from the perspectives of both the total effects and effects of multidimensional institutions, based on Table 3.

4.1. Effect of the Institutional Environment on Green Growth.

The coefficient of the lag term of GTFP was positive and significant at the 1% level in all models (Table 3), which is consistent with the results in [7]. That is, green economic growth in a specific year had a positive influence on the growth in the following year. This phenomenon can be described as the lock-in effect on economic growth; Thus, this implies that a certain district should concentrate on the dependence effect on economic growth, except for spillover effects in the future.

In Model 1, the coefficient of the institutional environment was positive, but after introducing the quadratic term of institutions (i.e., in Models 4 and 5), the linear and quadratic terms of INSTIL became significantly positive and significantly negative, respectively. This means that the relationship between the institutional environment and green economic growth is characterized by an inverse U shape. Accordingly, with institutional quality improvement, the effects of the institutional environment convert from improving positively to restraining green economic development, which is distinct with Hypothesis 1 to some extent. These unexpected results can be attributed to the control of government competition. In the context of the Chinese fiscal decentralization, the government plays the role of an

TABLE 3: Effect of the institutional environment on green growth.

| GTFP | Model 1 GLS | Model 2 FE | Model 3 GMM | Model 4 FE | Model 5 GMM |
|---------------------|----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| L. GTFP | | 0.6320*** (17.45) | 0.2933*** (7.91) | 0.6534*** (17.38) | 0.3405*** (7.29) |
| INSTIL | 0.0447* (1.90) | 0.0416** (2.33) | 0.0737*** (3.24) | 0.3364** (2.30) | 1.0150*** (3.00) |
| INSTIL ² | | | | -0.0245** (-2.03) | -0.0782*** (-2.90) |
| FDI | 0.2786 (0.69) | 0.3199 (1.05) | -3.3433** (-2.49) | 0.2761 (0.90) | -4.1805** (-2.18) |
| EDU | -0.0004 (-0.02) | 0.0518*** (3.86) | 0.1207*** (5.89) | 0.0472*** (3.48) | 0.1194*** (5.42) |
| OPEN | -0.0980** (-2.31) | -0.0471 (-1.27) | 0.0838 (0.84) | -0.0477 (-1.29) | 0.0689 (0.53) |
| MARKET | -0.0083 (-0.94) | -0.0081 (-1.19) | -0.0179*** (-2.98) | -0.0075 (-1.09) | -0.0173** (-2.29) |
| RD | -0.4809 (-0.21) | -3.4976 (-1.59) | -10.6540** (-2.51) | -1.8456 (-0.79) | -7.8992* (-2.03) |
| URBAN | 0.1376 (1.62) | 0.0902 (1.42) | -0.5194*** (-3.03) | 0.0823 (1.30) | -0.5229** (-2.75) |
| IS | 0.2277*** (7.98) | 0.0818*** (3.43) | 0.3239*** (3.14) | 0.0743*** (3.09) | 0.3147** (2.47) |
| Constant | 0.0238 (0.18) | -0.5248*** (-5.28) | -0.8919*** (-3.84) | -1.3847*** (-3.18) | -3.7132*** (-3.74) |
| Observations | 510 | 480 | 480 | 480 | 480 |
| Number of id | 30 | 30 | 30 | 30 | 30 |
| R-squared | 0.548 | 0.579 | | 0.583 | |
| AR (1) | | | -2.38** [0.017] | | -2.73*** [0.006] |
| P-AR (1) | | | 0.02 [0.983] | | -0.12 [0.905] |
| AR (2) | | | | | |
| P-AR (2) | | | | | |
| Hansen | | | 14.84 [0.463] | | 15.93 [0.317] |
| P-Hansen | | | | | |
| Hausman | 7.08 | 93.46 | | 124.38 | |
| P-Hausman | [0.528] | [0.000] | | [0.000] | |

Note. *t*-statistics are presented in parentheses; *p* values are mentioned in brackets or indicated as *** $p < 0.01$, ** $p < 0.05$, and * $p < 0.01$; GLS: generalized least squares regression; FE: fixed effect regression; GMM: generalized method of moments.

economic politician and shows enthusiasm for developing the economy. In a situation where there is a lack of power for green transformations, improving institutional quality promotes a pollution economy and hinders its management. Hence, all the situations are not favorable for green economy transformations.

The analysis of control variables referred to the results of Models 3 and 5. Under the premise that endogeneity was controlled, the FDI coefficient was significantly negative, which indicates that there are issues with the structure of China's use of FDI. Therefore, China needs to optimize its FDI structure and introduce clean FDI to eliminate dirty FDI. However, the education (EDU) coefficient was significantly positive, which suggests that current human capital accumulation in China could positively affect green growth. As for the marketization level (MARKET), its negative value indicates that it cannot contribute to green transformations. Green growth needs to include both economic growth and environmental protection, and market failure is a factor that hampers effectively solving environmental problems. Finally, the industrial structure (IS)

coefficient was significantly positive and differed from theoretical expectations. The main reason for this difference is that the green manufacturing industry has a positive impact on green economic growth within the green industry.

4.2. Effect of the Subenvironments on Green Growth. Following [37], we divided the institutional environment into three dimensions: the governmental, legal, and cultural subenvironments, and separately evaluated the effects of these subenvironments on green economic growth. We compared Models 1, 2, and 3 in Table 4 with the models that included quadratic terms, and the results suggest that for the models (Models 4, 5, and 6) that considered the quadratic terms of the GSE alone and those that gradually introduced quadratic terms, all regression coefficients were stable. This means that the regression results were robust, based on which we have obtained the model results described below.

The linear and quadratic coefficients of the GSE were significantly positive and significantly negative, respectively. There was a reverse U-shaped relationship between the GSE

TABLE 4: Effect of the subenvironments on green growth.

| GTFP | Model 1 GMM | Model 2 GMM | Model 3 GMM | Model 4 GMM | Model 5 GMM | Model 6 GMM |
|------------------|-----------------------|-----------------------|---------------------|---------------------|-----------------------|-----------------------|
| L. GTFP | 0.0942 (0.73) | 0.0390 (0.51) | 0.6793*** (5.13) | 0.5254*** (4.28) | 0.4947*** (7.20) | 0.4597*** (4.09) |
| GSE | -0.1305** (-2.45) | | | 1.6592* (1.89) | | |
| LSE | | 0.0627* (1.92) | | | 0.2356** (2.37) | |
| CSE | | | 0.0449* (1.98) | | | -0.1568** (-2.63) |
| GSE ² | | | | -0.1257* (-2.03) | | |
| LSE ² | | | | | -0.0171** (-2.11) | |
| CSE ² | | | | | | 0.0211*** (3.58) |
| FDI | -16.2412** (-2.33) | 0.6968 (0.39) | -0.9655 (-0.39) | -0.7689 (-0.40) | -0.6856 (-1.04) | -0.9687 (-0.39) |
| EDU | 0.1247* (2.00) | 0.1319*** (3.49) | 0.0332 (1.24) | 0.0065 (0.22) | 0.0752*** (5.22) | 0.0545 (1.39) |
| OPEN | 1.1243** (2.34) | 0.1264 (0.77) | -0.0089 (-0.06) | 0.1045 (0.71) | 0.0066 (0.11) | -0.2137 (-1.44) |
| MARKET | -0.0260 (-1.23) | -0.0476*** (-3.15) | -0.0024 (-0.21) | 0.0140 (0.75) | -0.0092 (-1.33) | -0.0567*** (-3.21) |
| RD | -37.6598* (-1.96) | -1.1538 (-0.13) | -7.6374 (-0.76) | -12.0741 (-1.25) | -8.8985* (-1.93) | 1.2157 (0.14) |
| URBAN | -0.8960 (-1.49) | 0.2411 (0.77) | -0.3852 (-0.75) | 0.1973 (0.74) | -0.0657 (-0.61) | -0.0799 (-0.53) |
| IS | 1.0922*** (2.86) | 0.3489** (2.70) | 0.1605* (1.78) | 0.2450 (1.67) | 0.3754*** (4.04) | -0.1896 (-1.23) |
| Constant | 0.5281 (0.68) | -1.2660*** (-2.82) | -0.1792 (-0.98) | -5.4638* (-1.73) | -1.3280*** (-3.88) | 0.6346** (2.39) |
| Observations | 480 | 480 | 480 | 480 | 480 | 480 |
| Number of id | 30 | 30 | 30 | 30 | 30 | 30 |
| AR (1) | -2.222** | -2.902*** | -2.420** | -2.562** | -2.454** | -2.211** |
| P-AR (1) | [0.026] | [0.004] | [0.016] | [0.010] | [0.014] | [0.027] |
| AR (2) | -0.299 | -0.569 | 0.883 | 1.562 | 1.084 | -0.582 |
| P-AR (2) | [0.765] | [0.569] | [0.377] | [0.118] | [0.278] | [0.561] |
| Hansen | 9.931 | 13.67 | 7.317 | 4.554 | 14.04 | 9.899 |
| P-hansen | [0.356] | [0.135] | [0.292] | [0.473] | [0.447] | [0.272] |

Note. *t*-statistics are presented in parentheses; *p* values are displayed in brackets or indicated as ***, $p < 0.01$, **, $p < 0.05$, and *, $p < 0.01$; GMM: generalized method of moments.

and green growth in China, and its inflection point was at 6.5998. Notably, this result is consistent with the effect of the entire institutional environment. In contrast to the scores of the GSEs of different Chinese provinces in 2018, almost all provinces were listed on the left side of the inflection point and were in the process of promoting green economic growth. This means that the improvement of the current GSE could serve as a green transformation, and it also indicates that the effects of institutional environment optimization have not been consumed by the competition between local governments.

The linear coefficient of LSE was significantly positive, whereas the quadratic coefficient was significantly negative, which indicates that a reverse U-shaped relationship exists between the LSE and green growth in China, with an inflection point at 6.8889. In contrast with the scores of the LSE in each city and province for the test period, the LSE in

most provinces was on the left side of the inflection point, which implies that the LSE is beneficial for green growth in the majority of Chinese districts. A possible explanation is that good opportunities for investments and productions, brought about by the optimization of the LSE, rapidly reflect on the traditional industries of mature markets and high technologies. As soon as the optimization of the LSE exceeds the inflection point, it will promote the development of the green industry and, finally, promote green economic growth. Therefore, the Chinese government should continue optimizing the LSE to reach the inflection point.

Finally, the linear coefficient of the CSE was negative, while the quadratic one was positive, highlighting the existence of a U-shaped relationship existing between the CSE and green growth in China, with an inflection point at 3.7156. Most regions were on the right side of the inflection point, which suggests that the improvement of the CSE

TABLE 5: Dominance statistics.

| GTFP | Model 1 | | Model 2 | | Model 3 | |
|--------|---------|------|---------|------|------------|------|
| | Domin. | Rank | Domin. | Rank | Domin. (%) | Rank |
| INSTIL | 13.41 | 3 | | | | |
| GSE | | | 10.17 | 2 | 3.28 | 9 |
| LSE | | | 7.76 | 3 | 5.43 | 7 |
| CSE | | | 82.07 | 1 | 9.20 | 3 |
| FDI | 8.08 | 4 | | | 6.84 | 5 |
| EDU | 5.57 | 6 | | | 5.48 | 6 |
| OPEN | 5.36 | 7 | | | 4.01 | 8 |
| MARKET | 22.21 | 2 | | | 23.80 | 2 |
| RD | 8.01 | 5 | | | 7.24 | 4 |
| URBAN | 2.97 | 8 | | | 2.43 | 10 |
| IS | 34.39 | 1 | | | 32.30 | 1 |

significantly can promote China's green growth. This demonstrates that we should strengthen R&D on green patents to promote green transformations with environmentally friendly technological innovations.

4.3. Relative Importance Analysis. The aforementioned results show that the institutional environment has a significant impact on China's green growth, but the main goal of the present study was to assess the contribution of the institutional environment relative to other factors. Therefore, a relative importance (RI) analysis was conducted. This analysis determines the relative importance of independent variables in an estimation model based on their contribution to an overall model fit statistic. We used the methods of [39, 40] to standardize the values of RI [41]. The results are shown in Table 5.

In Model 1, the influence of INSTIL on China's green growth ranked third, with a dominance of 13.41%. IS and MARKET ranked first and second, respectively, accounting for more than 50% of the total dominance in Model 1, and hence are the most important driving factors for China's green growth. Although the dominance of the institutional environment was lower than that of the other two variables, its effect on green growth cannot be ignored.

Model 2 and model 3 consider the impact of different dimensions of institutional environment on green growth. Notably, the relative importance of the CSE within the three subenvironments exceeded the sum of that of GSE and LSE. After adding the control variables, CSE ranked third, and the dominance of GSE and LSE was surpassed by R&D, FDI, and EDU. This means that the cultural system has played an important role in China's current green growth, but improvement is needed in its legal system and governance capabilities.

5. Conclusions

The present study has highlighted that there is an inverted U-shaped nonlinear relationship between China's overall institutional environment and green growth. The institutional environment can significantly improve green growth at the initial stage of economic development, but, as the

economy continues to develop, the institutional environment will hinder green growth. Notably, different dimensions of the institutional environment have distinct impacts on green growth. According to the analysis of relative importance, the cultural subenvironment is more important than both the governmental and the legal ones.

Enhancing the positive role of the institutional environment on green growth while overcoming its negative role is an important issue that China needs to solve. Based on the aforementioned results, we hereby provide policy guidelines for governments.

- (1) Emphasizing guidance on the effects of institutional efficiency and prioritizing services for green industry growth is crucial. The transformation of service effectiveness as a result of the promotion of institutional efficiency is greatly affected by government behavior. Therefore, for the governmental subenvironment to play a positive role in green growth, the government should prioritize green industries and further transform the governmental subenvironment into service for green transformation.
- (2) Efforts should be directed towards improving the rules of law and strengthening the optimization of the legal subenvironment. For instance, the current Chinese law system has not reached the inflection point yet, which means it is still suboptimal and could not improve green economic growth. Therefore, the government needs to gradually improve the law system, increase the efficiency of laws and regulations, ensure that law enforcement is strict and law breakers are handled accordingly, and construct a fair and safe environment to promote innovations, especially green ones, to a higher degree.
- (3) There must be a focus on emphasizing the promotion of and education on public environmental protection to support the formation of a green growth concept. As a part of a country's soft power, culture is important and significant for economic growth. However, the cultural subenvironment could not positively affect green economic growth. It is a weakness that should be addressed, but it also represents an opportunity for the country. The

government should strengthen the promotion of and education on environmental protection before forming a green growth culture. The effect of cultural methods on green innovations can eliminate its reliance on paths. Therefore, future system optimization processes should concentrate on the promotion of and education on environmental culture to form a common green growth idea, which would further be beneficial for the green transformations of the Chinese economy.

Although the GMM estimation and relative importance analysis are used to obtain consistent estimation results, the aspects described hereafter still need to be addressed in future studies. First, the mechanism of the impact of the institutional environment on green growth should be further evaluated. The institutional environment does not only directly affect green growth but also has intermediary or mediating effects, such as industrial upgrading, financial performance, and government organizations. Second, research at the microlevel should be promoted. Although an increasing number of studies have focused on the micro-impact of institutions on economic activities, they have concentrated on a single dimension, such as government enterprise collusion, political uncertainty, or CEO background characteristics. Therefore, a comprehensive analysis of the institutional environment is still lacking.

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

A Markov Chain Position Prediction Model Based on Multidimensional Correction

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User location prediction in location-based social networks can predict the density of people flow well in terms of intelligent transportation, which can make corresponding adjustments in time to make traffic smooth, reduce fuel consumption, reduce greenhouse gas emissions, and help build a green cycle low-carbon transportation green system. This paper proposes a Markov chain position prediction model based on multidimensional correction (MDC-MCM). Firstly, extract corresponding information from the user's historical check-in position sequence as a position-position conversion map. Secondly, the influence of check-in period, space distance, and other factors on the position prediction is linearly weighted and merged with the position prediction of the n -order Markov chain to construct MDC-MCM. Finally, we conduct a comprehensive performance evaluation of MDC-MCM using the dataset collected from Brightkite. Experimental results show that compared with other advanced location prediction technologies, MDC-MCM achieves better location prediction results.

1. Introduction

With the development of the world's industrial economy, the rapid increase in population, and the unrestrained production and lifestyles, the world climate faces more serious problems. Greenhouse gas emissions are increasing, and the earth's ozone layer is suffering from unprecedented crises. Catastrophic climate changes have repeatedly appeared globally, which have seriously endangered the living environment and health and safety of human beings. The communication network and the positioning system are combined to form a new type of social network—location-based social network [1]. In a location-based social network, people can share their location and location information at any time through communication devices, also known as sign-in. These data can be used for user location prediction, friend relationship prediction, and personal behavior patterns [2–4]. The user's location prediction is of great use in intelligent transportation. It can predict the density of people flow and make corresponding adjustments in time to make traffic smooth [5], reduce fuel consumption, reduce greenhouse gas emissions, and help build a green cycle low-

carbon transportation green system. In addition, it also plays an important role in smart cities and epidemiological communication research.

Currently, many methods of position prediction have emerged. Among them, Yuan et al. [6] explored the influence of time and space on location prediction in location-based social networks. Ye et al. [7] used power law distribution to model spatial factors and combined user preferences and friend relationships to predict location. Cheng et al. [8] used a first-order Markov chain based on the influence of the most recently visited location on the next location and integrated the matrix decomposition method to predict the location. Based on the high-order influence of n -order weighted Markov chain, Zhang and Chow [9] combined time and space with friend relationship and popularity factors for location prediction.

In this paper, we adopt the n -order Markov chain [10] and then consider the period of check-in, space distance, friend relationship, and popularity of check-in points and propose a Markov chain position prediction model based on multidimensional correction (MDC-MCM), which realizes the position prediction for LBSNs.

In short, our contribution to this research work has three aspects.

Firstly, we link user location prediction in location-based social networks with intelligent transportation to help build a green, circular, low-carbon transportation green system.

Secondly, Markov chain position prediction model based on multidimensional correction (MDC-MCM) comprehensively considers the check-in time period, spatial distance, friend relationship, and check-in point popularity. The dimensions considered are more comprehensive.

Finally, we evaluated the proposed location prediction method on the Brightkite dataset. The experimental results show that our proposed location prediction method has better prediction performance compared with other methods.

The rest of the paper is organized as follows. Section 2 describes the Markov chain position prediction model based on multidimensional correction in detail. In the third section, we will experiment with the proposed model in the Brightkite dataset to get the results and discuss further. Finally, in the fourth section, the conclusion is drawn and the future work arrangements are described.

2. MDC-MCM

2.1. LLTG Diagram. Figure [11]. A data structure composed of a set of vertices and a set of relations between vertices defined as $\text{Graph} = (V, E)$.

Out Degree [11]. The number of edges associated with a vertex is called a degree. In a directed graph, a vertex is the end of the arc and the number of arcs starting from the vertex.

Location to Location Transition Graph (LLTG graph, Location to Location Transition Graph). This contains a series of vertices L and edges $E = L^2$. Each vertex $l_i (l_i \in L)$ represents a point of interest, and each vertex l_i has an out-degree, denoted as $O \text{ Count}(l_i)$, and the transition frequency from l_i to l_j is denoted as $T \text{ Count}(l_i, l_j)$. For example, in Figure 1, the out-degree of location node l_1 is 8, the out-degree of location node l_2 is 3, the out-degree of location node l_3 is 7, and the out-degree of location node l_4 is 0.

It can be seen from Figure 1 that the LLTG graph describes the transfer frequency from one location node to another location node and the outgoing degree of each node.

Transition probability represents the probability of one location node to another location node, and the transition probability from l_i to l_j is recorded as $TP(l_i \rightarrow l_j)$. And, considering that the out-degree of the location node may be 0, we assume that the transition probability of the out-degree of the location node is 1:

$$TP(l_i \rightarrow l_j) = \begin{cases} \frac{T \text{ Count}(l_i \rightarrow l_j)}{O \text{ Count}(l_i)}, & O \text{ Count}(l_i) \neq 0, \\ 1, & O \text{ Count}(l_i) = 0. \end{cases} \quad (1)$$

2.2. n-Order Markov Chain. Markov chain [12] is a sequence of random variables X_1, X_2, X_3 , and so on. The range of these variables, the set of all their possible values, is called the state space. If the state corresponding to time n is X_n , then X_{n+1} is regarded as a function of X_1, \dots, X_n , also known as an n -order Markov chain [10], which has n -order memory. The matrix composed of transition probabilities is the transition probability matrix.

Assuming that user u has m location nodes and is now at time n and the location node is l_n , the transition probability matrix is as follows:

$$R = \begin{bmatrix} P_{11} & \dots & P_{1m} \\ \dots & \dots & \dots \\ P_{m1} & \dots & P_{mm} \end{bmatrix}. \quad (2)$$

Among them, $P_{ij} = TP(l_i \rightarrow l_j)$.

The probability distribution vector of the initial state is as follows: $P_1 = [1, 0, \dots, 0]$. Then, the probability distribution vector of user u going to each location node at time $n + 1$ is as follows:

$$P0_u^{n+1} = P_1 \cdot R^n. \quad (3)$$

2.3. Time Zone When Signing in. Studies have shown that the user's sign-in behavior largely meets the regularity of time [13]. Therefore, analyzing the data from the perspective of time is essential to improve the accuracy of position prediction. We select the Brightkite dataset and make a map of the week distribution and hour distribution of user sign-in (Figures 2 and 3).

From Figure 2, it is found that the proportion of check-in times varies periodically with the week. The number of check-ins from Monday to Thursday is relatively even, the number of check-ins on Friday and Saturday has increased significantly, and the number of check-ins on Saturday is the highest, and the number of check-ins on Sunday and Monday to Thursday is similar.

From Figure 3, it is found that the proportion of the number of check-ins changes periodically with the hour. From 0:00 in the morning, the number of user check-ins showed a downward trend, until the lowest peak of check-ins appeared at about 10 am. As the number of check-ins

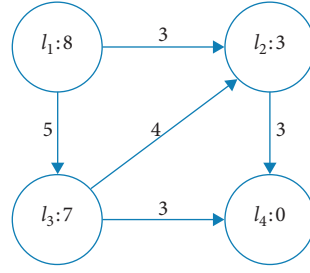


FIGURE 1: Example of position-position transition diagram (LLTG diagram).

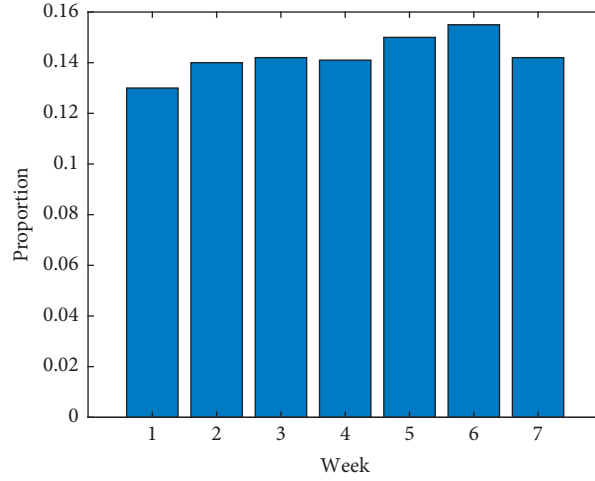


FIGURE 2: Weekly distribution of user sign-in.

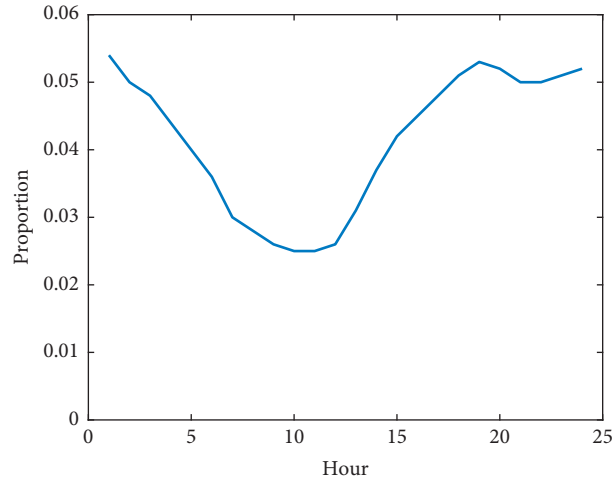


FIGURE 3: Hourly distribution of user check-in.

increased, the highest peak appeared at about 7 pm, after which the number of check-ins fluctuated within a small range. According to the law of change, a day is divided into three-time intervals: interval 1, interval 2, and interval 3. Let $T = \{\text{interval 1, interval 2, interval 3}\}$, then corresponding time range is 0:00–10:00, 10:00–19:00, and 19:00–24:00.

Consider the week and time interval comprehensively to study user sign-in location prediction.

Define the probability P_{u,l_i}^h of the user u checking in at location l_i in the time interval h as

$$P_{u,l_i}^h = \frac{N_{u,l_i}^h}{\sum_{j=1}^m N_{u,l_j}^h}. \quad (4)$$

Among them, h is the element in the previously defined time interval T , m is the size of the location set

$L = \{l_1, l_2, \dots, l_m\}$, and N_{u,l_i}^h indicates that the user u checked in at the location l_i in the time interval h frequency.

Therefore, the check-in probability P_{u,l_i}^t of the user u at the location node l_i on the t day of the week can also be obtained:

$$P_{u,l_i}^t = \frac{M_t^h P_{u,l_i}^h}{M_t}, \quad h \in T, l_i \in L. \quad (5)$$

Among them, M_t^h is the number of check-ins in interval h on the t day of the week and M_t is the total number of check-ins on the t day of the week.

To simplify the calculation, the obtained probability is subjected to min-max normalization processing [14]:

$$P_{u,l_i}^{t*} = \frac{P_{u,l_i}^t - \min\{P_{u,l_1}^t, P_{u,l_2}^t, \dots, P_{u,l_m}^t\}}{\max\{P_{u,l_1}^t, P_{u,l_2}^t, \dots, P_{u,l_m}^t\} - \min\{P_{u,l_1}^t, P_{u,l_2}^t, \dots, P_{u,l_m}^t\}}, \quad 1 \leq i \leq m. \quad (6)$$

Then, the probability distribution vector of user u going to each location node at time $n+1$ is as follows:

$$P1_u^{n+1} = [P_{u,l_1}^{t*}, P_{u,l_2}^{t*}, \dots, P_{u,l_m}^{t*}]. \quad (7)$$

2.4. Spatial Distance. Since the spatial distances of the two consecutive check-in points are different, it is necessary to

estimate the distribution of the two consecutive check-in points with the spatial distance.

The sampling data of the space are collected from the check-in set D as shown in the following:

$$D = \{\text{Haversine}(l_i, l_j)\}. \quad (8)$$

Among them, the Haversine distance formula [15] is as follows:

$$\text{Haversine}(l_j, l_{j+1}) = 2r \cdot \arcsin\left(\sqrt{\sin^2\left(\frac{\text{lat}_{j+1} - \text{lat}_j}{2}\right) + \cos(\text{lat}_j) \cdot \cos(\text{lat}_{j+1}) \cdot \sin^2\left(\frac{\log_{j+1} - \log_j}{2}\right)}\right), \quad (9)$$

where r is the radius of the Earth, about 6371 km.

Assuming that the spatial distance d between two consecutive check-in points approximately obeys the power law distribution [16], the probability density formula of the power law distribution is as follows:

$$f(d) = (\gamma - 1)(d + 1)^{-\gamma}, \quad d \geq 0, \gamma > 1. \quad (10)$$

According to the maximum likelihood estimation method [17], we can estimate from sample D

$$\gamma = 1 + |D| \left(\left[\sum_{d \in D} \ln(d + 1) \right] \right)^{-1}. \quad (11)$$

The Brightkite dataset is selected to plot the probability density and the spatial distance of two consecutive check-in points, as shown in Figure 4.

In Figure 4, we find that the spatial distance between the probability density and two consecutive check-in points is very similar to the estimated power law distribution. It shows that our hypothesis is reasonable and effective. The spatial distance d of two consecutive check-in points can be regarded as obeying the power law distribution.

Assuming that user u has m location nodes and is now at time n and the location node is l_n , the probability of going to each node is as follows:

$$F(d_{l_n, l_i}) = \int_{d_{l_n, l_i}}^{+\infty} f(d) dy = (d_{l_n, l_i} + 1)^{1-\gamma}, \quad 1 \leq i \leq m. \quad (12)$$

Among them, l_i is the i -th sign-in point.

To simplify the calculation, the obtained probability is subjected to min-max normalization processing [14].

$$F^*(d_{l_n, l_i}) = \frac{F(d_{l_n, l_i}) - \min\{F(d_{l_n, l_1}), F(d_{l_n, l_2}), \dots, F(d_{l_n, l_m})\}}{\max\{F(d_{l_n, l_1}), F(d_{l_n, l_2}), \dots, F(d_{l_n, l_m})\} - \min\{F(d_{l_n, l_1}), F(d_{l_n, l_2}), \dots, F(d_{l_n, l_m})\}}, \quad 1 \leq i \leq m. \quad (13)$$

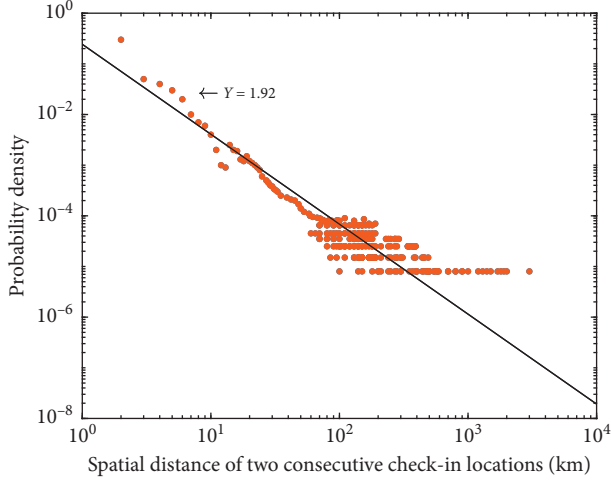


FIGURE 4: The spatial distance distribution of two consecutive check-in points.

Then, the probability distribution vector of user u going to each location node at time $n+1$ is as follows:

$$P2_u^{n+1} = [F^*(d_{l_n, l_1}), F^*(d_{l_n, l_2}), \dots, F^*(d_{l_n, l_m})]. \quad (14)$$

2.5. Friendship. Based on the previous research [9], user sign-in points are related to friends. Different friends have different influences. In order to measure the influence of different friends, we have introduced the Jaccard coefficient to measure the similarity and difference between different friends.

2.5.1. Jaccard Coefficient. Jaccard coefficient [18] is widely used in the field of information retrieval. It is often used as an index to measure the similarity of two objects, that is, to judge the probability that a certain characteristic is shared by two objects. Here, a certain characteristic is defined as the number of common friends, that is, the number of common friends owned by two user accounts for the sum of the number of friends owned by two users. The formula is as follows:

$$S_{\text{jaccard}} = \frac{|\Gamma(i) \cap \Gamma(j)|}{|\Gamma(i) \cup \Gamma(j)|} \quad (15)$$

Among them, $\Gamma(i)$ is the set of neighbors of user node i and $\Gamma(j)$ is the set of neighbors of user node j . The larger the Jaccard coefficient value, the higher the similarity between friends and the closer the relationship.

Assuming that user u has m location nodes and p friends and he is now at time n and his location node is l_n , then the probability that a friend will influence user u 's check-in at location node l_i is as follows:

$$P_{\text{jaccard}}(l_i) = \sum_{k=1}^p S_{\text{jaccard}}(u, k) \cdot T_k(l_i), \quad 1 \leq i \leq m. \quad (16)$$

Among them, $T_k(l_i)$ represents the check-in frequency of the k -th friend of the user u at the location node l_i .

To simplify the calculation, the obtained influence probability is subjected to min-max normalization processing [14].

$$P_{\text{jaccard}}^*(l_i) = \frac{F(l_i) - \min\{P_{\text{jaccard}}(l_1), P_{\text{jaccard}}(l_2), \dots, P_{\text{jaccard}}(l_m)\}}{\max\{P_{\text{jaccard}}(l_1), P_{\text{jaccard}}(l_2), \dots, P_{\text{jaccard}}(l_m)\} - \min\{P_{\text{jaccard}}(l_1), P_{\text{jaccard}}(l_2), \dots, P_{\text{jaccard}}(l_m)\}}, \quad 1 \leq i \leq m. \quad (17)$$

Then, the probability distribution vector of user u going to each location node at time $n+1$ is as follows:

$$P3_u^{n+1} = [P_{\text{jaccard}}^*(l_1), P_{\text{jaccard}}^*(l_2), \dots, P_{\text{jaccard}}^*(l_m)]. \quad (18)$$

2.6. Popularity of Check-In Points. The popularity of check-in points can greatly affect the user's prediction of the next check-in location. The popularity of the check-in point can be directly determined by the historical check-in frequency of the location l_i of the user u .

Assuming that user u has m location nodes and is now at time n and the location node is l_n , the probability of going to each node is as follows:

$$F(l_i) = T_u(l_i), \quad 1 \leq i \leq m. \quad (19)$$

Among them, $T_u(l_i)$ represents the historical check-in frequency of the user u at the check-in node l_i .

To simplify the calculation, the obtained probability is subjected to min-max normalization processing [14].

$$F^*(l_i) = \frac{F(l_i) - \min\{F(l_1), F(l_2), \dots, F(l_m)\}}{\max\{F(l_1), F(l_2), \dots, F(l_m)\} - \min\{F(l_1), F(l_2), \dots, F(l_m)\}}, \quad 1 \leq i \leq m. \quad (20)$$

Then, the probability distribution vector of user u going to each location node at time $n + 1$ is as follows:

$$P4_u^{n+1} = [F^*(l_1), F^*(l_2), \dots, F^*(l_m)]. \quad (21)$$

The linear weighted fusion of the various predicted probabilities that affect the next check-in position proposed above is used to obtain a Markov chain position prediction model based on multidimensional correction (MDC-MCM). The probability distribution vector of each check-in point of user u at time $n + 1$ is as follows:

$$P_u^{n+1} = P0_u^{n+1} + \mu_1 \cdot P1_u^{n+1} + \mu_2 \cdot P2_u^{n+1} + \mu_3 \cdot P3_u^{n+1} + \mu_4 \cdot P4_u^{n+1}. \quad (22)$$

Among them, μ_1 , μ_2 , μ_3 , and μ_4 are all correction coefficients.

3. Experiment

In this section, the proposed model is compared with the latest position prediction technology, and the accuracy and recall rates are obtained on the Brightkite dataset [2].

3.1. Brightkite Dataset. The Brightkite dataset is a dataset based on user sign-in data in the LBSN sign-in website. The data format for check-in in Brightkite dataset is $\langle \text{userid}, \text{check-in time}, \text{latitude}, \text{longitude}, \text{locationid} \rangle$. Brightkite is the second-largest sign-in site after Foursquare. The statistics of the dataset are shown in Table 1.

In Table 1, we need to preprocess the data in Table 1 to ensure the quantity and quality of the data. In the preprocessing, to prevent the sparse data from affecting the experimental results, users with less than ten check-ins and points of interest with a total of fewer than ten check-ins are filtered out. According to the check-in time, the check-in data are divided into training set and test set. And, the first 80% of the check-in data are used as the training set, and the last 20% of the check-in data are used as the test set. In the experiment, the training set adopts the Markov chain position prediction model based on multidimensional correction to predict the test data.

3.2. Evaluation Technology. We will compare the Markov chain location prediction model (MDC-MCM) we built based on multidimensional corrections and previous location recommendation technologies, including the following:

STI. This method considers time and space factors, independently predicts the user's preference for location nodes in each time interval, and users are more inclined to visit nearby points of interest [6].

USG. This method uses comprehensive location prediction model spatial factors according to a power law distribution and combines user preferences and friend relationships [7].

FMC. This method is based on a first-order Markov chain, which uses the influence of the most recently

visited location on the next location and incorporates the matrix factorization method [8].

AMC. This method uses a sequence prediction algorithm based on an n -order weighted Markov chain, combined with a simple weight decay method, so that the recommendation results are more inclined to check-in to places that are closer [19].

LORE. This method uses a high-order sequential influence based on an n -order weighted Markov chain and combines time and space with friendly relations and popularity factors [9].

MDC-MCM. The MDC-MCM proposed in this paper is based on the high-order sequence influence of the n -order Markov chain and combines the check-in period, space distance, friend relationship, and check-in point popularity factors.

3.3. Performance Metrics. To evaluate the performance of each method, we selected two metrics, precision [20] and recall [20] as follows:

$$\text{precision} = \frac{1}{|U|} \sum_{u=1}^{|U|} \frac{H_u}{R_u}, \text{recall} = \frac{1}{|U|} \sum_{u=1}^{|U|} \frac{H_u}{C_u}. \quad (23)$$

Among them, $|U|$ is the number of users to be predicted, H_u is the predicted hit number of user u , R_u is the number of location prediction sequences of user u , and C_u is the set of locations visited by user u in the test set.

3.4. Result. The number of next positions (top- k) for each prediction is set from 1 to 20. Repeatedly adjust the correction coefficient in the training set, and finally get the current correction coefficient: $\mu_1 = 0.67$, $\mu_2 = 0.84$, $\mu_3 = 0.24$, and $\mu_4 = 0.13$. Better prediction results can be obtained in the test set, and draw precision and recall separately with other position prediction techniques curve. The results are shown in Figures 5 and 6.

3.5. Analysis. Here, we analyze the experimental results.

3.5.1. The Number of Check-In Points Recommended for Users Top- k . In Figures 5 and 6, it can be observed that as the number of recommended check-in point top- k increases, the accuracy rate gradually decreases and the recall rate gradually increases. This is also in line with expectations. As the number of recommended check-in point top- k increases, if the location visited by the user is already in the recommended check-in point, it will change as the remaining recommended check-in points increase and the user will be at the recommended check-in point. The proportion of CM becomes lower, and the accuracy rate decreases; as the recommended check-in points increase, the more likely the place users visit is in the recommended check-in points, the greater the recall rate.

TABLE 1: Statistics of the Brightkite dataset.

| Index | Brightkite |
|----------------------------------|----------------|
| Nodes | 58228 |
| Edges | 214078 |
| Nodes in largest SCC | 56739 (0.974) |
| Edges in largest SCC | 212945 (0.995) |
| Average clustering coefficient | 0.1723 |
| Number of triangles | 494728 |
| Fraction of closed triangles | 0.03979 |
| Diameter (longest shortest path) | 16 |
| 90-percentile effective diameter | 6 |
| Check-ins | 4, 491, 143 |

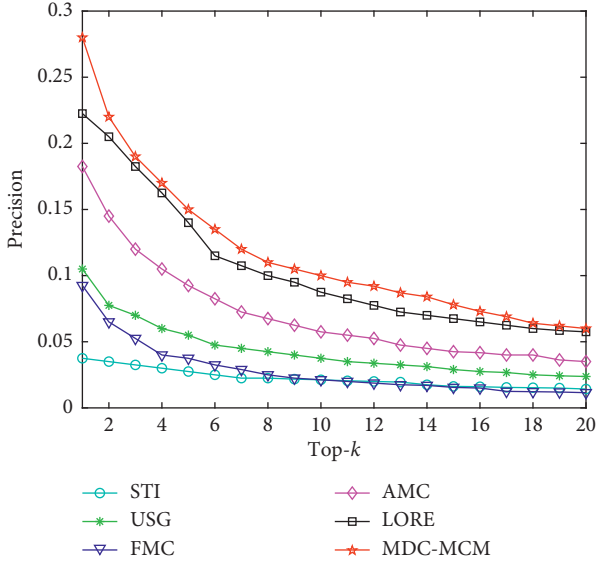


FIGURE 5: Precision curve.

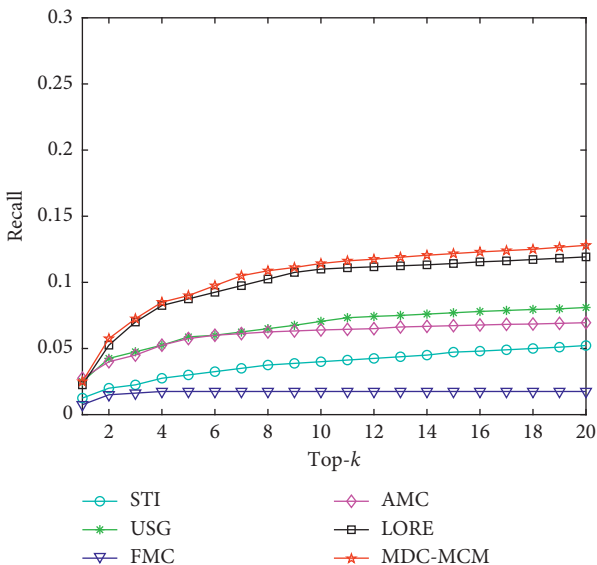


FIGURE 6: Recall curve.

3.5.2. The Effect of Different Factors on Recommendation Results. In Figures 5 and 6, through the prediction curve of the FMC method and the prediction curve of the STI method, it can be found that the time factor plays an important role in the position prediction. Through the prediction curve of the STI method and the prediction curve of the USG method, it can be found that the friend relationship plays an important role in location prediction. Through the prediction curve of the USG method and the prediction curve of the AMC method, it can be found that spatial distance plays an important role in position prediction. Through the prediction curve of the AMC method and the prediction curve of the LORE method, it can be found that the popularity of the check-in point plays an important role in the location prediction. MDC-MCM models the sequence influence based on the n-order Markov chain and considers the influence of check-in period, space distance, friend relationship, and check-in point popularity to ensure that MDC-MCM is superior to other location prediction algorithms. However, MDC-MCM uses an n-order Markov chain and has many correction parameters, which makes each run time very long; there are too many correction parameters, and parameter adjustment is cumbersome.

4. Conclusion

This paper proposes a Markov chain position prediction model based on multidimensional correction (MDC-MCM). First, MDC-MCM utilizes the high-order sequence influence based on the n-order Markov chain to consider all positions and transition probabilities in the user's check-in history. In addition, MDC-MCM combines the influence of check-in period, space distance, friendship, and popularity of check-in points. Finally, the experimental results on the Brightkite dataset show that the MDC-MCM position prediction works well. In the future, we will consider using the community as a unit to make predictions and then make predictions in the community to reduce the workload of computer operations. In addition, consider deploying the model on a distributed computing platform, which greatly shortens the running time and makes it easier to adjust the correction parameters.

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 regarding the publication of this paper.

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Research Article

Industrial Structure, R&D Staff, and Green Total Factor Productivity of China: Evidence from the Low-Carbon Pilot Cities

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Using data of 26 cities in China from 2004 to 2017, the green total factor productivity is investigated by the SMM-GML method. The corresponding empirical analysis is conducted with the DID model. This paper investigates the relation between low-carbon pilot policy (LCC) and green total factor productivity and discusses the mediating effect of industrial structure and the number of R&D staff (RDS). First, we find that LCC has a significant effect on pilot cities' GTFP. And, it also promotes GTFP via industrial structure. Second, LCC can improve industrial structure optimization and realization, and industrial structure realization affects GTFP significantly, while optimization cannot. Third, LCC cannot attract more RDS, and RDS harms local GDFP because of talent misallocation. At last, the rate of GTFP presented different upward trends in the order of non-eastern cities and eastern cities. The effect of LCC on GTFP is significant in non-eastern cities, but not eastern ones, which clearly demonstrates the imbalanced development of the green economy. Therefore, the governments of eastern and non-eastern regions should adopt different measures based on local conditions in industrial structure transformation and recruitment and strengthen environmental regulations to make the effect of the low-carbon policy lasting and promote GTFP growth balance in all regions.

1. Introduction

United Nations Secretary-General Guterres and World Meteorological Organization Secretary-General Taras held a press conference on September 9 and released a new report on global climate change in 2020. The report shows that in the first half of 2020, the greenhouse gas concentration has exceeded 410 parts per million, the highest level in three million years, and this number is still rising. And, according to the Global Carbon Budget Report 2019, in 2018, the main contributors to global CO₂ emissions were China (28%), the United States (15%), the 28 EU countries (9%), and India (7%). The growth rates of China, the United States, the 28 EU countries, and India in 2019 are predicted to be 2.6% (0.7%~4.4%), -1.7% (-3.7%~0.3%), -1.7% (-3.4%~0.1%), and 1.8% (0.7%~3.7%). China is clearly an important country responsible for reducing carbon emissions. According to the "China's Policies and Actions to Address Climate Change 2019 Annual Report," the national carbon emission intensity

in 2018 has been reduced by 45.8% compared with 2005, and it has reached the international commitment of reducing carbon emission intensity by 40% to 45% in 2020 compared with 2005.

The traditional economic growth model of China relies heavily on factor input, which has caused resource exhaustion and environmental deterioration and is difficult for economic development sustainable. In the process of carbon emission reduction, has it promoted green economic growth? The "green growth," a term rarely heard before 2008, has burst onto the international policy scene over recent years [1]. The "green growth" and low-carbon economy is a sustainable economic development model, which helps the transformation of economic development from relying on high-carbon emissions to low-carbon emissions [2]. The Chinese government has issued a series of policies to reduce carbon emissions and promote economic transformation, such as the low-carbon pilot policy. China has launched the first 8 low-carbon pilot cities in 2010,

released the second batch of pilot cities in 2012 which include 24 cities, and the third batch was launched in 2017. Currently, there are 67 low-carbon pilot cities nationwide. It has been nearly 10 years passed since the first pilot cities had been launched. Does the low-carbon policy contribute to the green growth of these cities?

An appropriate measure of green growth is essential for assessing the effectiveness of the reform conducted by the government. Productivity is one of the most important factors to measure economic growth and quality of life improvement. But productivity is not directly observable; many researchers focus on estimating the total factor productivity (TFP). Solow [3] indicates that the extensive growth pattern based on the continued expansion of inputs was unsustainable and that only the intensive growth pattern, which relied on TFP growth, was sustainable in the long run. However, traditional TFP evaluations fail to take resource and environmental factors into consideration, which can lead to distorted TFP implications [4]. Especially, the concept of Green Total Factor Productivity (GTFP) came out; it is drawn from the integration of two important developmental strategies: productivity improvement and environmental protection [5]. This means the GTFP determines the economic development pattern's transformation which in turn will affect the sustainable development of China's economy. Therefore, the GTFP is an appropriate index to evaluate the policies' effectiveness, and we use the SBM-GML method to measure GTFP. The Chinese city-level data collected by the National Bureau of Statistics and Provincial Statistics Bureau of China from 2004 to 2017 are considered. Considering its incompleteness, the data of 26 cities are selected and used for our modeling. Then, another question arises. How the low-carbon policy affects GTFP.

Many researchers pay their attention to industrial structure [6]. In this paper, we decompose the effect of industrial structure into two parts—industrial structure upgrading effect and industrial structure transformation effect—and use industrial structure optimization (SO) and industrial structure rationalization (SR) to measure these two indexes [7]. Because environmental regulations significantly facilitate local industrial structure upgrading [8] and industrial development is one of the key drivers of economic growth. So, we believe that the industrial structure is an important mediating variable between low-carbon policy and GTFP. The proposed DID-based empirical analysis clearly presents the evidence that the low-carbon pilot policy promotes the growth of GTFP through rationalization of the industrial structure.

Besides the industrial structure, the number of employed R&D personnel (RDS) also affects economic development. According to the "National Low-Carbon Provinces and Low-Carbon City Pilot Work Notice," local governments should "strengthen the building of low-carbon development capacity and talent team." This means from the perspective of city governments, to improve the low-carbon development capabilities in the region, they should pay attention to the accumulation of talents in related fields when low-carbon pilot policy is implemented. Noticing that the labor with higher skills can improve productivity [9], we can

rationally presume the low-carbon policy increases the number of employed R&D personnel to strengthen the economy. With the same method, we find that the number of R&D staff (RDS) hurts GTFP, and the low-carbon policy cannot increase the number of R&D staff. This blames to the misallocation of talents—concentrated in nonmarketable sectors.

At last, we investigate whether the difference of the economic foundation of the cities would bring different outcomes. The green economy growth rate of non-eastern cities is higher than that of eastern cities. We conduct a heterogeneity analysis for these two kinds of cities. The result shows the low-carbon pilot policy cannot affect the green total factor productivity of eastern cities due to the poor environmental foundation and large industrial volume. Different from non-eastern cities, it is difficult for the eastern cities to conduct a fast green transformation. The low-carbon pilot policy promotes the green total factor productivity of non-eastern cities.

The novelty of this paper lies in three aspects. First, different from She et al. [10], the rate of industrial solid waste is taken into consideration and incorporated into the SMB-GML method. Under the low-carbon policy, with the rise of environmental consciences and technique, the comprehensive utilization rate of industrial solid waste rise, which can be regarded as the outcome of green growth. This is a novel and effective framework for measuring GTFP. Second, the human capital is considered as a new pathway from the low-carbon policy to green total factor productivity. Apparently, according to our theory, human capital is a crucial factor in economic growth and environmental protection. However, this factor is usually ignored in the existing literature, not to mention considering it as a pathway between the low-carbon policy and GTFP. Third, the number of R&D staff is used to represent the high-level human capital. It is noted that the innovative consciousness of R&D individuals also benefits the research and innovation in green developments. Therefore, we can reasonably infer that the misallocation of talents would decelerate the development of the green economy.

The rest of the paper is organized as follows. The literature on low-carbon policy, GTFP, industrial structure, and labor structure relevant to our research is briefly reviewed in Section 2. Section 3 presents the methodology, data, and theoretical framework. Section 4 gives the empirical results. Some further discussions and conclusions are provided in Section 5.

2. Literature Review

2.1. Low-Carbon Policy and GTFP. Green total factor productivity (GTFP) is a more appropriate index than traditional total factor productivity (TFP) for evaluating the low-carbon pilot cities' economic growth. The traditional index is not capable of reflecting the value of natural resources and the negative externality of environmental pollution [11]. While GTFP incorporates resource and environmental issues into total factor productivity (TFP) analytical framework that pursues both quantity and quality in economic

growth and has been proved to be a scientific indicator for measuring green development [12, 13]. The measurement methods for GTFP are developed based on those for TFP and classified into two categories, i.e., parametric and nonparametric. Compared with parametric methods, nonparametric ones such as DEA are not restrained by the functional forms and can take various variables into consideration. However, the DEA method is not efficient enough for GTFP due to the biases caused by radial and oriented selection [14]. But, DEA is not effective enough to measure GTFP unbiasedly (bias caused by radial or oriented selection); Oh [15] proposed the global ML (GML) productivity index. And, Fukuyama and Weber [16] formulated a more general SBM directional distance function following the nonradial and nonoriented basis proposed by Tone [17]. Furthermore, the GML index based on SBM directional distance function is developed to solve the problems that exist in the literature. The SBM-GML can efficiently relieve the radial and oriented problems, achieve global comparability in the production frontier simultaneously, and has been received a lot of attention recently. Wang et al. [13] utilized the SBM-DEA method and found the GTFP of China's provinces presents an overall upward trend from 2004 to 2008. She et al. [10] based on the SBM-DEA method found, overall in China, the annual average value of GTFP is in the range of 0.2 to 0.7, which is at a low stage of development.

Environmental problem has a complex relationship with economic growth. And, addressing them simultaneously poses a dilemma. There is much research about the effect of China's environmental policy on GTFP. She et al. [10] show that the low-carbon pilot policy can directly promote urban green total factor productivity. This result is still significantly positive after the robustness test. This means that tightening environmental regulation is an effective measure of guaranteeing economic growth and optimizing environmental quality [18]. Using data of 36 industrial sectors from 2000 to 2014, Chen et al. [19], found that, in general, despite a significant carbon reduction effect by current policy, there is still much space for potential abatement to be developed. Li and Wu [20] show that the effect of local environmental regulation on green total factor productivity of China is significantly positive in high political attribute cities but negative in lower political attribute cities. Chen [11] analysis with 36 industrial sectors data from 2000 to 2014 of China found that considering energy consumption and environmental undesirable outputs; the industrial GTFP goes backward by 0.02% per year on average. These previous research illustrate that the environmental protection policy has an unclear clue on GTFP. Since the low-carbon pilot policy is a comprehensive environmental policy under the interaction between the central government and local governments, the impact on pilot cities is more reflected in the multiple policy welfare effects and the "halo effect" and "target restraint effect." This implies that the local government can receive policy support from central government, which increases the incentives to implement low-carbon pilot projects for completing the assessment of carbon emission reduction targets. In addition, the support policies

prompt the pilot cities to transfer the local industrial structure, develop the low-carbon industries, and attract amounts of R&D people. Based on the above analysis, this study attempts to propose the following 2 hypotheses.

Hypothesis 1. The low-carbon policy promoting GTFP directly.

Hypothesis 2. The low-carbon policy promoting GTFP indirectly;

2.2. Mediation of Industrial Structure. Lu et al. [21] provide empirical evidence based on the PSM-DID method to show that the implementation of low-carbon pilot policies has significantly promoted the upgrading of industrial structure. Zhang et al. [8] indicate that, in the long term, strict environmental regulations increase the proportion of the tertiary industry and promote the upgrading of the industrial structure. However, Zhao and Sun [22] believe that environmental regulations are not conducive to the sustainable development of the industry since severe environmental regulations may increase the production costs of companies and reduce their production activity [23, 24]. According to the policy, most of the low-carbon pilot construction plans announced by the government propose that low-carbon pilot cities should focus on optimizing their structure and improving energy efficiency and vigorously developing low-carbon industries. Enterprises that are difficult to transform will choose to move out of the region and conduct location migration and spatial reconfiguration [25]. Zheng and Shi [26] investigated the pollution haven hypothesis at the domestic level in China using panel data of 30 provincial-level regions for the period 2004 to 2013. And, it was found that the implementation of environmental regulations prevents polluting industries from relocating to other regions making the low-carbon and high tech industries remain with structure improved. This paper confers that the low-carbon policy does encourage local industrial structure upgrading.

An effective way to reduce a region's carbon dioxide emissions is to promote the upgrading and optimization of industrial structure [6], and the industrial structure adjustment is a vital driver of economic growth. Thus, the industrial structure is essential to GTFP. Recently, SO and SR are used to measure industrial structure adjustment [7, 27]. SR refers to the reconfiguration of production resources to higher-level industries and the upgrading of dominant industries of the economy; SO refers to the flow and allocation of production factors and resources between different industrial sectors to achieve the goal of coordinated development and benign interaction [28]. Some related researches show that these two indexes may have different influences. In Lu, both SO and SR significantly promote the development of GTFP of China. Zhou et al. [29] recognize that SR and SO both have a positive effect on green development efficiency. Compared with SR, SO has a greater effect on green development efficiency. Han et al. [30] reveal SR has a positive impact on local ecological efficiency, and the improvement of ecological efficiency brought by SO is

even more impressive. Treating industrial structure as mediation, She et al. [10, 17] argue low-carbon policy cannot impact GTFP through SR, but SO can. The low-carbon pilot policy can increase the SO, thereby affecting the improvement of urban GTFP. Chen et al. [27] tested the effects of environmental regulation and industrial structure changes on carbon dioxide emissions, and the results demonstrated that environmental regulation is able to reduce emissions with change of SR, when SO is high. Environmental regulation even promotes carbon dioxide emissions when the level of SO is low. These two results are diametrically opposite, and the reason is the dependent variables are different. She et al. focus on the GTFP, but Chen et al. care about carbon dioxide emissions. Compared to CO₂ emission, GTFP is a comprehensive index that includes capital input, economic growth, and a series of environmental variables. Considering that the secondary industry still occupies an important part of the national economy of China [31], the process of the SO will not be obvious in short term. The effect of the interactive relationship between low-carbon policy and the SO is not clear for GTFP. We have hypotheses 3 and 4:

Hypothesis 3. The low-carbon policy can increase GTFP by promoting SR.

Hypothesis 4. The low-carbon policy cannot increase GTFP by promoting SO.

2.3. Mediation of R&D Staff. To evaluate sustainability transition pathways, the approach of Higher Education Advancing Development for Sustainability (HEADS) has been developed. Horan et al. [32] applied this HEADS approach to analyze the High Education Institution in Ireland as the leader in facilitating national low-carbon society transitions. It is conceivable that high human capital can accelerate low-carbon economic transformation. R&D staff as a group of labor with high human capital is crucial for local green total factor productivity and low-carbon policy. There are two paths that the R&D staff increased by the low-carbon policy: (1) the path of industrial structure adjustment. The construction of low-carbon cities accelerates the elimination of pollution-intensive and energy-intensive industries. Thus, decrease the low-skilled labor and create demand for high-knowledge and high-skilled labor. This motivates local governments to improve the mechanism of recruiting, attracting, and using talents/R&D staff, enlarging the scientific and technological talent team, and improving labor quality. (2) The path of green-tech innovation and application. Green innovation is required by the low-carbon economy. The higher level of education of community members, the higher the chances of implementing innovative ideas [33]. New products, high-tech products, and new product technologies development also need research and development (R&D) staff. Besides, Human capital is utilized to adopt new pollution-free methods and technologies in industries. Higher education is important in industrial structure upgrades, cultivating talent for industries, since firms with large amount of human capital can reduce

environmental costs significantly [34]. For a region, it may bring the same effect. Thus, the low-carbon policy helps to improve the green economy, which needs more high-level human capital for the cause. Therefore, the number of R&D staff could be increased by the low-carbon pilot policy.

Du and Li [35] suggested that green technology innovations improve human capital which is commonly regarded as the key factor in economic growth. Jones [36] found the U.S. economy has benefited from increasing in both educational attainment and research intensity. In the long run, the increase in available ideas will bring greater population gains, which will decisively dominate the negative effects of resource shortages [37]. That is important to an economy-transforming country. Ma and Cheng [38] use the data of R&D staff, human capital stock, and innovation efficiency in 30 provinces and cities in China from 2009 to 2011 and show that the employment of R&D personnel plays a significant role in promoting regional economic development. China's human capital structure advanced index maintains a steady upward trend in general and illustrates a significant positive correlation with sustainable economic development [39]. Combining these two ideas, the number of R&D staff (RDS) can promote GTFP. Based on the theoretical analysis presented above, a hypothesis is formulated as follows:

Hypothesis 5. The low-carbon policy increases GTFP by increasing RDS.

Based on the above analysis, the main influence mechanism of each element is shown in Figure 1.

3. Methodology and Data

3.1. Model of This Paper

3.1.1. DID Model. This paper employs the DID method to evaluate the effects by implementing the low-carbon policy. The low-carbon pilot project could be treated as a quasi-natural experiment. The pilot cities and nonpilot cities are set as experimental and control group, respectively. Compare the spatial and temporal differences in the implementation results of the pilot policy. By comparing the differences between the treatment group and the control group, we can get the actual effect of the policy shock [40]. The DID model is set as

$$\log \text{CTFP}_{it} = \alpha_0 + \alpha_1 \text{LCC}_{it} + \alpha_2 X_{it} + \eta_i + \gamma_t + \mu_{it}, \quad (1)$$

where LCC is the core independent variable, representing the crossover between the low-carbon pilot city and the pilot time, X is the control variables, i is the city, t is the year, η is the city fixed effect, γ is the time fixed effect, and μ is the time disturbance term.

3.1.2. Mediating Effect Model. Based on Hypothesis 3 (2.4), to investigate whether the low-carbon pilot policy will indirectly affect urban GTFP by affecting the industrial structure and the number of R&D staff, this article draws on the mediation effect model of Baron and Kenny [41] and

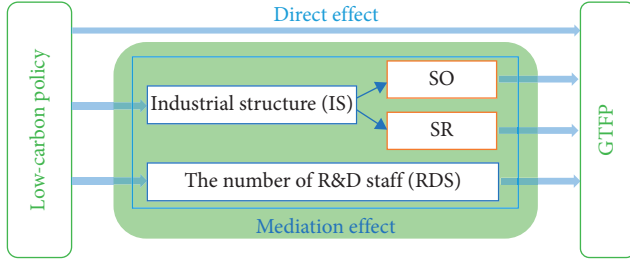


FIGURE 1: The influence of low-carbon policy on CTFP.

uses the gradual return method. The corresponding model is given as follows:

$$S_{it} = \lambda_0 + \lambda_1 LCC_{it} + \lambda_2 X_{it} + \eta_i + \gamma_t + \mu_{it}, \quad (2)$$

$$\log CTFP_{it} = \beta_0 + \beta_1 S_{it} + \beta_2 X_{it} + \eta_i + \gamma_t + \mu_{it}, \quad (3)$$

where S is the main variable of IS and RDS. IS is the industrial structure, analyzed with the variable of SO and SR. RDS is the number of R&D staff. If the low-carbon pilot policy affects the industrial structure, which in turn affects green total factor productivity, and then β_1 and λ_1 will be significant. If the signs of β_1 and λ_1 are consistent with the signs of α_1 in (1), it indicates that the mediating effect of industrial structure is $\beta_1 \times \lambda_1$. If the signs of β_1 and λ_1 are opposite to the signs of α_1 , the possible indirect effects of industrial structure will cover the actual impact of low-carbon pilot policy on green total factor productivity to a certain extent, and the masking effect is also $\beta_1 \times \lambda_1$.

Furthermore, to investigate whether the mediating effect of industrial structure and R&D staff is complete, one can refer to the practices of She et al. [10, 17] and establish the following model to examine the impact of low-carbon pilot policy on urban green total factor productivity after controlling two intermediate variables:

$$\log CTFP_{it} = \theta_0 + \theta_1 LCC_{it} + \theta_2 S_{it} + \theta_3 X_{it} + \eta_i + \gamma_t + \mu_{it}, \quad (4)$$

where S is the same as above. If the low-carbon pilot policy has both a direct impact on GTFP and an indirect impact through industrial structure and the number of R&D staff, then the coefficients θ_1, θ_2 will both pass the significance test. The indirect effects of industrial structure and R&D staff are $\lambda_1 \times \theta_2$. If θ_1 is not significant, while θ_2 is significant, it indicates the industrial structure and the number of R&D staff are completely intermediary variables.

3.2. Samples and Measurement of Variables and Data Source

3.2.1. Samples. The data utilized in our analysis is from “China City Statistical Yearbook,” “China Statistical Yearbook,” and “Statistical Year book” from 2004 to 2017. Considering the completion, the data of 26 cities are used for our modeling. 17 cities are low-carbon pilot cities launched in 2010 and 2012, and 10 are non-pilot cities during that period. The chosen cities are listed as in Table 1.

3.2.2. Measurement of GTFP and Data Source. This paper adopts the SBM-GML productivity index [42] to measure the GTFP growth. The software we use is MaxDEA8.0. The result we get from MaxDEA8.0 is the growth rate of the GTFP index. In order to obtain the absolute value of GTFP in Chinese cities, this paper uses 2003 as the base period (counting is 1) for cumulative calculations [43]. The factors to calculate GTFP are shown in Table 2:

For capital stock, the formula is

$$K_{it} = K_{it-1} (1 - \delta) + I_{it}, \quad (5)$$

where K_{it} and K_{it-1} represent the capital stock of city i in year t , δ_{it} represents the depreciation rate of city i in year t , and I_{it} is the total fixed-asset investment of city i in year t , and we collected its data from China City Statistical Yearbook. Since it is better to use the total fixed capital formation index to measure the capital stock, this article uses this index as the capital investment index. To guarantee the continuity and comparability of the data, we use 2003 as the base period and deflate with the fixed-asset price index (collected from China Statistical Yearbook) to measure the capital stocks at constant prices. The formula is

$$K_{0i} = \frac{(I_{0i} \times g_i)}{((g_i - 100\%) + \delta)}, \quad (6)$$

where K_0 represents the initial capital stock growth rate, I_0 represents the capital investment in base-year (2003 in this paper), and g is the capital investment price index in 2003. In this paper, supposes δ is a constant value and adopted as 10.96% [43, 44].

The data of labor input, energy input, GDP, urban green coverage rate of the city, and comprehensive utilization rate of industrial solid waste were collected from China City Statistical Yearbook. The data of industrial wastewater, waste gas, and waste solid production were collected from the Statistical Yearbook of each city.

3.2.3. Measurements of Independent Variables and Data Source. The low-carbon policy city (LCC) is a dummy variable; this paper uses it to represent whether it is a low-carbon pilot city multiplied by the time when it is approved as a pilot city. This data is from the official website of the National Development and Reform Commission of China. The nonpilot city in the non-pilot year is set to 0; otherwise, it is set to 1.

The industrial structure optimization (SO) is measured by the ratio of the added value of the tertiary industry to secondary industry. Data were collected from the China City Statistical Yearbook. For the industrial structure rationalization (SR) indicator, refer to She et al. [10, 17] and use the Theil index to measure the level of industrial structure rationalization according to the following formula:

$$SR_{it} = \sum_{i=1}^n \frac{Y_i}{Y} \ln \left(\frac{(Y_i/L_i)}{(Y/L)} \right) = \sum_{i=1}^n \frac{Y_i}{Y} \ln \left(\frac{(Y_i/L_i)}{(Y/L)} \right), \quad (7)$$

where (Y_i/Y) and (L_i/L) represent the proportion of the output value of the primary, secondary, and tertiary

TABLE 1: List of sample cities (according to the official website of the National Development and Reform Commission).

| Pilot year | Sample city |
|---------------|---|
| 2010 | Tianjin, Hangzhou, Shenzhen, Xiamen, Nanchang, Chongqing |
| 2012 | Shanghai, Shijiazhuang, Suzhou, Ningbo, Wenzhou, Guangzhou, Wuhan, Jincheng, Kunming, Urumqi, Zunyi |
| Nonpilot city | Nanjing, Dalian, Dongguan, Wuxi, Taizhou, Hefei, Changsha, Zhengzhou, Chengdu |

TABLE 2: The input and output factors of GTFP.

| Indicator | Secondary indicator | Measurement |
|------------------------------|---------------------|---|
| <i>Input 27</i> | Labor input | Number of nonagricultural employments of the city at the end of the year (million) |
| | Capital investment | Capital stock calculated by Goldsmith's perpetual inventory method (million yuan) |
| | Energy input | Total annual electricity consumption of the city (billion kWh) |
| <i>Desirable output 10</i> | Economic output | Real GDP calculated based on 2003 (million yuan) |
| | Ecological benefits | The urban green coverage rate of the city |
| | | The comprehensive utilization rate of industrial solid waste |
| <i>Undesirable output 10</i> | Pollution index | Comprehensive calculation of industrial wastewater, waste gas, and waste solid's production (million ton) based on the entropy method |

industries in the total local output value and the proportion of the labor force in the primary, secondary, and tertiary industries in the total local employments. These data come from the China City Statistical Yearbook. The number of R&D staff is from the Statistical Yearbook of each city; we use the logarithm of it for our modeling.

3.2.4. Measurement of Control Variables and Data Source.

For the control variables, this paper refers to She et al. [10, 17] and Zhou and Qin [43]. There are five control variables: foreign investment level (FDI), measured by the proportion of foreign investment in local GDP, the data of which come from the China City Statistical Yearbook; the regional GDP per capita measured by logarithm of the number (lnPGDP), the data of which is from the Statistical Yearbook of each city; the degree of government intervention (GI) measured by the proportion of government expenditures in local GDP, the data of which is from the Statistical Yearbook of each city; energy intensity (EI) is the ratio of the total energy consumption of each city to local GDP, the data of which is from the Statistical Yearbook of each city; the rate of industrialization (IR) adopts Yin's [45] formula:

$$IR_{it} = N_{it} \times S_{it}^* \times T_{it}^*, \quad (8)$$

where N is the proportion of nonagricultural industries and S^* and T^* are the contribution points of the secondary and tertiary industries:

$$N_{it} = SP_{it} + TP_{it}, \quad (9)$$

where SP and TP are the proportions of secondary and tertiary industries' output in the local GDP:

$$\begin{aligned} S_{it}^* &= \min\left(\frac{1, Sm_{it}}{0.48}\right), \\ T_{it}^* &= \min\left(\frac{1, Tm_{it}}{0.70}\right), \end{aligned} \quad (10)$$

where Sm and Tm are the maximum proportion of the secondary and tertiary industries during the sample period and 0.48 and 0.70 are the possible turning points of China's secondary and tertiary industries based on the development experience of developed countries and China's development history. These data come from the Statistical Yearbook of each city.

Except the green total factor productivity index, the other variables are calculated by Excel using the formulas presented accordingly.

3.3. Description of Variables. The variable description, model analysis, and robustness test are conducted by Stata16. Descriptive statistics of the main variables are shown in Table 3:

4. Results

4.1. Result of the Low-Carbon Policy on GTFP. Based on formula (1), the impact of the implementation of the low-carbon pilot policy on China's low-carbon economic transformation is investigated in this section. To show the impacts, two models, ordinary fixed effect model and multidimensional fixed effect model, are utilized. The results are shown in Table 4. Columns (1) and (2) are the results of the ordinary fixed effect model; column (3) and (4) are the results of the multidimensional fixed effect model.

TABLE 3: Descriptive statistics table.

| Variable | Obs. | Mean | Std. | Min. | Max. |
|----------|------|---------|--------|---------|---------|
| Log GTFP | 364 | 0.0137 | 0.0613 | -0.1485 | 0.2209 |
| LCC | 364 | 0.3736 | 0.4844 | 0.0000 | 1.0000 |
| SO | 364 | 1.0165 | 0.3456 | 0.4615 | 2.4890 |
| SR | 364 | 4.3442 | 0.1991 | 3.7832 | 5.0723 |
| RDS | 364 | 10.0773 | 1.1641 | 7.0901 | 12.4503 |
| FDI | 364 | 0.0193 | 0.0159 | 0.0001 | 0.0943 |
| ln PGDP | 364 | 10.8374 | 0.6995 | 8.4030 | 13.0784 |
| GI | 364 | 0.1239 | 0.0501 | 0.0308 | 0.3469 |
| EI | 364 | 0.0576 | 0.0827 | 0.0018 | 0.5811 |
| IR | 364 | 0.6036 | 0.0824 | 0.2899 | 0.7402 |

TABLE 4: Low-carbon pilot policy on GTFP of China.

| Variable | log GTFP (1) | log GTFP(2) | log GTFP (3) | log GTFP (4) |
|-----------|------------------|-------------------|------------------|-------------------|
| LCC | 0.014** (0.006) | 0.013** (0.006) | 0.014** (0.006) | 0.013** (0.006) |
| FDI | | 0.166 (0.169) | | 0.166 (0.169) |
| ln PGDP | | 0.021** (0.010) | | 0.021** (0.010) |
| GI | | 0.324** (0.137) | | 0.324** (0.137) |
| EI | | -0.038 (0.080) | | -0.038 (0.080) |
| IR | | -0.142*** (0.047) | | -0.142*** (0.047) |
| Constant | -0.039*** (0.01) | -0.233* (0.122) | 0.008*** (0.003) | -0.177 (0.122) |
| η | Yes | Yes | Yes | Yes |
| γ | Yes | Yes | Yes | Yes |
| R-squared | 0.7780 | 0.8000 | 0.7780 | 0.8000 |
| N | 364 | 364 | 364 | 364 |

Note: the values in parentheses are robust standard errors. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

As seen from Table 4, considering time fixed effects and urban fixed effects, the double-difference coefficients in columns (1) to (4) are all significantly positive, even with control variables, indicating that the low-carbon pilot policy leads to significant impact on the green total factor productivity of Chinese cities. The significant positive impact implies that the pilot policy has promoted the growth of green total factor productivity. The low-carbon pilot policy's direct impact on green total factor productivity is 0.013. It reveals the green total factor productivity of pilot cities are 1.3% higher than nonpilot cities. Besides, the coefficients are the same between these two models which illustrates the rational of our estimation method. Hypothesis 1 is proved.

Except for the policy effect, many other control variables significant impact GTFP, especially the government intervention (GI) with an impact of 0.324. Since the local governments take the greatest pressure from this policy, there is no wonder that government intervention is significant to GTFP at the level of 1%. The government intervention is measured by the proportion of government expenditures in local GDP. The main government expenditures involved are environmental protection expenditure and business services expenditure. From Table 4, we can see the local governments try their best to improve the green total factor productivity. On the one hand, a lot of efforts have been made on environmental protection, such as environmental monitoring and supervision expenditure, pollution control expenditure, natural forest protection project expenditure, and other expenditures; on the other hand, they introduce supporting policies to attract environment-friendly enterprises, high-

tech enterprises, and recruit talents. All of these expenditures are beneficial to local green total factor productivity.

The rate of industrialization (IR) harms green total factor productivity. It indicates that the higher rate of industrialization, the more pollution products and more waste of resources. This is a problem left over from the extensive economic development earlier. It also shows there is still a long way to go for the green economy. The regional GDP per capita (lnPGDP) promotes local green total factor productivity, and the richer cities have a better foundation to promote the growth of green total factor productivity. The effects from FDI and EI are not significant.

4.2. Robustness Test

4.2.1. Parallel Trend Test. It is not enough to show the policy effect's stabilization by simply using two kinds of regress methods. Thus, we test the parallel trend based on column (2); the result is shown in Figure 2. The line reflects the marginal effect of the dual-interaction term on China's green total factor productivity. The figure also shows the 90% confidence interval of the regression coefficient for each year. The value 0 on the X axis is the year of policy adoption in the first period, specifically, 2010. We can see from Figure 2 that, before the low-carbon pilot policy was taken, the estimated coefficient of the double interaction terms fluctuate around 0, and most of them are not significant; after the adoption year (0 value), the GTFP of each year is significantly different from 0, and its influence is increasing. This fluctuating trajectory is consistent with the time interval

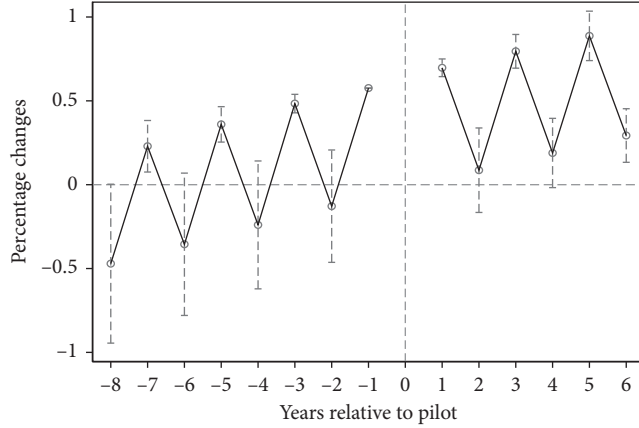


FIGURE 2: Parallel trend test results.

between the two phases of the pilot policy implementation. The 0 period is the year 2010, 2nd period is 2012, and the effect significantly promotes the green total factor production up after one year later. The first batch of pilot policies was effective in 2011 and was pulled down by the second batch of low-carbon policies in 2012, and this process goes repeatedly in the following years.

This shows that there is almost no difference in the growth rate of GTFP before the implementation of the pilot policy. It also shows that the low-carbon pilot policy has a significant positive impact on the city's green total factor growth rate, and the impact is getting stronger and stronger.

4.2.2. Other Robustness Tests. To further ensure the robustness of the results, this article also conducted some other tests. First, placebo test: in this part, we artificially advance the approval of the low-carbon pilot policy by one and three years and conduct the regression base on formula (1), without control variables (see column (5) and (6)). Second, reverse causality test: the test was conducted by controlling the initial GTFP level. Because in the process of selecting low-carbon pilot cities, the government may select cities with better economic foundation, which may create a two-way causal relationship between the approved low-carbon pilots and urban economic development. We include the sample lag term $l_loggtfp$ of $loggtfp$ in the model, and the dual-interaction term still has a significant impact on GTFP (column (7)). Third, performing a regression analysis after the data was processed with 1% tailing (column (8)). The LCC is still as significant to GTFP as before. The results are shown in Table 5.

4.3. Intermediary Mechanism Test

4.3.1. Mediation of Industrial Structure. The industrial structure is decomposed into two factors: industrial structure optimization (SO) and industrial structure rationalization (SR). We investigate the mediator effects by these two factors based on formulas (2), (3), and (4). The results are shown in Table 6.

From Table 6, the dual-interaction terms in model (1) and model (2) have a positive impact on SO and SR, indicating the low-carbon policies can help optimize and rationalize the industrial structure of pilot cities. Especially, industrial structure optimization can bring more benefits than industrial structure rationalization. In other words, industrial structure optimization progresses faster. Model (3) and model (4) describe the impact of industrial structure optimization and industrial structure rationalization on green total factor productivity. Industrial structure rationalization has a positive effect on green total factor productivity, while industrial structure optimization has none. When including the dual-interaction term to our model (model (5)), the low-carbon pilot policy and industrial structure rationalization have significant impacts on GTFP and industrial structure optimization has none. It indicates the industrial structure rationalization plays the role of half mediator between low-carbon policy and GTFP. The low-carbon pilot policy has an indirect effect of 0.004 (0.08×0.056) through promoting industrial structure rationalization and thus affecting green total factor productivity. The comprehensive impact of the low-carbon pilot policy on green total factor productivity is 0.016. Hypothesis 2 is verified.

The result can verify our assumptions, but the reason for the insignificant of the industrial structure optimization is not the slow optimization speed. Evidence can be seen from column (1). So, what is the reason? The industries are transforming and upgrading too fast in these cities. Some secondary industries are gone and the tertiary industries come up, but the tertiary industry can not contribute to local GDP as much as the secondary industry did before. Especially in a short term, the low-carbon pilot policy forces a number of secondary industries to move out due to the heavy pollution; while the introduction and development of enterprises in the tertiary industry need time. The undesirable output decreased, but the GDP has also decreased which makes industrial structure optimization unable to play its due role in green total factor productivity growth.

All in all, we find that the low-carbon pilot policy can encourage industrial structure rationalization and boost GTFP of pilot cities; the low-carbon pilot policy accelerates industrial structure optimization. However, the temporary drop of GDP caused by secondary industries' shut down cannot be compensated in a short time, even if the low-carbon pilot policy can accelerate industrial structure optimization. Hypothesis 3 and 4 are verified.

4.3.2. Mediation of R&D Staff. In this part, we test the mediation of the number of R&D staff based on formulas (2)–(4). We normalized the data to eliminate multicollinearity. The results in Table 7 indicate the low-carbon pilot policy can not attract more R&D staff. There reasons are as follows: first, the local governments are unable to provide higher subsidies due to their limited financial resources; second, there are few enterprises that need R&D staff in the short term, because they have not upgraded or established yet; third, the annual growth rate of R&D

TABLE 5: Other robustness test result.

| Variable | log GTFP (5) | log GTFP (6) | log GTFP (7) | log GTFP_tr (8) |
|---------------------|-----------------|-----------------|---------------------|-------------------|
| before ₁ | 0.013 (0.014) | | | |
| before ₃ | | 0.00 (0.015) | | |
| LCC | | | 0.01* (0.005) | 0.013** (0.006) |
| L_log GTFP | | | 0.4235*** (0.0841) | |
| Constant | −0.016* (0.008) | −0.016* (0.008) | −0.0265*** (0.0061) | 0.008*** (0.0026) |
| η | Yes | Yes | Yes | Yes |
| γ | Yes | Yes | Yes | Yes |
| R-squared | 0.1121 | 0.1138 | 0.8373 | 0.7713 |
| N | 364 | 364 | 338 | 358 |

TABLE 6: The intermediary mechanism of industrial structure.

| Variable | Model (1) SO | Model (2) SR | Model (3) log GTFP | Model (4) log GTFP | Model (5) log GTFP |
|-----------|-------------------|-------------------|--------------------|--------------------|--------------------|
| SO | | | −0.007 (0.014) | | −0.023 (0.016) |
| SR | | | | 0.052** (0.023) | 0.056** (0.026) |
| LCC | 0.128*** (0.028) | 0.080*** (0.016) | | | 0.012* (0.007) |
| FDI | −2.161*** (0.700) | −0.824* (0.445) | 0.069 (0.158) | 0.156 (0.164) | 0.163 (0.172) |
| ln PGDP | −0.317*** (0.062) | −0.100*** (0.033) | 0.019* (0.011) | 0.026*** (0.010) | 0.020* (0.011) |
| GI | −0.489 (0.422) | −0.228 (0.242) | 0.354*** (0.135) | 0.357*** (0.134) | 0.325** (0.139) |
| EI | 0.846*** (0.245) | 0.201* (0.114) | −0.052 (0.081) | −0.062 (0.078) | −0.030 (0.078) |
| IR | −0.693** (0.297) | 0.099 (0.098) | −0.146*** (0.047) | −0.147*** (0.047) | −0.164*** (0.047) |
| Constant | 4.875*** (0.727) | 5.374*** (0.373) | −0.137 (0.142) | −0.453*** (0.169) | −0.115 (0.111) |
| η | Yes | Yes | Yes | Yes | Yes |
| γ | Yes | Yes | Yes | Yes | Yes |
| R-squared | 0.8837 | 0.9032 | 0.7978 | 0.8007 | 0.8036 |
| N | 364 | 364 | 364 | 364 | 364 |

personnel is limited, about 0.064 in this sample, and the total amount is insufficient. In addition, due to the long-term nature of project work for R&D personnel, it is difficult to move. The energy intensity and the rate of industrialization can attract more R&D staff. Thus, we can conclude that R&D staff would not move to a region just because of the low-carbon policy or the higher per capita; they move because of the resources. Therefore, among the above three reasons, the first and second points are more likely to be established.

The real interesting phenomenon shown in Table 7 comes from model (7) and model (8). The number of R&D staff decreased the green total factor productivity. This phenomenon is not impossible taking talent misallocation into consideration. Murphy et al. [46] claimed that if human resources entered the productive sector, then human capital can improve production efficiency, promote technological innovation, and promote economic growth; however, if human resources become rent-seekers and rent-seeking is only a redistribution of wealth and is not productive, the economic growth will be harmed. The R&D staff in this sample include those who work in government agencies and institutions and also include those who work in private enterprise. On the whole, the proportion of R&D personnel in government agencies is larger. The composition of rent-seekers could be greater, leading to a decline in economic growth. It indicates the distorted R&D staff allocation of these cities. The deviation of talent allocation in government departments has a negative impact on economic innovation and transformation [47]. Li and Yin [48] also indicate that

China's limited human resources have been over-allocated in government departments, damaging the economic growth. For green total factor productivity, it has the same effect. Hypothesis 5 is not verified, and the number of R&D staff is not a mediator between low-carbon policy and green total factor productivity.

Why do these R&D personnel gather in government departments? Many scholars found that, in reality, the income of rent-seeking activities in most underdeveloped countries is higher than the income obtained in the corporate sector, and talent mismatch is an important factor that causes economic stagnation in underdeveloped countries [49]. This is true in China. Government departments can provide more superior and worry-free jobs. On the contrary, it is difficult for ordinary business sectors to meet these needs of R&D personnel.

4.4. Heterogeneity Analysis. The low-carbon pilot policy aims to reduce cities' carbon emissions and promote green economy. But, different cities have different economic foundations, such as the level of infrastructure, openness, and the number of talent pool. If these indexes are measured by a composite index, it is the level of economic development. This affects the carbon emission largely. The eastern region is the birthplace of China's modern economy, while the central and western regions are relatively backward in economic development. So, all of these differences are resulted from the location of the city, which leads to the

TABLE 7: The intermediary mechanism of the number of R&D staff.

| Variable | Model (6) RDS | Model (7) log GTFP | Model (8) log GTFP |
|-----------|------------------|--------------------|--------------------|
| RDS | | −0.022*** (0.006) | −0.022*** (0.005) |
| LCC | −0.031 (0.055) | | 0.012** (0.006) |
| FDI | −0.717 (1.454) | 0.077 (0.149) | 0.151 (0.159) |
| ln PGDP | −0.120 (0.126) | 0.018* (0.009) | 0.019** (0.009) |
| GI | −1.065 (0.645) | 0.330** (0.131) | 0.301** (0.134) |
| EI | 1.005*** (0.371) | −0.034 (0.077) | −0.017 (0.077) |
| IR | 1.038*** (0.314) | −0.119*** (0.045) | −0.120*** (0.045) |
| η | Yes | Yes | Yes |
| γ | Yes | Yes | Yes |
| Constant | 0.012*** (0.026) | 0.000 (0.002) | 0.005 (0.003) |
| R-squared | 0.7187 | 0.4271 | 0.4332 |
| N | 364 | 364 | 364 |

TABLE 8: Eastern and non-eastern cities' low-carbon policy effect.

| Variable | log GTFP (east 1) | log GTFP (east 2) | log GTFP (non-east 3) | log GTFP (non-east 4) |
|-----------|-------------------|-------------------|-----------------------|-----------------------|
| LCC | 0.009 (0.007) | 0.007 (0.006) | 0.018* (0.010) | 0.027** (0.012) |
| FDI | | −0.203 (0.144) | | 0.897 (0.682) |
| ln PGDP | | 0.024** (0.010)> | | −0.048* (0.025) |
| GI | | 0.118 (0.133) | | 0.243 (0.200) |
| EI | | −0.038 (0.080) | | 0.138* (0.080) |
| IR | | −0.338*** (0.137) | | −0.235*** (0.087) |
| Constant | −0.002 (0.003) | −0.177 (0.114) | 0.022*** (0.005) | 0.599** (0.288) |
| η | Yes | Yes | Yes | Yes |
| γ | Yes | Yes | Yes | Yes |
| R-squared | 0.8436 | 0.8641 | 0.7685 | 0.7954 |
| N | 196 | 196 | 168 | 168 |

eastern cities having more economic and human resources advantages. They have more finance to carry on this policy, reduce carbon emission, and promote green economic growth. But, these eastern cities may also bear much more pressures because of their longer extensive development history and larger industrial volume.

We divide our sample into two groups, the eastern cities and non-eastern cities, to test the low-carbon pilot policy's effect based on formula (1). The results are shown in Table 8. From Table 8, we find that the low-carbon policy does not play a role in the green total factor productivity for the eastern cities, while it plays an important role for the non-eastern cities.

Figure 3 shows the difference of eastern and non-eastern cities in green total factor productivity. From 2004 to 2017, at the beginning of this period, the green total factor productivity of these two groups is at the same level. Then, it rises during 2006–2010. After a short decline, it rises again at 2012. The policy is implemented in 2010. The decline illustrates the short-term negative shock by the policy. The positive effects on green total factor productivity by low-carbon policy arised since 2012. During 2004–2017, the green total factor productivity for eastern and non-eastern cities keep on rising but at different rates. For the eastern cities, the growth rate is steady but at a lower level. It reveals the imbalance development of green economy.

It can be inferred from our previous discussions and the results in Table 8 that the low-level growth rate of green total

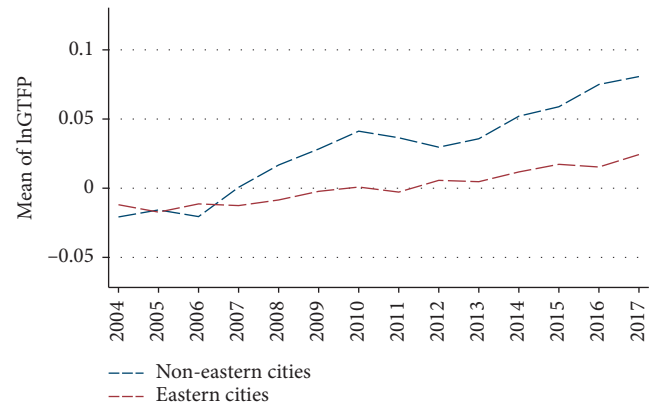


FIGURE 3: The trend of GTFP of eastern and non-eastern cities.

factor productivity does not caused by the low-level input factors including capital investment, human resources and energy input, nor does it come from GDP. It is the undesired output that drags GTFP down. In the early years, China's economy developed rapidly at the cost of high resource input, high pollution, and high waste. The eastern cities are the main developing areas. After a long time developing, eastern areas have been planted a lot environmentally unfriendly factories compared with non-eastern cities. This makes the eastern cities much harder to transform in a short period. The non-eastern cities just like a sheet of blank paper, leaving more zoom to attract environmentally friendly

companies, making the industrial transformation of these cities relatively easier. Moreover, with a cleaner environment foundation, the growth rate of green total factor productivity is higher. The rate of industrialization (IR) also alludes to this conclusion: the higher level of industrialization, the lower the green factor productivity. The reduction effect of industrialization on the GTFP of eastern cities was 0.338; for non-eastern cities, it was 0.235.

5. Conclusions and Policy Implications

5.1. Conclusions. Under the international pressures of carbon emission reduction, China has implemented active emission reduction policies, including the low-carbon pilot policy. Carbon reduction means that China must transform its traditional resource-dependent economy and develop green one. China has achieved its carbon emission reduction target ahead of schedule, but has it promoted the development of green economy? This study analyzes the low-carbon pilot policy (LCC) on green total factor productivity (GTFP) and explains the issue through two mechanisms—the industrial structure (SO, SR) and the number of R&D staff (RDS). The main conclusions of this paper are as follows.

First, the low-carbon policy has a positive effect on green total factor productivity. This conclusion is consistent with most of existing studies [10, 18]. It shows that, in the process of China's carbon emission reduction, the green economy has also been developed. It is a good sign of economic low-carbon transition.

Second, low-carbon pilot policies can promote the rationalization and optimization of the industrial structure. The industrial structure rationalization has a positive effect on green total factor productivity; while industrial structure optimization does not, indicating that industrial structure rationalization is an important pathway for low-carbon policies to promote the development of green total factor productivity. With the realization of low-carbon emission reduction, the development of a green economy must be more rationalized in the industrial structure.

Third, regarding the number of R&D personnel, the results show that it is not affected by low-carbon policies and harms green total factor productivity. The main reason for this result is the misallocation of talents. Talents must be used in a reasonable position to maximize utility. The misallocation of talents is a problem that seriously slows down China's economic growth.

At last, the green total factor productivity of eastern and non-eastern cities is in a different level. It shows the regional imbalance of green economy. The rate of non-eastern cities is higher than that of eastern cities. The empirical result shows the low-carbon pilot policy cannot affect the green total factor productivity of eastern cities because of the poor environmental foundation and large industrial volume. It is more difficult for eastern cities to conduct green transform, compared with the non-eastern cities. The low-carbon pilot policy promotes the green total factor productivity of non-eastern cities.

5.2. Policy Implications. According to this study, the low-carbon policy is a good and effective measure for economy green transformation. However, it did not work very well. To release the policy potential, we must solve several problems.

The intensity of the low-carbon pilot policy should be reinforced rather than weakened, but the concrete implementation should be more scientific and diversified based on local conditions. From the results, we understand that this policy is effective, but the policy does not work in some areas. That is because these regions have different advantages and disadvantages compared with other regions. The eastern cities have good economic foundations, human resources, infrastructure, high-tech, and openness, but they show limited green-land coverage, free space, etc. The non-eastern cities are on the contrary, which makes the local governments must formulate more detailed policies and measures based on main policies:

- (1) In terms of industrial structure. For the eastern cities, they should pay more attention to industrial structure optimization with their good foundation: ① encouraging high pollution enterprises to install sewage treatment equipments by tax subsidy; ② encouraging enterprises by financial reward to develop and utilize new tech and new equipment to produce in environment-friendly ways. For example, green supply chain management can improve corporate performance while protecting the environment Wang et al. [50]. For the non-eastern cities, they should focus on industrial structure realization. They do not have a large industrial volume, making them more efficient to attract environmental-friendly enterprises. They also have more sufficient rural surplus labor to work for these new enterprises. Specifically, local governments should use preferential tax policies and take advantage of the lower land rent and cheaper labor relative to the eastern cities to attract environment-friendly enterprises.
- (2) In the terms of R&D staff. For the eastern cities, they already have enough R&D staff to serve their economic green-transform, and their enterprises also have many R&D persons. The next step for them is to build a rapid transformation mechanism of innovation achievements. For the non-eastern cities, their R&D persons are most concentrated in government agencies and institutions. There is a misallocation of talents. At the same time, there is a shortage of talents elsewhere. They should ① formulate reasonable policies to release the economic vitality of government R&D staff, market their research results, and avoid rent-seeking; ② issue talent allowances to attract more R&D persons and labor with high-level human capital to improve the quality structure of local workers; ③ strengthen infrastructure construction to help local enterprises recruit and keep talents; ④ encourage firms to cultivate their unique personnel training mechanism, making R&D staffs more efficient for economy growth.

- (3) In terms of environmental regulation, the low-carbon policy is effective and the local governments should ① use mass supervision, establish teams of environmental protection volunteers, and call on environmental protection social organizations to strengthen environmental supervision and inspection; ② increase environmental pollution tax. Zhang et al. [51] indicate that the green governance capacity of government and the level of social supervision are important in achieving the green development. These measures will enhance the effect of the low-carbon policy.

By taking the measures discussed above, regional differences could be reduced, which corresponds to balanced development. Promoting the environmental protection and economic growth in the eastern and non-eastern regions will help to reduce the regional differences in GTFP and lead to achieve China's sustainable development.

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.

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Research Article

Fintech Penetration, Financial Literacy, and Financial Decision-Making: Empirical Analysis Based on Tar

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The level of financial literacy of rural residents will affect their financial decisions and the financial well-being behind the decisions. This paper uses mediating effect and moderating effect to test the influence path of rural residents' subjective and objective financial literacy on their financial decision-making with survey data from Henan and Anhui provinces in China. The results show that subjective and objective financial literacy have positive effects on financial market participation. Subjective and objective financial literacy have negative direct effects on insurance market participation. Subjective financial literacy plays an incomplete mediating effect in the impact of objective financial literacy on financial market and insurance market participation. Objective financial literacy is adjusted by subjective financial literacy on financial market participation and insurance market participation. At the same time, we introduce financial technology penetration as a threshold variable in the model and find that the financial literacy has stronger impact on financial decision-making if the financial technology penetration is above the threshold.

1. Introduction

The family is the basic unit of society and the micro-foundation of economic operation. As China's economy continues to maintain a momentum of growth and residents' income increases substantially, various financial investment products have gradually become important carriers of the wealth of Chinese residents. Under such realistic conditions, household financial literacy will have a significant impact on household financial investment decisions and wealth composition. Higher financial literacy helps family investors to achieve the best match between risk and return, thereby increasing income at the average risk level and reducing idle resources.

The academia has not yet unified the definition of financial literacy concepts. At present, they define concepts in the following ways: first, early scholars equated it with financial knowledge. For example, Lusardi and Mitchell examined the situation of consumers' mastery of basic

financial knowledge. Second, financial literacy is a comprehensive concept, including financial knowledge and people's ability to process various economic information and make wise decisions on many financial events, such as using financial capabilities to define people's ability to deal with various problems in financial activities [1]. Third, financial literacy includes not only financial knowledge, behavior, and attitude but also personal financial experience, as proposed by Moore [2]. Some scholars combine behavioral finance to interpret and further emphasize the importance of financial education. The OECD defined financial literacy as "awareness, knowledge, skills, attitudes, and behaviors related to financial affairs, which are used in financial decision-making to improve personal financial well-being" in the 2015 survey report [3]. In general, this article divides financial literacy into three dimensions: financial knowledge, financial skills, and financial attitude. Financial knowledge and skills belong to objective financial literacy, while financial attitude belongs to subjective financial literacy.

Xiao et al. proposed that “financial literacy can be divided into subjective financial literacy and objective financial literacy.” The measurement of objective financial literacy in the existing literature is mainly based on financial knowledge. The higher the degree of financial knowledge, the more beneficial to investors or consumers make reasonable financial decisions [4]. Dohmen et al. found that abundant financial knowledge can help families understand the profits and risks of financial markets and financial products which can reduce the preparation costs of families in the early stages of making financial decisions [5]. Rooij et al. researched on Dutch DHS data and found that the majority of respondents only understand basic financial knowledge, such as funds, which have higher returns than savings, and any investment is risky, but do not know about slightly professional financial knowledge, such as calculation of the interest rates of savings and investment returns and the relationship between bond prices and interest rates [6].

Although there are few researches on assessing financial behavior based on people’s subjective literacy, an upsurge surrounding subjective financial literacy is taking shape. More and more scholars have discovered that although objective financial literacy can affect personal financial decisions, the subjective willingness of individuals in making decisions also restricts decision-making behavior. Robb pointed out that both subjective and objective financial literacy will affect financial behavior, and subjective financial literacy has a greater impact [7]. Zhang and Xiong found that subjective financial literacy has a direct effect on residents’ financial decision-making and affects the role of objective financial literacy in financial decision-making [8].

At the same time, what we need to see is that with the gradual penetration of new digital finance such as financial technology into the rural financial market, more rural residents are participating in the financial market and increasingly complex financial products and services have continuously improved the financial literacy requirements of rural residents. The phenomenon of rational financial decision-making has gradually emerged. Under different financial technology popularization, the impact of rural residents’ financial literacy on financial decision-making may change significantly, but the existing literature lacks a combined analysis of financial technology, financial literacy, and financial decision-making. In view of this, this article attempts to embed financial technology in the analysis framework of “financial literacy and financial decision-making” and construct reasonable financial literacy indicators based on the survey data of China’s Henan and Anhui provinces to explore the impact of financial technology development on the mediating and moderating effects of the development of financial literacy on financial decision-making, thus expanding relevant research on financial literacy.

2. The Measurement and Mechanism of Financial Literacy

2.1. Evaluation Methods of Financial Literacy. There are many differences in the measurement of financial literacy in terms of objects, scope, and methods. The object of

measurement involves more consumers and young people and less exploration of farmers. The geographic scope of the measurement is mostly limited to provinces and cities and most sample sizes are under 500, which is not universal. However, after the 2008 financial crisis, national surveys began to emerge. Most of the measurement methods adopt single-choice or judgment methods. When scoring financial literacy, use comprehensive total scores or factor analysis to obtain comprehensive factors. When evaluating subjective financial literacy, most use self-evaluation methods, assigning points by five-point scale or seven-point scale. In terms of the specific content of the measurement, most domestic and overseas studies only measure the financial literacy level of residents from compound interest, inflation, and risk diversification [9, 10]. Some scholars have added several complex dimensions to these three dimensions [11]. On the whole, the existing research is not comprehensive enough to evaluate the level of financial literacy.

2.2. Development of Financial Literacy and Threshold Model Research. Noctor et al. first proposed the concept of financial literacy, pointing out that financial literacy is financial skills, including wealth management, financial analysis, and the ability to make full use of financial concepts [12]. Then, Huston formally proposed and defined the conceptual difference between financial literacy and financial knowledge and proposed that financial literacy includes understanding (personal financial knowledge) and application (personal financial application) based on the difference in the US President’s Advisory Council on Financial Literacy (PACFL) [13]. The domestic scholar Zhang used Huston’s practice to divide financial literacy into two dimensions and evaluated them, using mediating effect and moderating effects to test the impact of residents’ subjective and objective financial literacy on financial decision-making. It turns out that objective financial literacy has a positive direct effect on financial decision-making and this effect is also regulated by subjective financial literacy [14].

Wang measured the subjective and objective financial literacy of residents, using self-efficacy theory and behavioral finance theory to study the influence mechanism of financial literacy on financial decision-making in two paths and found that the ability for residents using financial tools to achieve financial decision-making which benefits family is insufficient and the education level, income, and basic grasp of financial knowledge and skills are the main factors that affect household financial decision-making [15]. Tan and Peng used factor analysis to construct a financial capability framework and used Probit model, mediating effect model and instrumental variable method to analyze the relationship between financial capability, financial decision-making, and poverty and found that financial capability can significantly suppress poverty. Financial capacity and poverty present a “U-shaped” relationship and financial ability can alleviate poverty by improving financial decision-making, which has certain practical significance [16].

Tong proposed a threshold autoregressive model and later extended this idea to the regression model [17]. Based on the localized research of domestic scholars, this article attempts to introduce the threshold model into the influence path of financial literacy on financial decision-making and analyze it. The contributions of this article are as follows: first of all, through extensive data collection in many counties in Henan and Anhui provinces, to initially understand the status quo of farmers' financial literacy. Secondly, factor analysis is used to objectively empower farmers' financial literacy questionnaires to construct a more accurate index of farmers' financial literacy, which embodies financial decision-making from financial market participation and insurance market participation; then, this paper explores the impact of financial literacy on participation in the two markets and considers the mediating effect of subjective financial literacy when objective financial literacy affects financial decision-making. Finally, taking the popularity of financial technology as the threshold variable and exploring the impact of financial decision-making from the two dimensions of subjective financial literacy and objective financial literacy, and it is concluded that the path of financial literacy on financial decision-making remains unchanged.

2.3. Research Hypothesis. Based on the research by scholars' mentioned above and combined with the threshold effect model, this article proposes the following hypotheses:

H1: on the basis of controlling other variables, the subjective financial literacy of rural residents has a direct influence on financial decision-making.

H2: on the basis of controlling other variables, the objective financial literacy of rural residents has a direct influence on financial decision-making.

H3: on the basis of controlling other variables, the objective financial literacy of rural residents has an indirect effect on financial decision-making through subjective financial literacy.

According to social research and actual conditions, individuals' subjective financial literacy tends to be overestimated in self-assessment, resulting in the failure to match the objectively evaluated financial literacy status. At the same time, it is also difficult for residents with a high level of objective financial literacy to make correct judgments about themselves (subjective financial literacy) thus will not use a rational way to invest in financial assets and other investment. This article further proposes the following hypotheses:

H4: on the basis of controlling other variables, the subjective financial literacy of rural residents has a significant moderating effect on the impact of objective financial literacy on financial decision-making.

In addition, studies by scholars have shown that other control variables are also having a certain amount of influence on financial decision-making, including gender, age, education level, health status, marital status, occupational status, and total income in 2017

and 2018. This article sets up the individual characteristics of financial technology exposure as a threshold variable to explore the impact path of rural residents' financial literacy on financial decision-making under the exposure level.

H5: on the basis of controlling other variables and assuming that H1, H2, H3, and H4 are all established, the higher the financial technology penetration, the more the significant impact of financial literacy on financial decision-making.

Based on the abovementioned assumptions and existing research conclusions, this paper constructs a framework diagram of the influence path of rural residents' financial literacy on financial decision-making (Figure 1). It should be noted that subjective financial literacy is the most direct factor that affects household financial decision-making (H1), while objective financial literacy can directly affect household financial decision-making (H2); it can also use subjective financial literacy as an intermediary and adjustment channel to affect household financial decision-making (H3 and H4). Among all the influence mechanisms, the popularity of financial technology is expected to play a nonlinear threshold adjustment role (H5).

3. Data and Model

3.1. Descriptive Analysis of Data Sources and Samples. This paper uses the data from the "Financial Education for Rural Revitalization-Baseline Investigation of the Jinhui Project in Sichuan, Anhui, and Henan" conducted by the China Financial Education Development Foundation from July to August 2019, which conducted field investigations rural residents in Susong County, Yuexi County, Huoqiu County, Yingshang County, Funan County, Linquan County in Anhui Province and Lankao County, Taikang County, Shenqiu County, Nanzhao County, Tongbai County, Shangcheng County, Henan Province, Xinxian, and other counties. A total of 2,600 questionnaires were distributed, and 2,234 valid questionnaires were returned. Taking the popularity of financial technology as the threshold variable, this paper uses the threshold model to analyze the impact of financial literacy on financial decision-making from the two dimensions of subjective financial literacy and objective financial literacy, using mediating and moderating effects to test the impact of rural residents' subjective and objective financial literacy on the influence path and influence mechanism of their financial decision-making.

Among the 2234 valid samples, the age of the survey subjects is mainly distributed between 40- and 60-year olds, accounting for 51%; the number of people aged 60 and over account for 31% and the number of people under 40 years account for only 18%. The aging phenomenon of the sample is serious. At the same time, the sample shows that the education level of the region is generally low, 33% of the samples are junior high school education level, 28% of the samples are elementary school education level, the proportion of illiterate samples is 16% and the proportion of high school, junior college, and above is only 23%. The

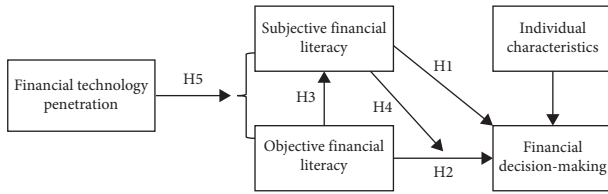


FIGURE 1: Framework diagram.

overall health status of the survey sample is at the upper-middle level, 1132 people are in good physical condition, more than 50%, and the overall situation is considered optimistic. However, 642 people are in average physical condition and 460 people are in poor physical condition. Regarding the occupational distribution of the survey sample, the survey sample is mainly engaged in agricultural work, 62% of them are farming, only 13 people are engaged in the rural e-commerce industry, and 31 people have joined rural enterprises. Entrepreneurship, self-employed, or private enterprises account for 7%, 11% of the survey samples are national staff. It is worth noting that the survey stage is in the mid-year period, so there are only 5% of the returnees from migrant workers (Table 1).

3.2. Variable Selection and Indicator Construction. This article uses Cronbach's alpha and factor loading values to test the reliability of the survey questionnaire and survey data. Results are within the interval of 99% confidence level, the Cronbach coefficient value of the subjective financial literacy dimension index reached 0.653, and the Cronbach coefficient value of the objective financial literacy dimension index was 0.608, indicating that the objective financial literacy survey part of the questionnaire needs improvement, and the reliability coefficient of the entire survey questionnaire data sheet is close to 0.7, and the factor loading value of each indicator reaches the upper and lower range of 0.5, which indicates that the questionnaire has high reliability and the survey sample has passed the internal consistency reliability test.

3.2.1. Evaluating Subjective Financial Literacy. Based on the three indicator evaluation frameworks of the content, process, and background of PISA developed by the Organization for Economic Cooperation and Development (OECD) in 2000 and four dimensions system constructed by China Financial Education Development Foundation: financial awareness, financial knowledge, financial behavior and financial skills, improving, and sublimating on the evaluation framework constructed by Huanhuan Zhang, this article constructs the evaluation system of the subjective financial literacy of Chinese rural residents from 2 aspects and 7 indicators in Table 2. We believe that when measuring the financial literacy of rural residents, the respondent's wrong answer may be due to the long questioning process, carelessness, and failure to hear the question clearly, or the level of understanding is still not enough after exposure to relevant concepts and knowledge. But the answer to "do not know" is mostly because they have never heard of the

relevant concept. Therefore, we continue to use Zhichao Yin, Lusardi, and Mitchell's approach to deal with financial capability indicators, distinguishing "do not know" from answering errors and believe that respondents who answered "do not know" lack financial literacy. According to the distribution of the respondents' subjective financial literacy scores at each level, it can be clearly seen that the subjective financial literacy of rural residents is concentrated in the middle-to-lower regions (3 to 5 points) [18, 19].

3.2.2. Evaluating Objective Financial Literacy. In Table 2, this article constructs an evaluation framework with five-level and ten-level indicator through the objective financial literacy of the respondents. For true and false questions and multiple choice questions, the coefficient of variation method is used to score their financial literacy, and the financial literacy scores of rural residents are concentrated in the central region (4~5 points).

3.2.3. Conducting Correlation Tests on Subjective and Objective Financial Literacy and Financial Decision-Making. Table 3 lists the Pearson correlation test results and partial correlation results of subjective and objective financial literacy on financial market participation, insurance market participation, and financial decision-making. Subjective and objective financial literacy has a significant positive correlation with financial market participation and financial decision-making, but the correlation with insurance market participation is negative. While controlling for other variables is unchanged, the overall correlation has dropped significantly. At the same time, the correlation between subjective financial literacy and objective literacy has also decreased to a certain extent, but it is still a significant positive relationship.

3.2.4. Selection of Instrumental Variables. As financial literacy has a certain endogeneity, it can be seen from Arrow's "Learning by Doing" model that people obtain knowledge through learning; technological progress is the product of knowledge and the result of learning. Learning is the continuous summary of experience and experience comes from action. Participation of rural residents in the financial market is also a process of gradual accumulation of learning experience and skills, so there will be a situation in which respondents have accumulated a certain degree of financial literacy in daily life before accepting the interview. According to this situation, this article uses approach of Tan and Peng [16] and selects the subjective evaluation "attention to economic and financial information" as an instrumental variable of financial literacy which can directly affect personal financial literacy but has little relevance to financial decision-making.

3.2.5. Interpreted Variables and Control Variables. In the process of exploring the influence path of rural residents' financial literacy on their financial decision-making, this article regards the residents' financial market participation

TABLE 1: Basic situation of valid samples.

| Category | Option | Number of samples | Percentage |
|--------------------------|--|-------------------|------------|
| <i>Gender</i> | Male | 1439 | 64 |
| | Female | 795 | 36 |
| <i>Age</i> | Over 60 | 693 | 31 |
| | 40–60 | 1139 | 51 |
| | Under 40 | 402 | 18 |
| <i>Education level</i> | High school, junior college, and above | 514 | 23 |
| | Junior high school | 737 | 33 |
| | Primary school | 626 | 28 |
| | Illiterate | 357 | 16 |
| <i>Health conditions</i> | Good | 1132 | 51 |
| | General | 642 | 29 |
| | Bad | 460 | 20 |
| <i>Occupation</i> | Farming | 1385 | 62 |
| | Rural e-commerce | 13 | 0.6 |
| | Agribusiness | 31 | 1.4 |
| | Self-employed | 156 | 7 |
| | National staff | 246 | 11 |
| | Migrant workers | 112 | 5 |

TABLE 2: The evaluation index system of rural residents' financial literacy.

| First level indicator criteria | Second level indicator | Third level indicator | Marking |
|---|--|---|---|
| <i>Subjective financial literacy</i> | Financial products self-awareness | Ability to analyze whether financial products are legal or not, determining risk and return and accepting information | Adding the scores of the seven indicators directly |
| | Financial knowledge self-assessment | RMB authenticity recognition, bancassurance business understanding, policy understanding, internet payment | |
| | Basic financial knowledge | Stock knowledge understanding, financial knowledge mastery | |
| | Understanding and application of financial knowledge | Interest rate comparison, compound interest calculation, insurance limit selection | Using the coefficient of variation method to assign weights and score comprehensively |
| | Awareness of financial responsibility | Credit responsibility awareness, credit status disclosure | |
| | | | |
| <i>Objective financial literacy</i> | Risk and reward | Risk and return perception | Adding the two levels of scores together |
| | Asset planning | Choice of saving methods, preference for investment and financial management | |
| <i>Financial technology penetration</i> | Financial technology supply and demand status | Supply status Demand scale | |

and insurance market participation as the two major components of financial decision-making and explores the influence path of financial literacy on dependent variable, financial decision-making. Financial assets defined in this article include bank savings deposits (time deposits and demand deposits), other financial products of banks, insurance, wealth management products of securities and fund companies, gold, futures, and stocks. The variable of rural residents' participation in the financial market is defined as follows: the variable value is assigned as 2, if rural

residents have financial assets other than deposits; the variable value is assigned as 1, if they have only savings assets; the variable value is assigned as 0, if they have funds deposited at home and other else. Insurance market participation indicates whether residents hold insurance assets; if they hold, the variable value is assigned as 2, otherwise, assigned as 0.

The control variables selected in this paper are gender, age, education level, health status, marital status, occupational status, and total income in 2017 and 2018 (Table 4).

TABLE 3: Pearson correlation test of subjective and objective financial literacy and financial decision-making.

| | Financial market participation | Insurance market participation | Financial decision-making | Subjective financial literacy | Objective financial literacy |
|---------------------------------|--------------------------------|--------------------------------|---------------------------|-------------------------------|------------------------------|
| <i>Person correlation</i> | | | | | |
| Subjective financial literacy | 0.4794** | −0.0268 | 0.4566** | 1.0000 | 0.4997** |
| Objective financial literacy | 0.4455** | −0.0470*** | 0.4181** | 0.4997** | 1.0000 |
| <i>Partial correlation test</i> | | | | | |
| Subjective financial literacy | 0.3333 | −0.0042*** | 0.3183*** | 1.0000 | 0.3848*** |
| Objective financial literacy | 0.2646*** | −0.0381*** | 0.2369 | 0.3848*** | 1.0000 |

Note: ***The significance level is 1%. **The significance level is 5%.

TABLE 4: Variable overview and assignment status, basic statistics, and coefficient symbol.

| Variable name | | Variable properties and assignment status | Variable assumed total score | Mean | Standard deviation | Coefficient symbol |
|-----------------------------|---|--|------------------------------|-------|--------------------|--------------------|
| <i>Dependent variable</i> | Financial market participation | Dummy variable (more than one = 2, yes = 1, no = 0) * 4 | 8 | 2.39 | 1.21 | |
| | Insurance market participation | Dummy variable (yes = 2, no = 0) * 1 | 2 | 1.86 | 0.51 | |
| <i>Independent variable</i> | Subjective financial literacy | Dummy variable: self-awareness of financial products (good = 2, bad = 1, do not know = 0) * 4 | 10 | 4.72 | 2.29 | + |
| | Objective financial literacy | Order variable: self-assessment of financial knowledge (understand much = 2, general understanding = 1, do not understand = 0) * 1 | | | | |
| | Gender | Numerical variable (specific score value/point) | 10 | 4.60 | 1.48 | + |
| | Age | Dummy variable (male = 1, female = 0) | 1 | 0.64 | 0.48 | + |
| | | Numerical variable (specific age/year) | Age | 51.70 | 12.10 | First + then − |
| <i>Control variable</i> | Education level | Order variable (college and above = 5, high school, vocational high school or technical secondary school = 4, junior high school = 3, elementary school = 2, illiteracy = 1) | 5 | 2.70 | 1.14 | + |
| | Health status | Dummy variable (good = 2, general = 1, bad = 0) | 2 | 1.30 | 0.79 | + |
| | Marital status | Dummy variable (married = 1, divorced, widowed, unmarried = 0) | 1 | 0.86 | 0.34 | + |
| | Occupational status | Order variable (state-owned enterprise = 6, private enterprise, individual = 5, e-commerce, rural enterprise = 4, working abroad = 3, part-time agriculture = 2, pure agriculture = 1) | 6 | 2.10 | 1.68 | + |
| | Average annual income in the past two years | Numerical variable (specific amount/10,000 yuan) | Amount | 5.83 | 8.5 | + |
| <i>Tool variable</i> | Attention to economic and financial information | Order variable (pay close attention = 4, pay attention = 3, pay attention occasionally = 2, never pay attention = 1) | 4 | 1.89 | 1.47 | + |

3.3. Model Selection. Based on the above research hypotheses, this article needs to construct direct effect model, mediating effect, moderating effect model, and threshold regression model between variables. Given that both financial market participation and insurance market participation are dummy

variables, while subjective and objective financial literacy are ordered variables, this paper uses the Probit model to analyze the impact of rural residents' financial literacy on financial market participation and insurance market participation and use a multiple choice model to analyze the impact of rural

residents' objective financial literacy on subjective financial literacy and the impact of financial literacy on financial decision-making under different levels of financial technology penetration. The model of this article is as follows:

- (1) The mediating effect model of financial market participation or insurance market participation:

$$\text{SFL} = \alpha_{11} + \text{OFL} + \beta X + \mu, \quad (1)$$

$$Y = 1 (\alpha_{21} \text{OFL} + \beta X + \mu > 0), \quad (2)$$

$$Y = 1 (\alpha_{31} \text{OFL} + \alpha_{32} \text{SFL} + \beta X + \mu). \quad (3)$$

In formulas (1)–(3), SFL is the subjective financial literacy, OFL is the objective financial literacy, X is the controlled variable, Y are the financial market participation (finance) and insurance market participation (insurance), where, $Y = 1$ represents financial market participation or insurance market participation and $Y = 0$ means no participation.

- (2) The moderating effect model of financial market participation or insurance market participation:

$$Y = 1 (\alpha_{41} \text{OFL} + \alpha_{42} \text{SFL} + \alpha_{43} \text{OFL} \times \text{SFL} + \beta X + \mu > 0). \quad (4)$$

In (4), $\text{OFL} \times \text{SFL}$ is the cross-product of subjective financial literacy and objective financial literacy.

- (3) Threshold regression models of rural residents' financial literacy on financial decision-making under different financial technology popularity:

$$Y = \alpha_{51} \text{OFL} + \alpha_{52} \text{SFL} + \alpha_{53} Z + \beta X + \mu, \quad 0 < Z < d_1, \quad (5)$$

$$Y = \alpha_{61} \text{OFL} + \alpha_{62} \text{SFL} + \alpha_{63} Z + \beta X + \mu, \quad d_1 < Z < d_2, \quad (6)$$

$$Y = \alpha_{71} \text{OFL} + \alpha_{72} \text{SFL} + \alpha_{73} Z + \beta X + \mu, \quad Z > d_2. \quad (7)$$

In formulas (5)–(7), Z is called the threshold variable, and d_1, d_2 are called the threshold values.

4. Empirical Test Results

In this paper, when testing the financial literacy of rural residents on financial decision-making under different levels of financial technology penetration, first, the permutation regression method is used to search, and after the threshold value is determined, the Bootstrap method is used to simulate LM tests, the asymptotic distribution of the F statistic, and its critical value to determine whether there is a threshold effect. Finally, the two optimal threshold values for this threshold regression are determined by 1 and 3 after repeated inspections for many times.

Then, by establishing regression models of subjective financial literacy and objective financial literacy on financial market participation and insurance market participation in two types of financial decision-making, this article tests whether subjective and objective financial literacy has a direct impact on financial decision-making and uses hierarchical regression analysis to test the mediating effect of subjective financial literacy in the impact of objective financial literacy on these two types of financial decision-making. In order to ensure that the hierarchical regression analysis method can produce a higher statistical effect, this paper uses the coefficient product test method (Sobel test) to determine the mediating effect. In order to maximize excluding the impact of possible endogenous problems in financial literacy, this article uses "attention to economic and financial information" as an instrumental variable of financial literacy, carries out two-stage estimation and GMM estimation, and uses Hausman's test method to test the model. Finally, in certain three-stage financial technology penetration and threshold regression model, the significance of the financial literacy on financial decision-making is tested.

4.1. Path Test of the Influence of Rural Residents' Financial Literacy on Financial Market Participation. In order to comprehensively explore the influence mechanism of rural residents' financial literacy in participating in the financial market, this paper conducts related tests on the direct impact of rural residents' subjective financial literacy and objective financial literacy on financial decision-making, as well as the intermediary and regulatory effects. In the process of regression, the heteroscedastic White test was used to test all models, and it was found that the probability value of $\text{Obs} * R\text{-squared}$ in all models was far less than the significance level of 0.05, the null hypothesis was rejected, and heteroscedasticity existed. The weighted least squares method (WLS) is used to correct the heteroscedasticity and the forward search method in the automatic stepwise regression method which is used to perform regression secondary test on the revised model in order to eliminate multicollinearity problems in the model. The regression results obtained are shown in Table 5.

Model M1 tests whether there is a significant direct effect of subjective financial literacy on financial decision-making. The regression results show that the coefficient value of subjective financial literacy is 0.212, indicating that under the control of other conditions unchanged, the higher level the subjective financial literacy rural residents have, the more they tend to participate in the financial market. Hypothesis H1 is confirmed.

Model M2 tests whether objective financial literacy has a significant direct effect on financial decision-making. The regression results show that the coefficient value of objective financial literacy is 0.290, indicating that under the control of other conditions unchanged, the higher the objective financial literacy of rural residents, the more inclined to participate in the financial market. Hypothesis H2 is confirmed.

TABLE 5: Regression results of rural residents' financial literacy on financial market participation models.

| | Model M1 | Model M2 | Model M3 | Model M4 | Model M5 |
|--|--------------------------------|--------------------------------|-------------------------------|--------------------------------|--------------------------------|
| Variable | Financial market participation | Financial market participation | Subjective financial literacy | Financial market participation | Financial market participation |
| Subjective financial literacy | *** (15.81) | | | *** (11.42) | *** (3.23) |
| Objective financial literacy | | *** (15.04) | *** (18.52) | *** (9.86) | *** (3.84) |
| Cross-term of subjective and objective | | | | | |
| Gender | | | *** (-4.54) | | (1.51) (-0.62) |
| Age | (-0.56) *** | (-1.62) ** | | (-0.61) *** | (-0.62) *** |
| Age ² | (-3.65) ** | (-2.22) ** | (4.20) ** | (-3.24) ** | (-3.19) ** |
| Education level | (2.43) *** | (0.92) *** | (-5.30) *** | (2.17) *** | (2.11) *** |
| Health status | (7.11) ** | (7.59) ** | (7.66) *** | (5.95) ** | (5.83) ** |
| Marital status | (-2.16) ** | (-0.99) ** | (4.04) ** | (-2.10) ** | (-2.12) ** |
| Occupations | (-1.07) *** | (-1.14) ** | (-0.03) ** | (-1.15) ** | (-1.11) ** |
| Average annual income | (2.91) *** | (2.55) *** | (1.37) *** | (2.35) *** | (2.29) *** |
| _cons | (4.24) *** | (5.48) *** | (5.52) *** | (4.28) *** | (4.20) *** |
| P value (<i>F</i> test) | (7.57) | (5.19) | (-0.85) | (5.57) | (5.77) |
| Endogenous test, <i>P</i> value (χ^2 statistics) | 0.00001 | 0.00001 | 0.00001 | 0.00001 | 0.00001 |
| <i>N</i> | 0.56 | 0.87 | | | |
| R ² | 2229 | 2232 | 2229 | 2229 | 2229 |
| r ² _a | 0.313 | 0.304 | 0.374 | 0.342 | 0.342 |
| | 0.31 | 0.30 | 0.37 | 0.34 | 0.34 |

Note: ***The significance level is 1%. **The significance level is 5%. *The significance level is 10%.

Since the models have heteroscedasticity, GMM iterative estimation is performed on models M1 and M2 and the final Hausman test results show that models M1 and M2 cannot reject the null hypothesis with the probability of $P = 0.56$ and $P = 0.87$, respectively, indicating that subjective financial literacy and objective financial literacy are both exogenous explanatory variables in the model.

In the test of the mediating effect, three regressions are required: first, carry out the return of objective financial literacy to financial market participation (model M2). The results show that objective financial literacy variables are significant, which is the prerequisite for the existence of the mediating effect of the main body effect. Second, carry out the regression of objective financial literacy to subjective financial literacy (model M3). The results show that objective financial literacy variables are significant, indicating that objective financial literacy has a significant impact on subjective financial literacy. Finally, carry out subjective and objective financial literacy to the return of financial market participation (model M4). The result shows that both subjective financial literacy and objective financial literacy variables are significant. The *Z* value obtained by the Sobel test is -1.63 which rejects the null hypothesis without mediating the effect at the 5% significance level. The

conclusion is that subjective financial literacy plays a certain degree of mediating effect in the influence of objective financial literacy on financial decision-making and the mediating effect accounts for 26.7%. Hypothesis H3 is confirmed.

When testing the moderating effect, the intersection of subjective financial literacy and objective financial literacy is used to evaluate its significance. Model M5 (subjective financial literacy, objective financial literacy, subjective financial literacy, and objective financial literacy return to financial market participation) is built and the results obtained show that subjective and objective financial literacy and their cross-terms all play a positive role in promoting financial market participation and the cross-term of subjective financial literacy and objective financial literacy has more significant positive effect on the regression coefficient value of objective financial literacy relative to subjective financial literacy. It appears that the impact of objective financial literacy on financial decision-making is regulated by subjective financial literacy and hypothesis H4 is confirmed. From the empirical results, due to the existence of the positive promotion effect of the subjective and objective financial literacy cross-term, rural residents with higher subjective financial literacy will promote their participation

in the financial market with the improvement of their objective financial literacy level.

Rural residents of different ages have an “M distribution” in participation in the financial market (the two peaks are 23 and 48 years old, respectively). Obviously, the results show that the higher the level of education, the higher the average annual income, and the better the health of the respondents, the higher their interest in financial market participation. There is no significant amount of statistical data indicating that married people are more inclined to participate in the financial market than other unmarried and divorced groups. At the same time, rural residents engaged in nonagriculture are more willing to participate in the financial market.

4.2. Test of the Influence Path of Rural Residents’ Financial Literacy on Insurance Market Participation. With the increasing activity of the rural insurance market, more and more farmers have the awareness of avoiding risks and reducing losses caused by risks. Therefore, exploring such an active market is particularly necessary for the exploration of financial decision-making. First, carry out relevant tests on the direct influence of rural residents’ subjective financial literacy and objective financial literacy on financial decision-making and the mediating effect and moderating effect and perform heteroscedasticity tests on all models. It is found that there is heteroscedasticity and the FGLS method is used to modify. All models use the forward search method in the automatic stepwise regression method to perform regression to eliminate the multicollinearity in the model. The model test results are shown in Table 6.

Model M1 tests whether subjective financial literacy has a direct effect on insurance market participation. The regression results show that the coefficient of subjective financial literacy is negative, which is completely opposite to the direction of financial literacy participation. Hypothesis H1 is confirmed. Model M2 tests whether objective financial literacy has a direct effect on insurance market participation. The regression results show that the objective financial literacy coefficient is negative, which means that when the respondent has higher objective financial literacy, the less likely it is to participate in the insurance market. This is different from what we usually understand. It is not surprising that financial literacy and insurance market participation show a negative relationship. Firstly, the terms of Chinese insurance products are full of professional terms, which are difficult for ordinary people to understand, and insurance intermediaries in rural areas are very underdeveloped, causing residents with higher financial literacy to show greater resistance to insurance products; secondly, in recent years, a substitute for commercial insurance, social insurance, has been continuously improved, making commercial insurance products less attractive to residents with high financial literacy; thirdly, because the designed questionnaire puts insurance and bank products alongside each other, the interviewees may mistakenly believe that the insurance products in the questionnaire refer to wealth management products, thereby exacerbating this negative relationship.

In the same way, the Hausman test is provided to learn that the Models M1 and M2 cannot reject the null hypothesis with the probability of $P = 0.23$ and $P = 0.19$, respectively, which indicates that subjective financial literacy and objective financial literacy are both exogenous explanatory variables in the model.

In the test of the mediating effect, three regressions are required: first, the regression of objective financial literacy to insurance market participation (Model M2). The results show that objective financial literacy variables are significant, which is the premise for the existence of the mediating effect of the main body effect. Second, the regression of objective financial literacy to subjective financial literacy (Model M3). The results show that objective financial literacy variables are significant, indicating that objective financial literacy has a significant impact on subjective financial literacy. Finally, the regression of subjective financial literacy and objective financial literacy on financial market participation (Model M4). The result shows that the subjective financial literacy and objective financial literacy variables are both significant. The Z value obtained by the Sobel test is -2.43 and the null hypothesis is rejected without mediating effect at the 5% significance level. It is concluded that subjective financial literacy plays a certain degree of mediating effect in the influence of objective financial literacy on financial decision-making and the mediating effect accounts for 12.07%. Hypothesis H3 is confirmed.

When testing the moderating effect, the intersection of subjective financial literacy and objective financial literacy is used to evaluate its significance. The results obtained from Model M5 (subjective financial literacy, objective financial literacy, subjective financial literacy, and objective financial literacy return to financial market participation) show that subjective and objective financial literacy plays a positive role in promoting insurance market participation, but the cross-term of subjective financial literacy and objective financial literacy has a weaker reverse effect on the regression coefficient value of objective financial literacy than subjective financial literacy. It can be seen that the impact of objective financial literacy on financial decision-making is regulated by subjective financial literacy and hypothesis H4 is confirmed. From the empirical results, due to the existence of the reverse hindrance effect of the subjective and objective financial literacy cross-term, for rural residents with higher subjective financial literacy, improving their objective financial literacy level will not necessarily promote their participation in the insurance market. It may play a blocking role.

The higher the average annual income, the higher the interest of the surveyed persons engaged in nonagricultural occupations in participating in the insurance market. There is no significant amount of statistical data indicating that married persons are more inclined to participate in the insurance market than other unmarried, divorced, and other groups, which means married people have poor insurance awareness. At the same time, the lower the education level and the lower the age, they are more inclined to participate in the insurance market.

TABLE 6: Regression results of rural residents' financial literacy on insurance market participation models.

| | Model M1 | Model M2 | Model M3 | Model M4 | Model M5 |
|---|--------------------------------|--------------------------------|-------------------------------|--------------------------------|--------------------------------|
| Variable | Insurance market participation | Insurance market participation | Subjective financial literacy | Insurance market participation | Insurance market participation |
| Subjective financial literacy | (-0.17) | | | (0.28) | (1.43) |
| Objective financial literacy | | | *** | | |
| | | (-1.22) | (18.52) | (-1.19) | (0.61) |
| Cross-term of subjective and objective | | | | | (-1.44) |
| Gender | * | * | *** | * | * |
| | (-1.90) | (-1.93) | (-4.54) | (-1.90) | (-1.89) |
| Age | | | *** | | |
| | (0.79) | (0.77) | (4.20) | (0.73) | (0.68) |
| Age ² | | | *** | ** | ** |
| | (-0.58) | (-0.58) | (-5.30) | (-0.54) | (-0.49) |
| Education level | ** | ** | *** | ** | ** |
| | (-2.47) | (-2.27) | (7.66) | (-2.30) | (-2.19) |
| Health status | | | | | |
| | (0.16) | (0.15) | (4.04) | (0.14) | (0.16) |
| Marital status | | | | | |
| | (0.66) | (0.67) | (-0.03) | (0.66) | (0.63) |
| Occupations | | | | | |
| | (0.77) | (0.86) | (1.37) | (0.84) | (0.89) |
| Average annual income | ** | ** | *** | ** | *** |
| | (1.19) | (1.24) | (5.52) | (1.20) | (1.27) |
| _cons | *** | *** | | *** | *** |
| | (10.37) | (10.40) | (-0.85) | (10.40) | (9.37) |
| P value (F test) | 0.00001 | 0.00001 | 0.00001 | 0.00001 | 0.00001 |
| Endogenous test, P value (χ^2 statistics) | 0.23 | 0.19 | | | |
| N | 2229 | 2231 | 2229 | 2229 | 2229 |
| R 2 | 0.008 | 0.009 | 0.374 | 0.009 | 0.010 |
| r2_a | 0.00 | 0.00 | 0.37 | 0.00 | 0.00 |

Note: ***The significance level is 1%. **The significance level is 5%. *The significance level is 10%.

4.3. Test of the Effect of Rural Residents' Financial Literacy on Financial Decision-Making under Different Financial Technology Popularization

4.3.1. *Model interpretation.* Based on the threshold autoregression model (TAR) proposed by Tong [17] and draws on the idea of the endogenous panel threshold regression model proposed by Hansen [20], this paper first expresses the single threshold regression model without partition as follows:

$$Y = \{\alpha_{51}OFL + \alpha_{52}SFL + \alpha_{53}Z + \beta X + \mu\} (d \leq Z) + \{\alpha_{61}OFL + \alpha_{62}SFL + \alpha_{63}Z + \beta X + \mu\} (d > Z) + \varepsilon. \quad (8)$$

Among them, ε are the residual items and the coefficients α_{51} , α_{52} , α_{61} , α_{62} , Z are parameters to be estimated.

Carrying out least square estimation on regression model (8) and obtaining the residual sum of squares can obtain the threshold estimated value Z . Since the obtained threshold is proposed on the null hypothesis of no threshold effect, it needs to be confirmed whether there is a threshold

effect in the model. The null hypothesis and alternative hypothesis tested are

$$\begin{aligned} H0: \alpha_{51} &= \alpha_{61}, \\ H1: \alpha_{52} &\neq \alpha_{62}. \end{aligned} \quad (9)$$

Let $S0$ be the sum of squares of the residual items under the null hypothesis (no threshold effect), and $S1$ is the residual sum of squares under the condition of threshold effect. The F statistic of the corresponding Lagrange multiplier test can be easily obtained:

When $F <$ the corresponding critical value under the given significance level, the null hypothesis is not rejected, indicating that the model does not have a threshold effect;

When $F >$ the critical value corresponding to the given significance level, the null hypothesis is rejected, indicating that the model has a threshold effect, and under different mechanisms, the coefficient values of α_{51} , α_{52} , α_{61} , α_{62} are different.

Whether the second threshold exists and its estimation method and test method are the same as the first threshold are judged.

TABLE 7: Parameter estimates of double thresholds for financial technology penetration.

| Variable | Coefficient | Standard error | t value |
|-------------------------------|-------------|----------------|---------|
| <i>Z < 1-1210 obs</i> | | | |
| Financial decision-making | 0.0000 | 0.0137 | 0.0000 |
| Subjective financial literacy | 0.0000 | 0.0124 | 0.0000 |
| Objective financial literacy | 0.0000 | 0.0084 | 0.0000 |
| <i>1 ≤ Z < 3-506 obs</i> | | | |
| Financial decision-making | 0.1400 | 0.0175 | 7.9824 |
| Subjective financial literacy | 0.0126 | 0.0128 | 0.9851 |
| Objective financial literacy | 0.0655 | 0.0156 | 4.1855 |
| <i>3 ≤ Z-514 obs</i> | | | |
| Financial decision-making | 0.2487 | 0.01421 | 7.5607 |
| Subjective financial literacy | 0.19141 | 0.0118 | 6.2230 |
| Objective financial literacy | 0.2649 | 0.01491 | 7.7320 |

4.3.2. Empirical Analysis. The confidence interval constructed by the measurement software and the number of corresponding interval values are clearly pointed out that 1 and 3 are the two threshold values under the threshold effect model and the threshold regression parameter values obtained are shown in Table 7.

From the estimated results, it can be seen that under different levels of Fintech penetration, the financial literacy of rural residents has different elasticities of influence on financial decision-making, and with the expansion of Fintech contact, the elasticity of influence is gradually increasing, which shows that Fintech penetration has nonlinear structural characteristics of influence on subjective financial literacy and objective financial literacy. When Fintech penetration is less than 1, the coefficient value is 0. However, this does not mean that when financial technology is not fully popularized in rural areas, Fintech penetration has no effect on farmers' financial literacy and financial decision-making. It is just not relevant from a statistical point of view. But from the reality, without the popularization of financial technology, farmers' financial literacy is likely to have a negative and significant impact in making financial decisions. When Fintech penetration is between 1 and 3, the coefficients of financial decision-making and subjective and objective financial literacy are all positive and the increase in objective financial literacy is the most obvious. Through direct influence and the adjustment effect of subjective financial literacy, the coefficient of financial decision-making finally reaches 14%. As a relatively exogenous variable, Fintech penetration has played a good role in enhancing the influence of rural residents' financial literacy on their financial decision-making. When Fintech penetration reaches a relatively high level, the intermediary adjustment effect of subjective financial literacy is more significant. At this time, the affected variable (financial decision-making) is not only directly affected by subjective and objective financial literacy but also by the effective use of intermediary models and cross-terms, allowing rural residents' financial decision-making to reach a relative peak value. So far, hypothesis H5 is verified.

5. Conclusion and Inspiration

Subjective financial literacy and objective financial literacy have a significant positive impact on financial market participation but have a negative direct effect in insurance market participation. Subjective financial literacy plays an incomplete intermediary role in the impact of the objective financial literacy on financial market participation and insurance market participation and the mediating effects account for 26.7% and 12.07%. Objective financial literacy is regulated by subjective financial literacy in financial market participation and insurance market participation. The higher the degree of financial technology penetration, the financial literacy of rural residents will have a more significant impact on their financial decision-making under the mediating and regulatory effects.

The financial market participation of respondents of different ages shows an "M-shaped" distribution (the peak is around 23 and 48). Married people have weak financial participation capabilities and poor insurance awareness, thus making it more difficult for them to participate in the financial market and the insurance market. The higher the education level of individuals, the higher the possibility of participating in the financial market and the more optimistic about participating in the financial market, but the lower the probability of participating in the insurance market. The higher the degree of nonagricultural occupation, respondents are more likely to participate in the financial market and insurance market. The higher the average annual household income, the higher the possibility of participating in the financial market will be. The better their health is, the greater their enthusiasm for participating in the financial market.

Promoting the popularization of financial technology in rural areas has profound significance for rural revitalization. A series of chain reactions driven by financial technology include the improvement of financial services, financial education, and financial literacy. Each country or region has different policies and measures to improve residents' financial literacy; however, their focus is on the improvement of objective financial literacy and ignores the impact of subjective financial literacy on residents' financial decision-making. Our research shows that the financial decisions made by rural residents are not only directly influenced by subjective and objective financial literacy but also influenced by objective financial literacy on financial decision-making and subjective financial literacy has mediating effect. When financial technology penetration is introduced as a threshold variable, this path of influence remains unchanged. Therefore, while paying attention to the improvement of residents' objective financial literacy, national policy makers and implementers should also give equal attention to subjective financial literacy. Financial institutions can also rely on financial technology to pay attention to residents' subjective demands and design-personalized financial products. When promoting financial technology penetration in rural areas,

we should also pay attention to individual characteristics such as age level, income status, health status, marital status, occupation type, education level, and financial education. In this way, the effect of the policy implementation will be better and financial institutions will pay more attention to the characteristics of differentiation. Financial technology penetration, financial literacy, and financial decision-making will also form a good circular and mutually beneficial effect.

At the same time, the conclusions of this article show that a financial literacy improvement plan should be formulated to strengthen the popularization of financial education in rural areas, encourage farmers to participate in the financial market, and improve individual financial well-being through asset allocation. The focus is on the middle-aged and young people in rural areas. As a vital part of improving financial literacy, adolescents are the main group to achieve poverty reduction in rural areas in the future. Improving their financial literacy is conducive to the formation of a chain effect and the realization of sustainable poverty reduction, allowing farmers to experience the benefits of asset allocation through actual financial operations, so as to break the shackles of rural residents' traditional ideas of small farmers and establish models, thus achieving the autonomous driving effect of village residents, rather than relying solely on the government's up-to-down propaganda.

Data Availability

The data used to support the findings of this study were supplied by China Foundation for Development of Financial Education under license and so cannot be made freely available. Requests for access to these data should be made to China Foundation for Development of Financial Education.

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

Carbon Tax, Subsidy, and Emission Reduction: Analysis Based on DSGE Model

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Carbon emission has negative externalities, which will cause severe natural and social problems. In recent years, more and more attention has been paid to carbon emission reduction issue both in academic and application fields. This paper aims to explore the impact of punitive carbon tax and incentive carbon emission reduction subsidy on economy and environment through the dynamic stochastic general equilibrium (DSGE) framework. The results show that both carbon tax and carbon emission reduction subsidy policies can help to reduce carbon emissions and to improve environment quality. In addition, carbon emission reduction subsidy has a positive impact on economy, while carbon tax has the opposite impact. It follows that the incentive carbon emission reduction policy is more conducive to the coordinated development of economy and environment. This research can be a guideline for the government to formulate carbon emission abatement policies from the perspective of coordinated development.

1. Introduction

With the continuous increase in production scale and carbon emission, the world is facing more and more severe environment problems such as air pollution and climate change. On the one hand, the report “global air condition 2019” released by the American Institute of Health Effects pointed out that air pollution ranked the fifth among all health risk factors in the world, ranking after dietary risk, hypertension, smoking, and high fasting blood glucose. On the other hand, the Intergovernmental Panel on Climate Change (IPCC) suggested that global warming needed to be limited to 1.5 degrees Celsius or the planet would experience devastating climate change by 2030. And Nordhaus pointed that carbon dioxide would be the first man-made emission to affect climate on a global scale by the end of the century [1]. In 2007, one of the IPCC’s reports showed that, according to the annual data of different continents, human’s impact on the climate system is clear and ceaselessly growing. If left unchecked, air pollution and climate change would increase the likelihood of severe, widespread, and irreversible risk on humans and ecosystems [2, 3]. Therefore, it is urgent to reduce carbon emissions.

Facing the challenge of carbon emission reduction, China has proposed a green development path with Chinese characteristics in light of its unique national condition. The green development path is not only the inheritance of sustainable development but also the theoretical innovation of sustainable development in China [4]. It is also a major theoretical contribution of socialism with Chinese characteristics to the objective reality of global ecological environment deterioration [5]. China’s green development path includes developing a low-carbon economy, developing a stronger circular economy, continuing to promote energy conservation, and reducing carbon emission. Among them, developing a low-carbon economy and reducing carbon emission will help to improve the deteriorating international ecological environment.

Previous studies have shown that both carbon tax and carbon emission reduction subsidy had a great impact not only on the economy but also on the environment (e.g., Nordhaus [6], Jeong et al. [7], and Acemoglu et al. [8, 9]). In order to analyze which policy is more conducive to balance the economic development and environmental improvement, this paper builds a DSGE framework including household, firm, government, and environment sector. The

contributions lie in that as follows: (1) An environmental DSGE model is built to analyze the impact of carbon tax and carbon emission reduction subsidy on the economy and environment, which supplements the relevant literature of environmental DSGE modeling. (2) The results demonstrate that both the punitive carbon tax and incentive carbon emission reduction subsidy can reduce carbon emissions and promote the environment quality. (3) The difference between two carbon emission reduction policies is that carbon emission reduction subsidy is beneficial to both environment improvement and economy development, while carbon tax is only beneficial to the former, which indicates that incentive policy is more conducive to the coordinated development of economy and environment.

2. Literature Review

Facing the worsening environment problems, how to effectively abate carbon emissions has become an important practical issue [10]. Grossman and Krueger [11] first proposed the environmental Kuznets curve to analyze the relationship between environment pollution and GDP per capita. And they found an inverted *U*-shaped relationship between air pollutants and economic growth. Some researchers support the view of the environmental Kuznets curve. For example, Galeotti and Lanza [12] collected new types of data including carbon emission and GDP from more than 100 countries to verify the environmental Kuznets curve. In addition, there are also some researchers who were against Grossman and Krueger's view, such as Agras and Chapman [13] and He and Richard [14]. The environmental Kuznets curve only provides an influence mechanism for pollution emission on economic growth and the fact that the curve showed warned us to pay more attention to carbon emission reduction, which sparked a wave of research boom on it.

The above-mentioned scholars' studies on carbon emissions showed that the fundamental principle of carbon emission reduction policies is to stimulate carbon emission abatement initiatives or to directly curb carbon emissions, such as Choi's opinion on nonrenewable energy taxes and renewable energy subsidies [15]. As a result, carbon emission reduction policies can be divided into two aspects, one is the punitive policy such as imposing carbon tax to punish those who pollute, and the other is the incentive policy such as providing subsidies to stimulate those who make emission reduction efforts. Therefore, the government can control the firm's carbon emissions by formulating scientific and reasonable incentives and punitive carbon emission abatement policies. The following part combs the literature of these two aspects.

2.1. Punitive Carbon Tax Policy. Punitive carbon tax has been regarded as an effective carbon emission abatement policy with market features [16]. The concept of the environmental tax is first mentioned by Pigovian, which is, the government is able to adjust the negative externalities of the pollution through taxation [17], such as carbon tax policy. Jia and Lin

[18] applied a dynamic computable general equilibrium framework to study the Chinese carbon emission reduction strategy choice, and the results showed that the carbon tax is more effective than carbon trading. By reviewing literature about carbon tax, we found that most of them are linked to supply chain management. Yin et al. [19] investigated the optimal carbon emission policy in supply chain management and analyzed the implementation conditions of carbon tax and subsidy. Dou and Cao [20] explored the environmental and economic performances of the closed-loop supply chain under carbon tax policy and pointed out that a higher tax rate can bring better environmental performance. Zou et al. [21] developed a Stackelberg game to investigate the retailer's low-carbon investment decision on supply chain under carbon tax regulation and put forward a sharing contact which is beneficial to both economy and environment. Zhou et al. [22] reviewed plenty of literatures about supply chain management under carbon taxes, which shows that carbon tax is a powerful tool for carbon emission abatement. In addition, there are also some other studies on carbon tax. Chan [23] constructed an environmental DSGE model between two countries to determine the optimal carbon tax rate under different economic shocks. Zhang et al. [24] utilized an evolutionary game method to explore the manufacturer's green innovation-decision under carbon tax and innovation subsidy, and the results demonstrate that carbon tax is more effective than innovation subsidy. Zhu et al. [25] studied the green financial strategies for Chinese energy companies under carbon tax and concluded that the carbon tax can be conducive to help energy companies achieve green development.

The viewpoints of the above scholars have all verified that the carbon tax is a powerful and widely applied carbon emission reduction policy. Therefore, it is of great significance to study the impact of carbon tax on economy and environment.

2.2. Incentive Carbon Emission Reduction Subsidy Policy. Incentive carbon emission reduction subsidy policy is capable of promoting the firms' carbon emission abatement initiatives [26]. Argentiero et al. [27] built a DSGE model that included carbon taxes and subsidies to compare the cost-effectiveness under technology-driven shock and demand-driven shock. Xu et al. [28] studied the interaction scenario in which the government imposes carbon taxes on manufacturers and gives subsidies to consumers who purchase green products. Su et al. [29] developed a Stackelberg game to investigate the optimal pricing strategies under different subsidy modes, such as subsidy to manufacturers who produce low-carbon products or consumers who buy low-carbon products. Cao et al. [30] explored the optimal production and carbon emission abatement level in the context of cap-and-trade and low-carbon subsidy policies and discussed which policy is more beneficial to society. Han et al. [26] used game theory to study the optimal decisions in the low-carbon e-commerce supply chain, and the results showed that the government subsidy can help to encourage the manufacturer to produce low-carbon products. On the

basis of the above researchers, subsidy policy is an effective way to stimulate the firm's carbon emission abatement initiatives.

By combining the above literatures on carbon tax and carbon emission reduction subsidy, we found that there is barely research studied the carbon tax and carbon emission reduction subsidy policies' impact both on economy and environment. Therefore, based on the previous researches, our work aims to investigate the economic and environmental impact of carbon tax and carbon emission reduction subsidy, which would supplement the literature gap in this field and provide theoretical reference for policy-makers.

3. Model

In this part, we construct a DSGE framework which consists of household, firm, government, and environment sectors. The logic among each sector of the proposed DSGE model is as follows: the household supplies labor and capital to firm, gains wage income, and capital return and makes the optimal consumption, labor, and capital decisions by maximizing the lifetime utility under the constraint of the budget. The firm input technology, capital, labor, and green production factor to obtain the profitable product, pays for production factor and carbon emission reduction cost, pays carbon tax to the government, gets carbon emission reduction subsidies from the government, and pursues profit maximization. The government satisfies the budget constraint and balances its books. The environment sector follows the dynamic equation of ecological environment quality. The logical structure of each sector under carbon tax and carbon emission reduction subsidy policies is shown in Figure 1.

3.1. Household. Household's utility is influenced by consumption, labor, and environment quality. The abstract form of household objective function is set as follows:

$$\max E_0 \sum_{t=0}^{\infty} \beta^t U(C_t, N_t, Q_t), \quad (1)$$

where E_0 is the conditional expectation operator formed based on the information of phase 0. $0 < \beta < 1$ represents the subjective discount rate. $U(\cdot)$, C_t , N_t , and Q_t are household utility function, consumption, labor, and environment quality.

The household aims to maximize its intertemporal utility. Referring to the research by Annicchiarico and Diluiso [31], the concrete form of household utility function can be described as follows:

$$U(C_t, N_t, Q_t) = \frac{C_t^{1-\theta_1}}{1-\theta_1} - \frac{N_t^{1+\theta_2}}{1+\theta_2} + \eta \ln Q_t, \quad (2)$$

where θ_1 and θ_2 are the relative risk aversion elasticity of household consumption and labor supply, respectively. η represents household's preferences for environment quality.

Household's budget constraint is set as follows:

$$C_t + I_t = R_{K,t}K_t + W_tN_t, \quad (3)$$

where I_t and K_t represent household's investment and capital, respectively. $R_{K,t}$ and W_t are capital return rate and wage level, respectively.

The equation of capital motion can be written as follows:

$$I_t = K_{t+1} - (1 - \delta)K_t, \quad (4)$$

where $\delta \in (0, 1)$ represents the capital depreciation rate.

According to formulas (1)–(3), the household's Lagrange function can be depicted as follows:

$$L_{F,t} = E_0 \sum_{t=0}^{\infty} \beta^t \left\{ \begin{aligned} & \frac{C_t^{1-\theta_1}}{1-\theta_1} - \frac{N_t^{1+\theta_2}}{1+\theta_2} + \eta \ln Q_t \\ & + \xi_t [C_t + K_{t+1} - (1 - \delta + R_{K,t})K_t - W_tN_t] \end{aligned} \right\}, \quad (5)$$

where ξ_t represents the Lagrange multiplier, that is, the shadow price. By solving the first-order partial derivatives of (5) with respect to consumption, labor, and capital, the optimal conditions of the household can be calculated as follows:

- (1) Let $\partial L_t / \partial C_t = 0$; one can obtain the following equation:

$$\xi_t = -C_t^{-\theta_1}. \quad (6)$$

- (2) Let $\partial L_t / \partial N_t = 0$; one can obtain the following equation:

$$W_t = N_t^{\theta_2} C_t^{\theta_1}. \quad (7)$$

- (3) Let $\partial L_t / \partial K_t = 0$; one can obtain the following equation:

$$\left(\frac{C_t}{C_{t-1}} \right)^{\theta_1} = \beta(1 + R_{K,t} - \delta). \quad (8)$$

3.2. Firm. The firm aims to maximize its profits denoted by the difference between incomes and costs. The incomes mainly include sales volume and carbon emission subsidies. The costs mainly include labor wage, capital rent, green production factor cost, carbon tax, and carbon emission abatement cost. Assuming that the firm's production function meets the form of the Cobb–Douglas production function as follows:

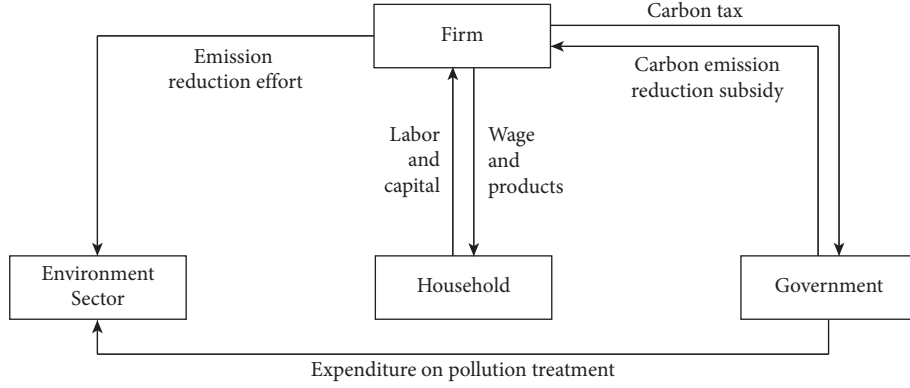


FIGURE 1: Logic structure diagram of the DSGE model.

$$Y_t = A_t K_t^{\alpha_1} N_t^{\alpha_2} S_t^{1-\alpha_1-\alpha_2}, \quad (9)$$

where Y_t , A_t , K_t , N_t , and S_t are firm's output, technical level, capital input, labor force input, and green production factor input at time t , respectively. α_1 and α_2 represent firm's capital and labor output elasticity, respectively. Assuming that the firm's technical level is subject to the exogenous shocks of the AR (1) process as follows:

$$\ln A_t = (1 - \rho_A) \ln A^* + \rho_A \ln A_{t-1} + e_{A,t}, \quad (10)$$

where ρ_A and A^* are the first-order autoregressive coefficient and the steady-state value of the technical level, respectively. $e_{A,t}$ represents the exogenous impact on the firm's technical level, which obeys the standard normal distribution.

Referring to the studies by Annicchiarico and Di Dio [32] and Heutel [33], we suppose that the firm would reduce its carbon emissions in pursuit of a more environmental friendly productive way under the carbon tax and carbon emission subsidy policies. Therefore, the actual carbon emission quantity can be depicted as

$$X_t = \kappa Y_t (1 - ER_t), \quad (11)$$

where X_t and ER_t are the actual carbon emission quantity and carbon emission reduction efforts of the firm, respectively. κ represents the carbon emission coefficient per unit output.

According to equation (11), the carbon emission reduction quantity RX_t can be described as follows:

$$RX_t = \kappa ER_t Y_t. \quad (12)$$

Referring to the research by Chan [23], the firm's carbon emission reduction cost ERC_t is set as follows:

$$ERC_t = \mu_1 (ER_t)^{\mu_2} Y_t, \quad (13)$$

where $\mu_1 > 0$ and $\mu_2 > 1$ refer to the technical parameters of the firm's carbon emission reduction cost.

The firm's carbon emission reduction effort belongs to green behavior, which helps to improve the quality of ecological environment. Therefore, according to the carbon emission reduction quantity, the firm will get carbon emission reduction subsidy which can be depicted as follows:

$$G_{2,t} = \psi_t RX_t, \quad (14)$$

where $G_{2,t}$ is the government's carbon emission reduction subsidy to the firm. ψ_t denotes carbon emission reduction subsidy rate at time t , and we assume ψ_t is subject to the exogenous shocks of the AR (1) process as follows:

$$\ln \psi_t = (1 - \rho_\psi) \ln \psi^* + \rho_\psi \ln \psi_{t-1} + e_{\psi,t}, \quad (15)$$

where ρ_ψ and ψ^* are the first-order autoregressive coefficient and the steady-state value of the carbon emission reduction subsidy rate, respectively. $e_{\psi,t}$ represents the exogenous impact on the carbon emission reduction subsidy rate, which obeys the standard normal distribution.

In conclusion, the firm's objective function can be depicted as follows:

$$\pi_t = Y_t - K_t R_{K,t} - N_t W_t - ERC_t - \tau_{X,t} X_t - p_{S,t} S_t + G_{2,t}, \quad (16)$$

where π_t represents the firm's total profit. $\tau_{X,t}$ denotes the carbon tax rate at time t , which is assumed to be subject to the exogenous impact of the AR (1) process as follows:

$$\ln \tau_{X,t} = (1 - \rho_{\tau_X}) \ln \tau_X^* + \rho_{\tau_X} \ln \tau_{X,t-1} + e_{\tau_X,t}, \quad (17)$$

where ρ_{τ_X} and τ_X^* are the first-order autoregressive coefficient and the steady-state value of the carbon tax rate, respectively. $e_{\tau_X,t}$ represents the exogenous impact on the carbon tax rate, which obeys the standard normal distribution.

Suppose that the green production factor price $p_{S,t}$ obeys the following exogenous shock of AR (1) process:

$$\ln p_{S,t} = (1 - \rho_{p_S}) \ln p_S^* + \rho_{p_S} \ln p_{S,t-1} + e_{p_S,t}, \quad (18)$$

where ρ_{p_S} and p_S^* are the first-order autoregressive coefficient and the steady-state value of the green production factor price, respectively. $e_{p_S,t}$ represents the exogenous impact on the green production factor price, which obeys the standard normal distribution.

By solving the first-order partial derivatives of equation (16) with respect to capital input, labor input, green production factor input, and carbon emission reduction efforts, we can get the following conditions:

- (1) Let $\partial\pi_t/\partial K_t = 0$; one can obtain the optimal capital input:

$$R_{K,t} = \frac{\alpha_1(1 - \mu_1(\text{ER}_t)^{\mu_2} + \kappa(\tau_{X,t}\text{ER}_t + \psi_t\text{ER}_t - \tau_{X,t}))Y_t}{K_t}. \quad (19)$$

- (2) Let $\partial\pi_t/\partial N_t = 0$; one can obtain optimal labor input:

$$W_t = \frac{\alpha_2(1 - \mu_1(\text{ER}_t)^{\mu_2} + \kappa(\tau_{X,t}\text{ER}_t + \psi_t\text{ER}_t - \tau_{X,t}))Y_t}{N_t}. \quad (20)$$

- (3) Let $\partial\pi_t/\partial S_t = 0$; one can obtain the optimal green production factor input:

$$p_{S,t} = \frac{(1 - \alpha_1 - \alpha_2)(1 - \mu_1(\text{ER}_t)^{\mu_2} + \kappa(\tau_{X,t}\text{ER}_t + \psi_t\text{ER}_t - \tau_{X,t}))Y_t}{S_t}. \quad (21)$$

- (4) Let $\partial\pi_t/\partial \text{ER}_t = 0$; one can obtain the optimal carbon emission reduction effort:

$$\text{ER}_t = \left(\frac{\kappa(\psi_t + \tau_{X,t})}{\mu_1\mu_2} \right)^{1/\mu_2 - 1}. \quad (22)$$

3.3. Government. We assume that the government mainly applied carbon tax levied from firms into pollution treatment and carbon emission reduction subsidy. Therefore, the government's balance equation can be depicted as follows:

$$\tau_{X,t}X_t = G_{1,t} + G_{2,t}. \quad (23)$$

Among it, the government's expenditure on pollution treatment $G_{1,t}$ obeys the following exogenous shock of AR (1) process:

$$\ln G_{1,t} = (1 - \rho_{G_1})\ln G_1^* + \rho_{G_1} \ln G_{1,t-1} + e_{G_{1,t}}, \quad (24)$$

where $\rho_{G_{1,t}}$ and G_1^* are the first-order autoregressive coefficient and the steady-state value of the government's expenditure on pollution treatment, respectively. $e_{G_{1,t}}$ represents the exogenous impact on the government's expenditure on pollution treatment, which obeys the standard normal distribution.

3.4. Environment Sector. Referring to the research by Jovet [34], the ecological environment quality at time t is related to its initial state, the state at time $t - 1$, the firm's carbon emission, and the government's pollution treatment. Therefore, the dynamic equation of environment quality Q_t is set as follows:

$$Q_t = h\bar{Q} + (1 - h)Q_{t-1} - X_t + \gamma G_{1,t}, \quad (25)$$

where Q_{t-1} represents the environment quality at time $t - 1$. h denotes the environment's self-purification capacity. \bar{Q}

represents the initial environment quality. γ refers to the government's pollution treatment efficiency.

3.5. Market Clearing Condition. The market-clearing condition means that the firm's output is equal to all summed up by the household's consumption and capital accumulation, the government's expenditure, and the firm's emission reduction cost which also includes green production factor input cost. It is assumed that all the household's capital is invested in the firm's production and only the clearing out of the commodity market is considered. Therefore, the market-clearing condition satisfies the following equation:

$$Y_t = C_t + I_t + G_{1,t} + \text{ERC}_t + p_{S,t}S_t. \quad (26)$$

4. Parameters and Impulse Response Analysis

There are two types of parameters in the DSGE model: static and dynamic parameters. The static parameters which reflect the model's static characteristics are usually determined by the calibration method. The dynamic parameters which reflect the model's dynamic characteristics are mostly settled by the estimation method.

4.1. Static Parameters Calibration. On the household's side, the static parameters that need to be calibrated include β , θ_1 , θ_2 , η , and δ . On the firm's side, the static parameters comprise α_1 , α_2 , κ , μ_1 , and μ_2 . On the environment sector's side, the static parameters contain \bar{Q} , h , and γ . Referring to the studies by Annicchiarico and Di Dio [32], Heutel [33], Chan [23], and Fischer and Springborn [35], the above-mentioned static parameters' definitions and calibrated values are shown in Table 1.

4.2. Dynamic Parameters Estimation. The proposed DSGE model includes 5 exogenous shocks: $e_{\tau_{X,t}}$, $e_{\psi,t}$, $e_{A,t}$, $e_{G_{1,t}}$, and $e_{p_{S,t}}$. To estimate the dynamic parameters, we select China's GDP from 1996 to 2018 as the external observation data. The parameters to be estimated in the determining equation of each exogenous shock include the first-order autoregressive coefficient and the random disturbance term. Referring to the research studies by Gerali et al. [36] and Khan et al. [37], we select the prior mean values, set that the first-order autoregression parameters satisfy that the beta distribution and the fluctuation parameters (random shocks) is subject to the relatively smooth inverse gamma (Inv. Gamma) distribution. We use Dynare (11.4) toolbox under Matlab (2017b) software to estimate the posterior distribution of dynamic parameters under a given prior distribution by the Bayesian estimation method.

The Bayesian estimation results of dynamic parameters are shown in Table 2, and the prior distribution and posterior distribution diagrams are shown in Figure 2.

5. Results and Analysis

In this section, we analyzed the impulse response of five economic variables including the output Y_t , consumption

TABLE 1: Calibration results of static parameters.

| Parameter | Definition | Value |
|------------|--|-------|
| β | Household discount factor | 0.97 |
| θ_1 | Relative risk aversion elasticity of consumption | 0.8 |
| θ_2 | Inverse of the Frisch elasticity of labor supply | 0.2 |
| η | Household environment preference coefficient | 1 |
| δ | Capital depreciation rate | 0.11 |
| α_1 | Elasticity of output with respect to capital | 0.4 |
| α_2 | Elasticity of output with respect to labor | 0.45 |
| κ | Carbon emission factor per unit of output | 0.16 |
| μ_1 | Coefficient of mitigation costs scale | 0.2 |
| μ_2 | Emission reduction effort index | 1.8 |
| \bar{Q} | Initial environment quality | 1 |
| h | Environment self-purification capacity | 0.1 |
| γ | Government efficiency in pollution control | 1.16 |

TABLE 2: Bayesian estimation results of dynamic parameters.

| Parameter | Prior distribution | Prior mean | Posterior mean | 90% HPD interval |
|-----------------|--------------------|------------|----------------|------------------|
| ρ_{G_1} | Beta | 0.6000 | 0.5986 | [0.5612, 0.6332] |
| ρ_{p_s} | Beta | 0.6000 | 0.5987 | [0.5693, 0.6330] |
| ρ_{τ_X} | Beta | 0.6000 | 0.5953 | [0.5648, 0.6296] |
| ρ_{ψ} | Beta | 0.6000 | 0.6002 | [0.5737, 0.6323] |
| ρ_A | Beta | 0.6000 | 0.6098 | [0.5786, 0.6452] |
| $e_{G_1,t}$ | Inv. Gamma | 1.0000 | 0.8219 | [0.4274, 1.3774] |
| $e_{p_s,t}$ | Inv. Gamma | 1.0000 | 0.7857 | [0.3166, 1.3662] |
| $e_{\tau_X,t}$ | Inv. Gamma | 1.0000 | 0.7272 | [0.2937, 1.1170] |
| $e_{\psi,t}$ | Inv. Gamma | 1.0000 | 0.6747 | [0.2580, 1.0403] |
| $e_{A,t}$ | Inv. Gamma | 1.0000 | 0.4782 | [0.3452, 0.6078] |

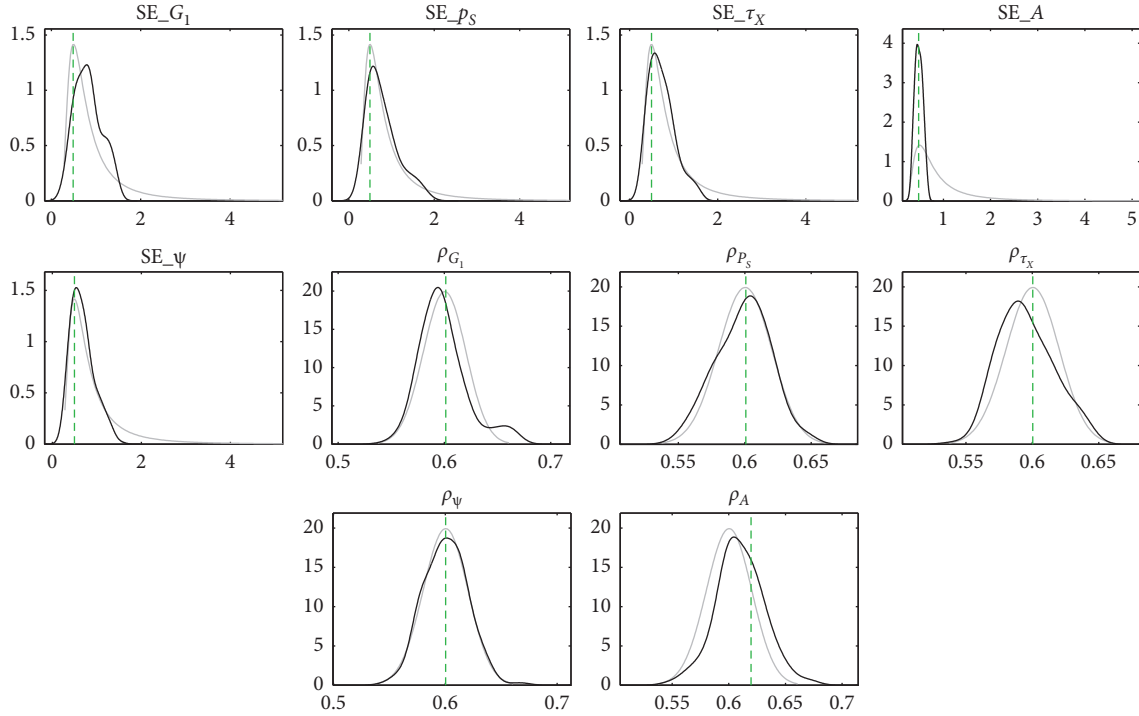


FIGURE 2: Prior and posterior distribution diagrams in Bayesian estimation.

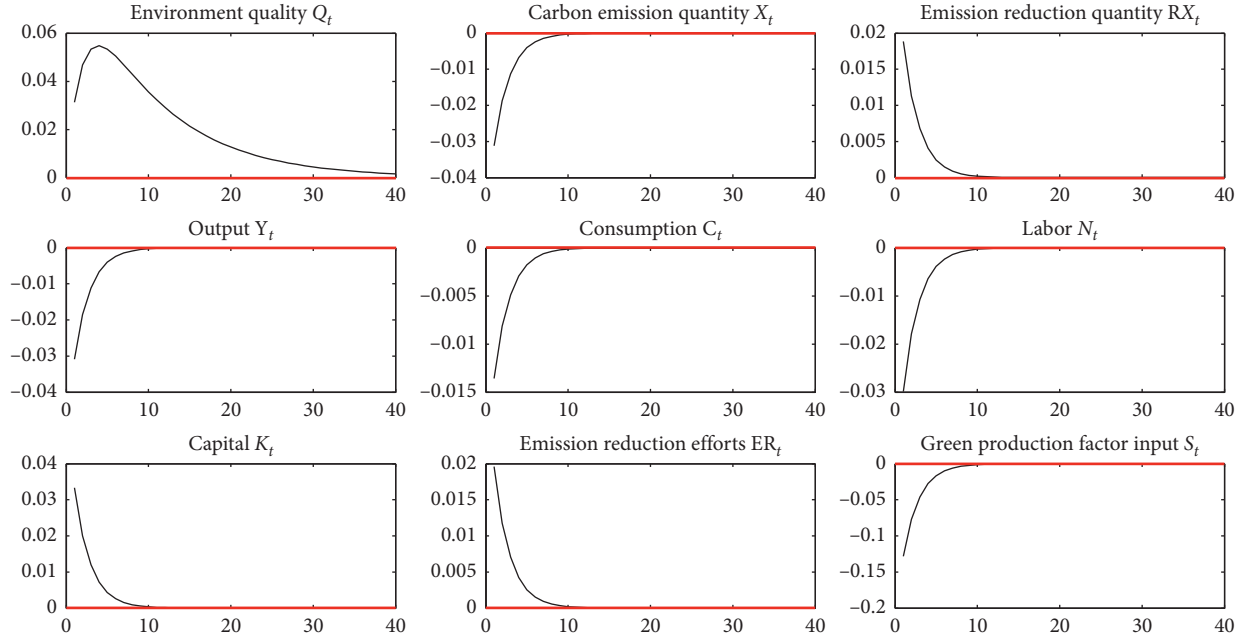


FIGURE 3: IRFs of carbon tax rate.

C_t , labor N_t , capital K_t , and green production factor input S_t , and four environment variables including environment quality Q_t , carbon emission quantity X_t , carbon emission reduction quantity RX_t , and carbon emission reduction efforts ER_t under the shock of carbon tax rate and subsidy rate. The impulse response results of each variable are shown as follows.

5.1. Impulse Response Functions (IRFs) of Carbon Tax Rate.

Figure 3 displays the IRFs of the carbon tax rate. The results showed that, in response to the carbon tax rate shock, K_t , RX_t and ER_t , increased, while X_t , Y_t , C_t , N_t , and S_t decreased before 10th period and all variables except Q_t remained unchanged after the 10th period. Q_t reached the peak of growth around the 4th period, and then, the growth rate declined. That may because in order to avoid paying high carbon taxes, firms are willing to make more emission reduction efforts to reduce carbon emissions. Eventually, continuous efforts of the firm will significantly improve environment quality. Although the imposition of carbon tax brought a greater environment quality, it would lead to the decline of output, consumption, labor, and green production factor input. Therefore, the economic benefit of the carbon tax is not as good as its environmental benefit.

5.2. IRFs of Carbon Emission Reduction Subsidy Rate.

Figure 4 displays the IRFs of carbon emission reduction subsidy rate. The results showed that, in response to the carbon emission reduction subsidy rate shock, except the descent of X_t or the sustained growth of Q_t , all other variables increased before the 10th period and remained unchanged after the 10th period. Under the impact of carbon

emission reduction subsidy rate, both economic and environmental benefits can be well satisfied.

5.3. Sensitivity Analysis on Carbon Tax Rate. In order to further analyze the dynamic effect of the carbon tax rate shock and examine the correctness of the impulse response, we, respectively, raised and reduced the carbon tax rate by 15% and analyzed the impulse response of five economic and four environmental variables under these two conditions. The results of sensitivity analysis on the carbon tax rate shock are shown in Figure 5.

Comparing three different carbon tax levels, we concluded that increasing or decreasing the carbon tax rate level will enlarge the original positive impact effect, such as the impact on Q_t , RX_t , K_t , and ER_t and will reduce the original negative impact effect, such as X_t , Y_t , C_t , N_t , and S_t . Whether the carbon tax rate is increased or decreased, the impact directions on the economic and environmental variables are consistent with the initial level, which verifies the robustness of the conclusion of IRFs.

5.4. Sensitivity Analysis on Carbon Emission Reduction Subsidy Rate. As same as the carbon tax rate, we, respectively, raised and reduced the carbon emission reduction subsidy rate by 15% and analyzed the impulse response of five economic and four environmental variables under these two conditions. The results of sensitivity analysis on the carbon emission reduction subsidy rate shock are shown in Figure 6.

Comparing three different carbon emission reduction subsidy rate levels, we concluded that increasing or decreasing the level of carbon emission reduction subsidy rate level will reduce the original negative impact effect on X_t and enlarge the original positive impact effect on the other

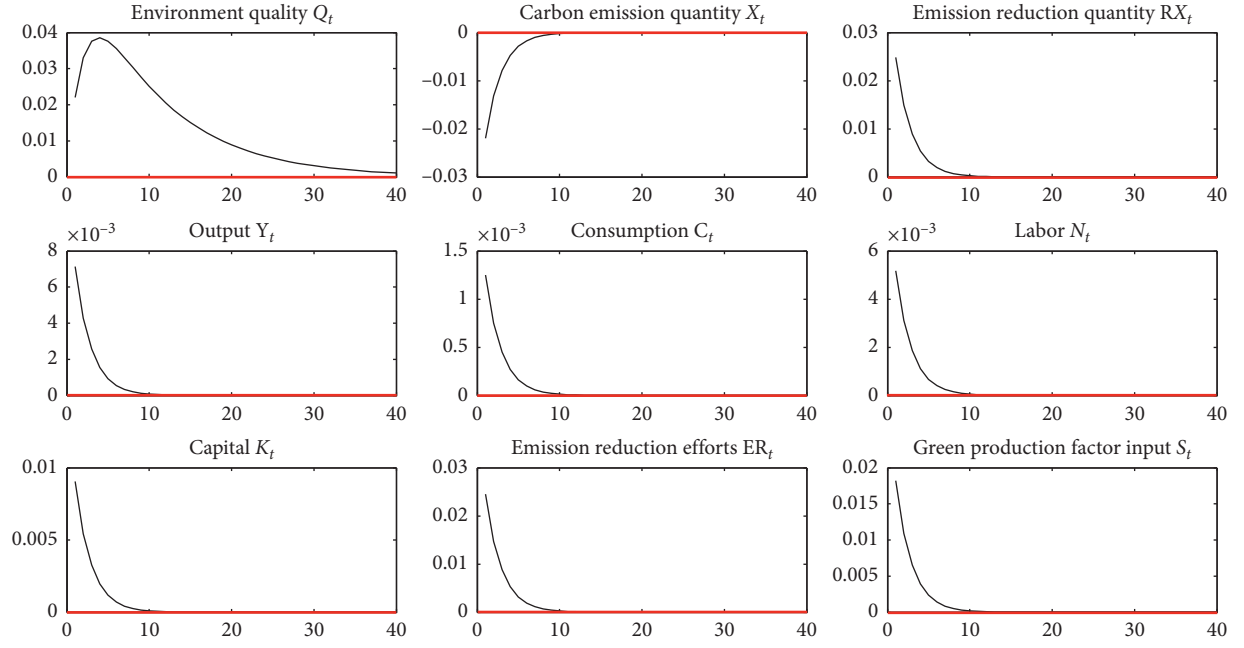


FIGURE 4: IRFs of carbon emission reduction subsidy rate.

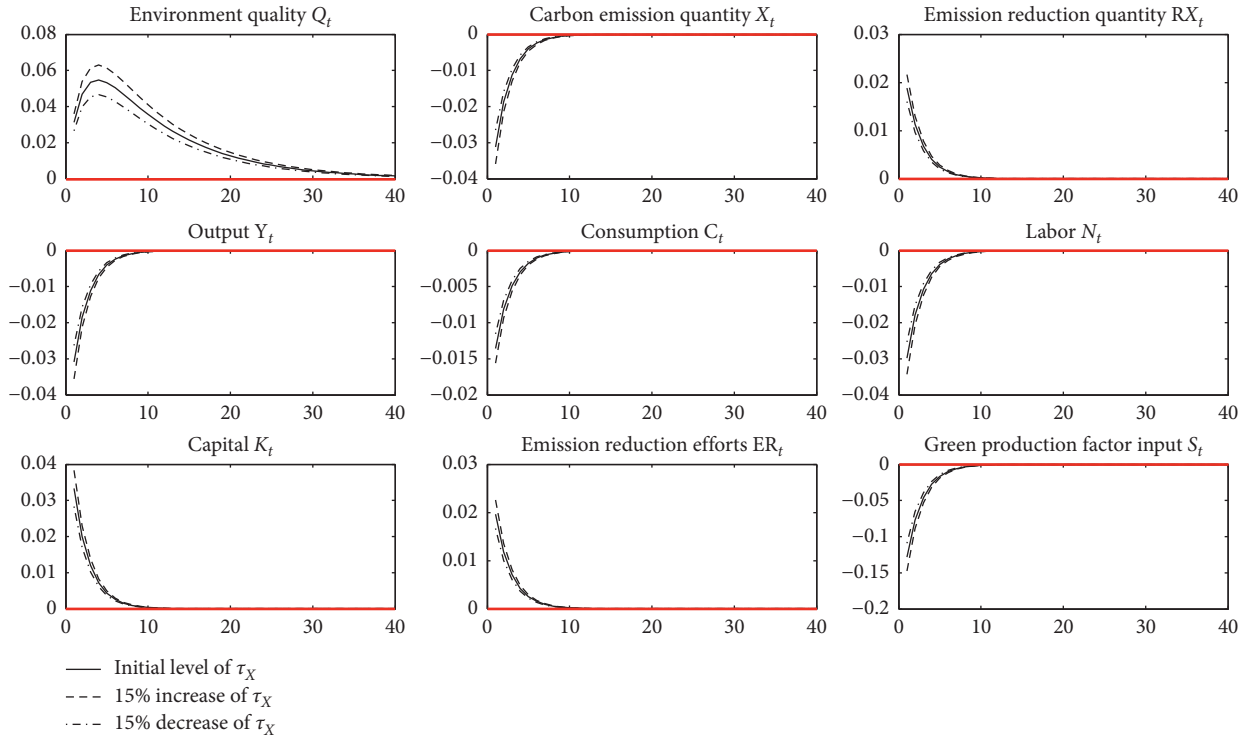


FIGURE 5: Sensitivity analysis on carbon tax rate.

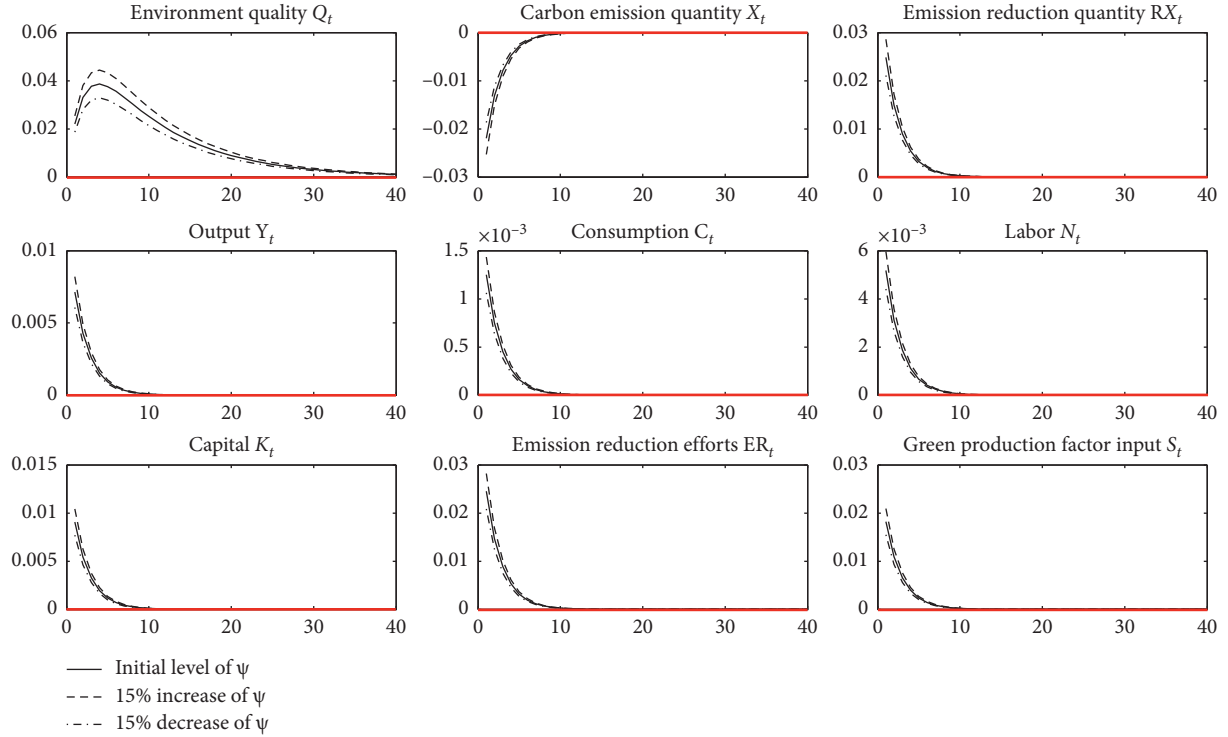


FIGURE 6: Sensitivity analysis on carbon emission reduction subsidy rate.

variables. The sensitivity analysis on the carbon emission reduction subsidy rate also verifies the robustness of the conclusion of IRFs.

6. Conclusion

This paper constructs an environmental DSGE framework to explore the impacts of carbon tax and carbon emission reduction subsidy policies on the environment and economy. Based on the results, we can draw the following conclusions:

- (1) Both punitive carbon tax and incentive carbon emission reduction subsidy policies can help to increase a firm's emission reduction efforts, reduce carbon emissions in the short term, and improve environment quality in the long term.
- (2) The difference between punitive carbon tax and incentive carbon emission reduction subsidy policies on the impact of economic variables lies in that the carbon tax will decrease the output, consumption, labor, and green production factor input, while carbon emission reduction subsidy will increase them.
- (3) Increasing or decreasing the carbon tax rate and carbon emission reduction subsidy rate only cause slight fluctuations in economic and environmental variables, but do not change the impact direction.

This study has reference significance to a certain degree for policy-makers to formulate environmental policies from the perspective of coordinated development of economy and

environment. However, our analysis is based on a new Keynesian framework, and future research might be more significant if extending the model to a more complex model with more sectors such as financial accelerators or open economy context.

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

Robust H_∞ Control for the Spacecraft with Flexible Appendages

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Aiming at the oscillation suppression of spacecraft with large flexible appendages, we propose a control strategy using H_∞ control. The weighting functions are designed for the specific flexible modes of the spacecraft and the frequency of harmonic interference in its operating environment. Taking into account the structural uncertainty of systematic modeling and the comprehensive performance requirements of system bandwidth constraint and attitude stability, the H_∞ comprehensive performance matrix is constructed. A space telescope with a large flexible solar array is presented as an illustrative example, and a control design that meets the requirement for pointing accuracy is proposed. The simulation results show that the designed controller satisfies the requirements of attitude stability and high pointing accuracy and has effectively suppressed the disturbance of endemic frequency. The design scheme and selection method of the weight function shown in this paper can be a reference for the controller design for oscillation suppression of this type of spacecraft with flexible structures.

1. Introduction

A spacecraft with flexible appendages, such as a spacecraft carrying large flexible solar panels, has a system structure with multiple resonance modes. The resonance mode of this type of flexible system changes its amplitude characteristics greatly, and the choice of bandwidth is greatly restricted by the inherent low-frequency interference caused by the complex launch environment and the high-altitude environment during on-orbit operation and the flexible mode of the system itself [1–3]. The difficulty of the control design of this kind of flexible system is not only to suppress the inherent resonance interference but also to meet the control accuracy requirements, as well as to take into account the requirements of attitude stability and bandwidth limitation of the system [4, 5].

With the development of aerospace engineering and the increasingly diversified missions of the spacecraft, the control accuracy of the spacecraft is becoming increasingly demanding. In addition, due to the development of new composite materials and their wide application in the aerospace field, the flexible proportion of large spacecraft is

continuously increasing, which makes the control of the system more complicated and difficult. The oscillation suppression of the spacecraft with large flexible appendages has always been an active research topic in the field of aerospace all time. In [6], a flexible spacecraft model with external disturbance and model uncertainty is established, and an observer is constructed to observe the attitude, angular velocity, and disturbance of the system. In addition, the stability control and disturbance suppression of the system are realized by dynamic compensation linearization. Literature [7] researched the classic control design for the Hubble Space Telescope with flexible appendages and gave a redesign scheme of the classic control. In the proposed scheme, a notch filter in series with a PID controller is used to achieve stability control and interference suppression, and an internal model controller is connected in series to suppress the unique resonance interference. The proposed controller can suppress the resonant mode of the particular frequency well, but it cannot take into account the stability and robustness of the system. The research shows that it is difficult to use classical control to balance the multiple performance requirements for the integrated control of

flexible spacecraft with multiple performance requirements [8]. However, H_∞ control theory is a synthetic control theory, which can include multiple performance requirements in the design [9–18], and it solves the control problems with multiple performance requirements and takes into account the multiple performance requirements of the system under the premise of ensuring the robustness of the system. In recent years, H_∞ control theory has been widely used in the control of the spacecraft. At present, modern control theories such as robust H_∞ control, robust adaptive control, and μ synthesis control are useful for the oscillation suppression of flexible spacecraft and have been discussed in detail in [19–23].

In this paper, a space telescope with a large flexible solar array is presented as an illustrative example to study the oscillation suppression problem of the large flexible spacecraft. Aiming at the system's specific interference frequency, the corresponding H_∞ weighting function is designed to achieve disturbance attenuation and the H_∞ controller that satisfies the robustness and attitude stability of the system is given. The simulation results show that the controller designed in this paper can suppress the resonance interference in the spacecraft natural frequency and satisfies the stability and bandwidth constraints. The design scheme and selection method of the weight function shown in this paper can be a reference for the controller design for oscillation suppression of this type of spacecraft with flexible structures. The structure of this paper shows that the system model and control problems are briefly described in Section 2, and the performance requirements of the H_∞ design and the selection scheme of the weighting function are shown in Section 3; Section 4 is a performance analysis, and Section 5 is the conclusion.

2. Analysis of System Model and Control Problems

A space telescope with large flexible appendages, illustrated in Figure 1, is composed of gyros that provide speed and attitude information, precision guidance sensors and trackers that supplement the attitude information, reaction wheels that provide control torque, and two large flexible solar panels carried on the other side.

In this paper, we consider only the pitch axis of the Hubble Space Telescope control design problem, and the other axes employ the same control structure. According to the relevant data [7], the Hubble Space Telescope actuator output u to the pitch-axis pointing error output angle θ can be modeled as the sum of a rigid body module and several flexible modules:

$$\frac{\theta(s)}{u(s)} = \frac{1}{Is^2} + \sum_{i=1} \frac{K_i/I}{s^2 + 2\zeta\omega_i s + \omega_i^2}, \quad (1)$$

where s is the Laplace transforming variable, $I = 77076 \text{ kg} \cdot \text{m}^2$ is the spacecraft pitch inertia, K_i is the i th flexible mode gain in the pitch axis, ω_i is the i th flexible mode frequency in rad/s, and ζ is the passive damping ratio assumed as 0.005.

The parameters of other flexible modules are shown in Table 1.

Figure 2 shows the system block diagram of the Hubble Space Telescope. The reaction wheel has an actuator saturation limit of 2.5 Nm. The time-prolonging link is introduced to characterize the time difference between the controller output and the actuator. Therefore, the delay link parameter $T = 0.008$ sec. The rate gyro can be represented by a second-order oscillation element, where $\omega_g = 18 \text{ Hz}$ and $\zeta_g = 0.7$.

The inherent low-frequency disturbances caused by the high-altitude environment of the Hubble Space Telescope on the orbit are modeled as

$$d(t) = 0.2 \sin(P_1 t + \phi_1) + 0.2 \sin(P_2 t + \phi_2), \quad (2)$$

where $P_1 = 2\pi(0.12) \text{ rad/s}$ and $P_2 = 2\pi(0.66) \text{ rad/s}$ are the frequencies of low-frequency disturbances and the phases ϕ_i are unknown parameters.

According to the Hubble Space Telescope pitch-axis model given by formula (1), the Bode magnitude plot of the loop transfer function of the system without the controller is shown in Figure 3. As can be seen in this figure, the system model of this flexible spacecraft contains multiple resonant modes, which make the frequency domain characteristics of the spacecraft vary greatly in amplitude. These flexible modes with weak damping cause great disturbance to the performance of the system, and the inherent low-frequency interference in the operating environment and the flexible modes of the system greatly limit the choice of bandwidth. For high-precision space photography missions, the system's output error is required to be no more than 0.007 arc-seconds. Therefore, the designed controller should be able to effectively solve the disturbance suppression of the solar panel and the inherent flexibility suppression of the system, and it should meet certain bandwidth requirements. In summary, the control design goals can be stated as follows:

- (1) Give the Hubble Space Telescope system high pointing accuracy
- (2) Maintain the system bandwidth more than 1.5 Hz
- (3) Provide at least 20 dB additional disturbance attenuation for the disturbance caused by the solar array
- (4) Provide at least 6 dB gain suppression for the flexible structure of the system

3. Robust H_∞ Control Design

3.1. System Performance Requirements. As can be seen in Figure 3, the system has a 0.16 Hz gain crossover frequency, which is extremely low. Therefore, the bandwidth of the system is very small, and the interference suppression performance is poor. One of the performance requirements of the system is that the crossover frequency needs to be increased. The bandwidth increased, and the oscillation of the flexible solar panel is suppressed.

In addition, it can be seen from Figure 3 that there are several dominant bending modes at 13 Hz to 14 Hz in the

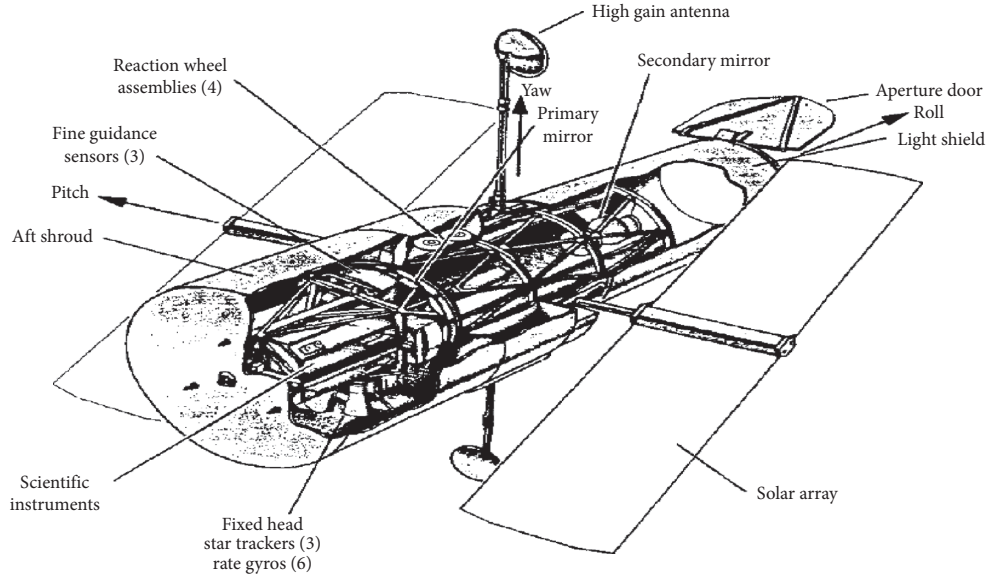


FIGURE 1: Diagram of Hubble Space Telescope structure.

TABLE 1: Hubble Space Telescope modal data [7].

| K_i (kg·m ²) | ω_i (Hz) |
|----------------------------|-----------------|
| 0.018 | 0.110 |
| 0.012 | 0.432 |
| 0.057 | 0.912 |
| 0.024 | 10.834 |
| 0.155 | 12.133 |
| -1.341 | 13.201 |
| -1.387 | 14.068 |
| -0.806 | 14.285 |
| -0.134 | 15.264 |

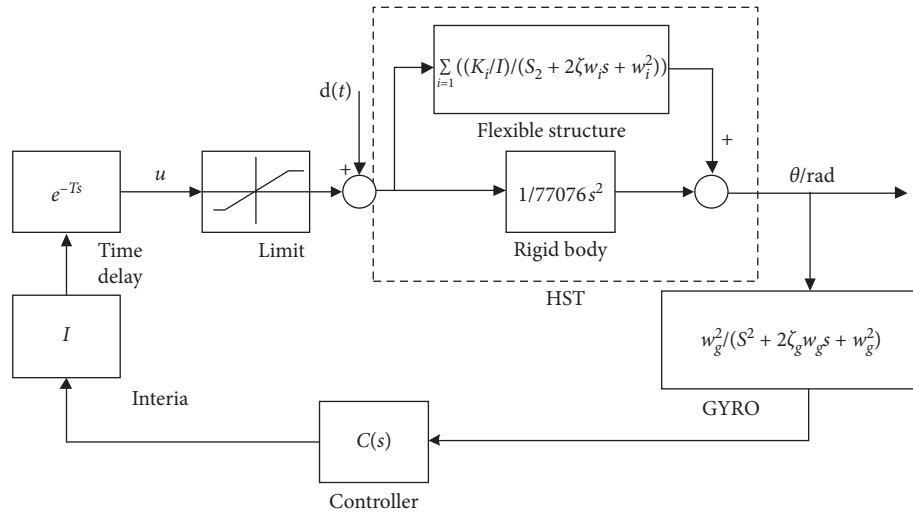


FIGURE 2: Block diagram of the Hubble Space Telescope control system.

system, which can be regarded as high-frequency unmodeled dynamics, namely, the uncertainty of the system. When the system has such uncertainty, the control structure block

diagram of the system is shown in Figure 4. In the study of the control problem, only the rigid body module of the Hubble Space Telescope is modeled, and the other flexible

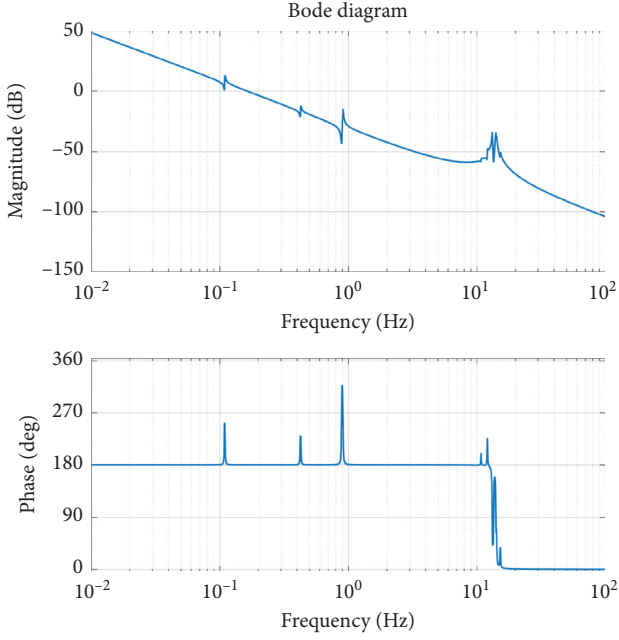


FIGURE 3: Bode magnitude plot of the loop transfer function of the Hubble Space Telescope without the controller.

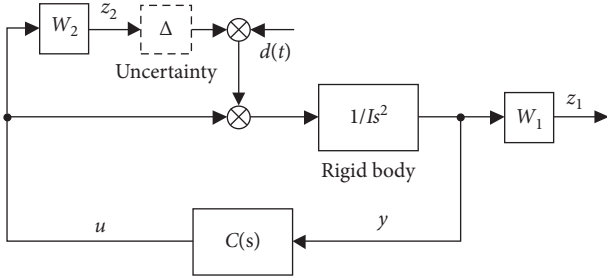


FIGURE 4: Block diagram of the system structure with uncertainty.

modules are regarded as the uncertainty of the system. The uncertainty of the system is expressed by multiplicative uncertainty:

$$G_{\text{actual}}(s) = G(s, \delta) [1 + \Delta G(s)], \quad (3)$$

where $G(s, \delta)$ is the mathematical model of the controlled object constructed based on the researched problem, $\Delta G(s)$ represents the structural uncertainty of the system, δ represents the nonstructural uncertainty of the system, and $G_{\text{actual}}(s)$ is the real mathematical model of the controlled object. Therefore, the second performance requirement of the system is robust stability.

In Figure 4, Δ represents the structured uncertainty and unstructured uncertainty of the system, W_1 , W_2 , and W_3 are the performance weighting function, uncertainty weighting function, and input weighting function of the system, respectively, y is the error output of the system, and z_1 and z_2 are the performance output of the system.

3.2. Selection of Weighting Function. According to the above analysis, the performance requirements of the control

system design are system bandwidth requirements and robust stability requirements. Next, we will select appropriate weighting functions based on the two performance requirements.

According to experience, the performance weighting function W_1 should generally include integral control laws. Aiming at the solar array oscillations at 0.12 Hz and 0.66 Hz, the system should be able to provide sufficient attenuation to the disturbance without affecting the stability of the medium-frequency domain of the system. A very small artificial damping (about 0.01) is needed for pure imaginary poles for the convenience of avoiding numerical problems in solving the H_∞ controller. After a certain amount of trial and error, we select the performance weighting function of attenuating disturbance, as shown in the following formula, and the Bode graph of this weighting function is shown in Figure 5:

$$W_1(s) = \frac{0.1225(s + 0.12 \times 2\pi)(s + 0.66 \times 2\pi)}{(s + 0.01)^2}. \quad (4)$$

It can be seen from the Bode diagram of the Hubble Space Telescope system without the controller, as shown in Figure 3, that the system performance is strongly affected by several dominant bending modes at 13 Hz to 14 Hz in the system. Therefore, the weighting function $W_2(s)$ should have good notch performance. Moreover, due to the rank requirements of the generalized plant in the H_∞ control theory, the numerator and denominator of $W_2(s)$ should have the same order. Finally, we select the following robust stability weighting function:

$$W_2(s) = \frac{0.532((s/30) + 1)^2}{(s^2/(2\pi \times 13.8)^2) + (((2 \times 0.004)/(2\pi \times 13.8)s) + 1)}. \quad (5)$$

It can be seen from Figure 6 that the weighting function W_2 has an amplitude gain of 55.9 dB at 13.8 Hz and 20 dB at high frequency. The weighting function can ensure that the system has a suppression effect on flexible modules at 13~14 Hz and attenuation effect on high-frequency noise signals. Therefore, the choice of the weighting function is reasonable.

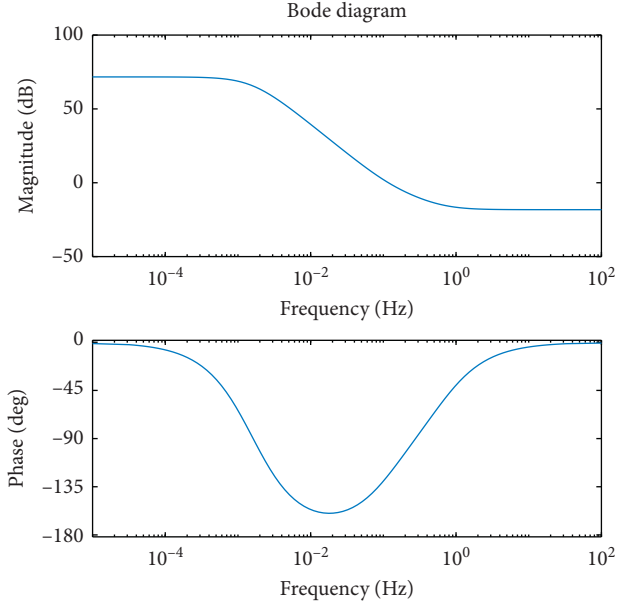
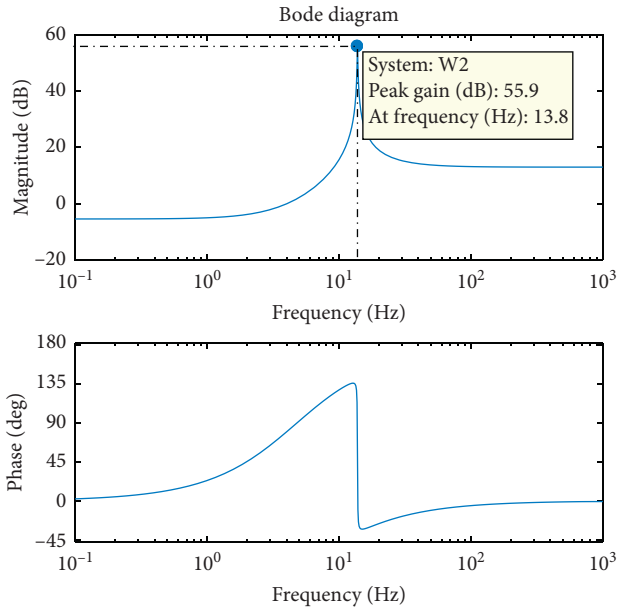
3.3. H_∞ Controller. After repeated iterative calculations, the H_∞ controller at $\gamma = 8.125$ is finally obtained, as shown in formula (8):

$$C_{h1}(s) = \frac{k(s + 0.6402)(s^2 + 0.002009s + 1.609 \times 10^{-6})}{(s + 0.01)^2(s^2 + 3357s + 3.763 \times 10^{-6})}, \quad (6)$$

$$C_{h2}(s) = \frac{s^2 + 0.0003605s + 0.002128}{s^2 + 0.00022s + 0.002118}, \quad (7)$$

$$C_h(s) = C_{h1}(s) \cdot C_{h2}(s), \quad (8)$$

where the parameter $k = 3.4927 \times 10^7$. The zeros and poles of the function C_{h2} are so close to each other that they can be

FIGURE 5: Bode diagram of the weighting function W_1 .FIGURE 6: Bode diagram of the weighting function W_2 .

considered as two pairs of dipoles. Thus, the simplified H_∞ controller can be obtained by pole-zero cancellations and removing the tiny perturbation introduced in the denominator:

$$\tilde{C}_h = \frac{k(s + 0.6402)(s^2 + 0.002009s + 1.609 \times 10^{-6})}{s^2(s^2 + 3357s + 3.763 \times 10^{-6})}. \quad (9)$$

The designed controller needs to be verified at this point by the corresponding H_∞ norm indicator $\gamma = 8.125$. The singularity curve of the closed-loop transfer function T_{dz} from the perturbation input d to the performance output z is shown in Figure 7. It can be seen from the figure, the

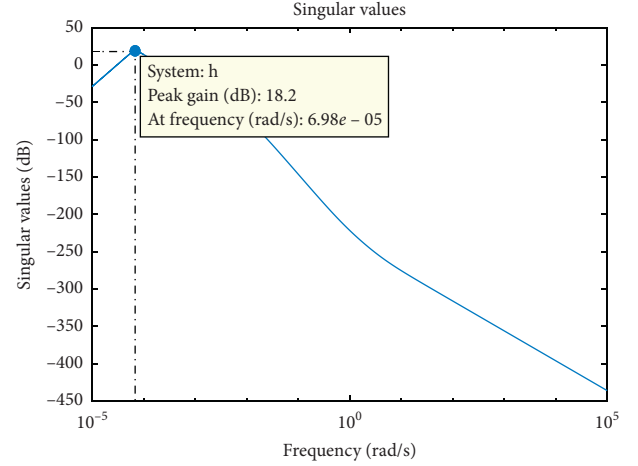
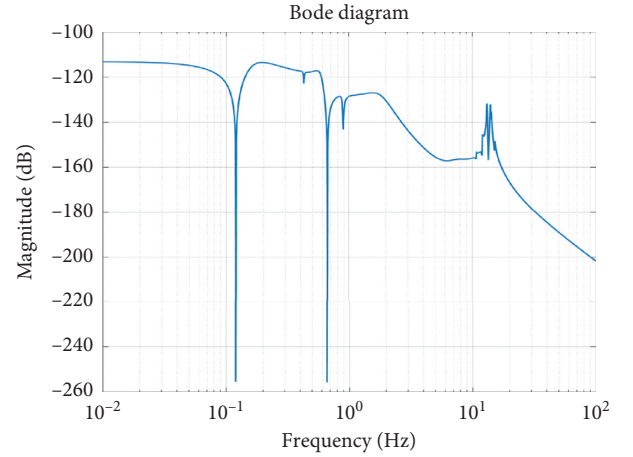


FIGURE 7: The singular performance of the system.

FIGURE 8: Closed-loop frequency magnitude response of the system with the H_∞ controller.

maximum singularity is about 18.2 dB = 8.17, which is consistent with the obtained norm indicator γ .

Furthermore, we analyze the performance of the designed controller being applied to the pitch-axis control system. From the closed-loop Bode diagram of the system shown in Figure 8, we can see that the system performs a dramatic gain attenuation for specific frequency interference.

As can be seen in the Bode magnitude plot of the open-loop transfer function (Figure 9), the system with the controller given by equation (9) has a 1.6 Hz gain crossover frequency, which meets the bandwidth requirement of not less than 1.5 Hz. Moreover, aiming at the oscillation suppression of the high-frequency bending modes, the controller provides a gain suppression of over 100 dB. The designed H_∞ controller not only suppresses the inherent resonance interference but also meets certain bandwidth requirements.

4. Performance Analysis

The time responses of the system controlled by the designed H_∞ controller are shown in Figure 10. It can be seen that an

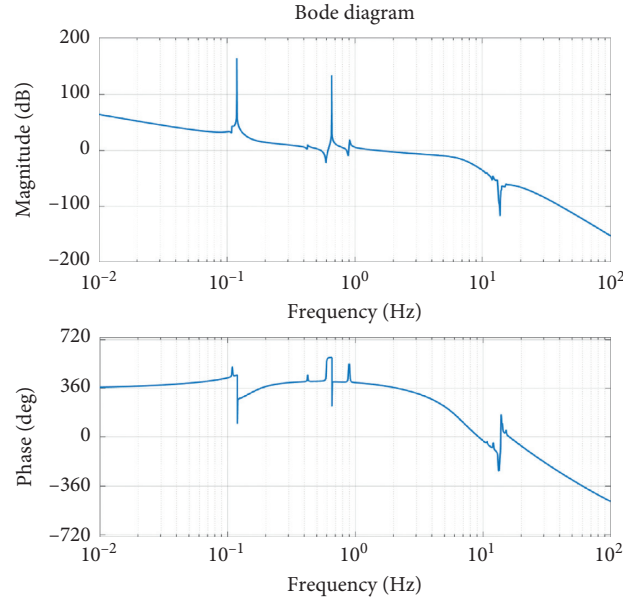


FIGURE 9: Open-loop frequency magnitude response of the system H_{∞} controller.

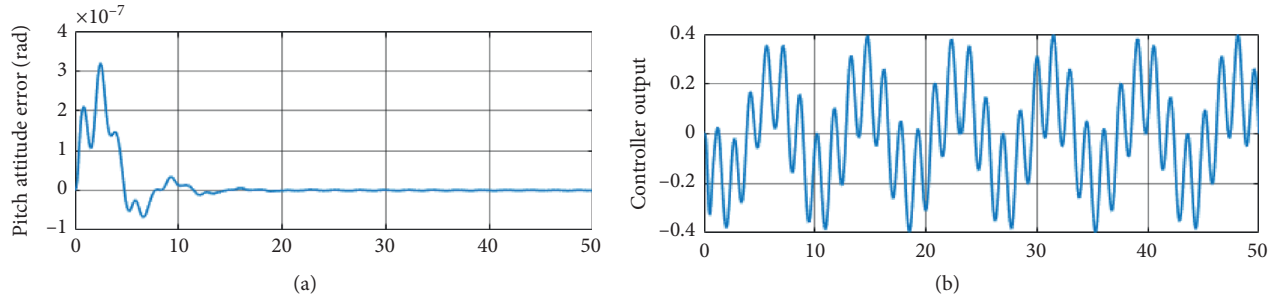


FIGURE 10: Time response of the system with the H_{∞} controller.

effective rejection of the solar array disturbances at 0.12 Hz and 0.66 Hz has been achieved, which meets the requirements of oscillation suppression and high pointing accuracy of the system, without exceeding the actuator limit of 2.5 Nm. It can be seen from Figure 8 that the controller achieves the control goal of gain attenuation for the disturbance of the solar panel.

In this paper, the performance of the designed H_{∞} controller is compared to a classical PID controller, and their system time response is shown in Figure 11. From the figure, we can see that the PID controller is able to stabilize the rigid module of the system well and suppresses perturbations at specific frequencies because of the introduction of the internal mode filter and notch filter. However, the designed H_{∞} controller has better interference suppression than the PID controller, resulting in better dynamic and steady performance of the system. Furthermore, the H_{∞} controller eliminates the need for an additional filter design.

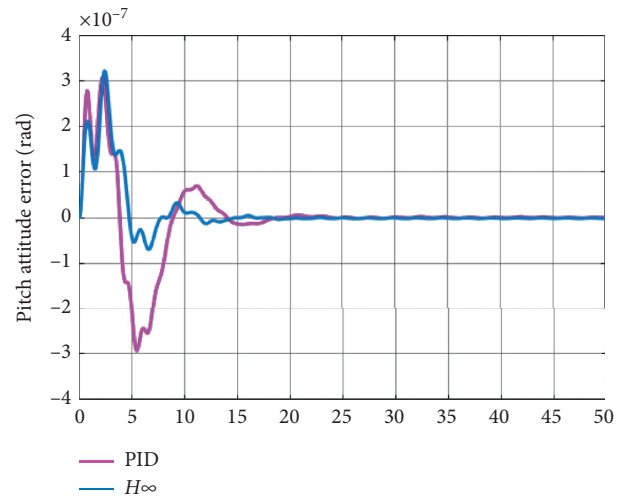


FIGURE 11: Time responses of the system with different controllers.

5. Conclusion

Aiming at the comprehensive problems of the spacecraft with flexible appendages, such as flexible structure vibration, deficient bandwidth, low pointing accuracy, and uncertainty caused by structural changes, the H_∞ control method is adopted in this paper. Appropriate weighting functions are selected by analyzing the performance requirements to suppress the oscillation of the flexible structure and increase the bandwidth of the system. Finally, a H_∞ controller with robust stability is given. The simulation results show that the designed controller can effectively suppress the vibration of solar panels. While maintaining the bandwidth of the system, it also dampens the vibrations of the high-frequency resonant modules, enabling the system to satisfy high pointing accuracy requirements.

Data Availability

The data used to support the findings of this study are included within the article and other data or programs used can obtain 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

Heterogeneity of Green TFP in China's Logistics Industry under Environmental Constraints

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In the context of China's supply-side structural reform and the concept of green development, we introduce the energy and environmental factors into the analytical framework of the total factor productivity (TFP) of the logistics industry and use the Global Malmquist–Luenberger index method to analyze the evolution trend and heterogeneity of green TFP in the logistics industry of 30 provinces (cities and districts) in China from 2003 to 2017. The results show that, firstly, the green TFP and traditional TFP of China's logistics industry are both on the rise and the absence of energy and environmental factors will lead to the overestimation of TFP of the logistics industry. Whether it is green TFP or traditional TFP, the main source of its growth is technical progress. Secondly, there is obvious regional heterogeneity in green TFP of logistics industry. Under the three regional division standards, the average annual growth rate of green TFP is from high to low in the order of eastern, western, and central regions. Under the eight regional classification standards, the eastern coastal economic zone, the southern coastal zone, the northern coastal zone, the northeast region, the middle reaches of the Yellow River, the southwest region, the middle reaches of the Yangtze River, and the northwest region are in order from high to low. Thirdly, there is obvious interprovincial heterogeneity in green TFP of the logistics industry. The highest growth rate of green TFP is in Zhejiang, followed by Jiangsu and Guangdong, and the slowest growth rate is in Chongqing. The technical progress of logistics industry in most provinces contributes more to the growth of green TFP. Fourthly, the differences of green TFP in the three regions of the east, center, and west are shrinking, which may be σ convergence, but the differences among the three regions are expanding. Compared with the existing literature, this paper applies the measurement framework of green TFP to China's logistics industry and investigates the regional and provincial heterogeneity of green TFP in logistics industry. The conclusions are significant to understand and grasp the heterogeneity of green TFP growth in China's logistics industry under environmental constraints and how to promote the development of green logistics in China.

1. Introduction

Since the beginning of the new century, China's logistics industry has been developing rapidly. The added value of the industry has gradually increased from 616.19 billion yuan in 2000 to 4280.21 billion yuan in 2019, with an average annual growth rate of 10.7% (data source: National Bureau of Statistics). The logistics industry in this paper refers to the transportation, storage, and postal industry in the "National Economic Industry Classification." However, the rapid development of the logistics industry has also brought great

negative externalities to the society, and the problems of energy consumption and pollutant emission caused by its economic activities have become increasingly prominent. National statistics show that, in 2017, the terminal energy consumption of the logistics industry reached as high as 421.191 million tons of standard coal, accounting for 9.41% of the total national energy consumption and far exceeding the 4.46% of its added value in GDP. It can be seen that the problem of energy consumption caused by the production activities of China's logistics industry is becoming increasingly serious, and the CO₂ emission caused by it cannot

be ignored. In the context of low-carbon economy and green development in the new era, reducing energy consumption and pollutant emission is not only a part of the theme of ecological civilization construction, but also a mandatory requirement of sustainable economic development [1–3]. In fact, China faces enormous pressure on carbon emission reduction. Therefore, China has set the ambitious goal of reducing CO₂ emissions per unit of GDP by 17% in the 12th Five-Year Plan. In order to reduce carbon emissions and achieve the stable economic growth, it is necessary to transform into a “resource-saving and environment-friendly” society. The transformation of economic growth mode from extensive form to intensive form is imminent. In this context, low-carbon economy is increasingly becoming a hotspot in the world. The development of low-carbon economy is in line with China’s basic national policy of implementing sustainable development strategy and building a harmonious society. Low-carbon economy has gradually become a “new normal” of China’s economic growth. Similar to the situation faced by the industrial industry, the service sector such as the logistics industry should adhere to the concept of green development while stimulating economic growth, to minimize the negative impact of industrial development on resources and environment [4, 5]. How to realize the green growth of logistics industry is a difficult problem for China, and the effective way to solve this problem is to improve the green total factor productivity (green TFP) of logistics industry [6, 7]. Green TFP is an effective indicator to measure the quality of economic growth. Compared with the traditional total factor productivity (TFP) mentioned later, green TFP can scientifically reflect the energy consumption and undesired output of economic activities, which is a better explanation for economic growth performance. Therefore, we introduce the energy and environmental factors into the measurement framework of total factor productivity of logistics industry, measure the green TFP of this industry, and compare and analyze it with the traditional TFP. On this basis, empirical analysis of the regional heterogeneity and interprovincial heterogeneity of the TFP change, in addition to the evolution trend characteristics of regional differences. This study is not only conducive to evaluate the green growth performance of the logistics industry, but also conducive to analyze the regional differences and evolution of the growth of green TFP of the logistics industry. This paper is of great practical significance for China to formulate reasonable development policies and promote the green growth of the logistics industry.

The logistics industry is an important sector of the service industry. However, the current academic research on the total factor productivity of the logistics industry is relatively limited and mainly focuses on its traditional productivity. Jing et al. [8] estimated the traditional TFP of the logistics industry based on C-D production function and found that the TFP index of the logistics industry in different regions is significantly different, which is mainly attributed to the regional differences of input factors such as capital and technology. Chen [9] used the Malmquist index to evaluate the traditional TFP of

China’s logistics industry, and the results showed that the traditional TFP of the logistics industry decreased by 2.4% annually from 2005 to 2009, and the deterioration of pure technical efficiency was the source of the decline of TFP. At the same time, the traditional TFP growth rate of logistics industry presented the situation of east, middle, and west decreasing in turn. In recent years, some scholars have begun to pay attention to the energy and environmental problems of the logistics industry. For example, Jiang et al. [10] measured the total factor of energy efficiency of the logistics industry by using the super-efficiency nonexpected SBM model. Unfortunately, the current research on green TFP of China’s logistics industry is still insufficient. In addition, scholars began to analyze the evolution trend or convergence of TFP in the service sector. For example, Yuan et al. [11] found that the subsectors of producer services show a trend of σ convergence, while absolute β and conditional β convergence exist within sectors. Xiao [12] also analyzed the convergence of traditional and green TFP in the service industry and found that the two types of TFP subsectors of China’s service industry had only conditional β convergence but not absolute β convergence characteristics. During this period, scholars also made a preliminary discussion on the TFP convergence of the logistics industry, an important service sector. Studies such as Jing et al. [8] show that there is no σ convergence in the traditional TFP of China’s logistics industry.

The previous literature has provided the possibility for this study, but there are still some deficiencies in the following aspects. Firstly, the existing studies are almost all to investigate the changes of traditional TFP in China’s logistics industry, and the green TFP measurement research in the logistics industry under the constraints of energy and environment is lacking now, while the logistics industry has generated very serious environmental problems. Therefore, the traditional TFP cannot truly reflect the actual situation of TFP in the current logistics industry. Secondly, there are few literatures about the productivity convergence of logistics, but the TFP of China’s logistics varies greatly, so it is necessary to study the evolution trend of its productivity, especially the green TFP. Thirdly, the existing studies have divided China into three regions, east, middle, and west, which cannot fully reflect the differences in the TFP growth of the logistics industry in the subdivided economic zones (such as the eight economic zones). In view of the above problems, the marginal contribution of this study includes the following. Firstly, we use the Global Malmquist–Luenberger index to estimate the green TFP in the logistics industry of 30 provinces (cities and districts) in China from 2003 to 2017 and compare it with the traditional TFP without considering the energy and environment constraints. Secondly, we study the regional and interprovincial heterogeneity of green TFP in logistics industry on the basis of overall analysis. Thirdly, when we analyze the evolution trend of green TFP in logistics industry on the basis of national level, we not only start from the traditional three regions of east, middle, and West, but also further analyze based on the eight economic regions.

2. Measurement Methods, Variables, and Data

2.1. Measurement Methods

2.1.1. Current and Global Production Possibilities Set. First, we need to build a set of production possibilities, called environmental technologies. This production probabilities set includes both “good” outputs such as GDP and “bad” outputs such as CO₂ emissions [13–15]. Suppose that, in different periods t ($t = 1, \dots, T$), the logistics industry in any province k ($k = 1, \dots, K$) uses N kinds of inputs $x = (x_1, \dots, x_N) \in R_N^+$ to produce M kinds of “good” outputs $y = (y_1, \dots, y_M) \in R_M^+$ and I kinds of “bad” outputs $b = (b_1, \dots, b_I) \in R_I^+$. For each input vector x , environmental technologies can produce a combination of expected and unexpected outputs simultaneously (y, b) . Based on the hypothesis of Wang et al. [16], we use the data envelopment analysis (DEA) method to convert the current environmental technology into

$$P^t(x^t) = \left\{ \begin{array}{l} (y^t, b^t): \sum_{k=1}^K z_k^t y_{km}^t \geq y_{km}^t, \quad m = 1, \dots, M, \\ \sum_{k=1}^K z_k^t b_{ki}^t = b_{ki}^t, \quad i = 1, \dots, I, \\ \sum_{k=1}^K z_k^t x_{kn}^t \leq x_{kn}^t, \quad n = 1, \dots, N, \\ z_k^t \geq 0, \quad k = 1, \dots, K. \end{array} \right\}. \quad (1)$$

In (1), z_k^t is the weight measurement index of the observed values of each cross section and $z_k^t \geq 0$ means the constant returns to scale. When measuring GML index, the current production possibility set $P^t(x^t)$ should be replaced by the global production possibility set $P^G(x)$, which can be expressed as formula (2) with DEA method:

$$P^t(x^t) = \left\{ \begin{array}{l} (y^t, b^t): \sum_{t=1}^T \sum_{k=1}^K z_k^t y_{km}^t \geq y_{km}^t, \quad m = 1, \dots, M, \\ \sum_{t=1}^T \sum_{k=1}^K z_k^t b_{ki}^t = b_{ki}^t, \quad i = 1, \dots, I, \\ \sum_{t=1}^T \sum_{k=1}^K z_k^t x_{kn}^t \leq x_{kn}^t, \quad n = 1, \dots, N, \\ z_k^t \geq 0, \quad k = 1, \dots, K. \end{array} \right\}. \quad (2)$$

2.1.2. SBM Directional Distance Function. According to Fukuyama and Weber [17], the global SBM directional distance function incorporated into CO₂ emissions in the logistics industry is expressed as

$$\begin{aligned} S_V^G(x^{t,k'}, y^{t,k'}, b^{t,k'}, g^x, g^y, g^b) &= \max_{s^x, s^y, s^b} \frac{1/N \sum_{n=1}^N (s_n^x / g_n^x) + (1/(M+I)) (\sum_{m=1}^M (s_m^y / g_m^y) + \sum_{i=1}^I (s_i^b / g_i^b))}{2}, \\ \text{s. t. } \sum_{t=1}^T \sum_{k=1}^K z_k^t x_{kn}^t + s_n^x &= x_{k'n}^t, \quad \forall n, \\ \sum_{t=1}^T \sum_{k=1}^K z_k^t y_{km}^t - s_m^y &= y_{k'm}^t, \quad \forall m, \\ \sum_{t=1}^T \sum_{k=1}^K z_k^t b_{ki}^t + s_i^b &= x_{k'i}^t, \quad \forall i, \\ \sum_{k=1}^K z_k^t &= 1, z_k^t \geq 0, \quad \forall k; \\ s_n^x &\geq 0, \quad \forall n, \\ s_m^y &\geq 0, \quad \forall m, \\ s_i^b &\geq 0, \quad \forall i. \end{aligned} \quad (3)$$

In (3), $(x^{t,k^t}, y^{t,k^t}, b^{t,k^t})$ is the input and output vector of logistics industry in province k . (g^x, g^y, g^b) is a direction vector, which represents the decrease of input, the increase of “good” output, and the decrease of “bad” output. (s_n^x, s_m^y, s_i^b) is a relaxation vector reflecting the input and output. If the relaxation vectors of both inputs and outputs are positive numbers greater than 0, it means that the actual input and carbon emission of logistics industry in each province are larger than the input-output value of the boundary, while the actual output value is smaller than the boundary output value. To sum up, s_n^x, s_m^y, s_i^b represents the situation of excessive input, relatively insufficient “good” output, and excessive pollution emissions in the logistics industry of each province [16].

2.1.3. Global Malmquist–Luenberger Productivity Index. After the construction of the SBM directional distance function, we need to construct output-oriented GML index to measure green TFP. According to Oh [18], the GML index can be expressed as

$$GML_t^{t+1} = \frac{1 + S_C^G(x^t, y^t, b^t; g)}{1 + S_C^G(x^{t+1}, y^{t+1}, b^{t+1}; g)}. \quad (4)$$

Furthermore, the GML index can be divided into two parts: the efficiency change index (GEC) and the technology change index (GTC):

$$GML_t^{t+1} = \frac{1 + S_C^t(x^t, y^t, b^t; g)}{1 + S_C^{t+1}(x^{t+1}, y^{t+1}, b^{t+1}; g)} \times \left[\frac{(1 + S_C^G(x^t, y^t, b^t; g)) / (1 + S_C^t(x^t, y^t, b^t; g))}{(1 + S_C^G(x^{t+1}, y^{t+1}, b^{t+1}; g)) / (1 + S_C^{t+1}(x^{t+1}, y^{t+1}, b^{t+1}; g))} \right]. \quad (5)$$

When the GML_t^{t+1} (GEC or GTC) index is greater than 1, the green TFP (technical efficiency or technical progress) of the logistics industry shows an increasing trend. When the index is equal to (or less than) 1, the green TFP (technical efficiency or technical progress) remains unchanged (or decreases).

2.1.4. Global Malmquist Productivity Index. In order to more intuitively reflect the constraints of environmental factors such as energy and pollution emissions on China’s logistics industry, we also estimate the traditional TFP of this industry and apply the DEA-Malmquist productivity index method (Global Malmquist index method) based on the Global technology and compare it with the GML index. The Global Malmquist index can be expressed as

$$GM(y^{t+1}, x^{t+1}, y^t, x^t) = \frac{D^{t+1}(x^{t+1}, y^{t+1})}{D^t(x^t, y^t)} \left[\left(\frac{D^g(x^{t+1}, y^{t+1})}{D^{t+1}(x^{t+1}, y^{t+1})} \times \frac{D^t(x^t, y^t)}{D^g(x^t, y^t)} \right) \right] = EC \times TC. \quad (6)$$

For the related materials of the decomposition methods, refer to Ang [19], Ang and Liu [20], Zhang et al. [21], Zhang et al. [22], Wang et al. [23], and Zhang et al. [24].

2.2. Variable Selection and Data Sources. We collected the input-output data of the logistics industry from 2003 to 2017 in 30 provinces, autonomous regions, and municipalities in China (Tibet is not included as a sample due to a large amount of missing data). We took capital, labor, and energy as input indicators and the added value and CO₂ emissions as “good” output and “bad” output, respectively. The data are collected from the website of the National Bureau of Statistics, China Statistical Yearbook, and China Energy Statistical Yearbook.

2.2.1. Logistics Output: “Good Output”. Learning from Chen [9], we regard the added value of the logistics industry as a “good” output and use the added value index of the tertiary industry of each province to convert it into real value (2003 as the base period).

2.2.2. Logistics Output: “Bad Output”. At present, there is no uniform definition of “bad” output in the academic circles, and the “bad” output adopted in measuring green TFP is also different. We measure a total factor green productivity index considering CO₂ emissions, so we take CO₂ emissions as “bad” output. CO₂ emissions of logistics industry can be calculated by the following formula:

$$CO_2 = \sum_{i=1}^8 CO_{2,i} = \sum_{i=1}^8 E_i \times NCV_i \times CEF_i \times COF_i \times \frac{44}{12}. \quad (7)$$

Among them, i is the type of final energy consumption (fossil fuels); E_i represents the consumption of type i fossil fuels. NCV_i represents the low calorific value of type i fossil fuels. CEF_i is the carbon content of type i fossil fuels. COF_i is the oxidation rate of type i fossil fuels. Accordingly, the carbon emission coefficient calculation formula of various fossil fuels can be obtained: carbon emission coefficient = low calorific value \times carbon content \times oxidation rate. The carbon emission coefficients for each type of fossil fuels are shown in Table 1.

TABLE 1: The carbon emission coefficients for each type of fossil fuels.

| Fossil fuel type | Low calorific value | Carbon content | Oxidation rate | Carbon emission coefficient |
|------------------|---------------------|----------------|----------------|-----------------------------|
| The raw coal | 20908 | 26.4 | 0.94 | 0.5183 |
| Coke | 28435 | 29.5 | 0.93 | 0.7801 |
| Crude oil | 41816 | 20.1 | 0.98 | 0.8237 |
| Gasoline | 43070 | 18.9 | 0.98 | 0.7978 |
| Diesel | 42652 | 20.2 | 0.98 | 0.8443 |
| Fuel oil | 41816 | 21.1 | 0.98 | 0.8647 |
| Natural gas | 38931 | 15.3 | 0.99 | 0.5897 |
| Kerosene | 43070 | 19.5 | 0.98 | 0.8231 |

Compiled according to China Energy Statistics Yearbook.

2.2.3. Capital Investment. We use the capital stock of logistics industry in each province to express the capital investment and use the perpetual inventory method to estimate it:

$$K_{it} = K_{i,t-1}(1 - \delta_{i,t}) + \frac{I_{it}}{P_{it}}. \quad (8)$$

In (8), K_{it} and $K_{i,t-1}$, $I_{i,t}$, respectively, represent the capital stock of t year and $t-1$ year and the nominal fixed capital investment of t year of the logistics industry in province i . $\delta_{i,t}$ is the capital depreciation rate, and P_{it} is the price indices of fixed assets investment. The base year capital stock adopts the steady-state method proposed by Harberger [25]. Based on the assumption that “the ratio of capital output in steady state is constant or the growth rate of physical capital is equal to the growth rate of total output,” the estimation formula of the physical capital stock in the base year (2003) is deduced:

$$K_{i,t-1} = \frac{I_{i,t}}{(g_{i,t} + \delta_{i,t})}. \quad (9)$$

This method has a clear and reasonable economic basis, so it has been applied widely, such as Lee and Hong [26], Barro and Lee [27], and Wu [28]. Meanwhile, according to Harberger’s suggestion [25], $g_{i,t}$ is expressed in terms of the average annual growth rate of the real added value of the logistics industry in the sample period to control the impact of the economic cycle fluctuations and short-term output fluctuations. Nominal fixed capital investment $I_{i,t}$ represented fixed assets investment of the whole society. Subject to limited data, P_{it} is represented by the industry-wide fixed asset investment price index. In accordance with the existing studies, the depreciation rate $\delta_{i,t}$ was set at 6%, but the 4% and 9.6% depreciation rates were also adopted for robustness tests.

2.2.4. Labor Input. Theoretically, labor input should comprehensively consider factors such as labor size, labor time, and labor quality (efficiency), but the selection of indicators in actual research will ultimately depend on the availability of data. In fact, some scholars have considered the quality of labor input in their studies. For example, Fox and Smeets proposed four methods to measure the labor quality when using Danish enterprise level data to examine whether the input quality affects the enterprise productivity dispersion

[29]. Zheng et al. adjusted the quality of labor by using the number of years of education per worker while examining China’s growth model [30]. In order to consider the impact of the labor input quality on results, we also try to adjust the quality of the number of employees of the logistics industry in each region. Unfortunately, the relevant data on the quality adjustment of labor input cannot be accessed through the existing statistical data, no matter which method is adopted. Therefore, the “number of employees at the end of the year” of logistics industry is selected as the proxy variable of labor input index.

2.2.5. The Energy Input. As energy resource is an intermediate input, the traditional TFP of logistics industry has not been regarded as an input variable in the existing research. However, energy consumption is in fact the key factor to undesirable outputs such as CO₂ emissions [16]. Based on this, we also introduced energy into the green TFP measurement system and adopted the terminal energy consumption of the logistics industry in each province as the measurement index of this variable. The basic data were taken from the China Energy Statistics Yearbook.

Table 2 reports the descriptive statistical results for each variable.

3. Temporal Characteristics and Heterogeneity Analysis of Green TFP in Logistics Industry

3.1. Overall Temporal Characteristics. Table 3 reports the TFP index and its decomposition results of China’s logistics industry. Without the introduction of energy and environmental factors, the average annual growth rate of TFP (TFPC) in China’s logistics industry from 2003 to 2017 was 2.22%, in which the average annual improvement rate of technical progress (TPC) was 2.85%, while the average annual decrease rate of technical efficiency (TEC) was 0.61%. After the introduction of energy and environment factors, the average annual growth rate of green TFP in the logistics industry dropped to 1.93%, in which the average annual growth rate of technical progress declined to 2.1%, and the average annual growth rate of technical efficiency was still negative, dropping by 0.16%. Comparing the two sets of data, we can find that the growth rate of TFP in logistics industry and the growth rate of technical progress under the constraints of energy and environment are 0.29 and 0.75 percentage points lower than those without energy and

TABLE 2: Descriptive statistical results of input-output variables.

| Variable types | The variable name | Unit | Sample size | Mean | Median | Standard deviation | Minimum | Maximum |
|----------------|---------------------------|--------------------------|-------------|---------|---------|--------------------|---------|----------|
| "Good" output | Real added value | One hundred million yuan | 450 | 880.08 | 665.89 | 773.76 | 38.91 | 5141.41 |
| "Bad" output | CO ₂ emissions | Ten thousand tons of | 450 | 1679.39 | 1377.87 | 1268.89 | 90.03 | 7958.30 |
| Input | The number of labor | Ten thousand people | 450 | 23.52 | 21.44 | 14.22 | 2.81 | 85.40 |
| | The capital stock | One hundred million yuan | 450 | 3614.44 | 2813.75 | 2911.78 | 229.66 | 16844.09 |
| | Energy consumption | Ten thousand tons of | 450 | 942.29 | 765.91 | 645.80 | 51.05 | 3495.89 |

TABLE 3: TFP index of logistics industry and its decomposition (2003–2017).

| Year | Energy and environmental factors are not introduced | | | Introduce energy and environmental factors | | |
|------|---|--------|--------|--|--------|--------|
| | TEC | TPC | TFPC | TEC | TPC | TFPC |
| 2004 | 1.0076 | 1.0290 | 1.0368 | 0.9839 | 1.0057 | 0.9896 |
| 2005 | 1.0105 | 1.0350 | 1.0459 | 1.0193 | 1.0179 | 1.0376 |
| 2006 | 0.9930 | 1.0418 | 1.0344 | 1.0035 | 1.0266 | 1.0301 |
| 2007 | 0.9963 | 1.0431 | 1.0392 | 1.0079 | 1.0297 | 1.0379 |
| 2008 | 1.0178 | 1.0081 | 1.0261 | 0.9879 | 1.0270 | 1.0146 |
| 2009 | 0.9813 | 1.0233 | 1.0042 | 0.9824 | 1.0572 | 1.0386 |
| 2010 | 0.9793 | 1.0362 | 1.0148 | 0.9900 | 1.0106 | 1.0004 |
| 2011 | 0.9897 | 1.0439 | 1.0332 | 0.9935 | 1.0138 | 1.0072 |
| 2012 | 0.9925 | 1.0403 | 1.0325 | 1.0016 | 1.0051 | 1.0067 |
| 2013 | 0.9347 | 1.0000 | 0.9347 | 0.9941 | 1.0008 | 0.9949 |
| 2014 | 1.0017 | 1.0000 | 1.0017 | 1.0196 | 1.0070 | 1.0267 |
| 2015 | 1.0212 | 1.0000 | 1.0212 | 0.9979 | 1.0274 | 1.0252 |
| 2016 | 1.0314 | 1.0116 | 1.0434 | 1.0023 | 1.0386 | 1.0410 |
| 2017 | 0.9624 | 1.0897 | 1.0487 | 0.9944 | 1.0277 | 1.0220 |
| Mean | 0.9939 | 1.0285 | 1.0222 | 0.9984 | 1.0210 | 1.0193 |

environment factors, respectively, while the growth rate of technical efficiency increased by 0.45 percentage points after the introduction of energy and environmental factors. However, the increase rate of technical efficiency cannot offset the negative impact of the decline rate of technical progress on TFP growth rate, and finally the Green TFP growth rate declined. It can be seen that China's logistics industry TFP estimation is influenced by energy and environment factors, and neglecting energy and environment factors will lead to an overestimation of TFP growth rate and technical progress growth rate.

From 2003 to 2017, green TFP and traditional TFP in China's logistics industry have positive growth trend in most years. Further analysis shows that the green TFP of the logistics industry increased negatively in 2004 and remained positive after 2005 (except for a slight decrease of 0.51% in 2013), which may be caused by the stricter policy of energy saving and consumption reduction during the 11th Five-Year Plan period and the 12th Five-Year Plan period. Both the 11th Five-Year Plan and the 12th Five-Year Plan emphasize the need to vigorously promote energy conservation and reduce consumption and reduce pollutant emissions. According to the outline of the 11th Five-Year Plan, China's total emission of

major pollutants will be cut by 10% on the 2005 level. In 2008, both TFP indexes showed a significant decline, indicating that the logistics industry has also been negatively impacted by the financial crisis [31]. From 2013 to 2015, the green TFP index was higher than the traditional TFP index. Combined with the research of Fare et al. [32], it shows that the reduction rate of "bad" output in China's logistics industry exceeds the growth rate of "good" output, and the environmental management efficiency of China's logistics industry has been improved, moving towards the direction of green growth.

According to the decomposition in terms of TFP index, the technical progress index in both cases is greater than 1, while the technical efficiency index is less than 1 in most years, which means that the technical progress of logistics industry shows a continuous rising trend, but the technical efficiency fails to show an obvious growth pattern. It can be seen that, on the whole, technical progress is the main source of TFP growth in China's logistics industry, whether or not energy and environmental factors are introduced. This shows that China's logistics industry has not fully tapped the potential of existing resources and technologies, and there is still a great room to promote the performance growth of the logistics industry through efficiency improvement.

3.2. Investigation of Regional Heterogeneity. In order to investigate the regional heterogeneity of TFP change in logistics industry, respectively, the country is divided into three areas (the east, central, and west) and the eight economic zones (the northeast economic zone, the northern coastal economic zone, the eastern coastal economic zone, the southern coastal economic zone, economic zone in the middle reaches of the Yellow River, the Yangtze River economic zone, the southwest economic zone, and the northwest economic zone) standard based on the division of the National Development and Reform Commission: the country is divided into the eastern region (including 11 provinces and cities, namely, Beijing, Shanghai, Tianjin, Hebei, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Hainan, and Liaoning), the central region (including eight provinces, namely, Shanxi, Henan, Anhui, Jiangxi, Hubei, Hunan, Heilongjiang, and Jilin), and west (including 11 provinces, Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Tibet, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang). At the same time, we drew lessons from the criteria in the report strategies and Policies for Coordinated Regional Development released by the Development Research Center of the State Council to the national integrated into the northeast economic zone (including Heilongjiang, Liaoning, and Jilin), the northern coastal economic zone (including Shandong, Hebei, Beijing, and Tianjin), east coastal economic zone (including Jiangsu, Zhejiang, and Shanghai), southern coastal economic zone (including Guangdong, Fujian, and Hainan), economic zone in the middle reaches of the Yellow River (including Inner Mongolia, Henan, Shanxi, and Shaanxi), economic zone in the middle reach of Yangtze River (including Anhui, Jiangxi, Hunan, and Hubei), southwest economic zone (including Guangxi, Sichuan, Chongqing, Guizhou, and Yunnan), and the northwest zone (including Qinghai, Gansu, Ningxia, and Xinjiang). Because of the availability of data, the above two categories do not include Xizang. It can be seen from Table 4 that the two types of TFP indexes and their decomposition in China's logistics industry have great regional differences.

Under the three regional classification standards, without the introduction of energy and environmental factors, the regional ranking of average annual growth rate of TFP in the logistics industry from high to low is in the western, eastern, and central regions. After the introduction of energy and environmental factors, it follows the eastern, western, and central regions. The growth rate of green TFP in the eastern region is higher than that in the central and western regions, which is closely related to the relatively developed economy and natural geographical advantages of the eastern region. In addition, the eastern region pays more attention to the introduction of talents and invests more in the research and development of clean technology and environmental protection technology [31]. The growth rate of green TFP in central region is lower than that in western region, mainly due to the lower growth rate of technical progress in central region. The relative rank of TFP index (TFPR) in each region will be affected by energy and environment factors, so failure to take energy and environment factors into account will misjudge the relative level

of green growth performance in each region. In addition, regardless of the introduction of energy and environmental factors, technical progress is the main driving factor for the growth of TFP in the logistics industry in each region, and the technical efficiency has a negative impact on the growth of TFP.

Under the eight regional classification standards, when energy and environmental factors are not taken into account, the regional ranking of the average annual growth rate of TFP in the logistics industry from high to low is the eastern coastal economic zone, the southwest region, the middle reaches of the Yangtze River, the middle reaches of the Yellow River, the northwest region, the southern coastal region, the northern coastal region, and the northeast economic zone. After considering the energy and environment factors, the TFP growth rate of the eastern coastal economic zone still ranks the first, followed by the southern coastal region, the northern coastal region, the northeast region, the middle reaches of the Yellow River, the southwest region, the middle reaches of the Yangtze River, and the northwest region. It can be seen that, after the introduction of energy and environment factors, the ranking of TFP of various economic zones has changed again. The logistics industry in the southwest region, the middle reach of the Yangtze River, and the northwest region is more constrained by energy and environmental factors, and the TFP index and its ranking drop significantly. The traditional TFP index in most areas is larger than the green TFP index, which again indicates that if energy and environmental factors are ignored, the measurement results will deviate from the actual situation. In addition, regardless of the introduction of energy and environmental factors, the main driving factor of TFP growth in each region is technical progress, which is consistent with the research conclusions of the three regions.

3.3. Investigation of Interprovincial Heterogeneity. Table 5 reports the TFP index and its decomposition results of logistics industry in various provinces of China. It can be found that the TFP index of China's logistics industry has great interprovincial differences. Without the introduction of energy and environmental factors, the fastest growth rate of TFP was in Yunnan province, followed by Zhejiang and Inner Mongolia, and the lowest growth rate was in Liaoning (with an average annual decrease of 2.67%). After the introduction of energy and environment factors, the province with the highest TFP growth rate was Zhejiang, followed by Jiangsu and Guangdong, and the lowest growth rate was Chongqing (with an average annual decrease of 0.46%). From the numerical comparison of TFP index, after the introduction of energy and environment factors, there are 15 provinces (Beijing, Tianjin, Shanxi, Liaoning, Jilin, Heilongjiang, Shanghai, Hubei, Guangdong, Guangxi, Hainan, Chongqing, Shaanxi, Gansu, and Ningxia) of TFP index which rose, the TFP index rank also has some promotion mostly (except in Guangxi, Ningxia, and Chongqing).

From the decomposition of the TFP index, the technical progress of logistics industry in most provinces contributes more to the TFP index. When the energy and

TABLE 4: Mean of national and regional TFP index and its decomposition terms (2003–2017).

| Province | Energy and environmental factors are not introduced | | | Introduce energy and environmental factors | | |
|-------------------|---|--------|--------|--|--------|--------|
| | TEC | TPC | TFPC | TEC | TPC | TFPC |
| National average | 0.9939 | 1.0285 | 1.0222 | 0.9984 | 1.0210 | 1.0193 |
| Eastern | 0.9938 | 1.0283 | 1.0220 | 1.0037 | 1.0226 | 1.0264 |
| Central | 0.9979 | 1.0148 | 1.0127 | 0.9984 | 1.0145 | 1.0128 |
| Western | 0.9895 | 1.0379 | 1.0270 | 0.9918 | 1.0235 | 1.0151 |
| Northeast | 0.9818 | 1.0059 | 0.9876 | 1.0059 | 1.0124 | 1.0184 |
| Northern coast | 0.9932 | 1.0205 | 1.0135 | 1.0013 | 1.0211 | 1.0225 |
| East coast | 1.0122 | 1.0431 | 1.0559 | 1.0093 | 1.0308 | 1.0403 |
| Southern coast | 0.9847 | 1.0323 | 1.0165 | 1.0050 | 1.0210 | 1.0261 |
| Mid- Yellow River | 1.0022 | 1.0228 | 1.0250 | 0.9988 | 1.0178 | 1.0166 |
| Mid-Yangtze River | 1.0054 | 1.0229 | 1.0284 | 0.9968 | 1.0175 | 1.0143 |
| Southwest | 0.9846 | 1.0446 | 1.0285 | 0.9901 | 1.0247 | 1.0146 |
| Northwest | 0.9893 | 1.0310 | 1.0199 | 0.9883 | 1.0220 | 1.0100 |

TABLE 5: TFP Index and its decomposition of logistics industry in all provinces of China (2003–2017).

| Province | Energy and environmental factors are not introduced | | | | Introduce energy and environmental factors | | | |
|----------------|---|--------|--------|------|--|--------|--------|------|
| | TEC | TPC | TFPC | TFPR | TEC | TPC | TFPC | TFPR |
| Beijing | 0.9764 | 1.0020 | 0.9784 | 28 | 1.0000 | 1.0173 | 1.0173 | 17 |
| Tianjin | 1.0063 | 1.0183 | 1.0247 | 13 | 1.0147 | 1.0201 | 1.0350 | 4 |
| Hebei | 1.0000 | 1.0442 | 1.0442 | 9 | 1.0000 | 1.0321 | 1.0321 | 7 |
| Shanxi | 0.9904 | 1.0048 | 0.9952 | 26 | 1.0001 | 1.0103 | 1.0104 | 23 |
| Inner Mongolia | 1.0134 | 1.0594 | 1.0736 | 3 | 1.0017 | 1.0308 | 1.0325 | 6 |
| Liaoning | 0.9697 | 1.0036 | 0.9733 | 30 | 0.9926 | 1.0092 | 1.0018 | 28 |
| Jilin | 0.9876 | 1.0115 | 0.9990 | 23 | 1.0069 | 1.0156 | 1.0226 | 12 |
| Heilongjiang | 0.9882 | 1.0026 | 0.9908 | 27 | 1.0185 | 1.0123 | 1.0310 | 8 |
| Shanghai | 1.0221 | 1.0096 | 1.0319 | 11 | 1.0173 | 1.0156 | 1.0332 | 5 |
| Jiangsu | 1.0193 | 1.0402 | 1.0602 | 5 | 1.0056 | 1.0309 | 1.0368 | 2 |
| Zhejiang | 0.9956 | 1.0808 | 1.0760 | 2 | 1.0049 | 1.0459 | 1.0511 | 1 |
| Anhui | 0.9924 | 1.0194 | 1.0117 | 17 | 0.9913 | 1.0201 | 1.0112 | 20 |
| Fujian | 0.9831 | 1.0715 | 1.0534 | 7 | 1.0000 | 1.0306 | 1.0306 | 9 |
| Jiangxi | 1.0183 | 1.0376 | 1.0567 | 6 | 0.9982 | 1.0192 | 1.0174 | 16 |
| Shandong | 0.9901 | 1.0181 | 1.0081 | 18 | 0.9908 | 1.0152 | 1.0058 | 26 |
| Henan | 1.0138 | 1.0162 | 1.0302 | 12 | 0.9890 | 1.0137 | 1.0025 | 27 |
| Hubei | 0.9939 | 1.0118 | 1.0056 | 20 | 1.0044 | 1.0130 | 1.0175 | 15 |
| Hunan | 1.0174 | 1.0228 | 1.0406 | 10 | 0.9934 | 1.0179 | 1.0111 | 21 |
| Guangdong | 0.9862 | 1.0124 | 0.9984 | 25 | 1.0130 | 1.0220 | 1.0353 | 3 |
| Guangxi | 0.9803 | 1.0222 | 1.0021 | 22 | 0.9935 | 1.0176 | 1.0111 | 22 |
| Hainan | 0.9848 | 1.0141 | 0.9987 | 24 | 1.0021 | 1.0104 | 1.0125 | 19 |
| Chongqing | 0.9606 | 1.0164 | 0.9764 | 29 | 0.9777 | 1.0181 | 0.9954 | 30 |
| Sichuan | 0.9757 | 1.0421 | 1.0168 | 15 | 0.9854 | 1.0225 | 1.0076 | 24 |
| Guizhou | 1.0058 | 1.0585 | 1.0647 | 4 | 0.9982 | 1.0316 | 1.0298 | 10 |
| Yunnan | 1.0013 | 1.0851 | 1.0865 | 1 | 0.9959 | 1.0336 | 1.0294 | 11 |
| Shaanxi | 0.9915 | 1.0115 | 1.0029 | 21 | 1.0044 | 1.0166 | 1.0211 | 13 |
| Gansu | 0.9976 | 1.0083 | 1.0059 | 19 | 1.0017 | 1.0140 | 1.0156 | 18 |
| Qinghai | 0.9747 | 1.0714 | 1.0443 | 8 | 0.9638 | 1.0364 | 0.9989 | 29 |
| Ningxia | 0.9909 | 1.0270 | 1.0176 | 14 | 0.9934 | 1.0250 | 1.0182 | 14 |
| Xinjiang | 0.9941 | 1.0184 | 1.0123 | 16 | 0.9948 | 1.0128 | 1.0075 | 25 |
| Mean | 0.9939 | 1.0285 | 1.0222 | | 0.9984 | 1.0210 | 1.0193 | |

environmental factors are not taken into account, only Shanghai's growth rate of technical efficiency is higher than that of technical progress. After accounting for energy and environmental factors, the number of provinces where technical efficiency has grown faster than

technical progress has risen to two, namely, Shanghai and Heilongjiang. This shows that, in the vast majority of provinces, through improving technical efficiency to further enhance the logistics industry productivity, there is a large space.

TABLE 6: Robustness tests of two kinds of TFP index measurement results.

| Depreciation rate (%) | Index indicator | Energy and environmental factors are not introduced | | Introduce energy and environmental factors | |
|-----------------------|-----------------|---|----------|--|----------|
| | | Method 1 | Method 2 | Method 1 | Method 2 |
| 6.0 | EC | 0.9939 | 0.9936 | 0.9984 | 0.9984 |
| | TC | 1.0285 | 1.0271 | 1.0210 | 1.0206 |
| | TFPC | 1.0222 | 1.0205 | 1.0193 | 1.0190 |
| 4.0 | EC | 0.9943 | 0.9939 | 0.9984 | 0.9984 |
| | TC | 1.0273 | 1.0261 | 1.0208 | 1.0205 |
| | TFPC | 1.0214 | 1.0198 | 1.0192 | 1.0189 |
| 9.6 | EC | 0.9936 | 0.9932 | 0.9979 | 0.9984 |
| | TC | 1.0302 | 1.0287 | 1.0215 | 1.0209 |
| | TFPC | 1.0237 | 1.0218 | 1.0194 | 1.0192 |

3.4. Robustness Test of TFP Results. To investigate the influence of the capital depreciation rate and base year capital stock on the calculation results, we make a robust analysis by changing the capital depreciation rate and the estimation method of the base year capital stock. The specific measures are as follows: first, keeping the depreciation rate unchanged (6%) and adopting the base year capital stock estimation method of Hall and Jones [33] (Method 2 in Table 6); secondly, keeping the estimation method of the base year capital stock unchanged (method 1 in Table 6), and setting the depreciation rate as 4% in Wu [28] and 9.6% in Zhang [34], respectively; finally, changing the depreciation rate and the estimation method of the base year capital stock simultaneously. The measurement results of all combinations are listed in Table 6. Due to space limitation, only the average results for various combinations are given here. According to the average value and the specific results of each province and year, after changing the capital depreciation rate and the estimation method of the base year capital stock, the results only change slightly in the specific value, but these changes do not change the basic conclusion of this paper. Therefore, the results of this paper are robust.

3.5. Analysis of the Evolution Trend of Regional Differences. Since green TFP can better reflect the green growth performance of the logistics industry, we only analyze the regional variation trend of green TFP. Referring to the practice of Rezitis [35] and Teng et al. [4], we use the variable coefficient to measure the degree of regional difference, and the formula is as follows:

$$S = \sqrt{\frac{\sum_i (TFP_{it} - t f p_t)^2}{N}}, \quad (10)$$

$$V = \frac{S}{t f p_t},$$

where S represents the standard deviation, TFP_{it} represents the green TFP of the logistics industry of i province in the t year, $t f p_t$ represents the average value of the t year green TFP of the sample provinces, N represents the number of provinces, and V represents the variation coefficient of TFP.

Figure 1 depicts the evolution characteristics of regional difference degree of green TFP index of logistics industry in the whole sample and the three regions of east, middle, and west. It can be found that the regional difference degree of green TFP in the national logistics industry generally decreases with the passage of time, which means that the green TFP in the national logistics industry may have σ convergence on the whole. In terms of the evolution of the internal differences of green TFP in the three regions, the differences of green TFP in the eastern, central, and western regions show a decreasing trend on the whole, and the evolution trajectory is consistent with the national samples, indicating that the differences of green TFP in each region is shrinking, and there may also exist a σ convergence. The mean value of the variation coefficient from high to low is in western, eastern, and central regions. From the perspective of interregional differences, the difference of variation coefficient among the three regions in 2017 is greater than that in 2004, indicating that the interregional differences are expanding.

According to the variation of the degree of difference of green TFP in the eight economic zones (Figure 2), similar to the situation in the whole sample and the eastern, central, and western regions, the variation coefficient of most economic zones also shows a decreasing trend, and there may be a σ convergence. Specifically, in 2017, the variation coefficients of the eastern coast, the southern coast, the middle reaches of Yangtze River, the middle reaches of the Yellow River, the southwest, and the northwest area relative to the variation coefficient of 2004 decreased by 81.7%, 89.2%, 85.5%, 76.9%, 84.5%, and 10%. Thus, the largest decline was in the southern coastal areas, while the smallest decline was in the northwest region, indicating that the differences of green TFP index among the provinces in these economic zones are narrowing. In 2017, the variation coefficient in northeast China and the northern coastal economic zone increased by 11.3% and 286.3%, respectively, compared with 2004, indicating that the internal differences between the two regions are continuously expanding. Comparing with the mean value of the variation coefficient of green TFP, we can find that the difference of green TFP among the provinces in the middle reaches of the Yellow River economic zone is the greatest.

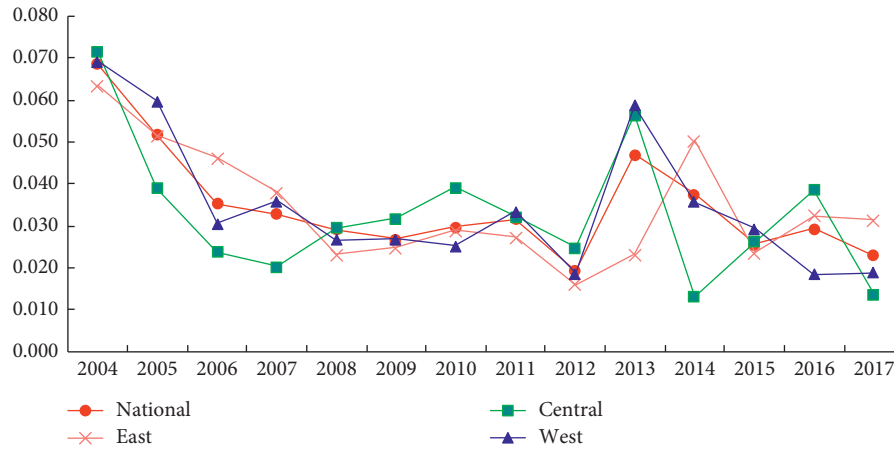


FIGURE 1: The change trend of regional differences in green TFP of logistics industry in China and three regions.

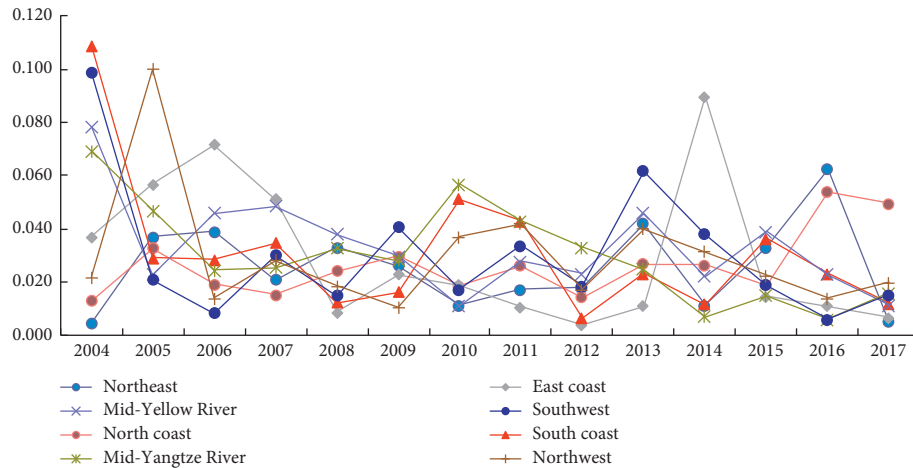


FIGURE 2: Variation trend of regional differences in green TFP of logistics industry in the eight economic zones.

4. Conclusions

This paper introduces the energy and environmental factors into the TFP measurement framework of China's logistics industry and compares it with the traditional TFP without considering energy and environmental factors. The main conclusions are as follows.

First, the green TFP and traditional TFP of China's logistics industry are both on the rise, with an average annual growth rate of 1.93% and 2.22%, respectively. It can be seen that the absence of energy and environmental factors will lead to the overestimation of TFP of the logistics industry, and energy and environmental factors will have a significant impact on the TFP estimation of the logistics industry. Whether green TFP or traditional TFP, the main source of its growth is technical progress, and there is still much room for further enhancing the TFP in the logistics industry through the improvement of technical efficiency.

Second, the growth of green TFP in China's logistics industry has great regional heterogeneity. Under the three regional division standards, the average annual growth rate of green TFP is from high to low in the eastern, western, and

central regions. Under the eight regional classification standards, the average annual growth rate of green TFP is successively from high to low in the eastern coastal economic zone, the southern coastal zone, the northern coastal zone, the northeast region, the middle reaches of the Yellow River, the southwest region, middle reaches of the Yangtze River, and the northwest region. The logistics industry in the southwest region, the middle reach of the Yangtze River, and the northwest region is more constrained by energy and environmental factors, and its TFP index and ranking decline significantly after considering energy and environmental factors.

Third, the growth of green TFP in China's logistics industry has great interprovincial heterogeneity. The province with the highest growth rate of green TFP is Zhejiang, followed by Jiangsu and Guangdong, and the slowest growth rate is Chongqing, with an average annual decrease of 0.46%. From the perspective of the decomposition term of the green TFP index, the technical progress of the logistics industry in most provinces contributes more to the green TFP index, indicating that there is a large space for the vast majority of provinces to further improve the green

productivity of logistics industry by improving the technical efficiency.

Fourth, from the evolution trend of the internal differences of green TFP in the logistics industry of the three regions, the regional differences of green TFP in the east, the middle, and the west are generally decreasing, and the evolution trajectory is consistent with the national samples, indicating that the differences of green TFP in the logistics industry within each region are shrinking, and there may be σ convergence. However, from the perspective of the differences among the three regions, the difference of the variation coefficient among the three regions in 2017 is greater than that in 2004, indicating that the differences among the three regions are expanding. From the results of the eight economic regions, the variation coefficients of most economic regions also show a downward trend.

Based on the above conclusions, the main implications are as follows: firstly, in the context of China's supply-side structural reforms and the concept of green development, we should pay more attention to the role of logistics industry TFP (especially green TFP) in the green growth and sustainable development of the logistics industry, to promote the growth pattern of China's logistics industry from factor-driven to green TFP-drive, to further promote the development of green logistics. Secondly, while maintaining the contribution level of technical progress to TFP of logistics industry, we can further focus on improving technical efficiency of logistics industry to promote the growth of green TFP. Thirdly, the government can formulate regional difference policies to promote the growth of green TFP and the development of green logistics according to the factor endowments of different regions. By promoting the introduction, R&D, and application of green and low-carbon technologies, the government can strengthen the regional exchanges and cooperation on green technologies to gradually reduce the regional differences in the growth of green TFP in the logistics industry. Fourthly, the efficiency of R&D innovation in transforming scientific and technological achievements into final productivity is low due to some problems in the use of R&D expenditure in logistics industry in China. Therefore, it is necessary to pay attention to the structure of R&D investment in the use of logistics R&D expenses to prevent the phenomenon of industry university research disconnection in the future. Fifthly, under the constraints of energy and environmental factors, in order to improve the green TFP of China's logistics industry, how to achieve CO₂ emission reduction without damaging economic benefits needs to be paid more attention. This requires that the proportion of high carbon energy consumption must be reduced as far as possible, such as vigorously developing new energy, improving energy utilization efficiency, and product innovation, so as to fundamentally promote the green TFP growth of China's logistics industry. Finally, it should be pointed out that although we have carefully studied the change trend of green productivity and the interprovincial and regional differences in China's logistics industry by using existing methods, due to careful consideration, deeper reasons and policy interpretation are yet to be further analyzed in the future.

Data Availability

The data that support the findings of this study are openly available in China Statistical Yearbook and China Energy Statistical Yearbook at <http://www.stats.gov.cn/tjsj>.

Conflicts of Interest

The authors declare no conflicts of interest.

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Research Article

Environmental Investment Decision of Green Supply Chain considering the Green Uncertainty

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The uncertainty of eco-friendly intermediate components has an important impact on green supply chain decisions. In this paper, the Stackelberg game model of green investment decision-making among enterprises is established by considering the case of the supplier's green investment alone and the case of the manufacturer and the supplier's joint green investment. The influence of green uncertainty on enterprise's decision-making is analyzed, and the green investment decision-making strategies of both sides in two cases are compared. There are four main conclusions derived from the results: (i) with the increase in the supplier's green cost coefficient, the supplier will reduce the green investment and the manufacturer will reduce the share of the green costs; (ii) with a decrease in uncertainty for eco-friendly intermediate components and the increase in their feasibility factor, the supplier will increase the greenness of intermediate components and increase the investment in environment, and the manufacturer will reduce the share of the green costs; (iii) the increase in the manufacturer's share of green costs will promote the supplier to increase the greenness of intermediate components and increase its green investment, which shall increase the supplier's optional choice space of for green investment; (iv) in the case of the manufacturer and the supplier jointly making a green investment, the threshold value for the environmental input of the supply chain members (i.e., the manufacturer and the supplier) is lower, and the supply chain members will have more choice space. At the same time, the care for environment in the case of a cooperative is higher than that in the case of a supplier investing alone.

1. Introduction

With the development of economy, the manufacturing industry has been developing rapidly. The rapid development of manufacturing industry provides abundant choice of products to humans, and it also leads to many environmental problems such as resource depletion and environmental pollution. Since the industrial era, the energy consumption is too high, the resource consumption is excessive, the industrial wastes emissions are excessive, the ecological environment is deteriorating, and the sustainability of economy and social development is seriously restricted [1]. Due to the increasingly prominent global environmental problems, sustainable development has been widely accepted. Green supply chain considers resource consumption and has been paying more attention to

environmental impact. Therefore, more and more enterprises have begun to produce “green” products and implement green supply chain management in practice [2].

In practice, the Canon Group issued the “Global Canon Green Procurement Standards” in 1997, which has been promoting green purchasing activities for 20 years. Compliance with the green procurement standard is listed as one of the basic requirements and is an important condition for starting and continuing business transaction. Canon believes that not only they should comply with environmental regulations but that all suppliers should comply with them. Therefore, the standard book reflects the global environmental regulations and industry standards. Canon's production outlets in China strictly abide by the national and local environmental regulations, such as cleaner production and discharge standards and sound waste water and waste

gas treatment facilities. For instance, the self-discharge standard for wastewater is 20% lower than that of environmental laws and regulations, so as to ensure that the actual discharge will not exceed the standard. In addition, Canon pays attention to technological innovation, carries out energy-saving transformation of equipment, selects energy-saving equipment within the scope of technology and economy, strives to improve their energy utilization rate, and actively uses renewable energy [3]. Similarly, the Lenovo Group not only abides by the Code of Conduct of the Electronic Industry Citizenship Coalition (EICC) and all applicable rules but also pays attention to energy consumption in the production process. They reduce emissions in general by reducing carbon emissions in business activities, increasing the use of renewable energy and strengthening the development and promotion of green technologies. Lenovo's purchasing department has standardized procedures covering a wide range of areas and has developed a comprehensive code of conduct for suppliers. Lenovo takes into account suppliers' environmental performance, such as compliance and emission reduction of hazardous substances, use of recycled materials after environmental protection consumption, transparency and emission reduction of greenhouse gas emissions, and avoidance of conflict minerals [4].

However, the process of making a green supply chain is a process of technology transformation, which requires the participation of upstream and downstream of a supply chain and often faces uncertainties. The reality also shows that most of the technology transforming products fails to enter the market, with this failure rate being between 25% and 45%. A study has shown that, out of every seven new product ideas, four products enter the development stage, one-point-five products enter the market, and only one is successful [5]. The uncertainty of green products in supply chain comes from two main aspects: first, the technological uncertainty of green products. Although some ideas about green development of products are technically attractive and feasible at first, many technological problems cannot be solved once they are implemented. The dilemma is whether the new product function brought by green technology is really what consumers want, or the new technology cannot be further improved due to the lack of sustainable development skills of enterprises. Second, the market uncertainty of green products is an aspect that bifurcates into three segments: market demand, scale of demand, and market growth rate. The uncertainty of the market means that the enterprise does not know enough about the market. The failure of green development for many products is not due to technology defects but due to mistakes in market decision-making. It is beyond doubt that a new green product needs a potential market to succeed. Therefore, before beginning the green development of a product, it is necessary to conduct a full market analysis. Although market analysis can help enterprises in making green product development plans, they are still not aware whether they have obtained accurate customer demand information. Subsequently, there is the uncertainty of market scale. For instance, even when market demand for green products appears, the scale of this market

demand cannot be predicted, which leads to wrong production and marketing strategies. Lastly, due to the uncertainty of market growth rate, it is difficult for enterprises to predict when and how fast the market will grow in the introduction stage of the green product's life cycle. If the growth period and the maturity period are shorter than expected, they may not be able to obtain the supposed profits or even experience losses on green projects. For the reasons above, supply chains should have uncertainty in mind when considering green products.

The main purpose of this paper is to analyze the impact of uncertainty of green products on decision for environmental investment in supply chain. For the purposes of our analysis, we consider a supply chain consisting of one manufacturer and one supplier. A Stackelberg game model of green investment decision-making among enterprises was established. In this model, we introduce green uncertainty factors, analyze the impact of green uncertainty on enterprise decision-making, and compare the green investment decision-making strategies of both sides in two cases. We analyze the two cases when only the supplier is "green" and the case where the manufacturer's and the supplier's cooperative is "green". The specific research questions of this paper include the following: (i) what is the impact of supplier's green costs coefficient on the manufacturer's share of green cost and the supplier's input? (ii) What is the impact of product uncertainty on product greenness and green investment of the manufacturer and the supplier? (iii) What is the impact of the manufacturer's share of green cost on product greenness and the supplier's choice space?

The main contribution of this paper is twofold: (i) we consider the impact of green uncertainty in the green supply chain model by introducing the green feasibility factor and alternative choice space to analyze the cooperation of all members in the supply chain; (ii) we analyze the impact of green uncertainty on the environmental input in the supply chain by establishing a multistage game-theoretical model considering the case of the supplier's green investment alone and the case of the manufacturer and the supplier's joint green investment.

The rest of this paper is organized as follows: Section 2 provides the literature review. Section 3 is to establish basic model. Section 4 is to analyze the green decision for the supplier alone. Section 5 is to analyze the green decision of the manufacturer and the supplier's cooperative. Section 6 is to analyze a numerical example. Sections 7 and 8, provide results and draw conclusions.

2. Literature Review

The concept of green supply chain was first proposed by the manufacturing research association of Michigan State University in 1996. The green supply chain (GSC) is defined as a kind of modern management that considers environmental impact and resource efficiency in the whole supply chain [6]. Green supply chain management includes green material management, green product production management, and green product sales management [7].

This research is closely related to the coordination and decision-making of the green supply chain. There are several researches about it in recent years. Barari et al. use an evolutionary game approach to discuss the sales of green and non-green products by two manufacturers in dual distribution channels [8]. Cao and Zhang coordinate a green channel between providers and manufacturers with a pricing strategy [9]. Hafezalkotob develops a price competition model between a green and a regular supply chain, both under the influence of government financial intervention, where the effects of government's tariffs on the actors' optimal strategies are analyzed. It was found that there are specific boundaries for tariffs, which guarantee a stable and competitive market [10]. Aydin et al. study the coordination between a supplier and other actors to design a production line in a closed-loop supply chain. They use the Stackelberg game to analyze a multiobjective optimization model for the production line, which includes new and remanufactured products [11]. Yang and Xiao study the optimal price and "greenness" of a product in a green supply chain under government intervention [12]. Zhu and He use a game-theory approach to investigate pricing competition and the degree of competition among green products in different structures of the supply chain [13].

In recent years, the literature is abundant with papers regarding the topics of supply chain and environment protection. Jamali and Barzoki investigate the decision on pricing for two substitute products, a green product produced by one manufacturer, and a non-green product produced by the other one, under two dual-channel supply chains including retail and Internet channels [14]. Taleizadeh et al. use Nash and Stackelberg games to investigate the coordinated contracts in a two-echelon green supply chain considering pricing strategy [15]. Modak et al. investigate a revenue-sharing contract in a two-echelon supply chain consisting of one retailer and one manufacturer, considering trade regulation to control carbon emission [16]. Hong and Guo investigate coordination contracts in a two-echelon supply chain considering consumer environmental awareness, where the coordination contracts include a two-part tariff, cost sharing, and price contracts [17]. Cao and Yu study coordinated contracts in a two-echelon supply chain by considering cap-and-trade regulation to reduce the amount of carbon, where they find that the coordinated contracts include revenue sharing, buyback, and quantity discount forms [18]. Song and Gao discuss the impact of two revenue-sharing models on green supply chain's product greening levels, prices, and profit considering consumer sensitivity [19]. Dey and Saha discuss the joint impact of the retailer's strategic decision and consumer's continuous expectation on the investment and wholesale pricing decision of the manufacturer when it comes to improving the greening level of the product in a green supply chain [20]. Liu and Xiao investigate the decisions on price and collection rate and reverse channel structure strategy of a dyadic closed-loop supply chain with corporate social responsibility and green consumers, within which the manufacturer and green consumers exhibit environmental responsibility behaviors [21]. Nielsen et al. explore the

repercussions of a dominant intermediary in a three-echelon green supply chain considering price and greening level sensitive demand [22]. Murali et al. study green product development among competing firms considering the impact of voluntary ecolabels and mandatory environmental regulation [23]. Luo et al. study the optimal procurement decision in a two-echelon green supply chain with options under capital constraints and financing credit support [24]. Kang et al. investigate the member's efforts to reduce pollution in the green supply chain considering the Green Credit Policy [25]. Zhang et al. investigate green supply chain decision-making under different government policies [26]. Yuan et al. examine different government subsidy strategies in green supply chain management based on dynamic game theory and the principal-agent theory [27]. Shahzad et al. identify the influence of organizational compatibilities on green supply chain management (GSCM) efforts and estimate their influence on organizational performance [28]. Pakseresht et al. deal with Green Product Families (GPFs), which are produced based on the Assemble-to-Order (ATO) approach in order to cover diverse customer needs. They design GPFs with Stackelberg game toward a sustainable optimal selection of green components, modules, and product variants [29]. Wang et al. study the competitive and sustainable supply chain network design problem by considering the chain-to-chain competition between two supply chains [30]. Zhang et al. compare the optimal green decisions and profits under single-channel or dual-channel strategies with and without green investment [31]. Wang et al. study the decisions and coordination of green e-commerce supply chain under green manufactures' fairness concerns considering the product green degree and the e-commerce platform's service [32]. Wu et al. investigate the coordination of store brand product's green supply chain based on negotiation [33]. Ghomi-Avili et al. propose a robust bilevel model of the single-product multiperiod network design problem for a competitive green supply chain considering pricing and inventory decisions under uncertainty and disruption risks [34].

Some of these papers discuss coordination and decision-making of green supply chain. For example, Shahzad et al. identify the influence of organizational compatibilities on green supply chain management (GSCM) efforts [28]; Wang et al. investigate the decisions of green e-commerce supply chain under green manufactures' fairness concerns, albeit in neither of them is the impact of green uncertainty on decision-making of green supply chain's environment has not been investigated [30]. This paper attempts to cover this gap by proposing a Stackelberg game model and analyzing its influence on decision-making. In this paper, the green uncertainty factor is added into the environmental investment decision in a green supply chain. It is found that this uncertainty factor has an important impact on the environmental investment. With the green uncertainty of intermediate components decreases and the green feasibility factor increases, the supplier will increase the greenness of intermediate components and increase the green investment, and the manufacturer will reduce the share of green costs.

3. Modelling

In order to facilitate this study, we make the following assumptions:

- (i) A green supply chain is composed of one supplier and one manufacturer, deemed as a two-echelon supply chain.
- (ii) The market demand function of the product is $p = a - q$, where p is the price of the final product, a is the market capacity and is a constant greater than zero, and q is the sales volume of the final product and $q \geq 0$. The price of the intermediate components sold by the supplier to the manufacturer is w , the cost of the final product of the manufacturer is c_1 , and the cost of the intermediate component produced by the supplier is c_2 , where $a > c_1 + c_2$. Therefore, the profit functions of the two actors, the supplier, and the manufacturer are as follows:

$$\begin{aligned}\prod_s &= q(w - c_2), \\ \prod_m &= q(p - w - c_1).\end{aligned}\quad (1)$$

- (iii) In the green supply chain, the benefits brought by the green investment of intermediate components can be shown as follows: reducing the environmental management costs, recycling costs, or rework costs caused by unqualified quality. In short, the production cost of green materials can be reduced. We assume that the greenness of an intermediate component is e , where $e \geq 0$, which translates into a decrease in the production cost of intermediate components. After the supplier's green technology innovation, the unit production cost of green materials is $(c_2 - e)$. The cost function of the supplier's green investment is a quadratic function, and the cost is $(1/2)\mu e^2$, where μ is the cost coefficient of the supplier's greenness. Accordingly, the revenue functions of the supplier and the manufacturer are as follows:

$$\prod_s = q(w - c_2 + e) - \frac{1}{2}\mu e^2, \quad (2)$$

$$\prod_m = q(p - w - c_1), \quad (3)$$

Although equations (2) and (3) are the same in form, the price of green materials in equation (3) is bound to decrease due to the influence of green input by the supplier, thus increasing the income of the manufacturer in equation (3).

- (iv) As mentioned above, the green input of the supplier can reduce the price of products, and for manufacturers, the supply price of intermediate components can be reduced. If the manufacturer

wants to obtain a lower supply price of intermediate components, the supplier needs to increase the green investment. However, the supplier may not be able to meet the requirements of the manufacturer for any reason. For example, the supplier may be limited in funds or hesitant to increase investment in technology innovation due to the uncertainty of green products. Therefore, if the manufacturer wishes to obtain a lower price w of green materials, they would need to subsidize the green costs of the supplier. This way, the price of the product is reduced through a green cooperative. When we assume that the manufacturer's share of the green investment is t ($0 < t < 1$), the revenue functions of the green supplier and the manufacturer in a cooperative are as follows:

$$\prod_s = q(w - c_2 + e) - \frac{1}{2}(1 - t)\mu e^2, \quad (4)$$

$$\prod_m = q(p - w - c_1) - \frac{1}{2}t\mu e^2. \quad (5)$$

- (v) The results of a green investment in intermediate components are uncertain and do not necessarily bring benefits. This uncertainty has an important impact on the performance of a green supply chain and green investment. In the result, we should consider the impact of the uncertainty of green intermediate components in the model. The green uncertainty includes technological uncertainty and economic uncertainty. On the one hand, technological uncertainty occurs due to the rapid technological changes in modern society. This uncertainty leads to the uncertainties of the product's R&D cycle, investment, and product's success rate. Sometimes, even if the technology is at the cutting-edge, it may not be feasible or desirable. On the other hand, economic uncertainty runs through the whole process of the product's green innovation. It is especially caused by factors such as product positioning, market selection, promotion methods, and marketing opportunity. These factors make it more difficult to evaluate the benefits of green technology innovation.

The symbols used in this study are summarized in Table 1.

Because of the uncertainty of investment in green technology, the green supply chain should consider whether the green technology is feasible and what be the probabilities of achieving the expected return on the innovation when making the decision of investing in environmental components. We assume that, under the external conditions, the green feasibility factor is θ , the greenness of components e is actually the target performance of the product cost reduction, and the actual innovation performance of green is $e + \varepsilon$,

TABLE 1: Introduction of the symbol.

| Symbol | Symbolic meaning |
|-----------|---|
| p | Price of the final product |
| a | Market capacity |
| q | Sales volume of the final product |
| w | The price of the intermediate components sold by the supplier to the manufacturer |
| c_1 | The cost of the final product of the manufacturer |
| c_2 | The cost of the intermediate component produced by the supplier |
| \prod_s | The profit of the supplier |
| \prod_m | The profit of the manufacturer |
| e | The greenness of the intermediate component |
| μ | The cost coefficient of the supplier's greenness |
| t | The manufacturer's share of the green investment |

where e is the determined target innovation performance, ε represents the deviation between the objective innovation performance and the actual innovation performance of the green supply chain and follows the normal distribution $N(0, \sigma^2)$ [35–37]. The uncertainty of a green investment will affect the decision-making, which shall be considered in Sections 4 and 5.

4. Green Investment Decision-Making: Case of a Single Supplier

In the case of the supplier's single green investment, the supplier first determines the greenness e of the intermediate component. If the green product is successful, the supplier asks the manufacturer for the price w of the intermediate component. According to the price of the component, the manufacturer determines the output q and price p of the final product. The decision-making sequence of this green supply chain is shown in Figure 1.

By the first-order condition of the manufacturer's profit function in equation (3), we can get the output decision of the manufacturer's final product as follows:

$$q(w) = \frac{1}{2}(a - w - c_1). \quad (6)$$

It can be seen from equation (6) that the supply price of intermediate components will affect the manufacturer's choice of output. By substituting formula (6) into equation (2), the supplier's revenue function is transformed into

$$\prod_s = \frac{(a - w - c_1)(w - c_2 + e) - \mu e^2}{2}. \quad (7)$$

Let $(\partial \prod_s / \partial w) = 0$ in equation (7), the optimal demand price w of intermediate components can be obtained by a first-order derivation:

$$w(e) = \frac{a - c_1 + c_2 - e}{2}. \quad (8)$$

Substituting equation (8) into equation (7), we can get the supplier's revenue function:

$$\prod_s(e) = \frac{(a - c_1 - c_2 + e)^2}{8} - \frac{1}{2}\mu e^2. \quad (9)$$

It is worth noting that equation (9) is the profit obtained by the supplier when the green investment in intermediate components is successful. The uncertainty in the process of making a green investment in the component is not considered. Without considering the uncertainty of the green investment, the gross profit of the supplier (i.e., the profit before deducting the cost) is $(a - c_1 - c_2 + e)^2/8$. If we consider the impact of uncertainty of the intermediate component's green input, the actual performance brought by the green input e is $e + \varepsilon$.

If the supplier's green feasibility factor is θ and the expected gross profit is discounted by this feasibility factor θ , then under the uncertainty of the green input, the expected return of the supplier is $\prod_s(e) = E[\theta \cdot ((a - c_1 - c_2 + e + \varepsilon)^2/8)] - (1/2)\mu e^2$ [38, 39]. After further simplification, the equation can be obtained as

$$\prod_s(e) = \theta \cdot \frac{(a - c_1 - c_2 + e)^2}{8} - \frac{1}{2}\mu e^2, \quad (10)$$

where the first derivative of e is performed, let $\partial \prod_s(e) / \partial e = 0$, and we can get the optimal green level of the supplier considering the uncertainty of the green input as follows:

$$e^*_s = \frac{\theta(a - c_1 - c_2)}{4\mu - \theta}. \quad (11)$$

By observing equation (11), we can induct the first proposition of this paper:

Proposition 1. *In the case of a single supplier's green investment, the following is observed:*

- (i) *The optimal green input level of the supplier decreases with the increase in the cost coefficient and increases with the increase in the green feasibility factor*
- (ii) *Only when the technological feasibility factor is higher than a certain threshold value can the supplier carry out the green investment*

Proof. firstly, because $(\partial e^*_s / \partial \mu) = (-4\theta(a - c_1 - c_2) / (4\mu - \theta)^2)$, $a > c_1 + c_2$, it is easy to prove $(\partial e^*_s / \partial \mu) < 0$, since it means that the optimal green level of the supplier e^*_s is a decreasing function of the input cost coefficient μ .

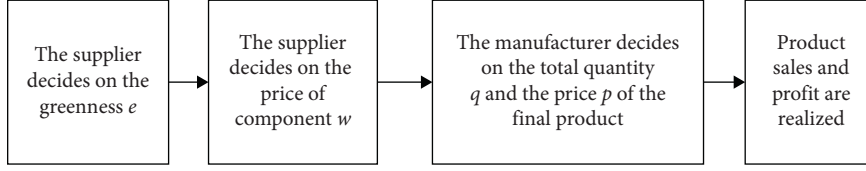


FIGURE 1: Sequence diagram of the supplier's decision single green investment.

Secondly, because $(\partial e^*/\partial \theta) = (4\mu(a - c_1 - c_2)/(4\mu - \theta)^2)$, $a > c_1 + c_2$, it is easy to prove that $(\partial e^*/\partial \theta) > 0$, which means that the optimal green input level of the supplier e^* is an increasing function of the green feasibility factor θ .

It is easy to understand that with the increase in the input cost coefficient, the cost of the green investment of the supplier will increase, thus reducing the supplier's investment enthusiasm. With the improvement of the technological feasibility of the green product, the supplier faces less technological uncertainty in the process of a green investment. In return, this can reduce the possibility of failure of the green product and increase the supplier's enthusiasm to increase the green investment.

Finally, in the case when the supplier does not make the green investment, the model can be written as $e = 0$. At this time, there is no uncertainty about the greenness of the component, that is, the feasibility of green products is $\theta = 1$, so the supplier's revenue is $\Pi_s^N = ((a - c_1 - c_2)^2/8)$. When the green product is uncertain, only when the profit of green investment is greater than that of no green investment, the supplier will make the green investment, that is, the condition $\Pi_s(e) \geq \Pi_s^N$ must be met. In other words, the following inequality must be satisfied:

$$\theta \cdot \frac{(a - c_1 - c_2 + e)^2}{8} - \frac{1}{2}\mu e^2 \geq \frac{(a - c_1 - c_2)^2}{8}. \quad (12)$$

By substituting the supplier's optimal green level e_s^* in equation (11) into inequality (12), we can get the inequality as follows:

$$\theta \cdot \frac{[a - c_1 - c_2 + (\theta(a - c_1 - c_2)/(4\mu - \theta))]^2}{8} - \frac{1}{2}\mu \left[\frac{\theta(a - c_1 - c_2)}{4\mu - \theta} \right]^2 \geq \frac{(a - c_1 - c_2)^2}{8}. \quad (13)$$

By solving inequality (13) and simplifying it, we can get the following result:

$$\theta \geq \frac{4\mu}{4\mu + 1}. \quad (14)$$

Let $\xi = (4\mu/(4\mu + 1))$, where ξ is the threshold value of the supplier's green investment when the product is in the case of the single supplier. Only when the green feasibility factor $\theta \geq \xi$ exists, the supplier's green investment in the product will occur.

It shows that the supplier should consider the uncertainty of a green investment when it invests in green products. When the green feasibility factor is in the range

$[4\mu/(4\mu + 1), 1]$, the supplier will choose to invest. The larger the feasibility threshold $\xi = (4\mu/(4\mu + 1))$ is, the smaller is the choice space of the green investment. The smaller the feasibility threshold $\xi = (4\mu/(4\mu + 1))$ is, the larger is the choice space for the green investment of the supplier.

Besides, because $(\partial \xi/\partial \mu) > 0$, the feasibility threshold value of the supplier's green investment increases with the increase in the cost coefficient. Understandably, if the cost of the supplier's green investment increases, it will reduce the enthusiasm of the supplier for the green investment and shall reduce the scope of the suppliers' choices. \square

5. Green Investment Decision-Making: Case of a Cooperative between the Supplier and the Manufacturer

When the manufacturer and the supplier jointly invest in a green intermediate component, the manufacturer, as the leader, first determines the share of green cost t . As a follower, the supplier decides the green level e of the intermediate component according to the manufacturer's cost share. The supplier then asks the manufacturer for the price w of the intermediate component. At last, the manufacturer determines the output and price of the final product according to the price of the intermediate component. The decision-making sequence of a green supply chain in the case of green cooperative is shown in Figure 2.

We use the inverse method to solve the problem. According to the first-order condition of the profit function in equation (5), we can get the output decision of the manufacturer's end product as follows:

$$q(w) = \frac{1}{2}(a - w - c_1). \quad (15)$$

Substituting equation (15) into the supplier's revenue function of equation (4), it can be transformed into as follows:

$$\Pi_s(w, e) = \frac{1}{2}(a - w - c_1)(w - c_2 + e) - \frac{1}{2}(1 - t)\mu e^2. \quad (16)$$

We take the derivative of w in equation (16). Let $(\partial \Pi_s(w, e)/\partial w) = 0$, we can obtain the optimal price of the intermediate component:

$$w(e) = \frac{a - c_1 + c_2 - e}{2}. \quad (17)$$

Substituting equation (17) into equation (16), the supplier's revenue function can be rewritten as follows:

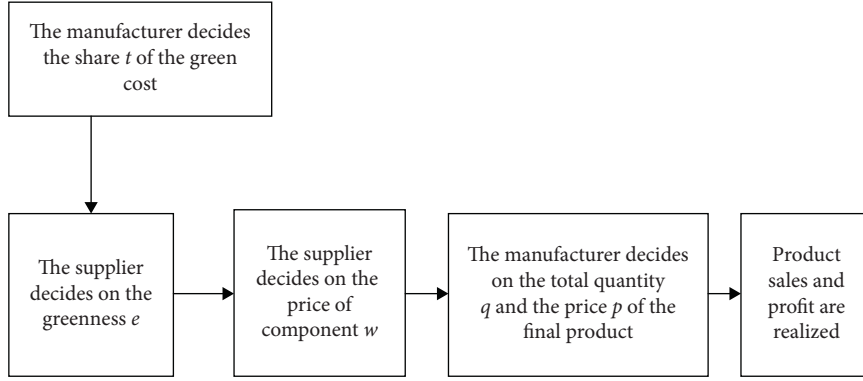


FIGURE 2: Decision sequence diagram of green supply chain under cooperative green.

$$\prod_s(e) = \frac{(a - c_1 - c_2 + e)^2}{8} - \frac{1}{2}(1-t)\mu e^2. \quad (18)$$

We add the uncertainty factor of the green product to equation (18) and the expected revenue function of the supplier is changed into

$$\prod_s(e) = \theta \bullet \frac{(a - c_1 - c_2 + e)^2}{8} - \frac{1}{2}(1-t)\mu e^2. \quad (19)$$

We take the derivative of e in equation (16). Let $(\partial \prod_s(e)/\partial e) = 0$, we can get the optimal green level of the supplier under the condition of considering the uncertain factor of greenness as follows:

$$e_c^* = \frac{\theta(a - c_1 - c_2)}{4(1-t)\mu - \theta}. \quad (20)$$

We note that e_c^* must satisfy the condition $e_c^* > 0$, because we have the assumption that $a > c_1 + c_2$, $4(1-t)\mu - \theta > 0$ must be satisfied in equation (20). In equation (20), e_c^* is the optimal green level considering the uncertainty when the manufacturer decides to share the green cost as t . As in Proposition 1, the optimal green input level e_c^* determined by the supplier decreases with the increase in the green cost coefficient μ . Moreover, it increases with the increase in the green feasibility factor θ , which is not elaborated and proved in detail here.

Proposition 2. *In the case of the supplier's and the manufacturer's cooperative green investment:*

- (i) *In the case of cooperative green investment, the greenness e_c^* of products determined by the supplier is higher than that in the case of single supplier's green investment.*
- (ii) *The greenness e_c^* with a cooperative increases with the increase in the manufacturers' share t of green products.*
- (iii) *In the case of a cooperative green investment, the green feasibility threshold value of the supplier's green investment is lower than that of the single supplier's green investment. Therefore, the supplier's choice*

space for a green investment is larger under the cooperative green situation.

Proof

- (i) Firstly, it is seen that $(\theta(a - c_1 - c_2)/4\mu - \theta) < (\theta(a - c_1 - c_2)/4(1-t)\mu - \theta)$ by comparing equation (11) with equation (20) because $0 < t < 1$. That is, in the case of cooperative, the greenness of a product determined by the supplier is higher than that in the case of a single supplier investment. When the manufacturer takes part in the green investment in intermediate components, the supplier is enthusiastic to carry out more green investment.
- (ii) Secondly, in equation (20), we use the optimal green level e_c^* to derive the manufacturer's green share t , we can get the result $(\partial e_c^*/\partial t) = (4\mu\theta(a - c_1 - c_2)/[4(1-t)\mu - \theta]^2)$, because $a > c_1 + c_2$, and $(\partial e_c^*/\partial t) > 0$ is calculated. That is to say, e_c^* is the increasing function of t , which increases with the increase in share t . It is understood that as the manufacturer's share of the green investment in intermediate components increases, the risk of the supplier will be reduced, and the efforts for green investment will be increased.
- (iii) Finally, it is similar to the case of the single supplier's green investment, that in the case of cooperative green, when the green product is uncertain, the supplier will only carry out the green investment if the profit of the green product is greater than that of no green investment. In other words, the condition $\prod_s(e) \geq \prod_s^N$, must be satisfied. That is to say, the following inequality must be satisfied:

$$\theta \bullet \frac{(a - c_1 - c_2 + e)^2}{8} - \frac{1}{2}(1-t)\mu e^2 \geq \frac{(a - c_1 - c_2)^2}{8}. \quad (21)$$

By substituting formula (20) into equation (21), the inequality can be rewritten as

$$\theta \bullet \frac{[a - c_1 - c_2 + (\theta(a - c_1 - c_2)/4(1 - t)\mu - \theta)]^2}{8} - \frac{1}{2}(1 - t)\mu \left[\frac{\theta(a - c_1 - c_2)}{4(1 - t)\mu - \theta} \right]^2 \geq \frac{(a - c_1 - c_2)^2}{8}. \quad (22)$$

The following result can be obtained by simplifying inequality (22):

$$\theta \geq \frac{4\mu(1 - t)}{4\mu(1 - t) + 1}. \quad (23)$$

Let $\bar{\omega} = (4\mu(1 - t)/4\mu(1 - t) + 1)$, where $\bar{\omega}$ is the green feasibility threshold value of the product in the green cooperative case. Only when the green feasibility factor $\theta \geq \bar{\omega}$, the supplier's green investment in the product will occur.

Comparing inequality (14) and inequality (23), it is easy to find that $(4\mu(1 - t)/(4\mu(1 - t) + 1)) < (4\mu/(4\mu + 1))$ and $\bar{\omega} < \xi$ because $0 < t < 1$. Because the supplier's selection range of green feasibility factors is $[4\mu/(4\mu + 1), 1]$ in the case of a single supplier's green investment, and the supplier's selection range of green feasibility factors is $[4\mu(1 - t)/(4\mu(1 - t) + 1), 1]$ in the case of cooperative green, as a result, the supplier's green feasibility threshold value in the case of a cooperative green is lower than that of the case of a single supplier. The supplier has more choice space for green investment in the case of a cooperative. For example, when the green feasibility factor of the green supply chain is in the range of $[\bar{\omega}, \xi]$, the feasibility factor θ does not reach the threshold value ξ because $\theta < \xi$ in the case of a single supplier. At this time, the expected revenue of the supplier from a green investment is negative, and the supplier will reject the green investment in the process of decision-making. However, the feasibility factor θ can reach the threshold value ξ because $\theta > \bar{\omega}$ in the case of green cooperative. At this time, the expected revenue of the supplier from the green investment is positive, and the supplier will accept the green investment in the process of decision-making.

It is understood that when the manufacturer shares the green investment in intermediate components, the minimum capital required for green products will be reduced, the supplier is more likely to make green investment. \square

Proposition 3

- (i) The share of the manufacturer's green cost decreases with the increase in supplier's green cost coefficient.
- (ii) The share of the manufacturer's green cost decreases with increase in the green feasibility factor.

Proof

- (i) First, the goal of the decision-making process of the manufacturer is to maximize its own profits in the case of green cooperative. Substituting equations (15) and (17) into equation (5), the manufacturer's revenue function can be rewritten as follows:

$$\prod_m = \frac{(a - c_1 - c_2 + e)^2}{16} - \frac{1}{2}t\mu e^2. \quad (24)$$

Substituting equation (20) into equation (24), the manufacturer's revenue function can be rewritten as follows:

$$\prod_m = \frac{[a - c_1 - c_2 + (\theta(a - c_1 - c_2)/4(1 - t)\mu - \theta)]^2}{16} - \frac{1}{2}t\mu \left[\frac{\theta(a - c_1 - c_2)}{4(1 - t)\mu - \theta} \right]^2. \quad (25)$$

- (i) In equation (25), we derive the manufacturer's revenue function \prod_m to the share t . Let $(\partial \prod_m / \partial t) = 0$, which allows to calculate out the green cost share of the manufacturer's profit maximization as follows:

$$t^* = \frac{4\mu(1 - \theta) + \theta^2}{4\mu(1 + \theta)}. \quad (26)$$

- (ii) In equation (26), we derive the supplier's green cost coefficient μ , and we obtain the following result:

$$\frac{\partial t^*}{\partial \mu} = \frac{\theta^2}{4(1 + \theta)} < 0. \quad (27)$$

- (iii) From equation (27), it can be seen that the green cost share of the manufacturer is a decreasing function of the supplier's green cost coefficient. That is, with the increase in the supplier's green cost coefficient, the cost and risk of the manufacturer's green cost will be increased, and the enthusiasm of the manufacturer for an investment will be reduced.

- (i) Secondly, in equation (26), we derive the green feasibility factor θ and can obtain the following result:

$$\frac{\partial t^*}{\partial \theta} = \frac{(\theta/2\mu) + (\theta^2/4\mu) - 2}{(1 + \theta)^2}. \quad (28)$$

- (ii) In equation (28), θ is in the range $[0, 1]$, so it can be proven that the range of μ is $\mu > (1/2)$ in this green supply chain model. We will prove it in the following way:
- (iii) In the process of green products, the revenue of the whole green supply chain is as follows:

$$\prod_T = \prod_s + \prod_m = q(a - q - c_1 - c_2 + e) - \frac{1}{2}\mu e^2. \quad (29)$$

- (iv) We can get the function of maximizing the revenue of the whole green supply chain through an optimization solution as follows:

$$\Pi_T^*(e) = \frac{(a - c_1 - c_2 + e)^2}{4} - \frac{1}{2}\mu e^2. \quad (30)$$

- (v) Because the marginal return rate of the green supply chain's input is decreasing, that is to say, it must meet the following condition:

$$\frac{\partial \Pi_T^*(e)}{\partial e^2} = \frac{1}{2} - \mu < 0. \quad (31)$$

It is easy to obtain $\mu > (1/2)$ from inequality (31). In equation (28), because $\theta \in [0, 1]$, $\mu > (1/2)$, it is to get the result $(\partial t^*/\partial \theta) < 0$ in equation (28), thus proving the conclusion.

$(\partial t^*/\partial \theta) < 0$ means that the manufacturer's share of green costs decreases with the increase in the green feasibility factor and vice versa. This result is a bit unexpected, but it can be explained. If the feasibility factor of green products is high and the uncertainty is small, the supplier itself will have a strong enthusiasm to invest in green products, whereas the manufacturer shall not need to share the cost of the green products. If the feasibility factor of the green product is reduced, the supplier will reduce the green investment. In extreme cases, if the feasibility factor of green product is lower than the threshold value $4\mu/(4\mu + 1)$, the supplier will reject the green investment. Therefore, the manufacturer should increase their share of green costs to encourage the supplier to carry out green investments when the feasibility factor of the green product is reduced. Otherwise, the benefits of the green product in the whole supply chain will be reduced.

In the result, we find that the green uncertainty will affect the investment level of the supplier and the investment share proportion of the manufacturer. With the increase of green feasibility, the supplier will make more green investment, and the share proportion of green investment undertaken by the manufacturer will be reduced. \square

6. Numerical Analysis

- (1) In order to explain the relationship between the supplier's optimal green input level and the cost coefficient, we let $\theta = 0.3$, $a = 1$, $c_1 = c_2 = 0.2$ and we take step length 0.1 in the range of $\mu \in [1, 5]$. It can be seen from Figure 3 that the optimal green input level of the supplier decreases with the increase in supplier's cost coefficient.
- (2) In order to explain the relationship between the optimal green level and the green feasibility factor and to compare the green level of the supplier under the condition of single green and cooperative green, we let $c_1 = c_2 = 0.2$, $t = 0.1$, and we take step length 0.1 in the range $\theta \in [0, 1]$. It can be seen from Figure 4 that the green level of the supplier increases with the increase in the green feasibility factor both in the case of a single supplier and a cooperative. The green level of the supplier in the case of a cooperative

is always higher than that in the case of single supplier.

- (3) In order to explain the difference of the optional choice space between the case of a single supplier and the case of a cooperative, we take the step length 0.1 in the range $\mu \in [1, 5]$ according equation (14) and equation (23). As can be seen in Figure 5, the critical threshold of the in the case of a single supplier is higher than in the case of a cooperative. The optional choice space S in the case of a single supplier is smaller than that in the case of a cooperative (i.e., C). The blue area is the extra choice space obtained as the difference of the choice space of a cooperative minus the choice space of a single supplier case.
- (4) In order to explain the relationship between the optimal green input level and the share of the manufacturer in the case of a cooperative, we let $\mu = 1$, $a = 1$, $c_1 = c_2 = 0.2$, and $\theta = 0.3$. In equation (20), we note that it must satisfy the condition $4(1 - t)\mu - \theta > 0$, thus satisfying $t < ((4\mu - \theta)/4\mu)$, that is, the range of t is $[0, 0.9]$. We take 0.1 as step in order to obtain figure. As seen from Figure 6, the optimal green input level increases with increase in the manufacturer's share of green cost.
- (5) In order to explain the relationship between the manufacturer's share of green costs and the supplier's green cost coefficient, we let $\theta = 0.3$ and we take step 0.1 in the range $\mu \in [1, 5]$ according equation (26). It can be seen from Figure 7 that the manufacturer's share of green costs decreases with the increase in the supplier's green cost coefficient.
- (6) In order to explain the relationship between the manufacturer's share of green cost and the green feasibility factor, we let $\mu = 1$ and we take step 0.1 in the range $\theta \in [0, 1]$ according to equation (26). It can be seen from Figure 8 that the manufacturer's share of green costs decreases with the increase in the green feasibility factor.

7. Results and Discussion

This paper studies the uncertainty of an environmental investment in a green supply chain. By constructing a Stackelberg model, we obtained the following results:

- (i) In this paper, the green uncertainty factor is added into the environmental investment decision in a green supply chain. It is found that this uncertainty factor has an important impact on the environmental investment. Although Zhang et al. considered the impact of different channel strategies (single channel or dual-channel) on the environmental investment decision-making in a green supply chain, uncertainty was not taken into account. Furthermore, we found the impact of green uncertainty factors was ignored in the previous literature.

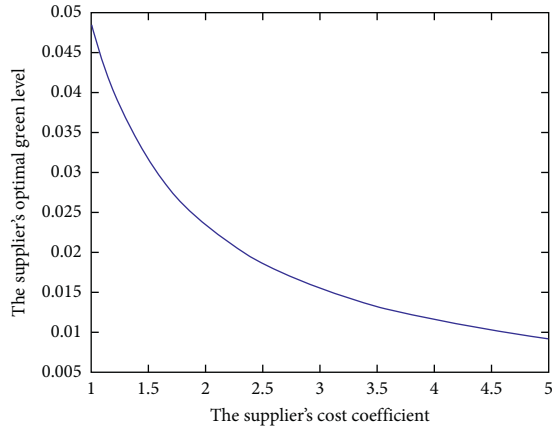


FIGURE 3: The relationship between the supplier's optimal green input level and the cost coefficient.

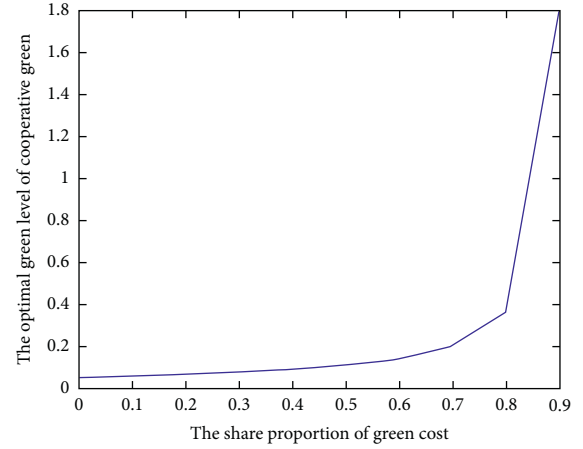


FIGURE 6: The relationship between the optimal green input level and the share of the manufacturer's green cost in the case of a cooperative.

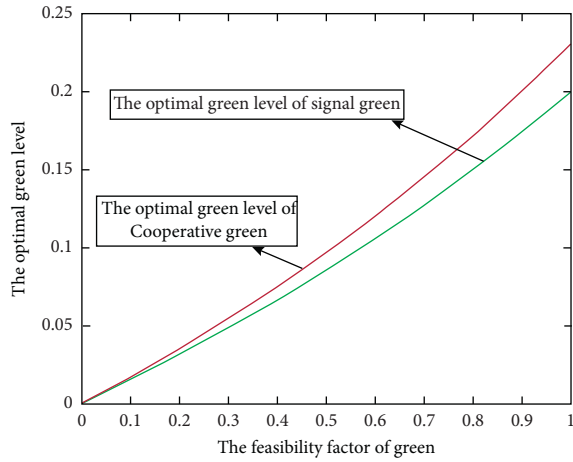


FIGURE 4: Comparing the green level of the supplier in the cases of a single supplier and a cooperative.

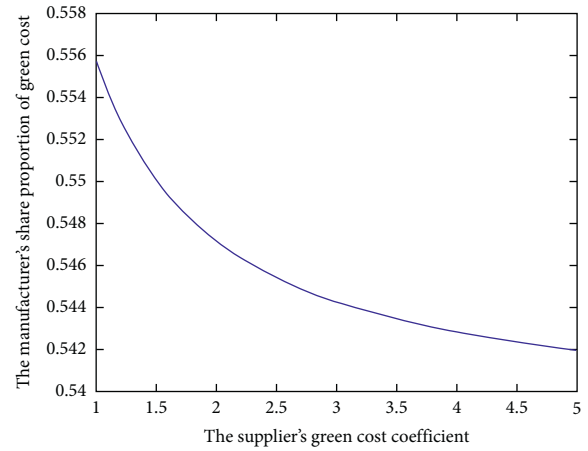


FIGURE 7: The relationship between the manufacturer's share of green cost and the supplier's green cost coefficient.

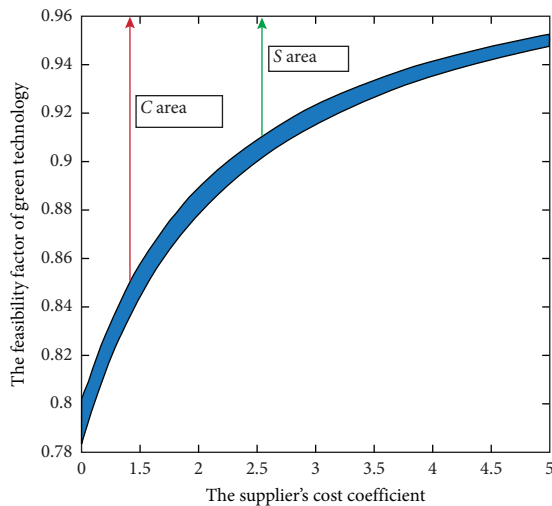


FIGURE 5: Comparing the choice space.

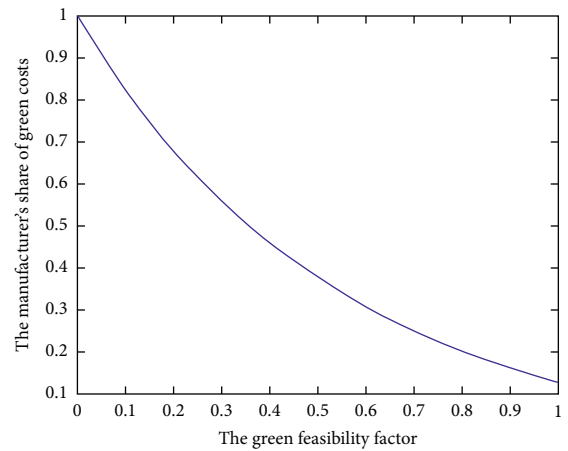


FIGURE 8: The relationship between the manufacturer's share of green cost and the green feasibility factor.

- (ii) In the case of a single supplier's green investment in intermediate components, the optimal green investment level of the supplier decreases with the increase in the green cost coefficient and increases with the increase in the green feasibility factor. Only when the green feasibility factor is higher than a certain threshold value can the supplier carry out a green investment. The possible reason is that, in the case of the single supplier's green investment, the supplier needs to consider the cost and risk factors for the green investment. The increase in the green cost coefficient will directly increase its cost, while the reduction of the green feasibility factor will increase the risk of its greening. Both of these can, in contrast, lead to the decrease in the supplier's return on the green investment and finally reduce their investment enthusiasm.
- (iii) In the case where the supplier and the manufacturer jointly carry out the green investment, the optimal green investment level of the supplier increases with the manufacturer's share of the green investment. The greenness of the products in this cooperative is higher than in the case of single supplier. Also, the choice space of the supplier for the green investment is also larger. The possible reason is that the participation of the manufacturer will reduce the cost and risk of the supplier's green investment. This shall reduce the threshold of the supplier's green investment and improve the supplier's choice space for the green investment, overall improving the supplier's enthusiasm for a green investment.
- (iv) The manufacturer's share of the green cost decreases with the increase in the supplier's green cost coefficient and increases with the decrease in the green feasibility factor. Consequently, the increase in the supplier's green cost coefficient will reduce the manufacturer's cost share, because the increase in the cost coefficient will increase the cost of the manufacturer's participation in the green investment. It seems unreasonable that the decrease in the green feasibility factor will lead to the increase in the manufacturer's cost share. One possible explanation is that the decrease in the green feasibility factor of the intermediate component means that the uncertainty of the green factors increases. To begin with, the supplier may not be willing to make a green investment, which will affect the income of the whole supply chain. As a response, the manufacturer should increase the share of the green cost and invest more in the greenness of the intermediate components' in order to encourage the supplier to make the green investment.

8. Conclusions, Managerial Implications, Limitations, and Future Research

8.1. Conclusions. Through this study of decision-making for an environmental investment in a supply chain, in the

presence of uncertainty of green products, it is found that the green uncertainty has an important impact on the green investment level of the supplier and the share of the green investment undertaken by the manufacturer. To better demonstrate the research contribution of this article, here we will answer the questions raised above:

- (i) What is the impact of supplier's green cost coefficient on the manufacturer's share of green cost and the supplier's input?

With the increase in the supplier's green cost coefficient, the supplier will reduce the green investment and the manufacturer will reduce the green share of costs.

- (ii) What is the impact of product uncertainty on product greenness and green investment of the manufacturer and the supplier?

With the green uncertainty of intermediate components decreases and the green feasibility factor increases, the supplier will increase the greenness of intermediate components and increase the green investment, and the manufacturer will reduce the share of green costs.

- (iii) What is the impact of the manufacturer's share of green cost on product greenness and the supplier's choice space?

The increase in the manufacturer's share of green cost will promote the supplier to increase the greenness of intermediate components and increase its green investment, and it will increase the supplier's optional choice space for the green investment. Considering the case when the manufacturer and the supplier are jointly making the green investment, the threshold value of the green input of the supply chain members (i.e., the manufacturer and the supplier) is lower. This allows the supply chain members to have more choice space. At the same time, the environmental effect in the case of this green cooperative is higher than that in the case of the single supplier.

8.2. Managerial Implications. Since there is little literature introducing the uncertainty into decision-making research with respect to the environmental investments in a green supply chain, this study attempts to fill in this research gap. We explore the impact of green uncertainty on investment, which can provide a reference for the manufacturer or the retailer in a green supply chain in adopting new strategies. Firstly, with the increase in the green cost coefficient of the supplier's intermediate components, both the supplier and the manufacturer will reduce the green investment. Therefore, in order to improve the greenness of products, the supplier should increase its green technology investment and reduce its green cost coefficient. Secondly, with the decrease in uncertainty and the increase in the green technology feasibility factor, the supplier should be more willing to increase the green investment in intermediate

components, and the manufacturer could rely more on the supplier for green products. The manufacturer can reduce the uncertainty of green products and encourage the suppliers to increase green investment by adopting various measures such as technology prediction and product demand prediction. Thirdly, since the increase in the manufacturer's share of green costs will promote the supplier to increase the greenness of intermediate components and reduce the risk for the supplier, it is an important means for the manufacturer to increase their share of green cost in the cooperation process, so as to encourage the supplier's green investment. Lastly, the manufacturers' participation in a green investment can reduce the level of the green investment in a supply chain and expand the feasibility range of the green investment for the supplier, which makes it more possible for the supplier to invest in a green technology that could have higher uncertainty. Therefore, the participation of the manufacturer in the process of investing in green products is particularly important.

8.3. Limitations and Future Research. There are several limitations to this paper, which may be worth further exploring. Firstly, we have studied the sequential green decision-making of a manufacturer and a supplier under the conditions of uncertainty. However, we did not investigate the coordination problem of the overall revenue maximization of the green supply chain, which is an important issue to be studied in the future. Secondly, in order to simplify the analysis, this paper only considers a two-echelon green supply chain composed of one manufacturer and one supplier and does not consider the supply chain composed of multiple suppliers and one manufacturer. In fact, there may be multiple participants that could affect the green decision of all supply chain parties. Thirdly, in the process of considering the impact of green uncertainty on the decision of supply chain members, this paper ignores that the green input of supply chain may lead to the change of consumer demand, which in turn affects the green input decision of supply chain. For this reason, future research should consider the green uncertainty's influence on the coordination of the supply chain and add factors such as consumer demand and multiple participants in green supply chain.

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.

Authors' Contributions

Shaobo Wu conceptualized the study. Xun Yao wrote the original study. Guangdong Wu reviewed and edited the article.

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Research Article

A Relationship Model between Top Management Team Cognitive Heterogeneity and Strategic Decision Quality and Its Implications for Sustainability

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To achieve sustainable development, a top management team (TMT) and the quality of its strategic decisions on sustainability are critical. This paper builds a relationship model between top management team (TMT) cognitive heterogeneity and the quality of strategic decisions. This research is important because TMT cognitive heterogeneity can comport decision-making schemes with complex and changing environments. Specifically, this paper explores the intermediary role of the team fusion process composed of different shareholders' agents in integrating TMT heterogeneous cognition to improve the quality of strategic decisions. It adopts the upper echelon theory, which proposes that decision-makers have limited rationality and face difficulty in collecting and analyzing information in complex and changing environments. A questionnaire survey of 107 Chinese enterprises was conducted. Through the research framework of "cognitive heterogeneity–team fusion–strategic decision quality," this paper constructs a moderated mediator model with entrepreneurial spirit as the moderating variable. Based on statistical analysis, the following results and contributions are obtained. First, TMT cognitive heterogeneity positively affected strategic decision quality. Second, two dimensions of team fusion—information integration and emotional fusion—mediated the relationship between TMT cognitive heterogeneity and strategic decision quality. Third, entrepreneurial spirit positively moderated the relationship between information integration and strategic decision quality, as well as the relationship between emotional fusion and strategic decision quality. The implications of our results related to sustainability are also discussed.

1. Introduction

Sustainability has become a critical issue worldwide. To this end, top management team (TMT) of a firm and the quality of their strategic decisions on sustainability play important roles. This is especially true in developing countries. In China, the reform of state-owned enterprises (SOEs) has been highly complex and challenging. It emphasizes not only optimizing ownership and governance structures but also improving management [1]. Given the complexities and uncertainties of reform, whether the mix of state-owned and private capital will promote high-quality sustainable development ultimately rests with the top management team (TMT), which oversees strategic decision-making. The low-

carbon sustainable development has become a potential mechanism for enterprises to gain competitive advantages and an important aspect of enterprise strategic management. TMT members representing different shareholders have different values, cognition, and behavioral habits, including those related to low-carbon and sustainable development. Managers from SOEs tend to be administratively focused, while those from private enterprises tend to be paternalistic. It is found that managers' perceptions of different types of shareholder drive the sustainability practices in firms [2]. Managers' different cognition of low-carbon and sustainable development leads to different strategies on sustainability. The reform process is bound to undergo adaptation, where a lack of TMT fusion will only increase friction and hinder the

reform. The fusion of TMT members will help maintain the sustainable development of mixed-ownership enterprises. Building TMTs through entrepreneurship is key to enhance innovation and sustain reform. Studies on mixed-ownership reform have mainly focused on ownership and governance structures, including how to mix the property rights or capital of enterprises [3–5]. However, there is a lack of research on how TMT members, representing different shareholders, can mutually integrate.

2. Literature Review

Green management of enterprises often requires the change of the existing corporate culture, which requires the support of TMT [6]. Managers with strong environmental awareness can identify the market opportunities of green innovation [7]. According to upper echelons theory proposed by Hambrick and Mason [8], the TMT is the main strategic decision-maker regarding enterprise strategy. Cognitive heterogeneity and behavior processes largely determine the quality of strategic decisions and the effects of corporate governance. According to information and decision theory, heterogeneity of team members positively affects team performance [9], while social classification theory does the opposite [10]. Olson et al. [11] found that Chinese TMT heterogeneity has a negative effect on decision-making performance due to collectivism and the avoidance of uncertainty. TMT members with different cognitions have different beliefs regarding strategic objectives, and the results of collecting and processing information are diverse [12]. The TMT is the actual executor of the mixed-ownership reform. Team members strengthen the complementary advantages and resources of state-owned and private capital, and they promote the mixed-ownership reform of SOEs through team processes, such as transmitting information as well as easing ideological barriers [13]. There is a need, therefore, to investigate how the cognitive heterogeneity of TMTs, after mixed-ownership reform, can promote cooperation and improve the quality of strategic decisions through psychological and behavioral integration.

Mixed-ownership reform encourages market mechanisms to improve SOE management; thus, an entrepreneurial spirit is preponderant for effectuating high-quality change and development [14]. According to Drucker [15], the entrepreneurial spirit is unrelated to ownership, and anyone with the courage to make decisions, implement reforms, pursue innovation, and create value can display it. Entrepreneurial spirit reflects the strategic orientation of decision-makers. At the individual level, innovation is the essential characteristic of entrepreneurship, whereas, at the team level, it has richer connotations. A TMT with an entrepreneurial spirit can help its heterogeneous members judge potential risks and, by jointly shouldering them, can alleviate the concomitant pressures and possible economic losses; thus, it is collaborative and progressive [16]. Currently, research on the entrepreneurial spirit at the team level is lacking.

Based on the research framework of “cognitive heterogeneity–team fusion–strategic decision quality,” this paper constructed a moderated mediator model with

entrepreneurial spirit as the moderating variable. The effects of TMT cognitive heterogeneity on strategic decision quality in mixed enterprises was empirically tested, along with the team fusion’s mediating function under the moderation of entrepreneurship. This work has theoretical and practical value for studying the influencing factors of strategic decision quality in mixed enterprises in China and for improving TMTs’ governance efficiency.

3. Theory and Hypotheses

3.1. Cognitive Heterogeneity and Strategic Decision Quality. Enterprises should consider environmental responsibility when formulating business strategy. The concept of sustainable development and green business model will redefine the traditional business models. Enterprises can actively consider the interactions between business and natural environment to form new competitive advantages. Green strategy is a new strategy for gaining competitive advantages, which involves not only financial benefits but also environmental benefits and corporate responsibility for nature and society. It is more complex than *strategic decision* in general. The TMT directly affects enterprise competitiveness and future sustainability, since it is at the heart of enterprise decision-making and development. In a complex business environment, TMTs’ choices and implementation of enterprise strategy are influenced by their cognitive ability, values, and so on [17].

Strategic decision quality usually refers to the contribution of decision-making to achieving organizational goals [18]. When evaluating strategic decision quality, it is important to consider the contribution of strategic decisions to realizing organizational innovation objectives and improving the allocation of resources. Decision-makers’ cognition includes their capacity to analyze and manage problems, as well as their strategic wisdom, which determine whether they can make strategic decisions and create competitive advantage [19]. According to upper echelons theory, decision-makers have limited rationality and face difficulty in collecting and analyzing information in complex and changing environments [20]. High-quality decisions should multidimensionally consider both internal and external information. Thus, enterprises need collaborative TMTs and those have diverse cognition so they will not be limited by prior experience or neglect important factors in decision-making [21].

TMT cognitive heterogeneity refers to differences in the cognition of important concepts among team members [22]. Due to the diversified ownership structure of mixed-ownership enterprises, TMT members represent the interests of different shareholders with different perceptions of corporate innovation and decision-making. Strategic decision-making involves the processing of information. Cognitive heterogeneity provides different perspectives for the TMT to discover opportunities and identify risks [23], increasing the possibility of making high-quality strategic decisions. The different backgrounds and expertise of TMT members in mixed enterprises can help them cope with business challenges related to environmental uncertainty and rapid

technological change, and such diverse cognitive resources can also positively influence enterprise innovation [24].

Diversified cognition can amplify the signals of key cognitive resources on the team and help members identify useful information, thus enhancing the team's core creativity [25]. According to Sahaym et al. [26], TMT heterogeneity can promote the use of venture capital (within certain limits), and the risk-taking propensity of team members is the driving factor of the company's risk-taking behavior. The reorganization and integration of different types of capital driven by innovation cause enterprises to face more risks and challenges. TMTs should have not only diversified cognition of fuzzy and complex information but also an innovative spirit for undertaking risks so they can make high-quality strategic decisions that will meet the requirements of mixed-ownership reform.

TMT cognitive heterogeneity can comport decision-making schemes with complex and changing environments. TMTs face complex innovation-driven environmental pressures from uncertainty; thus, high cognitive heterogeneity is especially needed for strategic decision-making. TMT's heterogeneous knowledge is important for overall managerial and innovation performances [27]. Therefore, when TMT members have heterogeneous cognitive and information-processing abilities, they will be more sensitive to both threats and innovation opportunities, which can increase the possibility of making timely decisions related to innovation and development. Meanwhile, a lack of heterogeneity will reduce the team's cognitive flexibility, hindering their willingness to obtain more information or make changes. Therefore, with mixed shareholders, TMT cognitive heterogeneity enables companies to make innovative, high-quality decisions that can create breakthroughs in business management and production technology. Thus, we propose the following hypothesis.

Hypothesis 1. TMT cognitive heterogeneity positively affects strategic decision quality in mixed enterprises.

3.2. Mediating Effect of Team Fusion. The sustainable strategy of enterprises requires the active participation of TMT to balance their interests. It also requires changing the traditional organizational culture. Enterprises should establish an environment-oriented thinking, consider the ecological environment in their work, establish a sense of responsibility for environmental protection, cultivate a sustainable oriented organizational culture, and establish an organizational environmental reputation. The SOEs typically bear more social responsibilities. Their contributions to environmental protection are an important measure of their managers' performance. Therefore, managers from SOEs are more aware of environmental protection and sustainability, while those of non-SOEs pay more attention to economic interests than to environmental protection.

Mixed capital is the external expression of the mixed-ownership reform of SOEs. To realize the complementary advantages of different ownerships and to avoid "mixture without fusion," it is important to integrate production factors for optimal resource allocation [28]. According to

Chen and Lu [13], mixed-ownership reform intends to overcome systemic barriers between SOEs and private enterprises and bridge their TMTs. Such fusion of TMT members is key to integrating shareholder resources, improving the efficiency of corporate governance, and achieving sustainable development.

Fusion is a process of team interaction, which can help the team become coherent through information exchange and emotional communication, thereby integrating resources and pursuing joint decision-making. The team effectiveness model (IPO model) incorporates a characteristic variable and a process variable into a unified research framework. The literature has found that the process variable not only plays an important role in team effectiveness but also functions as a mediator between the characteristic variable and the result variable [29]. Cognitive heterogeneity in TMTs is manifested through internal interactions [30], and team performance is improved via high-level interpersonal interactions within the teams [31]. Ge [32] proposed that decision-making interactions in TMTs include two processes: information and emotional. Therefore, our study examines the mediating effect between TMT cognitive heterogeneity and strategic decision quality in terms of information integration at the behavioral level and emotional integration at the psychological level.

The information integration of TMTs involves transmitting, communicating, and discussing information collected and processed by members. Through these activities, the integration of information can be realized, which is an important process for team members to integrate. TMT decision-making is the process of collecting and processing that information. In upper echelons theory, TMTs must promote cooperation and joint decision-making through high-quality information exchange to effectively formulate and implement organizational strategic plans [33]; decision-making levels can only be improved by fully sharing information and resources. High-level information exchange among TMTs in mixed enterprises can facilitate the full sharing of information needed for strategic decision-making. In addition, information sharing can reduce the pressures caused by disagreements among members.

From the perspective of interactive cognition, when members possessing different knowledge, skills, thinking styles, and perspectives communicate information and viewpoints, they also contribute to creative decision-making and to finding better solutions [34]. TMT cognitive heterogeneity can thus help overcome cognitive bias in group decision-making and identify optimal choices by increasing discussion through the dissemination of knowledge and information [35]. In mixed enterprises, TMT members collect and process information from the different perspectives of the shareholders, which can provide more diverse and comprehensive data for decision-making. This helps to facilitate joint decision-making, thus avoiding the "groupthink." Therefore, in decision-making interactions among members of mixed enterprises, cognitive heterogeneity affects the validity of information integration, which in turn affects strategic decision quality.

Thus, we propose the following hypothesis.

Hypothesis 2. Information integration mediates the process of TMT cognitive heterogeneity, influencing strategic decision quality in mixed enterprises.

Fusion means cohesion, which refers to the closeness of the connections between team members and their sense of team-belonging [36]. TMT heterogeneity can integrate various information for the team and may also lead to conflicts that impede TMT's ability to reach consensus. TMT cognitive conflict improves the quality of information exchange, but the emotion conflict triggered by cognitive conflict can hurt the team's cohesion and the quality of their decision-making [37]. Therefore, emotion conflict should be eliminated by emotional fusion. Emotional fusion in TMTs refers to interactive processes that enhance emotional trust, dissolve conflicts, and improve cohesive force among members. Team cohesion and team performance are closely related [38]. In a team with high cohesion, members' fidelity to the team can be improved, a good working atmosphere can be formed, and mutual influence among members can be strengthened. In this way, members can steadily respond to the team's demands, which can, in turn, improve team performance. Therefore, the emotional fusion of TMTs in mixed enterprises is an important factor that affects team decision quality. Improving team fusion results from continuously developing the team. From the beginning, team members are familiar with each other and jockey for position. After experiencing conflicts or disagreement, they gradually reach consensus and establish norms, focusing on efficiency and coordination and finally achieving integration [36]. Hence, by encouraging TMT members to express their own opinions and innovations, stimulating them to make strategic decisions together, and granting them decision-making power, they will be more willing to fully exercise their own power. It is an effective solution to reduce emotional conflict and create emotional fusion of TMT.

Organizations often experience friction and incompatibility [28]. This is because SOEs and non-SOEs have different corporate cultures and management styles, and, after integration, TMTs must deal with conflicting corporate management philosophies and values [39]. Thus, in the absence of emotional fusion, personal incompatibilities may arise, which can make the team atmosphere tense and hinder the dissemination of useful information for decision-making. The heterogeneous ownership of mixed enterprises creates a potential emotional fracture zone that can create conflicts of interest and affect decision-making quality [40]. Team cohesion can reduce such friction. Thus, emotional fusion among TMT members in mixed enterprises can help resolve conflicts and enhance team cohesion. Therefore, we propose the following hypothesis.

Hypothesis 3. Emotional fusion mediates the process of TMT cognitive heterogeneity, influencing strategic decision quality.

3.3. Moderating Effect of Entrepreneurial Spirit. Entrepreneurial spirit is the driving force of economic growth, and efficiency improvements brought about by innovation represent the optimal practice of

entrepreneurship [41]. According to Drucker [15], the essence of the entrepreneurial spirit consists of targeted, systematic organizational innovation that substantially improves productivity and creates value by changing products and services. Zhang [42] suggested that SOE managers are not truly entrepreneurial due to the peculiarity of the principal-agent relationship and the finiteness of the liabilities they assume. However, in the mixed-enterprise context, SOE managers must innovate to improve allocation efficiency, participate in intense market competition, and undertake market risks. In this sense, they too are entrepreneurs characterized by innovative thinking [43]. The cultivation of an entrepreneurial spirit among the TMTs of mixed-reform SOEs does not, therefore, contravene with the form of enterprise ownership. Only when an enterprise is managed by a TMT with a true entrepreneurial spirit can various problems facing the organization be effectively solved. Fritsch and Mueller [44] proposed three dimensions of entrepreneurship—innovation, risk taking, and proactive action—taking them as criteria for judging whether an individual or organization possesses an entrepreneurial spirit. Several studies have adopted these criteria. Chen [45], for example, added collective innovation, cognitive sharing, risk sharing, and collaborative progress to the criteria for assessing the entrepreneurial spirit of TMTs.

TMT members imbued with collective innovation will actively identify innovative opportunities, collect information, exchange opinions to deal with decision-making problems, and gladly adopt democratic decision-making practices. In making decisions, heterogeneous members can scientifically evaluate the potential risks and rewards of different decisions from different perspectives. Sharing cognition can broaden the individual's cognitive boundaries, improve the overall cognitive level of the team, reduce pick-up behavior, and provide sufficient information resources for high-quality decision-making.

Mixed-ownership reform faces various uncertainties, and risks can arise when members consider decision-making from their individual knowledge base, and heterogeneous members might also have different risk preferences. However, a sense of risk sharing can promote integration between risk-averse and risk-tolerant team members, helping to reach consensus so they will not miss opportunities for innovation. In addition, if TMT members are only willing to work independently and lack coordination with other, even with an innovative sense, the team ultimately lacks an entrepreneurial spirit. A cooperative and progressive entrepreneurial spirit can enable the heterogeneous knowledge and capacities of team members to work together, which will improve the efficiency and quality of information processing. Therefore, we propose the following hypothesis.

Hypothesis 4. Entrepreneurial spirit positively moderates the effect of information integration on strategic decision quality and moderates the mediating effect of information integration.

Since TMT cognitive heterogeneity can create conflict, collective innovation can consolidate team members' strength to produce a centripetal force for the organization,

thereby promoting decision-making. If team members lack a spirit of collective innovation, individuals or subgroups may jockey for position, destroying the harmonious atmosphere and hindering integration. Cognitive sharing can help eliminate information asymmetry, facilitate the heterogeneous cognition of decision-making problems, and enhance close connections. In a complicated and changing context of reform, decisions must be made based on a great deal of fuzzy information. Risk sharing can alleviate the pressure on team members to undertake risks independently, thus avoiding a failure to innovate over fears of potential risks. While heterogeneous TMT members will inevitably disagree, the desire for collaborative progress can facilitate consensus, avoid decision-making failure, and increase interdependence among members in the joint pursuit of goals. Therefore, we propose the following hypothesis.

Hypothesis 5. Entrepreneurial spirit positively moderates the effect of emotional fusion on strategic decision quality and moderates the mediation effect of emotional fusion.

Figure 1 shows the theoretical framework of the study.

4. Method

4.1. Research Objects and the Survey. Three commercial companies in Shanghai, one of the most developed regions of mixed-ownership enterprises in China, were selected for in-depth interviews, and a questionnaire was designed based on the literature and interview results. A total of 160 mixed-ownership enterprises (state-owned, private, and foreign cross-owned enterprises) in eight provinces and cities (Shanghai, Jiangsu, Zhejiang, Guangdong, Beijing, Heilongjiang, Inner Mongolia, and Xinjiang) were selected for the survey. The survey was conducted in two ways: (1) MBA students delivered questionnaires to TMTs and collected and returned the completed surveys, and (2) questionnaires were sent via e-mail or post, relying on management consultancies to contact the relevant people. The objects of the questionnaire were TMT members involved in decision-making within an enterprise. Each TMT member of the 160 enterprises had one questionnaire. In total, 1,249 questionnaires were distributed, and 906 were collected. Questionnaires from those with incomplete data were eliminated. Finally, 727 valid questionnaires from 107 enterprises were collected (effective recovery rate of questionnaires: 68.8%). Respondents below 30 years of age accounted for 0.4%; 29.7% were 31–40 years old; 53.8% were 41–50 years old; and 16.1% were 51 years old or older. Meanwhile, 8.8% had some college or no college; 44.7% had an undergraduate education; and 46.5% had a master's degree or above. Finally, 74.6% had been in their position for less than five years, while 25.4% had held their position for more than five years.

4.2. Measurement Tools. All items used the seven-point Likert scale (1 = “completely disagree” and 7 = “completely agree”). Their details are given in the Appendix.

Based on Zhao et al.'s work [46], cognitive heterogeneity was measured in three dimensions: enterprise development

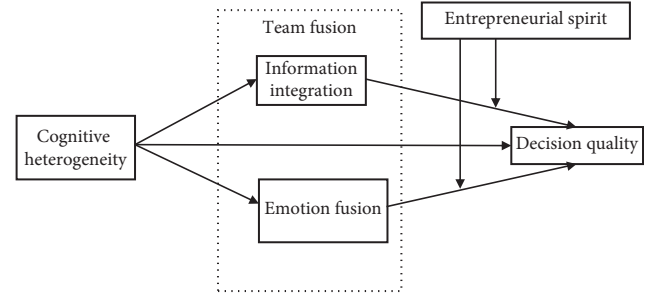


FIGURE 1: Theoretical framework of the study.

route, competitive advantage, and scheme implementation, such as the item “Long-term enterprise development routes are not unified within the team.” Cronbach’s α coefficient was 0.847.

Team fusion was mainly measured in the two dimensions of information integration and emotional fusion. The measurement of information integration referred to the questionnaire proposed by Simsek et al. [47]. There were three items, such as “Team members often communicate their different opinions on decision-making problems.” In our study, Cronbach’s α coefficient was 0.804. The measurement of emotional fusion referred to Ge’s [32] questionnaire for measuring emotional trust and conflict management. There were three items, such as “Team members can share freely their ideas, feelings, and expectations to create a good sharing atmosphere.” Cronbach’s α coefficient was 0.817.

The measurement of entrepreneurial spirit referred to Chen and Hao’s work [16] and included the four dimensions of collective innovation, cognition sharing, risk sharing, and collaborative progress. There were eight items, such as “Each member is willing to acquire resources in multiple ways to form innovative decision-making schemes.” Cronbach’s α coefficient was 0.829.

The measurement of strategic decision quality referred to the questionnaire designed by Huang et al. [48] to define the high-quality development of SOEs and included the two dimensions of resource allocation efficiency and innovativeness. It had three items, such as “The team’s decision-making scheme has positive effects for the enterprise to improve resource allocation efficiency.” Cronbach’s α coefficient was 0.792.

The control variables included the members of the TMT as well as age, education, and tenure. The values for education were as follows: 1 = some college or less; 2 = undergraduate degree; and 3 = master’s degree or above.

Amos 24.0 and SPSS 25.0 were used for statistical analysis.

5. Results

5.1. Confirmatory Factor Analysis and Validity Test. Confirmatory factor analysis in AMOS tested the validity of the five variables (i.e., cognitive heterogeneity, information integration, team fusion, entrepreneurial spirit, and strategic decision quality). Table 1 indicates that all fit indexes of the

TABLE 1: Confirmatory factor analysis.

| Fit indexes | | χ^2/df | RMSEA | TLI | CFI | IFI |
|--------------------|------------------------|-------------|-------|-------|-------|-------|
| Five-factor model | CH; II; EF; ES; DQ | 1.543 | 0.037 | 0.979 | 0.984 | 0.984 |
| Four-factor model | CH; II + EF; ES; DQ | 5.612 | 0.091 | 0.853 | 0.876 | 0.876 |
| Three-factor model | CH; II + EF + ES; DQ | 8.608 | 0.137 | 0.705 | 0.766 | 0.767 |
| Two-factor model | CH + II + EF + ES; DQ | 13.691 | 0.177 | 0.508 | 0.597 | 0.597 |
| One-factor model | CH + II + EF + ES + DQ | 17.691 | 0.203 | 0.353 | 0.461 | 0.462 |

Notes: CH is cognitive heterogeneity; II is information integration; EF is emotional fusion; ES is entrepreneurial spirit; DQ is strategic decision quality.

five-factor model are ideal ($\chi^2/df=1.543$, RMSEA = 0.037, IFI = 0.984, CFI = 0.984, and TLI = 0.979). The fit coefficients are better than those of the other models in the table, indicating that the variables have better discriminate validity.

5.1.1. Aggregation Test. To check whether the measurement results of the individual variables could aggregate to the team level, we adopted the intrateam consistency coefficient Rwg and the interteam diversity factors ICC(1) and ICC(2). Table 2 shows that all the five variables satisfied the aggregation standards of Rwg > 0.7, ICC(1) > 0.05, and ICC(2) > 0.5, indicating that the individual data of the five variables could aggregate to the team level for statistical analysis.

Since self-report questionnaires and single-source data can lead to common-method variance, Harman's single-factor test was adopted. Twenty terms were placed at the same time in one exploratory factor analysis. The variance explanation rate of the first common factor extracted from the analysis results of unrotated factors was 32.252%, which is below 40%, indicating that the influence of common-source deviation on the data was within the acceptable scope.

5.1.2. Descriptive Statistical Analysis and Correlation Analysis. Table 3 shows that strategic decision quality ($r=0.282$, $p<0.01$), information integration ($r=0.277$, $p<0.01$), and emotional fusion ($r=0.163$, $p<0.01$) were significantly positively correlated with cognitive heterogeneity. Information integration ($r=0.326$, $p<0.01$) and emotional fusion ($r=0.352$, $p<0.01$) were significantly positively correlated with strategic decision quality.

5.1.3. Test Results for the Hypotheses. Hierarchical regression was used to test the hypotheses; Table 4 shows the results. As can be seen from Model 1 and Model 2, the independent variable cognitive heterogeneity had a significant positive correlation with the mediating variable information integration ($\beta=0.78$, $p<0.01$) and emotional fusion ($\beta=0.275$, $p<0.001$). Model 3 shows that the independent variable cognitive heterogeneity has a significant positive correlation with the dependent variable strategic decision quality ($\beta=0.265$, $p<0.001$); thus, Hypothesis 1 is supported. From Model 4, we see that the mediating variables information integration ($\beta=0.223$, $p<0.001$) and emotional fusion ($\beta=0.240$, $p<0.001$) have significant positive correlations with the dependent variable, strategic decision quality. After adding the mediating variable, the positive influence of cognitive heterogeneity on strategic decision quality is still

significant ($\beta=0.161$, $p<0.001$) but weaker. It can thus be seen that information integration and emotional fusion have partial mediating effects between cognitive heterogeneity and strategic decision quality. From Model 5, we see that the interactive term between entrepreneurial spirit and information ($\beta=0.189$, $p<0.05$), emotional fusion ($\beta=0.151$, $p<0.05$), and strategic decision quality is positively correlated.

To further verify the mediating effects of information integration and emotional fusion and the regulating function of entrepreneurial spirit, we adopted the deviation-corrected percentile bootstrap method, as recommended by Fang et al. [49]. PROCESS 3.1 in SPSS was used to analyze the mediation model, the regulation model, and the combined model. A total of 5,000 bootstrapped samples were used, and the confidence interval result was 95%. Table 5 displays the results of bootstrapping analysis for the mediating effects. The indirect effects of cognitive heterogeneity on strategic decision quality through information integration and emotional fusion were 0.061 and 0.043, respectively; the total indirect effect was 0.104; and the direct effect was 0.161. Since 0 is not included in the confidence interval, the mediation relations were all significant, and some showed mediating effects. Thus, Hypotheses 2 and 3 are supported: information integration and emotional fusion have mediating effects between cognitive heterogeneity and strategic decision quality.

To verify the adjusted mediating effect, the indirect effect of the variable under different values was directly obtained through the process operation. This automatically operates different values by reducing one standard deviation and adding one standard deviation based on the mean value of the moderating variable (entrepreneurial spirit) to form the low and high groups. Table 6 shows that when entrepreneurial spirit is weak, the indirect effect of cognitive heterogeneity on strategic decision quality through information integration is 0.018. Zero is included in the confidence interval, indicating that when entrepreneurial spirit is weak, the indirect effect of cognitive heterogeneity on strategic decision quality through information integration is not significant. When entrepreneurial spirit is strong, the indirect effect of cognitive heterogeneity on strategic decision quality through information integration is 0.081. Zero is not included in the confidence interval, indicating that when entrepreneurial spirit is strong, the indirect effect of cognitive heterogeneity on strategic decision quality through information integration is significant. In addition, as seen in the adjusted coefficient of the mediating effect, the effect value is 0.052 (confidence interval [0.013, 0.096]). Zero is not

TABLE 2: Aggregation test.

| Variables | Rwg | ICC (1) | ICC (2) |
|----------------------------|-------|---------|---------|
| Cognitive heterogeneity | 0.801 | 0.491 | 0.870 |
| Information integration | 0.798 | 0.387 | 0.815 |
| Emotional fusion | 0.832 | 0.479 | 0.865 |
| Entrepreneurial spirit | 0.796 | 0.432 | 0.753 |
| Strategic decision quality | 0.757 | 0.488 | 0.869 |

Common-method variance test.

TABLE 3: Standard deviations, mean values, and correlation coefficients of the variables.

| | Mean value | Standard deviation | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------------------------------|------------|--------------------|---------|--------|---------|---------|---------|---------|---------|---------|
| (1) Team members | 6.793 | 1.841 | | | | | | | | |
| (2) Age | 43.580 | 5.627 | −0.027 | | | | | | | |
| (3) Education | 2.377 | 0.643 | 0.005 | 0.051 | | | | | | |
| (4) Tenure | 3.200 | 1.186 | 0.155** | −0.046 | 0.065 | | | | | |
| (5) Cognitive heterogeneity | 4.994 | 1.096 | 0.102 | −0.055 | 0.064 | 0.049 | | | | |
| (6) Information integration | 4.732 | 1.089 | 0.025 | 0.060 | 0.081 | 0.033 | 0.277** | | | |
| (7) Emotional fusion | 4.452 | 1.246 | −0.011 | −0.003 | 0.091 | 0.136* | 0.163** | 0.222** | | |
| (8) Entrepreneurial spirit | 4.679 | 1.132 | 0.280 | 0.419 | 0.383 | 0.265 | 0.121* | 0.257** | 0.358** | |
| (9) Strategic decision quality | 4.527 | 1.136 | 0.237** | −0.013 | 0.151** | 0.164** | 0.282** | 0.326** | 0.352** | 0.348** |

Note: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

TABLE 4: Results of hierarchical regression analysis.

| Dependent variables | Information integration | Emotional fusion | Strategic decision quality | | |
|--|-------------------------|------------------|----------------------------|-----------|-----------|
| | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 |
| Team scale | −0.028 | 0.002 | 0.102 | 0.109 | 0.112*** |
| Age | 0.001 | 0.012 | 0.002 | −0.001 | −0.002 |
| Education | 0.135 | 0.094 | 0.206 | 0.153 | 0.161* |
| Term | 0.130* | −0.008 | 0.106 | 0.076 | 0.071 |
| Cognitive heterogeneity | 0.178** | 0.275*** | 0.265*** | 0.161*** | 0.175*** |
| Information integration | | | | 0.223*** | 0.180*** |
| Emotional fusion | | | | 0.240*** | 0.180*** |
| Entrepreneurial spirit | | | | | 0.308*** |
| Information integration × entrepreneurial spirit | | | | | 0.189* |
| Emotional fusion × entrepreneurial spirit | | | | | 0.151* |
| R^2 | 0.048 | 0.084 | 0.140 | 0.267 | 0.334 |
| F | 4.013* | 7.366*** | 12.970*** | 20.695*** | 19.813*** |

Note: $N = 727$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

TABLE 5: Bootstrapping analysis results of the mediating effects.

| Effect | Effect | BootSE | BootLLCI | BootULCI |
|---|--------|--------|----------|----------|
| Total effect: cognitive heterogeneity → strategic decision quality | 0.265 | 0.048 | 0.170 | 0.360 |
| Direct effect: cognitive heterogeneity → strategic decision quality | 0.161 | 0.047 | 0.069 | 0.253 |
| Total indirect effect | 0.104 | 0.021 | 0.066 | 0.148 |
| Indirect effect of information integration | 0.061 | 0.015 | 0.033 | 0.093 |
| Indirect effect of emotional fusion | 0.043 | 0.015 | 0.015 | 0.075 |
| Difference comparison of indirect effects | −0.019 | 0.023 | −0.062 | 0.025 |

included in the confidence interval, indicating that entrepreneurial spirit has an adjusted mediating effect in the path of cognitive heterogeneity influencing strategic decision quality through information integration; thus, Hypothesis 4 is supported.

When entrepreneurial spirit is weak, the indirect effect of cognitive heterogeneity on strategic decision quality through emotional fusion is 0.016. Zero is included in the confidence

interval, indicating that when entrepreneurial spirit is weak, the indirect effect of cognitive heterogeneity on strategic decision quality through emotional fusion is not significant. When entrepreneurial spirit is strong, the indirect effect of cognitive heterogeneity on strategic decision quality through emotional fusion is 0.048. Zero is not included in the confidence interval, indicating that when entrepreneurial spirit is strong, the indirect effect of cognitive heterogeneity

TABLE 6: Analysis of moderate mediating effect.

| Indirect effect | Entrepreneurial spirit | Effect | BootSE | BootLLCI | BootULCI |
|--|------------------------|--------|--------|----------|----------|
| Cognitive heterogeneity \rightarrow information integration \rightarrow strategic decision quality | −1SD | 0.018 | 0.016 | −0.014 | 0.051 |
| | SD | 0.049 | 0.014 | 0.024 | 0.079 |
| | 1SD | 0.081 | 0.021 | 0.042 | 0.124 |
| | Moderated mediation | 0.052 | 0.021 | 0.013 | 0.096 |
| Cognitive heterogeneity \rightarrow emotional fusion \rightarrow strategic decision quality | −1SD | 0.016 | 0.012 | −0.005 | 0.043 |
| | SD | 0.032 | 0.012 | 0.010 | 0.058 |
| | 1SD | 0.048 | 0.018 | 0.017 | 0.087 |
| | Moderated mediation | 0.027 | 0.015 | 0.002 | 0.062 |

on strategic decision quality through emotional fusion is significant. In addition, as seen in the adjusted mediating coefficient, the effect value is 0.027. Zero is not included in the confidence interval, indicating that entrepreneurial spirit has an adjusted mediating effect in the path of cognitive heterogeneity influencing strategic decision quality through emotional fusion; thus, Hypothesis 5 is confirmed.

To more intuitively demonstrate the mediating effects of entrepreneurial spirit, we plot them in Figures 2 and 3, where the slopes with strong entrepreneurial spirit are steeper than those with weak entrepreneurial spirit. This suggests that the stronger the entrepreneurial spirit, the larger the increase in strategic decision quality caused by TMT information integration and emotional fusion.

6. Conclusion

Based on the data from 107 Chinese enterprises, this paper tested the effects of TMT cognitive heterogeneity on strategic decision quality in mixed enterprises, along with the team fusion's mediating function under the moderation of entrepreneurship. The following conclusions are obtained:

- (i) TMT cognitive heterogeneity had a significant positive effect on strategic decision quality. That is, given mixed-ownership reform, cognitive heterogeneity can enhance TMTs' strategic decision quality on sustainability.
- (ii) Team fusion with information integration and emotional fusion had a mediating effect between TMT cognitive heterogeneity and strategic decision quality.
- (iii) Entrepreneurial spirit positively impacted the relationship between information integration, emotional fusion, and strategic decision quality. The stronger the entrepreneurial spirit, the greater the influence of information integration and emotional fusion on strategic decision quality.

7. Discussion

7.1. Theoretical Significance. This paper discusses the practical problem of how to integrate a decision-making team to improve the quality of their strategic decision-making for

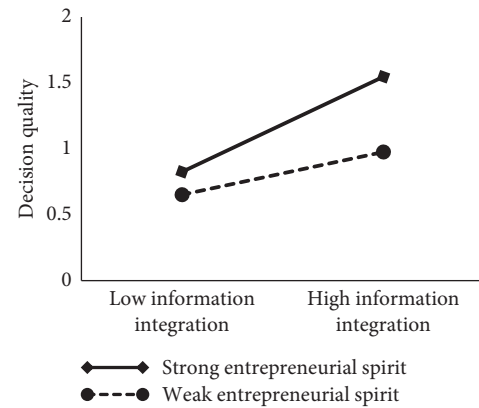


FIGURE 2: Moderating effect of information integration.

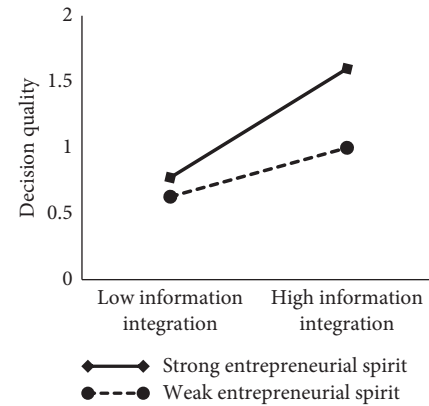


FIGURE 3: Moderating effect of emotional fusion.

sustainability. It addresses the research gap in the literature focusing only on share design and other institutional arrangements. Moreover, it provides a theoretical basis for solving the problem of “mixed but not fusion.” Based on upper echelon theory, this paper explored the effect of TMT cognitive heterogeneity on strategic decision quality. This work also examined the mediating effect of TMT entrepreneurial spirit; its theoretical significance is as follows.

First, based on Huang et al.'s work [48], the measurement dimensions of strategic decision quality were designed, including resource allocation efficiency and decision-making innovativeness. The empirical results are inconsistent

with Olson et al. [11] who found that cognitive heterogeneity was negatively correlated with team's decision-making performance. In our study, TMT cognitive heterogeneity not only positively correlated with strategic decision quality but also supported innovative decision-making. Given China's mixed-ownership reform, the stronger the TMT cognitive heterogeneity is, the more helpful it is for processing diversified, fuzzy information and identifying new opportunities from it, thereby supporting strategic decision-making in a complicated, changing environment.

Second, based on the concept of team fusion under the logic of "characteristic–process–result," the behavioral and psychological dimensions of TMT fusion were defined, and their mediating effects between TMT cognitive heterogeneity and strategic decision quality were examined. In addition, the mediating mechanism of TMT cognitive heterogeneity in strategic decision quality through information integration and emotional fusion was revealed. This expands our understanding of the black box of integration given China's mixed-ownership reform.

Third, this paper expanded research on entrepreneurial spirit from the individual level to the team level, enriching research on TMT entrepreneurship. Despite the considerable interest in entrepreneurial spirit, theoretical studies of TMT entrepreneurial spirit are lacking, especially whether the managers of SOEs can be considered entrepreneurs. Our study supports Wang and Xu [28] in that SOE managers are entrepreneurs with entrepreneurial spirit. Moreover, following Chen and Hao [16], our study found that the entrepreneurial spirit of collective innovation, cognition sharing, risk sharing, and collaborative progress can strengthen the positive effects of TMT fusion on strategic decision quality.

7.2. Implications for Sustainability. Our study has the following implications for sustainable development. First, the mixed-ownership reform of Chinese enterprises is an important measure to integrate resources and realize the sustainable development. TMT's heterogeneous cognition of sustainable development should consider the dual objectives of economic interests and environmental responsibility. Under the mixed-ownership reform, SOE TMTs should reallocate and integrate resources related to sustainability. Decision-making to achieve low-carbon development is a complex process. In the face of the need for environment-friendly operations, TMT cognitive heterogeneity can help TMTs collect more comprehensive information from diversified viewpoints and deepen their understanding of decision problems, which can support innovative, high-quality decision-making. Second, TMTs organize and coordinate the sustainable development of enterprises, and whether mixed-ownership reform succeeds depends on whether TMT members can effectively integrate to achieve win-win cooperation. Information integration and emotional fusion are effective ways to achieve team fusion. On the one hand, strengthening information exchange and cognition sharing within the team can integrate diverse viewpoints into comprehensive thinking about decision-

making problems, which can avoid decision failures caused by a lack of environmental perspectives. On the other hand, TMT cognitive heterogeneity will inevitably cause disagreements about low-carbon development, making it necessary to resolve conflicts through active communication and interaction, forge a harmonious working atmosphere, promote emotional fusion, enhance team cohesion, and stimulate members to make high-level contributions to the team. Third, it is important to cultivate TMTs' entrepreneurial spirit, especially among team members who represent state-owned capital. The entrepreneurial spirit of SOE managers is relatively weak, mainly because of the fear of risk and insufficient motivation. In addition, it is necessary to improve the environmental awareness of the managers of non-SOEs and promote the idea of gaining competitive advantages through green innovation and low-carbon strategy. With the mixed-ownership reform, emphasis should be placed on stimulating the TMT entrepreneurial spirit based on collective innovation, cognition sharing, risk sharing, and collaborative progress. In this way, mixed-ownership enterprises can develop under high-quality low-carbon strategies in sustainable practices.

7.3. Limitations and Future Research. This paper has some limitations. First, because of the difficulty of collecting TMT data in the psychological dimension, a vertical research design was not adopted. Cross-sectional data have some defects, and it is possible that the deduced causality had the opposite causal relationship. Future research should conduct longitudinal analysis to improve the results. Second, although the scales used in this paper were based on the literature, as well as discussions with experts and TMT members, there are still some measurement limitations. For example, the specificity of TMT cognition in mixed-ownership enterprises was not mentioned. As such, future research should develop high-quality scales. In addition, the sample size in this paper was not large, thus limiting universality and representativeness. Also, this research can be extended and enriched by directly addressing corporate social responsibility [50] or focusing on more specific decision scenarios such as dual-channel supply chains [51].

Appendix

Cognitive Heterogeneity

- (1) Long-term enterprise development routes are not unified within the team
- (2) There are different opinions on how to maintain the maximum competitive advantages of the enterprise within the team
- (3) There are frequent disputes over the implementation scheme of enterprise strategies within the team

Information Integration

- (1) Team members often communicate their different opinions on decision-making problems
- (2) Team members often raise creative innovation schemes and actively discuss them

- (3) Team members often communicate how the information they have collected affects the other members' work

Emotional Fusion

- (1) Team members can freely share their ideas, feelings, and expectations to create a good sharing atmosphere
- (2) Team members can share the difficulties they face in work and life with other members, who can express their concerns and make constructive suggestions
- (3) When faced with conflicts among team members, they can seek the solution most favorable to the group

Entrepreneurial Spirit

- (1) Each member is willing to acquire resources by multiple means to form innovative decision-making schemes
- (2) The team likes to perfect solutions based on collective wisdom
- (3) Members possess new knowledge that is required for decision-making and are willing to share it with other team members
- (4) Members have new ideas about problems under discussion and are willing to share them with the team
- (5) The team members are willing to deeply discuss the costs and revenues of new projects
- (6) The team members will not find fault with each other if the expected revenue of the project is not achieved
- (7) Members are sensitive to dynamic changes in the external environment and are good at identifying changes and opportunities
- (8) Members unanimously agree to pursue excellent standards

Strategic Decision Quality

- (1) The team's decision-making scheme has positive effects for the enterprise for improving resource allocation efficiency
- (2) The team's decision-making scheme is innovative and can improve the enterprise's way of creating value
- (3) The team's decision-making represents a forward-looking strategy based on changes in the external macroenvironment and the latest developments in the industry or field

Data Availability

Data are available 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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