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Research Article

Intellectual Capital and Firm Performance in the Context of Venture-Capital Syndication Background in China

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This paper is intended to investigate the role of Venture-Capital Syndication (VCS) background in the relationship between intellectual capital (IC) and portfolio firm performance (PFP); specifically, this article examines the moderating effect of VCS's leading firm background and member heterogeneity on the effect of IC on PFP. This study used a modified VAIC model to measure IC to compose a 4-component variable including human capital, structural capital, relational capital, and innovation capital. The data were collected from VCS-backed and listed firms in China during 2014 to 2018 applying the pooled OLS model for hypotheses test, Generalized Method of Moments (GMMs) to reduce endogeneity and unobserved factor control, and also return on equity (ROE) instead of ROA for the robustness test. Empirical results showed that IC and its components can improve PFP for VCS-backed firms in China; in detail, IC showed greater impact on performance of firms invested by foreign lead investors than in private or government VCS, specially reflected in the impact of innovation capital on PFP. Furthermore, IC showed weaker impact on PFP of mixed VCS-backed firms compared to pure VCS-backed firms and showed diminished effect on higher VCS member heterogeneity mainly reflected in the impact of relational capital on firm performance. These findings propose a new way of combining IC and VC to improve firm performance and are beneficial to theoretical development of IC and VC as well as a perspective for VC firm managers to choose suitable partners prior to join a VCS.

1. Introduction

In a knowledge-based economy, there have been growing consensus about the relevance of Intellectual Capital on firms long-term profit [1–3], even more, intangible assets are being identified as one of their core capabilities [4]. Intellectual capital (IC) is usually defined as the total of all knowledge that a firm can use as source of competitive advantage [5, 6]. Empirical evidence has shown that intellectual capital can improve firm's competitive advantage [7–9], and it is also closely related to high-level firm performance [2, 8, 10].

Being one of the most of the Asian emerging economies, China has experienced "high growth and high investment" for a long period after the reform and opening policy [11]; Chinese firms have consequently seen an accelerated growth on their own intellectual capital on the latest decades [12]; however, in comparison with developed countries in Europe and America, Chinese research on intellectual capital still needs further development [13]; although the gap between China and developed economies in terms hard power has been narrowed, the construction of soft power can be considered relatively backwards, even more, Chinese reserves in intellectual capital are still insufficient to follow the recent pace of development [14]. Even more, intellectual capital has been tagged by the government of China as a precious resource of a country, emphasizing its importance as a supporting force for the Chinese development strategy during this critical period of economic transformation and upgrade [14].

On intellectual capital, value-added intellectual coefficient (VAIC) is considered a standardized and logical measurement method [15]; it can use relevant data from financial reports to calculate firm value creation efficiency, enabling the possibility of making comparisons with other related firms [8]. In its original form, VAIC assessed IC only through human capital and structural capital [15]; nevertheless, further researchers refined this methodology to include neglected related components such as social capital, customer capital [16–18], and innovation capital [10, 19], innovation capital efficiency being a factor with direct impact on firms' performance [10, 20]; in China as well as other emerging economies, entrepreneurship and innovation are considered the new driving forces for economic growth; based on that importance, innovation capital is a component that needs to be included in the VAIC model to properly identify the impact of intellectual capital on firm performance.

Since capital is the foundation of firm development, knowledge and technology are sources for innovation; in terms of mass innovation, the effective combination of IC and venture capital not only can promote the integration of knowledge, technology, and capital within a firm but also present significance on improving firm performance [3, 19, 21]. Additionally, it is also conducive to innovation and sustainable development of emerging economies [22]. As a financing method to provide capital and service support to firms, venture capital (VC) has been rising for a long time in developed countries; it not only provides sufficient funding support for the portfolio firms but also provides other value-added services [23], such access to enhanced human capital as well as relational capital for firm's portfolio [24, 25] and technological performance [26]. With the notable economic growth of China, this country has seen the emergence of new entrepreneurial firms, while most of these firms have been facing financing constraints [27]; venture capital (VC) provides financing and rapid growth opportunities for some of them [23, 28, 29]. Since intellectual capital plays a key role in entrepreneurial firms [1, 2, 21, 30], it is necessary to investigate the impact of intellectual capital on performance for VC-backed firms' portfolio.

To share resources and risks, most venture capital institutions prefer joint investment [23, 31, 32]; more specifically, they rely on venture-capital syndication (VCS), where even different types of venture capital firms can share participation in entrepreneurships. According to the development background of Chinese VC Industry, capital types, and main funds of VC firms in the database of Zero2IPO Research Center [33], Chinese VC firms can be divided into three types: (1) foreign-funded venture capital (FVC); (2) domestic private venture capital (DPVC); and (3) government-funded venture capital (GVC) [34] as shown in Table 1.

Given its heterogeneity and complementarity, VCS can provide firms wider access to funding, resources, and extensive value-added services that promote faster firm development, overcoming the constraints of previous investment experience and geographical location [31, 35, 36].The impact of different backgrounds of VCS on portfolio firms is different [34, 37], and the impact of intellectual capital of portfolio firms in performance may differ depending on VCS background. Therefore, it makes it necessary to research the role of VCS background between intellectual capital and firm performance.

Although considerable number of studies have addressed the activity of IC in emerging economies [38–40], previous research has been focused on IC measurement [41–44], IC impact on value creation [8, 9, 20], and innovation [21, 41]; research on VCS effects is quite limited. (1) Does intellectual capital (including the four dimensions of human capital, structural capital, relational capital, and innovation capital) have a positive impact on portfolio firm performance? (2) Are these impacts varying with firms backed by FVC-led, DPVC-led, or GVC-led syndication? (3) What is the role of member background heterogeneity in the relationship of intellectual capital and firm performance? This study is oriented to address these questions within the framework of VCS background in China.

VC industry in China offers some advantages as a suitable setting to examine these issues: (1) With the rapid growth of China's venture capital industry in recent years, many VC firms have emerged, supporting also many small and medium-sized firms, providing an appropriate number of observable sample data for our research. (2) With the development of the Chinese market and the gradual dynamization of the economic system, an increasing number of FVC have entered to the Chinese market [45]. Their experience, management methods, and technologies have brought opportunities and challenges to Chinese firms. It is therefore helpful to empirically examine whether the impact of intellectual capital on firm performance vary depending on the VCS background.

For hypothesis testing, this empirical study used the modified Pulic's VAIC™ model to measure IC [41, 46], assessing it in terms of four components: (1) human capital, (2) structural capital, (3) relational capital, and (4) innovation capital. Our sample included 575 Chinese venture-capital syndication backed firms listed in the A-share market during 2014 to 2018. Our model expects that all components of IC may influence the performance of VCS-backed firms, moderated by the background of VCS. Additionally, this exercise also tested moderation by FVC-led, DPVC-led versus GVC-led syndication, as well as the moderating effect of cooperation model and member heterogeneity. Several methods were applied to address the empirical challenges of potential endogeneity: (1) first, the the pooled OLS model were used to test hypotheses; (2) second, the average value of IC of the sample firm's industry was used as its own instrumental variable [46, 47]; (3) third, the generalized method of moments (GMMs) was used to reduce endogeneity problems and control unobservable factors; and (4) finally, return on equity instead of ROA was used to test the models' robustness of the obtained results.

The contributions of this study are presented in three ways: (1) first, this study contributes to the literature on the relation between intellectual capital (IC) and portfolio firm performance (PFP), by filling the gap of empirical research on the relationship among IC, background of VCS, and firm

Table 1: Classification of Chinese venture capital firms.

Type	Main source of funds	Representative VC institutions	Investment target
Government venture capital (GVC)	Provided by local government, state-owned firms, government-affiliated institutions, and universities	(i) China Venture Capital (ii) Shanghai STVC Group (iii) Shenzhen Capital Group (iv) Wuhan Huagong Venture Capital, etc.	(i) Realize government policy goals (ii) Support entrepreneurial firms (iii) Cultivate small- and medium-sized technology firms (iv) Guide social capital investment
Domestic private venture capital (DPVC)	All provided by Chinese private firms and domestic wealthy individuals	(i) Fortune Capital (ii) Cowin Capital (iii) Detong Capital (iv) JD Capital, etc.	As a strategic tool for firms, seek new value-added opportunities to realize value creation and capital growth
Foreign venture capital (FVC)	Provided by foreign capital (such as foreign investment banks, foreign firms, and foreign wealthy individuals)	(i) IDG Capital (ii) SEQUOIA China (iii) Matrix Partners China (iv) NewMargin, etc.	(i) Use its rich management experience, professional skills, and financial advantages (ii) Value-added appreciation and profit

performance. Our main results are consistent with the view that human capital, structure capital, and relational capital have positive impact on PFP [30, 48, 49], and innovation capital also has positive association with PFP [10]. In addition, we gave special focus on the moderating effects of venture-capital syndication background. We argue that a positive influence of IC on portfolio firm performance is significantly higher in the context of FVC-led syndication than in DPVC-led or GVC-led syndication. Therefore, in emerging economies, especially the case of China, DPVCs and GVCs would need to learn from the advanced investment management experience and skills of FVCs in line with the local environment, to increase the efficiency of firm intellectual capital.

(2) Second, this study adds both academic and practical value to the field of venture capital and portfolio firms. Our results supported the view of [34, 50], where VC firms are more inclined to cooperate with other VC firms that have smaller differences with themselves. We argue that the positive influence of IC on portfolio PFP in pure VCS is significantly higher than that in mixed VCS, suggesting that when considering financing, portfolio firms may prefer pure VCS, more conducive to value creation of intellectual capital and the improvement of portfolio firm performance. Moreover, the particularity of this research setting provides a fresh perspective on intellectual capital management of portfolio firm for performance as well as relevant implications for portfolio firms in emerging countries.

2. Literature Review and Hypothesis Development

2.1. Intellectual Capital and Its Components. Intellectual capital (IC) was first proposed by Galbraith in 1969, who defined it as an intellectual activity that contribute to a dynamic kind of capital. Stewart [16] defined it as knowledge, intellectual property, information, and experience that can bring competitive advantage and created value for a firm; Sullivan and Patrick [51] considered it as knowledge and information that can be converted into a tangible profit for a firm. Although further consensus is needed, in [16], definition has been widely adopted, considering that IC includes human capital, structure capital, and relational capital [2, 16, 52]. Human capital is mainly reflected in knowledge, skills, culture, and other of employee-related aspects [53, 54]; Structural capital refers to intangible assets such as firm organizational structure, rules, and strategies [55, 56], It is considered relevant on improving business operations efficiency and promoting the maximum value of human capital [57, 58]. Relational capital mainly refers to the value created by stakeholders such as partners, suppliers, and customers [59–61] and can effectively help firms to deal with internal and external relationships reflected mainly in employees, customers, and strategic partners loyalty [48, 62].

As an intangible asset, an objective measure for intellectual capital may be difficult to develop; however, Pulic [15] through his value added intellectual coefficient model (VAIC) addressed this measurement through human capital and structure capital, based in a firm's financial data. Since the VAIC model can clearly reflect value creation efficiency of a firm intangible and tangible assets, it made possible to perform comparisons between organizations and have been extensively adopted in research [62–64]. Nevertheless, further research identified relevant components of intellectual capital that were previously ignored, such as in the case of [65] who identified 4 components: human capital, structural capital, innovation capital, and customer capital, proving the validity and rationality of the modified VAIC model; following the line, [66] introduced customer capital and process capital to the extended VAIC model; Chen et al. [41]

expanded the model including internal and external dimensions, both with its respective human capital, structure capital, and relationship capital. Even in recent years, the VAIC model has evolved giving space to innovation capital into the model [7, 10].

In emerging economies, innovation capital plays an important role in firm development. Previous research defined it as the intangible assets or capabilities that can promote innovation in knowledge, service, technology, and other aspects of the firm [7, 41] and regard it as the product of the firm's human capital, social capital, and reputational capital [41, 67]. It is conducted to the creation of knowledge and the increase of intellectual property [10, 68]. Since the VAIC model does not include innovation capital and its main components include firm's labor, physical capital [69], it designates the efficiency of the labor and capital investment rather than IC [70]. So, in this exercise, researchers modified the VAIC model by defining IC as composed by (1) human capital, (2) structural capital, (3) relational capital, and (4) innovation capital. The calculation of the modified VAIC model can be seen in variable definition and measurement chapter.

2.2. Venture Capital Syndication in China. Venture-capital syndication (VCS) is a common strategy in China; it enables VC firms to choose partners to share resources of capital, human talents, and scientific and technologic knowledge and also distribute venture associated risks [23]. It helps them to overcome boundaries of original investment industry and geographical limitations, being able to obtain information from distant sources, expanding the scope of their investment [36]. Existing literature suggests that VCS has a positive effect on entrepreneurial firms. Hochberg et al. [71] found that firms funded by from two or more VC firms are more likely to successfully exit through an IPO or being sold to another firm. Lu et al. [72] found stronger innovation capabilities in VCS-backed firms in comparison with individual VC-backed firms. Ren [73] pointed out that VCS not only can effectively make up for the human and material resources needed during further development of enterprises but also stimulate innovation capital and structural capital through human capital and constantly strengthen the original relationship capital of firms, effectively enhancing the value of portfolio firms.

According to the background of its members, VCS can be divided into two cooperation modes: "Pure" and "Mixed" [34]. Pure VCS mainly refers to the cooperation of the same type of VC firm, such as GVC with GVC and DPVC with other DPVC. Mixed VCS mainly refers to the cooperation between two or more types of VC firm. Giot and Schwienbacher [74] suggested that, for larger number of VC firms participating in a round of syndication, the larger will be the scale of investment, and the period from investment to successful realization of IPO exit will be reduced. Some literature points out that "mixed" VCS present significantly lower performance than that of "pure" VCS [34]. Different types of VC firms will face differences in resources, experience, and capabilities for management and monitoring, geographic locations, and even industry; their competitive advantages may be different [75]; it means that the value-added service provided for the portfolio will be different, making in some cases the difference an obstacle to articulation between firms; in other words, the effect of intellectual capital on portfolio firm's performance may be likely affected by the VCS background.

Previous research suggested that venture capital firms with higher shareholding ratio and better reputation can improve firm efficiency through material capital and human capital [46]; in the same line, there is evidence where GVC increased firm efficiency through material capital and structural capital [76]. For VC firms with shareholding ratio higher than a certain threshold, IC may accelerate the improvement of asset utilization efficiency and market value [77]. Since VC firms in syndication have different types -and reputation-, VCS with different backgrounds may present different effect for each IC elements to improve firm efficiency. Therefore, research on how differences on VCS background may have influenced the effect of intellectual capital on portfolio firm performance acquires relevance.

Despite the existence of previous research on performance of mixed syndication involving GVC and DPVC in China [75], there is still a gap on explaining the influence of venture capital syndication (VCS) type on the relationship between intellectual capital (IC) and firm portfolio performance (FPF). Therefore, in the context of the Chinese venture capital market, this empirical exercise considers the type of syndicate leaders and the cooperation model of its members, specifically investigating the moderating effect of VCS in the previously mentioned relationship.

2.3. Intellectual Capital and Portfolio Firm Performance. As knowledge economy grows in relevance, previous studies have explored the impact of IC on PFP; as an instance, Bontis [62] showed that three components elements of IC, (1) human capital, (2) structural capital, and (3) customer capital, have positive relationship with PFP in a Malaysian sample. In [78], using a sample of US multinational firms, they found that IC may significantly improve return rate on total assets. In [79], the Indian software industry was used as context to find that a 2-component IC (human capital and structural capital) had positive impact on firm profitability. For the case of Pakistan, Waseem [13] showed significant positive effect of three IC components (human, relational, and technological) on organizational performance of large textile companies in Pakistan.

For the Chinese context, in [80], by using data from listed firms in computer industry, they found that 3-component IC (human, physical, and structural) showed positive contribution to PFP. In [81], it is confirmed that their 4-component IC (human, innovation, process, and customer) presented positive impact on enterprise value creation for the Chinese pharmaceutical manufacturing industry. Xu and Wang [82] used VAIC^{TM} and Modified VAIC^{TM} model to analyze performance of IC in China and South Korea finding that human, relational, and structural capitals are all positively related to the profitability of textile firms.

Compared to the non-VCS-backed ones, VCS-backed firms are more likely to have higher values on fostering intellectual capital; this may be because various reasons: (1) first, given the reserved character the information in portfolio companies, observers can judge firm quality by referring the behavior of any third party with information advantage [83]; therefore, the availability of information for a VCS partner provides clearer insights on the operation of the portfolio company [23]. Thus, external investors and job seekers regard VCS-backed firms to be more trustworthy, making these firms more likely to attract better human talents and financial support, explaining enhancements in firm performance [31, 84]. (2) Second, VCS often has rich network resources, being able to provide head hunters, patent lawyers, investment bankers, or any other required talents that add value and contribute to portfolio firms [71]; it can also enhance relationships with partners, suppliers, customers, and government. [23, 35]. (3) Third, VCS can provide value-added services such as management, technology, consulting, and others to portfolio firms [23], increasing the utilization rate of existing IC and the subsequent firm innovation performance [72]; consequently, IC of VCS-backed firms will tend to have better market performance. Based on the previous literature, it is possible to define the first hypothesis for this empirical exercise.

H1: 4-component intellectual capital (human capital, structural capital, relational capital, and innovation capital) has significant positive impact on VCS' portfolio firm performance.

2.4. Influence of VCS Leadership Heterogeneity. Leading VC Firm plays a key role in VCS, especially in screening, structuring, and monitoring portfolio firms [85], as the primary decision makers lead VC firms normally exercises a disproportionate influence over various VCS processes [75], therefore having privileged influence in the creation of IC within VCS portfolio firms; therefore, each VC firm definition as leading or nonleading as well as his nature (FVC, DPVC, or GVC) need to be accounted in terms of influence over IC within portfolio VC firms.

It is different that FVCs, DPVC, and GVC faced a late development in China with certain lack on investment and management experiences [86]. In GVC-led syndication, GVCs have the responsibility of stimulating local economic development [87]. In consequence, supervision and value-added services provided in their portfolio firms may be different in comparison with DPVC-led or FVC-led. Analogically, there will be difference on the IC provided by portfolio firms. Previous research showed that most GVC lack on relevant professional knowledge and investment experience [88]. Other studies documented GVC underperformance, for example, Alperovych et al. [89] found that GVCs have poorer results on portfolio firms productivity when compared to DPVC; additional research showed similar results on human capital recruitment [90], sales growth [91], and innovation [88]. Thus, firms backed by GVC-led syndication will face lesser effectivity on IC and value creation.

On regard to FVC-led syndication, their partners are often invited to provide a second opinion on managing or diversifying value-added activities. In the Chinese case, most FVC comes from foreign professional investment banks, investment institutions, insurance institutions, and wealthy individuals from developed countries; compared with DPVCs or GVCs in China, FVCs have more resources in terms of social network, investment experience, management, and risk control [92], thus, FVCs may increase its IC through portfolio value-added services that can enhance firm value creation in higher proportion than GVC or DPVC in China [34]. Based on this, the next hypothesis can be constructed:

H2: compared DPVC-led or GVC-led syndication, intellectual capital shows more effectiveness in portfolio firm performance within FVC-led syndication.

2.5. Moderating Effect of VCS Members. VCS is composed of various VC firms that contribute with different funding sources, experience, talents, etc. Therefore, value-added services provided by each VCS portfolio firms have its own particularities, such as their IC and its ability to create value. The composition of VCS' members may influence the impact of IC on PFP. This exercise studied the role of VCS members in the relationship between IC and firm performance by studying the cooperation mode of VCS members and their heterogeneity.

Different from pure syndication, mixed syndication presents stronger member heterogeneity; in terms of resource-based theory, VCS with higher member heterogeneity implies higher diversity of resources, such as social relations, information access, and competitive advantages [93, 94] [31, 85]; this model based in complementary cooperation provides also advantages in terms of value-added services such as knowledge, technology, and network relations among others [29] helpful for invested firms management of and post investment supervision. For example, FVCs have advantage on helping firms to establish professional governance structure and operating model [34]. By forming a heterogeneous syndicate with other DPVC or GVC in China, they will gain better understanding of local firms and their culture [95], increasing portfolio firm information resources and relationship capital, at the end improving their firm performance [96]. Lu et al. [72] found also that VCS with high member heterogeneity is more likely to be familiar with various stages of firm development, helping firms to use specialized operating models to improve innovation efficiency and develop IC. Therefore, the third hypothesis is built as follows.

H3a: stronger VC syndication member heterogeneity can increase the positive impact of investee's intellectual capital on portfolio firm performance.

However, human behavior may bring over a downside on VCS portfolio firms related to value creation within IC. Following the Social Classification Theory and Social Identity Theory, similar attitudes and values within a team will make individuals to identify with each other, classify team members, develop crowd preferences, and outgroup biases, further making team heterogeneity a factor for member conflicts, impacting negatively the group decision process [97, 98], and moving people away from teamwork [99]. In the case of VCS, member background diversity means greater heterogeneity in terms of values, corporate culture, management models, and investment concepts; however, wider environment is developed for bias development against VC firms with different background, facilitating the appearance of potential conflicts [84].

In terms of portfolio firm management, stronger member heterogeneity within VCS may extend the time for firm's decision-making [32], increasing management costs [50] as well as its portfolio trade sale hazard [100]. The occurrence of this situation harms the ability of the portfolio firms to make full use of the extended resources provided by the VCS, intended to enhance the value creation ability of intellectual capital. In other words, common member background in pure syndication allows smoother in communication and coordination [34, 75] provides more efficient services having also better positive effect on firm performance than the mixed syndication. Given these findings, a complementary hypothesis has been developed as follows.

H3b: stronger VC syndication member heterogeneity can reduce the positive impact of investee's intellectual capital on portfolio firm performance.

3. Methodology

3.1. Sample Collection. This empirical study used data from firms that accepted VCS funding and got successfully listed on Shenzhen and Shanghai stock exchanges during 2014 to 2018. The sample data were composed by two components: (1) VC data, obtaining the sample firms from [33] research database and the CV source database [101]. This dataset included VC firm names, their participation in VCS, firm background information, investment amount, and number of shares. (2) Relevant financial data of the sample firms were obtained from wind financial database [102], widely recognized in China for financial data. After deleting missing data and using tailing treatment at 5%–99% level, also eliminating the impact of extreme data, an overall number of 575 valid observations were obtained.

3.2. Variable Definition and Measurement

3.2.1. Dependent Variables. To measure portfolio firm performance, this study used return on assets (ROA) consistent with the previous literature [2, 7, 10, 19]. It is a widely used indicator on firm profitability and is usually used to measure the efficiency of a firm. A higher ROA represents higher effectiveness of a firm's asset utilization.

For robustness check, this study used return on equity (ROE) as a proxy for firms' performance [10, 82].

3.2.2. Independent Variables. Based on the analysis presented in Section 2.1 of this article, this study measured intellectual capital by using the modified Pulic's VAIC^{TM} model, measurement of IC, and its constituent elements as shown in Table 2.

3.2.3. Control Variables. Consistent with previous studies [72, 103, 104], this empirical exercise included a set of 5 control variables as follows: (1) firm size, (2) debt ratio, (3) permanent asset ratio, (4) board size, and (5) total asset turnover ratio. The method of calculation for each variable is described in Table 2.

3.3. Empirical Models. According to the sample for this study, we assume that there is no individual effect. As the p value of the F test was 0.356 on the statistical assessment, the null hypothesis on individual effect could not be rejected. Therefore, a pooled OLS model was applied; to eliminate the heteroscedasticity and sequence-related problems and OLS + clustering robust standard error were chosen for regression.

3.3.1. Model for Hypothesis (H1). The following model (1) describes the model to assess H1:

$$\text{Perform}_{i,t} = \alpha_1 + \beta_1 X_{i,t} + \beta_2 \text{Size}_{i,t} + \beta_3 \text{Debt}_{i,t} + \beta_4 PPE_{i,t} + \beta_5 BN_{i,t} + \beta_6 TAT_{i,t} + \varepsilon_{i,t}, \quad (1)$$

where *Perform* represents performance, i represents the firm, t represents the year, and $X_{i,t}$ represents $VAIC_{i,t}$, $HCE_{i,t}$, $SCE_{i,t}$, $ICE_{i,t}$, and $RCE_{i,t}$, respectively.

3.3.2. Model for Hypothesis (H2). Regression analysis was ran based on the values on leading type by running it in three groups according to each case: $Lea\ d\_type = 1$; $Lea\ d\_type = 2$; $Lea\ d\_type = 3$; then, group regression coefficients were compared through SUEST command. If the regression coefficients were significantly different, then, heterogeneity was considered significant. To perform in-depth analysis, this study not only grouped regression between the dependent variable (DV) and IC but also grouped regression between the DV and the components of IC.

3.3.3. Model for Hypothesis (H3). To evaluate H3a and H3b, this study introduced two interaction terms: (1) IC and VCS member heterogeneity and (2) IC's elements and VCS member heterogeneity, to construct the model described in the following equation. Then, hierarchical regression test was performed. If the regression coefficient of the interaction term was significant, then significance of its moderating effect was also significant.

$$\begin{aligned}\text{Perform}_{i,t} = {} & \alpha_0 + \beta_1 X_{i,t} + \beta_2 VCtypeHeter_{i,t} \\ & + \beta_3 X_{i,t} * VCtypeHeter_{i,t} + \beta_4 \text{Size} \\ & + \beta_5 \text{Debt}_{i,t} + \beta_6 PPE_{i,t} + \beta_7 BN_{i,t} \\ & + \beta_8 TAT_{i,t} + \varepsilon_{i,t},\end{aligned} \quad (2)$$

Table 2: Variable definitions and measurement.

Type	Variable	Definition	Measurement
Dependent DV	ROA	Return on assets	Net incomes/average total assets
Independent IV	HCE	Human capital efficiency	VA/employee expenses
	SCE	Structural capital efficiency	VA/management expenses
	ICE	Innovation capital efficiency	VA/R&D expenses
	RCE	Relational capital efficiency	VA/sales expenses
	VAIC	Intellectual capital efficiency	HCE + SCE + ICE + RCE
Moderator	VctypeHeter	VCS heterogeneity	$-\sum_i p_i \ln\ p_i$, where p_i is the proportion of i-type VC institutions in the total number participants within a VCS)
Control	Scale	Enterprise size	Logarithm of total assets
	Debt	Debt ratio	Total liabilities/total assets
	PPE	Permanent asset ratio	Permanent assets/total assets
	BN	Board num	Number of board directors
	TAT	Total asset turnover	Operating income/average total assets

Note: VA is the value added of a firm; VA = net profit + depreciation expense + income tax + financial expenses + salary payable + welfare payable.

where *Perform* represents performance, i represents the firm, t represents the year, $VCtypeHeter_{i,t}$ represents heterogeneity, and $X_{i,t}$ represents $VAIC_{i,t}$, $HCE_{i,t}$, $SCE_{i,t}$, $ICE_{i,t}$, and $RCE_{i,t}$, respectively.

4. Empirical Results and Analysis

4.1. Descriptive Statistics. Descriptive statistical analysis was conducted based on the background of the VCS leading firm and VCS cooperation model as shown in Table 3.

Based on Table 3, it can be inferred that (1) from the perspective of IC components, independent of the type of supporting VCS, there is a value pattern, where ICE > RCE > SCE > HCE, meaning that, in terms of firm value creation ability, IC contribution follows the following pattern: innovation capital > relational capital > structural capital- > human capital. (2) From the perspective of VCS leading type, the ROA of DPVC-led syndication backed firms is higher than that those of FVC-led or GVC-led; however, VAIC-value on the GVC-led and DPVC-led are similar, both being higher than FVC-led ones. This result shows difference with previous research hypothesizes, so further analysis needs to be done.

4.2. Correlation Analysis. Table 4 shows the correlation matrix for main variables of study; based on it, it is possible to see the following: (1) there is significant positive correlation between the ROA and the set of IC-related variables (HCE, SCE, ICE, RCE, and VAIC); however, no significant correlation is seen between the ROA and *Lead_type* or *VctypeHeter*. (2) Significant positive correlation was found between VAIC and HCE, SCE, ICE, and RCE, as well as between VAIC and *Lead_type*; although the correlation between VAIC and *VctypeHeter* is not significant, there is negative correlation between HCE and *VctypeHeter* (−0.099). It is also relevant to mention that (3) significant positive correlation appeared between *Lead_type*, *VctypeHeter*; although the correlation between these two variables and ROA is not significant, negative significant correlation is found between these variables and some components of IC (HCE and *Lead_type* was 0.084**). While there is significant positive correlation between components of IC and ROA, further relationship validation will be needed.

4.3. Empirical Result Analysis

4.3.1. Relationship of IC and Firm Performance. Table 5 shows that IC, HCE, SCE, ICE, and RCE all have a significantly positive impact on the portfolio firm performance, consistent with H1, since the t values of regression coefficient for VAIC, HCE, SCE, ICE, and RCE are 12.61, 17.52, 17.87, 9.11, and 8.72, respectively, with significance at 1% level. Moreover, the effects of human capital (2.269) and structural capital (2.211) on PFP are significantly higher than innovation (0.312) and relationship capital (0.339). This finding is consistent with the first proposed argument that IC is composed of human capital and structural capital [15] and indicates that VCS can improve firm performance by providing value-added services such as human capital, organizational management operations, and social relationship resources.

4.3.2. Role of VCS Leader Background between Intellectual Capital and Firm Performance. Based on the results shown in Table 6, regression coefficient of VAIC in group 1 (0.647) is higher than in group 2 (0.283) and group 3 (0.227), meaning that compared with DPVC-led or GVC-led backed syndication firms, IC has a greater impact on performance of FVC-led firms supporting H2. As shown in Table 7, SUR estimation group analysis (1 vs 2, 1 vs 3) showed that the

Table 3: Descriptive statistical analysis of the main study variables.

Type		Variable	Sample	Mean	SE	Min	Max
VCS leader background	Backed by FVC-led syndication	ROA	64	5.919	3.501	0.1	14.843
		HCE	64	1.050	0.724	0.211	3.243
		SCE	64	1.426	0.757	0.402	3.893
		ICE	64	2.758	1.587	0.579	7.441
		RCE	64	2.201	1.901	0.212	7.868
		VAIC	64	7.435	3.530	1.878	15.186
	Backed by DPVC-led syndication	ROA	425	6.323	3.419	-1.881	15.572
		HCE	425	1.440	0.728	0.231	3.478
		SCE	425	1.727	0.822	0.259	4.549
		ICE	425	4.524	3.379	0.543	19.873
		RCE	425	3.427	2.633	0.213	13.931
		VAIC	425	11.117	5.528	1.666	36.034
	Backed by GVC-led syndication	ROA	86	5.483	3.128	-1.772	14.749
		HCE	86	1.346	0.717	0.328	3.298
		SCE	86	1.800	0.899	0.332	4.367
		ICE	86	4.589	3.267	1.158	16.674
		RCE	86	3.482	2.576	0.497	11.975
		VAIC	86	11.218	4.896	3.201	23.82
VCS cooperation model	Backed by pure syndication	ROA	380	6.279	3.568	-1.881	15.572
		HCE	380	1.425	0.755	0.211	3.478
		SCE	380	1.738	0.824	0.259	4.549
		ICE	380	4.388	3.188	0.543	19.873
		RCE	380	3.371	2.601	0.236	13.931
		VAIC	380	10.923	5.466	1.666	36.034
	Backed by mixed syndication	ROA	195	5.907	3.022	0.1	14.843
		HCE	195	1.300	0.688	0.252	3.243
		SCE	195	1.638	0.845	0.332	4.367
		ICE	195	4.236	3.392	0.579	19.595
		RCE	195	3.157	2.536	0.212	13.71
		VAIC	195	10.332	5.171	2.704	29.73

Table 4: Correlation matrix for main study variables.

Variables	ROA	HCE	SCE	ICE	RCE	VAIC	Lead_type	Vctype Heter
ROA	1.000							
HCE	0.425***	1.000						
SCE	0.446***	0.587***	1.000					
ICE	0.208***	0.301***	0.427***	1.000				
RCE	0.243***	0.328***	0.306***	0.198***	1.000			
VAIC	0.370***	0.568***	0.641***	0.809***	0.692***	1.000		
Lead_type	-0.043	0.084**	0.107**	0.129***	0.114***	0.161***	1.000	
VctypeHeter	0.015	-0.099**	0.015	0.037	-0.062	-0.021	0.112**	1.000

Note: ***significance at 1% level; **significance at 5% level; *significance at 10% level.

coefficient difference of VAIC was all significant at 1%; in the case of 2 vs 3, there was no significant difference on VAIC, indicating no significant difference in the impact of IC on firm performance between firms backed by DPVC-led or GVC-led syndication. This is result is similar to that in [34] and in line with those of [92].

From the perspective of the components of IC, this study found no significant differences in the impact of human capital and structural capital on firm performance among firms invested by FVC-led, DPVC-led, or GVC-led syndication. As seen in Table 7, the SUR group test (1 vs 2, 1 vs 3, and 2 vs 3) showed no significant difference on coefficients of HCE and SCE; however, there is significant difference in the impact of innovation capital on firm performance among them; from the coefficients of ICE in Table 6 and result of ICE's SUR-test in Table 7, it can be seen that the impact of innovation capital on firm performance is higher in firms on FVC-led syndication than in the ones backed by DPVC-led or GVC-led. Additionally, the relationship capital of firms backed by GVC-led syndication has no significant impact on performance, but firms backed by FVC-led or DPVC-led syndication can effectively use their relationship capital to foster performance. As seen from the empirical test for groups, regression coefficients of RCE are significant except for group 3 (Table 6).

Table 5: Influence of IC and its constituent elements on firm performance.

IV	ROA				
VAIC	0.283(8.69) ***				
HCE		2.269*** (11.98)			
SCE			2.211*** (12.23)		
ICE				0.312*** (5.62)	
RCE					0.339*** (6.17)
Scale	-0.444* (-2.55)	-0.377* (-2.42)	-0.899*** (-5.50)	0.331*** (9.11)	0.0688 (0.38)
Debt	-0.051*** (-6.07)	-0.043*** (-5.68)	-0.038*** (-4.99)	-0.055*** (-6.08)	-0.056*** (-6.16)
PPE	-9.545*** (-8.45)	-6.815*** (-6.84)	-9.977*** (-9.64)	-8.167*** (-6.89)	-8.735*** (-7.21)
BN	-0.135 (-1.53)	-0.134 (-1.67)	-0.095 (-1.18)	-0.028 (-0.31)	-0.110 (-1.16)
TAT	6.133*** (10.99)	6.602*** (12.97)	4.318*** (8.19)	5.647*** (9.48)	6.063*** (10.11)
Constant	14.75*** (3.97)	11.22*** (3.38)	23.35*** (6.70)	7.126 (1.83)	4.716 (1.21)
Observations	575	575	575	575	575
R-squared	0.3060	0.4023	0.4035	0.2274	0.2218
Mean VIF	1.10	1.09	1.13	1.10	1.09

Note: t statistics in parentheses. ***Significance at 1% level; **significance at 5% level; *significance at 10% level.

Table 6: Test results of VCS leading firm background heterogeneity.

Type	IV	ROA				
FVC-led syndication (group 1)	VAIC	0.724*** (4.20)				
	HCE		3.423* (2.28)			
	SCE			2.828*** (4.22)		
	ICE				1.966*** (5.05)	
	RCE					0.706** (2.23)
	Control	Y	Y	Y	Y	Y
	R^2	0.7207	0.570	0.721	0.771	0.502
	Observations	64	64	64	64	64
	Mean VIF	1.95	2.59	1.91	2.12	1.84
DPVC-led syndication (group 2)	VAIC	0.283*** (9.94)				
	HCE		2.146*** (9.95)			
	SCE			1.798*** (8.73)		
	ICE				0.308*** (5.67)	
	RCE					0.397*** (6.3)
	Control	Y	Y	Y	Y	Y
	R^2	0.408	0.382	0.344	0.213	0.271
	Observations	425	425	425	425	425
	Mean VIF	1.11	1.11	1.15	1.11	1.10
GVC-led syndication (group 3)	VAIC	0.227*** (3.66)				
	HCE		2.129*** (4.24)			
	SCE			2.529*** (5.65)		
	ICE				0.255*** (2.71)	
	RCE					0.048 (0.31)
	Control	Y	Y	Y	Y	Y
	R^2	0.530	0.513	0.599	0.486	0.345
	Observations	86	86	86	86	86
	Mean VIF	1.41	1.36	1.44	1.60	1.39

Note: t statistics in parentheses. ***Significance at 1% level; **significance at 5% level; *significance at 10% level.

4.3.3. Moderating Effect of VCS Member Heterogeneity. As shown in Table 8, the regression coefficient of the interaction between IC and heterogeneity type of VCS members is −0.259 significant at 5% level, implying that VCS member heterogeneity has significant negative moderating effect on the impact of IC on firm performance, indicating that stronger heterogeneity on VCS member background may reduce the positive impact of IC on firm performance, consistent with H3b.

From the perspective of IC components, regression coefficient of the interaction terms corresponding to relational capital is -0.531 significant at 5% level, in other words, stronger VCS member heterogeneity can also reduce the positive impact of relational capital on firm performance. However, the regression coefficient for the interaction terms corresponding to human capital (-0.665), structural capital (-0.602), and innovation capital (-0.382) is not significant, suggesting that more background does not imply better results within the VCS.

Table 7: SUR-group test (1 vs 2, 1 vs 3, and 2 vs 3) coefficient difference.

Main variable	"Foreign" and "private" (group 1 vs 2)		"Foreign" and "government" (group 1 vs 3)		"Private" and "government" (group 2 vs 3)	
	Chi2	p-value	Chi2	p-value	Chi2	p-value
VAIC	8.50	0.004***	9.09	0.003***	0.44	0.507
HCE	0.79	0.375	0.78	0.378	0.01	0.969
SCE	2.20	0.138	0.15	0.699	2.65	0.103
ICE	49.68	0.001***	31.81	0.001***	0.16	0.690
RCE	1.24	0.266	4.52	0.033**	4.33	0.037**

Note: ***Significance at 1% level; **significance at 5% level; *significance at 10% level.

Table 8: Moderating effect of VCS member heterogeneity.

IV	ROA				
IC/elements	VAIC 0.353*** (8.95)	HCE 2.612*** (10.01)	SCE 2.350*** (9.81)	ICE 0.435*** (5.13)	RCE 0.417*** (5.35)
$VCtypeHeter$	3.282** (2.74)	2.609* (2.37)	1.632 (1.53)	1.824 (1.86)	2.431** (2.66)
$VAIC * VCtypeHeter$	-0.259** (-2.94)				
$HCE * VCtypeHeter$		-0.665 (-0.89)			
$SCE * VCtypeHeter$			-0.602(-1.04)		
$ICE * VCtypeHeter$				-0.382(-1.90)	
$RCE * VCtypeHeter$					-0.531** (-2.49)
Scale	-0.512 (-1.88)	-0.243 (-0.94)	-0.960*** (-3.59)	-0.350 (-1.18)	-0.240 (-0.81)
Debt	-0.063*** (-5.20)	-0.06*** (-5.04)	-0.043*** (-3.68)	-0.06*** (-4.74)	-0.059*** (-4.40)
PPE	-7.081*** (-4.25)	-4.296** (-2.70)	-7.740*** (-4.87)	-7.19*** (-3.94)	-5.455** (-2.99)
BN	-0.144 (-1.19)	-0.254* (-2.16)	-0.100 (-0.87)	0.005 (0.04)	-0.106 (-0.79)
TAT	6.927*** (8.08)	7.598*** (9.25)	5.028*** (5.96)	7.611*** (8.09)	6.805*** (7.21)
Constant	14.20* (2.46)	8.103 (1.48)	23.80*** (4.21)	11.22 (1.79)	9.941 (1.58)
R^2	0.397	0.444	0.448	0.280	0.267
Observations	575	575	575	575	575
Mean VIF	2.42	2.18	2.24	1.96	1.63

Note: t statistics in parentheses. ***Significance at 1% level; **significance at 5% level; *significance at 10% level.

4.3.4. Endogeneity Problems and Robustness Check

(1) Endogeneity Problems. An increase of intellectual capital contributes to firm performance; nevertheless, considering that firms with higher performance may also attract intellectual capital improvement like better human resources, there may be reverse causation. Additionally, although multiple control variables have been selected in this research, there may be other endogenous problems such as missing variables. For these reasons, this exercise used the generalized method of moments (GMMs) to reduce endogeneity problems and control unobservable factors for the causality model. Following [46] and [47], the average IC value of the sample firm's industry was used as its own instrumental variable, which represents on average the impact of industry IC on firm performance. Generally, firms in the same industry learn and communicate with each other, influencing their IC and its components, but without directly affecting the firm's value-added activities.

The traditional Hausman test were used to carry out the endogeneity test on the main explanatory variables, showing that prob > chi2 = 0.0443; the DWH test with robust heteroscedasticity showed Durbin ($p = 0.0433$) and Wu Hausman ($p = 0.0443$). These results prove the existence of endogenous problems and the applicability of the GMM method in this empirical exercise.

Test results of instrument variables showed that ① Anderson canon corr: LM statistic was 23.556, with a p value of 0.000, strongly rejecting the under identification null hypothesis, indicating that the instrument variable is reasonable. ② Cragg-Donald Wald F statistic was 24.115, higher than the corresponding critical value of 16.38, rejecting the original hypothesis of "weak identification." Based on the above instrument variable tests and instrument variable method regression results, the results of this study appeared to be stable.

First-stage regression showed that all the coefficient of instrumental variable showed higher significance (p value = 0.0001), and second-stage regression was also consistent to the conclusion, as shown in Table 9.

(2) Robustness Check. As shown in Tables 5–9, the value of mean VIF stayed between 1.59 and 2.09, meaning the absence of multicollinearity problems. For the moderate effect model, ROE was used instead of ROA to test moderating effect models' robustness of our results. As shown in Tables 10–12, the empirical results were materially consistent

Table 9: Instrumental variables (GMM) regression.

IV	ROA				
VAIC	0.362*** (3.46)				
HCE		2.703*** (3.90)			
SCE			2.877*** (4.72)		
ICE				0.855** (2.81)	
RCE					0.675* (2.25)
Scale	-0.918** (-2.68)	-0.442* (-2.02)	-1.191*** (-4.20)	-0.383 (-1.48)	0.0504 (0.25)
Debt	-0.0491*** (-5.63)	-0.0428*** (-5.51)	-0.0348*** (-4.39)	-0.060*** (-5.88)	-0.063*** (-5.63)
PPE	-11.69*** (-6.56)	-6.952*** (-6.75)	-11.18*** (-7.24)	-10.33*** (-5.99)	-10.26*** (-5.53)
BN	-0.252* (-2.24)	-0.156 (-1.74)	-0.137 (-1.53)	-0.115 (-1.01)	-0.204 (-1.60)
TAT	6.432*** (9.98)	6.684*** (11.40)	3.891*** (5.94)	5.611*** (8.27)	6.446*** (8.76)
Constant	24.03*** (3.49)	12.34** (2.89)	28.96*** (5.05)	12.53* (2.42)	5.013 (1.18)
Observations	575	575	575	575	575
R-squared	0.189	0.398	0.370	0.011	0.151

Note: *t* statistics in parentheses. ***Significance at 1% level; **significance at 5% level; *significance at 10% level.

Table 10: Robustness check results of different VCS leading backgrounds.

Type	Main IV	ROE				
	VAIC	0.707*** (3.03)				
	HCE		3.597* (2.23)			
	SCE			3.458*** (3.93)		
	ICE				1.557** (2.73)	
FVC-led syndication	RCE					0.646 (1.2)
	Control	Y	Y	Y	Y	Y
	R^2	0.584	0.469	0.654	0.560	0.455
	Observations	64	64	64	64	64
	Mean VIF	1.58	2.25	1.51	1.51	1.94
	VAIC	0.316*** (7.80)				
	HCE		2.845*** (9.51)			
	SCE			2.790*** (10.18)		
	ICE				0.286*** (3.80)	
DPVC-led syndication	RCE					0.455*** (5.46)
	Control	Y	Y	Y	Y	Y
	R^2	0.327	0.380	0.401	0.223	0.261
	Observations	425	425	425	425	425
	Mean VIF	1.10	1.10	1.14	1.11	1.09
	VAIC	0.341*** (4.08)				
	HCE		2.818*** *** (4.34)			
	SCE			2.318*** (4.16)		
	ICE				0.400*** (3.15)	
GVC-led syndication	RCE					0.235(1.18)
	Control	Y	Y	Y	Y	Y
	R^2	0.530	0.545	0.534	0.480	0.398
	Observations	86	86	86	86	86
	Mean VIF	1.25	1.24	1.33	1.26	1.26

Note: *t* statistics in parentheses. ***Significance at 1% level; **significance at 5% level; *significance at 10% level.

Table 11: Robustness check results of SUR-test of group (Types 1 vs 2, 1 vs 3, and 2 vs 3) coefficient difference.

Main variable	"Foreign" and "private" (type 1 vs 2)		"Foreign" and "government" (type 1 vs 3)		"Private" and "government" (type 1 vs 2)	
	Chi2	*p* value	Chi2	*p* value	Chi2	*p* value
VAIC	4.19	0.040 **	3.12	0.077 *	0.05	0.820
HCE	0.76	0.381	0.73	0.392	0.00	0.962
SCE	0.49	0.481	1.15	0.284	0.56	0.452
ICE	9.02	0.003***	6.89	0.008***	0.43	0.513
RCE	0.41	0.521	1.44	0.229	1.12	0.290

Note: *t* statistics in parentheses. ***Significance at 1% level; **significance at 5% level; *significance at 10% level.

Table 12: Robustness check results of moderating effect of VCS member heterogeneity.

IV	ROE				
IC and its elements	VAIC	HCE	SCE	ICE	RCE
	0.379*** (6.78)	3.175*** (8.77)	2.866*** (8.60)	0.398*** (3.41)	0.453*** (4.24)
VCtypeHeter	3.156 (1.86)	2.801 (1.83)	1.893 (1.27)	1.391 (1.03)	3.091* (2.47)
VAIC ∗ VCtypeHeter	−0.211 * (-2.03)				
HCE ∗ VCtypeHeter		−0.289 (−0.28)			
SCE ∗ VCtypeHeter			−0.514 (-0.64)		
ICE ∗ VCtypeHeter				−0.186 (-0.67)	
RCE ∗ VCtypeHeter					−0.614* (-2.10)
Scale	−0.266 (-0.69)	0.0251 (0.07)	−0.865* (-2.33)	−0.0672 (-0.16)	0.0489 (0.12)
Debt	−0.056** (-3.23)	−0.051** (-3.17)	−0.032 (-1.94)	−0.055** (-2.97)	−0.051** (-2.77)
PPE	−10.68*** (-4.53)	−7.336*** (-3.33)	−11.58*** (-5.24)	−10.61*** (-4.22)	−8.713*** (-3.49)
BN	−0.232 (-1.36)	−0.392* (-2.40)	−0.197 (-1.23)	−0.076 (-0.42)	−0.190 (-1.03)
TAT	9.325*** (7.68)	10.22*** (8.98)	6.956*** (5.93)	9.991*** (7.70)	9.268*** (7.17)
Constant	9.137 (1.12)	2.186 (0.29)	21.65** (2.75)	5.679 (0.66)	3.967(0.46)
Observations	575	575	575	575	575
R^2	0.321	0.401	0.400	0.231	0.234
Mean VIF	2.52	2.27	2.36	1.96	1.64

Note: *t* statistics in parentheses. ***Significance at 1% level; **significance at 5% level; *significance at 10% level.

with previous research, demonstrating the robustness of the conclusions of this study.

5. Discussions and Conclusions

This study was intended to investigate the positive effect of intellectual capital (IC) on Chinese portfolio firm performance (PFP) and examine the influence of VCS leading firm heterogeneity as well as the moderating impact of member heterogeneity on this relationship (IC and PFP) by assessing three aspects: (1) VCS leading firm background, (2) VCS cooperation model, and (3) VCS member heterogeneity. Our results suggested that higher intellectual capital may provide advantages for VCS backed firms, and these advantages vary according to the nature of the syndication (FVC-led, DPVC-led, or GVC-led). The positive impact of innovation capital on the performance of firms backed by FVC-led syndication is higher than firms backed by DPVC-led or GVC-led syndication; the positive effect of relational capital on the performance between firms backed by DPVC-led or FVC-led is similar, but in firms backed by GVC-led syndication, there is no significant effect. Additionally, in pure syndication backed firms, IC positive effect in PFP is stronger than that in mixed syndication backed firms; on member heterogeneity, it reduces the positive effect of IC on PFP.

This study contributes to managerial theory and practice in various ways:

(1) First, this study considered the multidimensional characteristics of intellectual capital in Chinese portfolio firms by introducing innovative capital into the modified VAIC model. Most of previous studies have considered IC as composed by human capital, structure capital, or relational capital [30, 62, 79]; in contrast, just few studies gave attention to other components such as innovation capital. So, this study provides comprehensive analysis on IC efficiency within Chinese portfolio firms.

(2) Second, this empirical exercise contributes to existent literature on the association between intellectual capital and firm performance as most studies have focused on IC and firm performance in the context of developed countries [1, 10, 78] or specific industries in emerging economies [30, 40, 49, 82]. This study extended the field of study to the role of venture-capital syndication (VCS) background in the relationship of intellectual capital (IC) and VCS-backed firm performance, finding that the applied 4-component IC (human capital, structure capital, relational capital, and innovation capital) can effectively improve the performance of VCS-backed firms in China. This study presents a certain difference with [2] who found that relational capital has a negative effect on firm performance; nevertheless, this can be explained by the difference of samples that in this study represents VCS-backed and successfully conducted IPO firms in China; since VCS-backed firms have stronger competitive advantages compared to others [23, 29], these firms can efficiently use their relational capital to improve firm performance. This reminds us to carefully analyze the key elements of VC firm intellectual capital, especially in the context of emerging economies.

(3) Third, this study extends also the actual literature on cross-border VC syndicates; previous studies focused on the impact of cross-border VC syndicates on investment performance [34, 105] or portfolio companies [95, 106, 107]. This empirical exercise performed further analysis on the importance of VeCS leading VC firms in their portfolio, finding that, in FVC-led syndication backed firms, IC has stronger positive impact on firm performance than in GVC-led syndication or DPVC-led syndication backed firms, consistent with [34], also supporting [108], where venture capitalists seem to prefer cross-border partners over domestic ones. Moreover, this study found that the mentioned effect is specially

evidenced in the impact of innovation capital on firm performance; the impact of human capital and structural capital on PFP showed no significant difference between firms backed by FVC-led, DPVC-led syndication, or GVC-led syndication. However, whether FVC-led or FVC-led syndication backed firms, relational capital has significant positive impact on PFP but not in firms backed by FVC-led syndication. This may be explained by the Chinese GVC political connections and restrictions, making it unable to make full use of its social relationships to improve the firm performance [61, 86].

In empirical terms, this study contributes to the growing literature on social identity theory and intellectual capital of portfolio firms, by complementing the previous studies that usually used the resource-based theory to emphasize the role of VCS in improving IC and PFP [23, 29, 109]. However, fewer studies have focused on the impact of VCS's shortcomings on their portfolio companies [50, 75]. Based on the social identity theory, this research revealed negative effect of mixed VCSs on their portfolio companies, such as increase of communication costs [50] and growth of decision-making cycle [32], attenuating the positive effect of IC on PFP for firms backed by mixed VCS in comparison with pure VCS backed firms. These results also explain why VC firms would prefer to choose partners with similarities for joint investment, consistent with [50].

(4) This study contributes to managerial practice as new ventures can be more aware of the influence of VCS on the value creation ability of their IC. By one side, they could make comprehensive use of resources and capital advantages of VCS, by developing the elements of IC, especially human capital and structure capital, because based on these results, these components have stronger impact on PFP compared with innovation capital and relational capital. By the other side, VC firms could also pay attention to the downside of VCS, especially in relation with mixed VCS, as they need to minimize potential addition on coordination costs and maximize internal organizational management effectiveness. Therefore, firms can effectively combine the management of IC with VCS to enhance sustainable growth capabilities, combine the available VCS resources, improve the construction of their own relational capital, as well as introduce advanced knowledge, technology, and talents to increase the performance.

For VC firms, on the one hand, they can be aware of the differential influence of the VCS leading VC on their portfolio firms; this study showed that, for Chinese VC firms, it is relevant to strengthen the international cooperation and communication, in order to develop advanced capital operation methods and management concepts from FVC to improve their investment effectiveness; on the other hand, special attention should be given to the negative impact heterogeneity when selecting syndicate partners; this study showed that pure syndication may be a better choice to improve their PFP.

This study has some limitations: (1) first, it was mainly focused the role of VCS background between IC and PFP, the impact of factors such as experience heterogeneity and regional heterogeneity of VCS members were not included in this study; however, these can be included in future studies. (2) Second, given the difference of institutions between countries (especially compared with other in emerging economies), sample data did not include other countries or regions; further studies may expand the geographical range to a comparative study with referents in Asia and North America would be meaningful.

In summary, this study investigated the positive effect of IC on Chinese PFP and the role of Venture-capital syndication (VCS) background in the relationship between IC and PFP based on a sample of 575 VCS-backed and listed firms in Mainland China during 2014–2018. By using Pooled OLS model to test hypotheses, using GMM to reduce endogenous problems and control unobservable factors, and using return on equity instead of ROA to test the robustness of the results, this study results suggested that (1) intellectual capital (human capital, structural capital, innovation capital, and relational capital) has a positive impact on VCS' portfolio firms in China; results also showed that (2) VCS leading firm heterogeneity influences the relationship between IC and PFP; compared with DPVC-led or GVC-led syndication, IC is more effective to develop performance on firms backed by FVC-led syndication, which also suggest that (3) heterogeneity within syndication is less conducive to the value creation of the intellectual capital of their portfolio firms.

These results showed that VCS-backed firms, the increase of intellectual capital (including human capital, structure capital, innovation capital, and relational capital) is conductive to increase of firm performance; the relationship between intellectual capital and performance of portfolio firms is influenced by the background of syndicate members. This study highlights the importance of intellectual capital and the background of different syndication members in the promotion of firm value. It also points out that the effective combination of intellectual capital and venture capital firms can provide important value-added function for VC firms and its related actors.

Data Availability

The data sets used for this empirical study are publicly available in https://www.pedata.cn/data/index.html [33]and https://www.wind.com.cn/NewSite/data.html [99].

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

Materiality Conditions in the Interplay between Environment and Financial Performance: A Graphical Modeling Approach for EEA Oil and Gas Companies

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The recovery after the unprecedented pandemic crisis that Europe has currently been facing is strengthening the strong dependence between social, economic, and environmental fields, maintaining green investments and innovation at the core of the European strategies. Shifting to clean industries is a challenging mission that a complex network of stakeholders and their different interests must take into account. Within this network, the interplay between environmental and financial performance of a company represents a common point with a growing emphasis on the transparency and the materiality capacity of the disclosed information. This paper uses the Structural Equation Modeling and the Gaussian Graphical Models as graphical analysis approaches and offers a first insight about the interaction between environmental materiality measures and financial performance. A preliminary step of the scientific research consisted of a hand-mapping investigation about materiality conditions. Starting from the Materiality Map developed by the Sustainability Accounting Standards Board (SASB), this paper extends the main concept about materiality and investigates it on three different content ranges, which focus on the general environmental policy of the company, the targets set, and its concrete footprint. The methodology approaches were grounded on a newly compiled dataset provided by the Thomson Reuters database for 194 Economic European Area (EEA) oil and gas companies. The results provide significant evidences for the manifestation of materiality and emphasize the informational content of the individual environmental measures as an important condition for its financial impact. Adding to the environmental-financial performance relationship, our findings have both practical and academic relevance for the economic field and sustainable growth goals.

1. Introduction

The environmentally sustainable growth represents essential benchmarks for the European Economy, particularly for all countries inside the Economic European Area (EEA). The Annual Sustainable Growth Strategy for 2020 "puts the sustainability, in all of its sense, at the centre of all actions: an economy must work for the people and the planet" [1] (p.2). Environmental protection has progressively been considered as a core issue of societies, governments, and international organizations, with major economic and financial implications. To become more environmentally friendly, the European companies need to manage a significant increase in their operating costs. Consequently, the pursuing of the financial goals has been transformed into an ongoing sustainable challenge race. The unprecedented pandemic crisis that Europe is currently facing is strengthening the strong dependence between social, environmental, and economic fields, making this connection even more imperative. As the environmental concerns of key stakeholders have increased, climate change and environmentally sustainable growth have become pressing financial and social issues [2]. Besides the regulatory concerns, there is a growing interest regarding the mandatory involvement of companies in green strategies. Furthermore, at the end of 2019, in "The European Green Deal" [3] (p.2), it has been postulated that the European Union (EU) economy will register "no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use." In April 2020, the European Council reinforced the central role of "Green transition and Digital transformation in relaunching and modernising the economy" [4] (p.3).

The interaction between environmental performance and financial performance of companies plays an important role within the process of transforming European industries into being environmentally neutral. As a result of the environment regulations and the socioeconomic pressure, a growing number of companies has encompassed their global warming strategies within the core policies [2, 5], and has redounded to the mitigation of the environmental footprint, generated by their economic activities. Within the business literature, these strategies are deemed as "signals of firms' environmental performance" [6] (p.2) and they are enclosed by a large number of studies [7–12], with ambiguous findings. The main arguments of the inconclusive results are based on the diversity of tools used to express the environmental performance, the diminished attention paid to the heterogeneity and the complex nature of such nonfinancial dimensions, and also on the scientific techniques applied [12]. This research goes beyond these arguments and raises a new and complementary approach, grounded on in-depth empirical contributions. The environmental and the financial performance is important both for managerial team and for stakeholders. In the light of this approach, the theory of environmental performance materiality has arisen, with a focus on the importance and the usefulness of the measures related to ecological behavior into decision-making process. The new concept is a part of the Environment Social Governance' (ESG) materiality framework. The definition of the materiality of such nonfinancial issues is centered on whether omitting or misstating of this information would change the decisions of the relevant stakeholders [13, 14]. The Sustainability Accounting Standards Board (SASB) views the financially material issues as those "that are reasonably likely to impact the financial condition or operating performance of a company and therefore are most important to investors" [15]. Taking the investors position, SASB has developed the "Materiality Map" [16] that indicates industry by industry (e.g., Extractives and Mineral processing) and sector by sector (Coal operations, Construction materials, and so on), as to "which ESG issues are likely to be financial material, and to affect the financial condition or operating performance of companies" [15].

In this frame of fact, the main objective of our research is to assess the interaction between environmental measures and financial performance, by applying the conditions of materiality manifestation. For this purpose, we have used the recommendations developed by the SASB in the Materiality Map and extended them to a more integrative analysis. Considering the managing of the environmental impact as an extremely significant component of business strategy [17] for extractive companies, the entire design research of our paper is developed for the case of oil and gas companies (a final sample of 194 companies) located in the EEA Member States. The data sample is extracted from the Thomson Reuters/Refinitiv database [18], for the period 2009–2018. Studying the overall (direct, indirect, and total) implications of the environmental materiality measures on corporate financial performance (through structural equations modeling-SEM), and the network association between environmental performance (EP) and financial performance (FP) (by applying the Gaussian Graphical Models-GGM) is paramount to supplement previous conclusions and to support the managing of environmental issues into the business strategy of a company. The entire graphical modeling approach is built as an integrative system in order to gain scientific insights into the complex interactions between all considered variables, and to identify the most capable ones to have a financial impact. The SEM and the GGM are complementary methods that provide a powerful methodological combination that "allows for confirmative testing of network structures both with and without latent variables" [19] (p.3) and provides accuracy and robustness to the final observations. The SEM estimates the interlinkages (direct, indirect, and total) jointly with standardized path coefficients from variables belonging to the environmental materiality measures on corporate financial performance variables, and the GGM is used to estimate the intensity influences of environmental performance (EP) variables on FP, representing a complementary analysis to the SEM models.

The rest of this paper is structured as follows: after the literature review on the field of the EP-FP relationship and the materiality framework, the description of research methods, data preparation, and variables follow. The econometric processing provides the detailed results further presented, jointly with discussions of their relevance related to the mainstream literature underpinnings. The concluding remarks and the information enclosed in the Appendices complete this paper.

2. Literature Review

2.1. Relationship between Environmental Performance and Financial Performance. Understanding the nature of the connection between the environmental and the financial issues represents an important step in achieving sustainable growth goals. As the public and private concerns with regard to the unfavorable impact of the environment on the economy have increased, scholars have focused their attention on the relationship between the environmental performance (EP) and the financial performance (FP) of companies. Despite the impressive body of empirical evidences, this interaction is greatly nuanced, very complex, and set within a provocative framework. The company's environmental performance is not a gentle concept to grasp. This concept covers a broad variety of quantification techniques of different strategies, policies, targets, or regulations implemented by a company, in its effort to preserve the natural environment. An important number of studies has empirically analyzed the impact of environmental performance on corporate financial performance, including carbon disclosure tools [5–12], emissions/pollution impact [7], or environmental corporate social responsibility [9, 10]. A summary of these scholars' findings is drawn up as two-sense outputs: a positive relationship between the EP and the FP, on the one hand, and a negative one, on the other hand. The evidences of a positive relationship are numerically superior [5, 7, 8] to those of a negative association [10], meaning that the financial efforts of companies to invest in green technologies or green-actions are appreciated by the key stakeholders, and rewarded through a higher financial performance. Moreover, some findings did not reveal any relations between the environmental performance and the financial performance [9].

The divergent empirical outputs are presumably generated by a variety of measures with different ecological content [20]. However, the gap between the academic world and the practitioners seems to become deeper with the evolution of these measurement tools. From a practical point of view, the situation is likely to be more complicated, and we need to understand and to integrate it into the empirical research. The companies operate in a competitive economy with real and ongoing environmental constraints. Management teams act in response to environmental regulations, and the stakeholders make their decisions on the information available regarding the risk and opportunities related to the ecological footprints faced by the company. Thereby, not any type of nonfinancial environmental issues is important for the decision process and so, it is susceptible to influence the financial performance of the company. The primary studies on the environmental-financial performance relationship mainly omitted this fact.

2.2. The Materiality Framework. The growing informational value of incorporating nonfinancial data into the business decision process has been revealed as the "financial materiality" framework. This concept captures the usefulness or practical relevance of a piece of information as if "omitting or misstating of it could influence the decisions that users make on the basis of the financial information of a specific reporting entity" [21] (p. 66). International institutes, such as the United Nations (UN) [13] and the Global Reporting Initiative (GRI) [14], have based their description of the materiality of nonfinancial information, like environmental, social, and governance indicators, on the financial information, whether or not the information would change the decision made by the relevant stakeholders [22]. The practical significance of such nonfinancial disclosure has driven the necessity of comprising the financial report of the company including both quantitative and qualitative data, which are closely related to their operating activities. As the SASB suggests, in the research [15], the companies need to identify and invest in environmental and social issues that are strategically connected to their business. A disclosed measure can be material as long as its content is relevant both at the company level and for the business sector. In line with these remarks, we can say that materiality can be observed only in the context of the decision process, as an additional factor that has the capacity for influencing the operating conditions of a company and even its financial performance level. There is a considerable amount of Environment Social Governance (ESG) public information available, but the difficulty consists in identifying the piece of information that has the highest utility in the decision process. Going further, the nonfinancial measures (ESG) may contain both material (decisional relevant) and immaterial (decisional irrelevant) information and, to gain insights into their complex materiality manifestations, new and exploratory approaches are needed to be put in place.

An important tool in understanding materiality is the Map Materiality developed by the SASB. Focusing on material issues, this Map encloses five sustainable Dimensions (Environment, Social Capital, Human Capital, Business Model and Innovation, and Leadership and Governance), each of them being secondary detailed into three to seven General Issue Categories [16]. The SASB includes the environmental impact of a company into the Environmental Dimension "either through the use of non-renewable natural resources as imputes to the factor of production or through harmful releases into the environment that may result in impacts on the company's financial condition or operating performance" [15]. The Environmental Dimension is further detailed into six general issue categories: GHG Emissions, Air Quality, Energy Management, Water and Wastewater Management, Waste and Hazardous Materials Management, and Ecological Impact [16].

As a standpoint on the current level of knowledge, we stipulate the following research assumption: the environmental measures of oil and gas companies have a significant influence on the financial performance level, based on their materiality capacity.

3. Materials and Methods

3.1. Graphical Model Settings. The graphical modeling is a merge between the probability theory and the graph theory, and provides the framework necessary for the design and analysis of a new system. The fundamental goal of a graphical model is to capture and visualize, as a network representation, the conditional dependencies between a set of variables (Figure 1). In essence, a graph is a network made up of nodes (variables, or referred to as items or vertices) and linkages (dependencies among nodes, or referred to as lines or edges), defined as [23]

$$G = \{V, E\}, \tag{1}$$

where G is a graph model representing the network, in general terms; V is the set of variables or nodes (a-e) in the network; and E represents the set of links between nodes (indicating the direction and strength of the casual relationships).

Theoretically, a graphical analysis refers to a considered system of variables and the relationship between them,

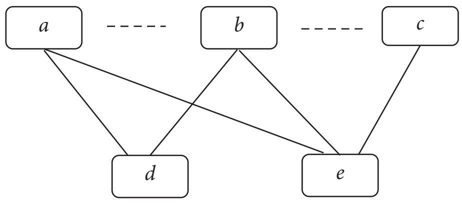

Figure 1: Generalized graphical model as a Bayesian network. Source: own conception.

estimated on a wide range of analytical techniques. In this paper, we have used two graphical approaches, namely, the Structural Equation Modeling (SEM) and the Gaussian Graphical Model (GGM), so as to provide accurate and robust evidences regarding the interaction between material environmental measures and the financial performance. The SEM and GGM are advanced methods, which complete against each other "by using the strength of one framework to overcome the shortcomings of the other framework" [19] (pp. 2). While SEM is focusing on the variance that is shared across all variables, the GGM highlights the variance that is unique to pairs of variables [24]. In particular, both methods rely on the assumption that "the covariances between observed variables are not caused by any latent or unobserved variable" [19] (pp.7).

3.1.1. Structural Equation Modeling (SEM). Structural Equation Modeling (SEM) is an advanced multivariate technique, which embodies mathematical models, statistical methods, and graphical representation that allows for the analysis and representation of the pattern of causal processes. The SEM method is used in social sciences and economics to define "a theoretical causal model consisting of a set of predicted covariances between variables and then test whether it is plausible when compared to the observed data" [25, 26].

As an "integrative procedure that appraises overall interlinkages among considered variables, direct, indirect, and total" [27] (p. 9), a structural equation model (SEM) is a system of linear equations among variables, similar to multiple regressions, but much more complex in their building, because in multiple regressions there is a limited number of dependent variables, while within the SEM pathway models there may be several dependent variables, as we enclosed in our analysis. Mainly, the SEM comprises two parts: a structural part, expressing the endogenous or dependent constructs as linear functions of the exogenous, or independent, constructs, and a measurement part, linking the constructs to observed measurements [28].

The SEM models are based on the general representation as depicted by [29] (p. 8)

$$\begin{cases} b_{11}y_{2t} + \cdots + b_{1m}y_{mt} + c_{11}x_{1t} + \cdots + c_{1n}x_{nt} = \varepsilon_{1t}, \\ b_{21}y_{2t} + \cdots + b_{2m}y_{mt} + c_{21}x_{1t} + \cdots + c_{2n}x_{nt} = \varepsilon_{2t}, \\ \vdots \\ b_{m1}y_{mt} + \cdots + b_{mm}y_{mt} + c_{m1}x_{nt} + \cdots + c_{mn}x_{nt} = \varepsilon_{mt}, \end{cases} \tag{2}$$

"where t is the number of observed time periods, b_{ij} represents the y_{ij} endogenous variable's parameters, c_{ij} are the x_{ij} exogenous variable's parameters, $i = 1, \ldots, m$, $j = 1, \ldots, n$, and ε comprises the error term (residuals)" [29] (p. 8).

Structural coefficients of SEM models are represented by the regression coefficients in equation (2), and indicate *two types of effects* [30, 31]: structural effects of endogenous variables (y_{ij}) on other endogenous variables (x_{ij}) (coefficients denoted by b); structural effects of exogenous variables (x_{ij}) on endogenous variables (coefficients denoted by c).

The basic principle of the function of the SEM is that the linear equations system proceeds in a specific casual order, which can be used to generate an implied covariance matrix [32]. Furthermore, the difference between the observed covariance structure and the covariance related to the path model included in the SEM is minimized by modifying "the path coefficients and residual variances iteratively until there is no further improvement in fit" [33] (p.6). For this, the maximum likelihood estimator technique or the weighted least-squares method can be used as tools to indicate a fit criterion in order to be maximized. Due to the estimation of the unobserved (latent) variables from the observed variables in the case of the SEM, the method permits the creation of composites by taking into account an explicit measurement error. Finally, the full model is estimated from a data set and can be tested to fit the sample data. Assessment of the model inference in the SEM is made by "comparing the goodness-of-fit between the model implied covariance matrix and the empirical covariance matrix" [33] (p.6). Hence, the rigorous explanation of the SEM results are grounded, firstly, on specific tests that assess the conformity of the models for the data used, namely, the *confidence tests*, such as Cronbach's alpha test (that measure the total scale of the coefficient Alpha), the Wald test (that provide the p value for each equation enclosed within the model), and *the goodness-of-fit tests* (mainly used are likelihood ratio (LR), Akaike's information criterion (AIC), Bayesian information criterion (BIC), comparative fit index (CFI), and Tucker–Lewis index (TLI)).

The STATA 16 software was used to develop and assess the SEM, capable of reflecting the natural dependency between the environmental measures (implied the materiality conditions) and the financial performance. To validate the SEM′ results, we have run several tests, namely, Cronbach's alpha, Wald tests for equations associated with the SEM models, and the goodness-of-fit tests.

3.1.2. Gaussian Graphical Model (GGM). Gaussian Graphical Modeling is a network analysis technique that provides an "easy to grasp overview of the relationships between items and variables included in a study" [34] (p.2). A visual representation, as a network structure of these relationships, helps researchers to gain insights about the casual dependency and interaction mechanism among modeled variables.

Considered as a partial correlation graph network, the GGM is different "from typical exploratory analysis based on partial correlational coefficients" [19] (p.8), with a more interesting structure and is easier to interpret. A GGM consists of a set of variables (items or nodes), represented by circles, and a set of links between them that takes the form of lines or edges and visualizes the relationship between the items or variables [35–37]. The size and color of the lines (edges) comprise information about the strength and the direction of the relationship between the variables (items or nodes). The thickness of the lines reflects the strength of the association between the variables, while the colored blue or green lines usually represent the positive relationship and red lines represent a negative relationship. Notably, the absence of a line "implies no or very weak relationship between the relevant items or variables" [34] (p.2). Consequently, the GGM allows for the assessment of the intensity of the links between the variables, as well as the evaluation of their structure within the network.

Within a GGM, the relationships between each pair of variables are estimated as partial correlation coefficients, which reduce the risk of finding a spurious correlation (i.e., the correlation between variables that are not directly related but are correlated through an unknown variable). Avoiding spurious correlation is a key advantage of partial correlation. As such, the partial correlation coefficient is sufficient to test the relationship as a degree of conditional independence between two items or variables, after conditioning all the other variables included in the data set [19, 34].

By assuming multivariate normality, a partial correlation network encodes a "*p x p, weight matrix, Ω,* in which element ω_{jk} represents the edge weight between node *j* and node k" [19] (p.7), as we can see in the following equation:

$$\mathrm{Cor}\left(y_j, y_k|\mathbf{y}^{-(j,k)}\right) = \omega_{jk} = \omega_{kj}. \quad (3)$$

The partial correlation coefficients used to express the strength of the connection between two variables in the GGM can be obtained according to the equation (4) [38] from the standardization of the *precision matrix* $(\widehat{K})$:

$$\mathrm{Cor}\left(y_j, y_k|\mathbf{y}^{-(j,k)}\right) = -\frac{k_{jk}}{\sqrt{k_{kk}}\sqrt{k_{jj}}}. \quad (4)$$

Two variables or nodes are connected through an edge of the network if "there is covariance between those nodes that cannot be explained by any other variables in the network" [37] (p.307). If the estimated partial correlation coefficient is zero, "there is conditional independence and hence no edge in the network" [19] (p.7).

To account for all the interdependencies between the considered variables, embodying the environmental and financial performance, we have developed three GGMs. The estimation of the models is based on the partial correlation (PCOR) methodology, provided by the *R* Studio 4 program.

3.2. Data Preparation, Variables, and Hypotheses. To get the set of variables, we have conducted an empirical investigation at the level of 194 oil and gas companies within the EEA countries. The data have been collected from the Thomson Reuters/Refinitiv database [18] and include all the information available in the Environmental measurement field. At the level of the oil and gas industry, there are 2,197 constituents in the Refinitiv database. The constituent companies available cover all the geographical regions, but in order to ensure the homogeneity and the comparability of the data sampled, we have selected only companies within the EEA (namely, the EU MS, Iceland, Liechtenstein, and Norway), and we have obtained a final sample of 194 companies. We justify and link our selection criteria to the common interests and regulations of these countries in achieving the environmentally sustainable green growth and a circular economy [39].

The Refinitiv database offers a company's ESG performance general score across three pillars, namely, Environment (E), Social (S), and Governance (*G*); 10 themes; and 178 relevant measures. All measures are based on considerations around materiality, data availability, and industry relevance [18, 40]. The Environmental issues are available both as a multidimensional measure (Environmental Pillar Score) and as one-dimension measures (95 relevant metrics organized in three themes: Resource Use, totaling 33 measures; Emissions, totaling 40 measures; and Innovation, totaling 22 measures) [41]. There is an important body of scientific research based on the data provided by specialized databases (such as Thomson Reuters/Refinitiv, MSCI, Vigeo, Bloomberg), the ESG score being the variable predominantly approached from these sources by the scholars [42, 43].

The first stage of our research has consisted in a hand-mapping investigation carried out by overlapping the SASB's Environmental Dimension Categories on Environmental issues, provided by Thomson Reuters/Refinitiv database. We followed the earlier literature's technique of Khan, Serafeim and Yoon [44] in adopting the SASB's guidance to identify relevant environmental measures. As in the case of Khan [45], there is no perfect match between their two contents of SASB and Thomson Reuters regarding the environmental issues. In fact, no matter how different scholars named it or used it [17, 21, 22, 44, 45], the hand-mapping investigation technique requires the identification of ESG factors.

Going further with this investigation technique, we have transposed the content of all six recommended categories into the Refinitiv's Environmental measures. Our first notice was that, in the case of oil and gas companies, the intensity of the financial materiality's impact varies across the six SASB's Environmental Categories. We have selected 95 environmental indicators that are the most appropriate ones. The entire hand-mapping investigation process has been based on the information usefulness of the indicators into the decision-making process, as their relevance for investors (according with SASB's guidance). Following the empirical evidences of materiality's existence and its manifestation, especially the findings of Serafeim regarding that "not all social and environmental initiatives are created equal, or similar related to the business" [17] (p.3), we have decided to introduce an additional selection criterion, namely, the cover range of the environmental measures' content. If the disclosed issues consist of mixed information's content, the stakeholders need to have the opportunity to make a distinction.

The nonfinancial indicators add value to the decision process as long as they contribute to a widening of the risks and opportunities spreadsheet. Offering different types and dimensions for corporate environmental behavior measures, the key stakeholders and especially the investors will have the opportunity to decide which measure is the most suitable to the business case and widely to the financial impact of the company's operating activity.

As one of the main contributions of the research, we have introduced three different degrees of information content to be considered as a potential condition, in order to achieve a financial impact of the environmental performance at the operating activity level. Thus, we have defined three subcategories of environmental measures, covering the content range from general to particular, namely:

(i) Policy environmental measures that give information about the presence or absence of a general policy of the company in the environmental field (a general content range)

(ii) Target environmental measures that provide information about the general targets set by the company in the environmental field (a medium general content range)

(iii) Concrete environmental measures that offer information about the footprint of the company on the environment (a particular content range)

For each of the six SASB's Environmental Categories, three measures were selected, a total of 18 measures (see Table 1), which were used as independent variables. To these environmental performance's measures, we have added the financial performance indicators, namely, the Return on assets (ROA), Return on equity (ROE), and Total Assets (see Table 2), and used them as dependent variables.

Each of the 18 environmental measures reveals information about the decisions and actions taken by a company, out of legal compliance, in order to achieve pollution reduction. We assess these efforts through six different categories, essential for environment protection, namely, GHG Emissions, Air quality, Energy, Water and Wastewater, Waste and Hazardous Materials, and Ecological Impact. The first step in becoming environmentally sustainable is to establish clear and adequate policies (Policy measures). Their objectives must be reflected in measurable targets (Target measures). Step two is to implement these policies and to track deviations from the targets outlined. Based on this analysis, step three consists in measuring the concrete achievements (Concrete measures) and settle the future actions in the field. The Refinitiv's Environmental measures disclose whether the company reports (True = 1) or not (False = 0) environmental policies, targets, and concrete measures in connection with the six essential ecological categories. Any action taken by a company to reduce the GHG emissions, the waste, and the ecological impact of its activity, or to improve the air quality, the energy, and the water efficiency will impact the operational and financial outputs of the company. The intensity of such influence may be different if a specific ecological action is at the policy stage, at pursuing the target stage, or it has generated concrete achievements.

Both categories of the selected variables (independent and dependent) are in line with the paramount perspective of the environmental-financial performance' relationship, according to which "building a sustainable business is difficult if the business is ultimately unable to provide an appropriate long-run return on shareholders' savings" [44] (p.105). Based on this, the financial performance measures are mainly expressed in the literature, through the Return on Assets (ROA), Return on Equity (ROE), or Tobin's Q ratio [6–8, 11, 20]. For the large companies (such as the sample analyzed in this study), the value of Total Assets is a defining indicator, and therefore its association with the environmental measure is used to control and validate the EP-FP economic implications.

The SASB's guidance was used to analyse the materiality impact of the selected environmental measures on the financial performance. Furthermore, three more dimensions were included within the study, namely, the policy, the target, and the concrete level. Through this, we stipulate, as an assumption to be tested, the necessity of measuring and disclosing the same environmental issue from an ongoing integrative point of view: the policy implemented by the managerial team, the targets set out, and the results of the implemented actions.

In line with the literature review, the paper follows the link between the environmental performance and the financial performance and employs, as a new research hypothesis background, the materiality theory. The principle of this theory was interplayed in the analysis of the EP-FP association, and we assume the following research hypotheses:

Hypothesis 1. The policy environmental measures, belonging to SASB's Environmental Categories, are connected with the financial performance.

Hypothesis 2. The target environmental measures, belonging to SASB's Environmental Categories, are connected with the financial performance.

Hypothesis 3. The concrete environmental measures belonging to SASB's Environmental Categories are connected with the financial performance.

As we have pointed out previously, the research hypotheses cumulate the basic SASB's materiality theory with some new potential conditions for the materiality manifestation (individual and ongoing stages of measuring the environmental performance of a company).

4. Results and Discussion

The main findings, obtained by applying the materiality manifestation conditions (policy/target/concrete as different content levels) on the environmental-financial performance

Table 1: Independent variables included within the econometric models.

Acronym	Details	Unit of measure	Category
P_emiss	*Policy Emissions*, if the company has a policy to improve emission reduction. *Policy measure*	Binary	EP (greenhouse gas, GHG, emissions category)
T_emiss	*Targets Emissions*, if the company has set concrete targets to achieve emissions' reduction. *Target measure*	Binary	
CO_2	*CO_2 Equivalent Emissions Total*, the total amount of carbon dioxide (CO_2) and CO_2 equivalents emitted. *Concrete measure*	Tones	
Nox	*NOx and SOx Emissions Reduction*, if the company reports any initiative to reduce, reuse, recycle, or cut out the NOx or the SOx emissions. *Policy measure*	Binary	EP (air quality category)
Voc_emiss	*VOC or Particulate Matter Emissions Reduction*, if the company reports any objectives to reduce or cut out the volatile organic compounds (VOC). *Target measure*	Binary	
Emiss	*NOx Emissions*, the amount of NOx emissions emitted. *Concrete measure*	Tones	
P_energy	*Policy Energy Efficiency,* if the company has a policy to improve energy efficiency. *Policy measure*	Binary	EP (energy management category)
T_energy	*Targets Energy Efficiency,* if the company has set targets to achieve energy efficiency. *Target measure*	Binary	
Energy	*Energy Use Total,* as total direct and indirect energy consumption. *Concrete measure*	Gigajoules	
P_water	*Policy Water Efficiency,* if the company has a policy to improve water efficiency. *Policy measure*	Binary	EP (water and wastewater management category)
T_water	*Targets Water Efficiency*, if the company has set targets to achieve water efficiency. *Target measure*	Binary	
Water	*Water Withdrawal Total,* the volume of water withdrawn. *Concrete measure*	Cubic meters	
P_waste	*Waste Reduction Initiatives,* if the company reports any initiative to reduce, reuse, recycle, or cut out the waste *Policy measure*	Binary	EP (waste and hazardous materials management category)
E-waste	*e-Waste Reduction*, if the company reports any initiative to reduce, reuse, recycle, or cut out the e-waste. *Target measure*	Binary	
Waste	*Hazardous Waste,* the amount of hazardous waste produced. *Concrete measure*	Tones	
P_chemic	*Toxic Chemicals Reduction,* if the company reports any initiative to reduce, reuse, recycle, or cut out the toxic chemicals. *Policy measure*	Binary	EP (ecological impact category)
Land_env	*Land Environmental Impact Reduction,* if the company reports any initiative to reduce environmental impact on land owned. *Target measure*	Binary	
Env_exp	*Environmental Expenditures,* total amount of environmental expenditures reported. *Concrete measure*	Monetary units	

Binary: true = 1; false = 0. Source: own contribution.

Table 2: Dependents variables included within the econometric models.

Acronym	Details	Unit of measure	Category
ROA	Return on assets (net income/total assets)	%	FP
ROE	Return on equity (net income/book value of equity)	%	FP
Total assets	The amount of total assets	Monetary units	Controlling variable

Source: own contribution.

relationship, are presented in this section. In this respect, we have deployed two graphical approaches, namely, the Structural Equations Modeling (SEM) and the Gaussian Graphical Models (GGM).

4.1. The Results of Structural Equations Modeling (SEM). We have assessed the overall interlinkages (direct, indirect, and total) between EP-FP from a dual presumption (determinants-impact interplay), by applying the Structural Equations Modeling with latent class analysis (SEM-LCA) procedure in a gradual approach, following each research hypothesis.

4.1.1. The Impact of Policy's Environmental Measures on the Financial Performance. The policy panel contains measures with a general content range regarding the policies adopted by a company in the environmental field. The measures replay only the presence or absence of such policies within the company's general management. In the case of oil and gas companies from the EEA MS, according to our first hypothesis, Hypothesis 1: *The policy environmental measures, belonging to SASB's Environmental Categories, are connected with the financial performance*, we assess if these measures could induce or not a material impact on the financial performance level. The results shown in Figure 2 point out that four of the six environmental measures influence both the ROA and the ROE.

The Policy environmental measures with statistically relevant influences on the ROA level are the *P_emiss* (−0.66), the *P_water* (−0.39), and the *P_waste* (0.31). The ROE level is statistically influenced by the following environmental policy measures: The *P_emiss* (−0.69), the *Nox* (0.32), the *P_water* (−0.5), and the *P_waste* (0.35). The Total Assets level is positively influenced by the *P_emiss* (0.84), the *P_energy* (1.6), the *P_water* (0.89), and negatively influenced by the *P_chimic* (−0.62).

The overall impact of the policy environmental measures upon the financial performance reveals the following economic implications. The *P_emiss*, from the GHG Emissions' category, and the *P_water*, belonging to the Water and Wastewater Management's category, have generated a negative impact, showing a reduction in both the ROA and the ROE levels. These outputs suggest that the managerial policy of the company to improve both the emissions reduction and the water efficiency generate important operating expenses, which lowers down the financial performance level of the company. The *P_waste*, from the Waste and Hazardous Materials Management's category, has positively influenced both the ROA and the ROE. Any reported initiative of the company to reduce, reuse, recycle, or cut out the waste generated represents an increase in the operating efficiency and the productivity. Based on this factor, the company's financial performance (ROA and ROE) has generated sustainable growth.

The policy acting for the NOx and the SOx Emissions Reduction (*Nox*) has performed as an incentive factor for the financial performance of oil and gas companies, on the one hand. Thus, the *Nox*, belonging to Air quality's category, has no impact on the ROA level, but it is positively influencing the ROE level. The reported intent of the company in reducing or cutting out the NOx or the *Sox* emissions contributes to a better image of the company in investors' perception, and through this, to an increasing of the ROE value, as a measure of owners' remuneration.

The controlling variable (Total Assets) is positively influenced by *P_emiss*, *P_energy*, and *P_water* environmental variables, confirming the fact that, in order to improve the environmental behavior, large investments into the tangible assets of the company have to be made. The *P_chemic* measure, from the Ecological Impact's category, has a negative influence on the Total Assets level, but it has no statistically relevant impact on the financial performance (both the ROA and the ROE).

Based on the SEM findings, we can summarize that the measures regarding the environmental policy of the oil and gas companies have a material impact on the financial performance, which confirms our *1st Hypothesis: The policy environmental measures, belonging to SASB's Environmental Categories, are connected with the financial performance*. At the same time, the findings obtained from the SEM technique support the SASB materiality's theory regarding the environmental impact upon financial performance. Although, it is considered only the first step in achieving sustainable development, the integration of the environmental policy within the overall business strategy is the stage with the highest decisional impact. During this phase, the future operational and financial implications are taken into consideration and budgeted. Stakeholders know the importance of this step and incorporate it in their evaluation.

4.1.2. The Impact of Target Environmental Measures on the Financial Performance. By assaying more in-depth measures than the general policy of a company regarding the environment protection, namely, the indicators that reflect the targets set by the company from the oil and gas field, we test the material impact within the six categories by Hypothesis 2: The target environmental measures, belonging to SASB's Environmental Categories, are connected with the financial performance.

The overall impact of the target environmental measures on the financial performance, assessed by the SEM procedure, show statistical relevant influences in the case of three environmental categories on the ROA and the ROE (Figure 3). These three categories with material impact are not the same for the ROA and the ROE levels. In the case of the ROA, its level is negatively influenced by the *T_emiss* measure (−0.43), belonging to the GHG Emissions' category, and is positively influenced by *T_water* (0.37) and *Land_env* (0.26) measures, belonging to Water and Wastewater Management and the Ecological Impact. The targets set by a company to get emission reduction put pressure on the operating costs and thereby diminish its financial performance reflected by the ROA. At the same time, targeting an increase in water efficiency and a reduction in the environmental impact on the company's land leads to cost cuts, with a direct impact on the increase in ROA.

In the case of the ROE, the SEM findings have revealed that its level is negatively impacted by the *T_emiss* (−0.48) and *Voc_emiss* (−0.15) measures, and positively impacted by the *T_energy* (0.39) measure. The negative impact reflected by the correlation coefficients of the measures from the categories of GHG Emissions and Air quality suggests that the concrete targets assumed by a company to reduce air pollution are appreciated by stakeholders as a factor in reducing their remuneration (ROE). At the same time, achieving energy efficiency at the oil and gas companies' level represents important reductions of operational costs, and thereby an increase in the ROE level.

Total Assets, as a controlling variable, are positively associated with three of the previous environmental measures, namely, *T_emiss* (1.1), *T_energy* (0.46), and *Land_env* (1.3), confirming the economic implications of these variables upon financial performance. Any target assumed by oil and gas companies closely related to their environmentally

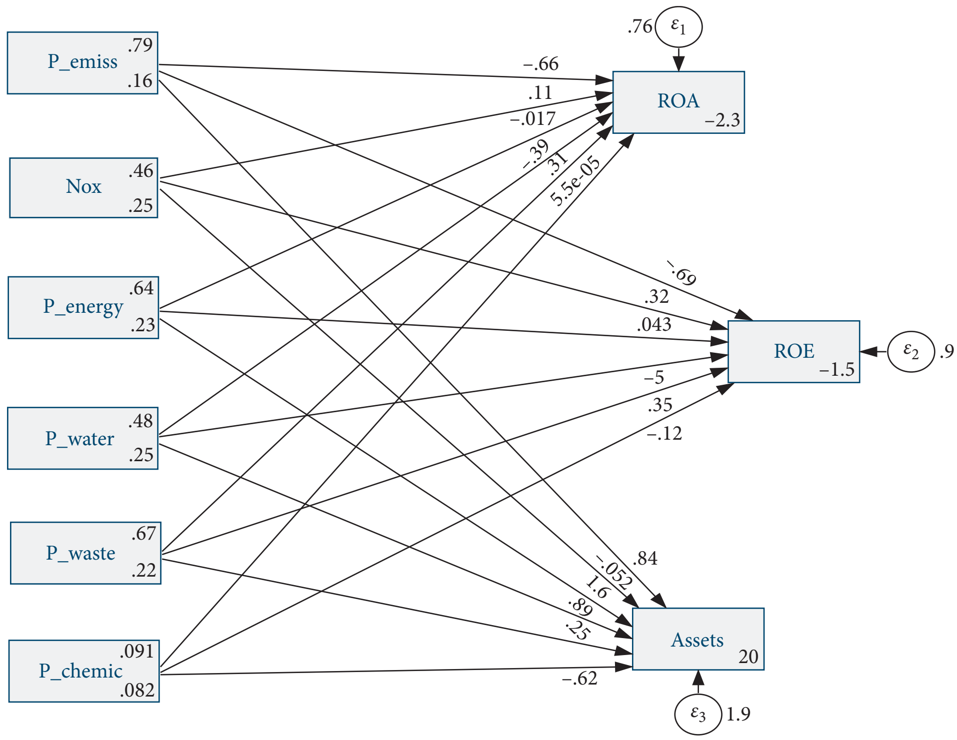

Figure 2: The association between policy measures and the financial performance (SEM-LCA), for oil and gas companies from the EEA, 2009–2018. Source: own contribution in Stata 16.

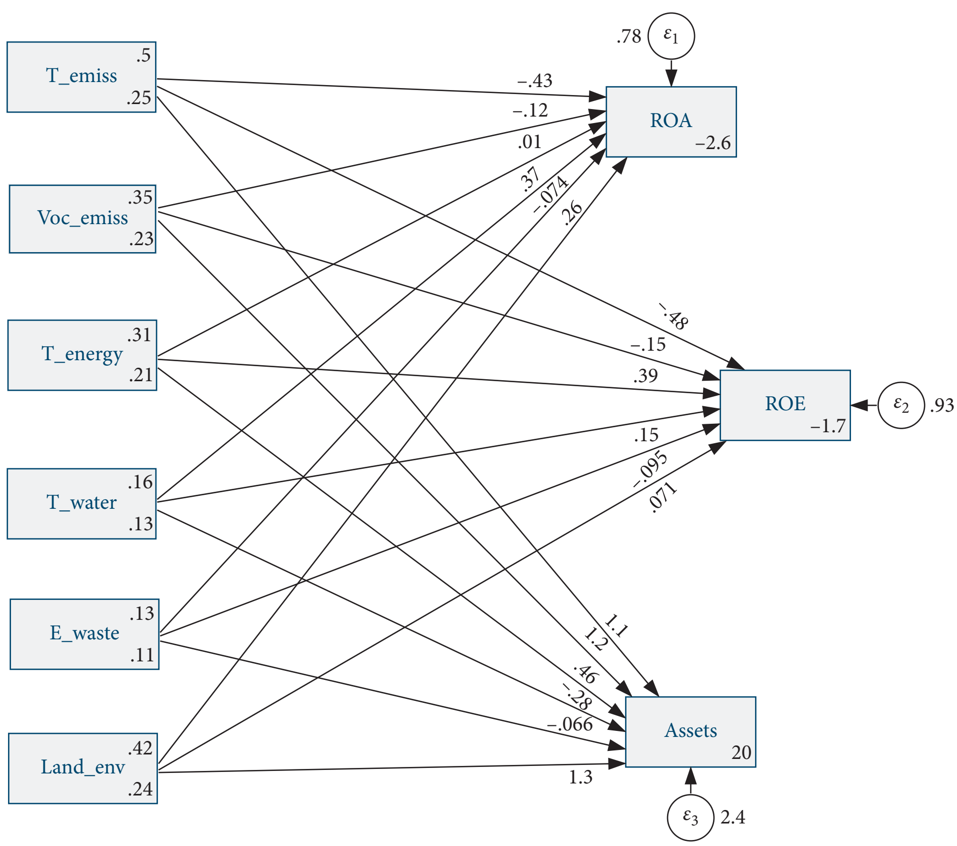

Figure 3: The association between targets measures and the financial performance (SEM), for oil and gas companies from the EEA, 2009–2018. Source: own contribution in Stata 16.

sustainable goals will lead to large investments in operational assets.

As a conclusive remark, only the target measures belonging to three of the six SASB categories impact the financial performance. Thus, in the case of SEM results, *our 2nd Hypothesis: The target environmental measures, belonging to SASB's Environmental Categories are connected with the financial performance* is partially confirmed. The lower relevance that the stakeholders give to the targets set out for each environmental category can be seen as the main reason behind the empirical findings. The presence or the absence of the environmental targets can be appreciated as a consequence of the policy stage, and therefore, is less important for the stakeholders. At the same time, a company can have an environmental policy but without adequate targets to pursue. This situation needs a much deeper analysis.

4.1.3. The Impact of Concrete Environmental Measures on the Financial Performance. The environmental measures with the most detailed information content have been identified as the specific metrics that express, in particular units, the effective amount of natural resources used or the emissions released. Different units of measurement have been harmonized through a logarithm's action.

The association between the environmental measures with concrete content and the financial performance reveals a very low materiality manifestation (Figure 4). The financial performance variables (ROA and ROE) are influenced by two different environmental measures. The ROA level is negatively influenced by CO_2 (−0.059), as a measure belonging to GHG Emissions' category, which cumulates the total amount of CO_2 and CO_2 equivalents emitted by the company's activity, on the one hand, and is positively influenced by the Waste (0.36), as a measure belonging to the Waste and Hazardous Materials Management category, which accumulates the total amount of waste produced by the company, on the other hand.

The ROE level is negatively influenced by two concrete measures, namely, Emiss (−0.05), as a measure belonging to the Air quality category that cumulates the amount of NOx emissions emitted by the company's activity; and Energy (−0.59), as a measure belonging to the Energy Management category that cumulates the amount of total direct and indirect energy consumption.

The Total Assets level is influenced by four concrete measures (CO2 (−0.58), Water (0.082), Waste (−0.075), and Env_exp (0.067)), confirming the importance of this indicator in the case of large companies' management.

In the case of environmental measures covering the concrete level of the ecological impact of a company, their materiality impact on the financial performance is poorly supported in the case of SEM findings. Thus, our 3rd Hypothesis: *The concrete environmental measures, belonging to SASB's Environmental Categories, are connected with the financial performance* is rejected. The concrete level of the company's ecological footprint, a very important step in the sustainable goal's achievement, has no significant connection with the financial performance (ROA and ROE). A practical argument for these findings can also be put on the account of the relevance of the decision-process. The financial decisions are adopted during the policy-making stage and the implementation stage. Consequently, the stakeholders are more interested in assessing the metrics related to these stages.

The graphical modeling outputs, generated by the SEM technique, validate the integrating role played by the materiality theory within the association of EP- FP variables. New insights of this association are postulated by the conditions assumed for the materiality manifestation, which are less supported by the findings (only the individual environmental measures covering the Policy and the Target of the company influence the financial performance). At the same time, the mixed association (positive and negative) between individual environmental variables (with different range of content) and financial performance confirms a new literature supposition that materiality manifestation varies between different settings [12, 22].

4.2. The Results of the Gaussian Graphical Models (GGM). To further enhance the graphical visualization of the network structure between the environmental metrics and the financial performance of oil and gas companies, we have deployed the Gaussian Graphical Model procedures. The estimation of the models was configured based on the Partial correlation technique (PCOR), separately for each of the three content levels of the environmental measures, namely, policy, target, and concrete.

4.2.1. The Impact of Policy's Environmental Measures on the Financial Performance. Furthermore, we can see that the results of the GGM procedure support the findings of the SEM analysis and offer, at the same time, a much deeper insight into the manifestation in the EP-FP relationship, regarding the general policy in the field of environment (Figure 5).

Within the estimated Gaussian graphical network (Figure 5), it can be observed that the ROA is intensely negative associated with P_Emiss and P_Chemic variables, and intensely positive correlated with P_Waste. There is also a positive connection with P_Water, but the intensity is lower. In the case of the ROE, there are intensive and negative connections with P_Water and P_Waste variables, and an intensive and positive connection with P_Energy. A positive but lower connection with NOx_Sox variable can be noticed. The control variable (Total Assets) is intensively connected with four environment variables (negatively with NOx_Sox, P_Chemic, and P_Water, and positively with P_Energy), supporting the relevance of the GGM findings.

Reported through the annual statement of the company or the social media channels, the presence or the absence from the general management policy of the issues related to the environmental concerns represents an essential stage in the assessment of environmental performance. The operational activity of oil and gas companies generates a considerable environmental footprint. Hence, the environmentally sustainable core policy is strongly

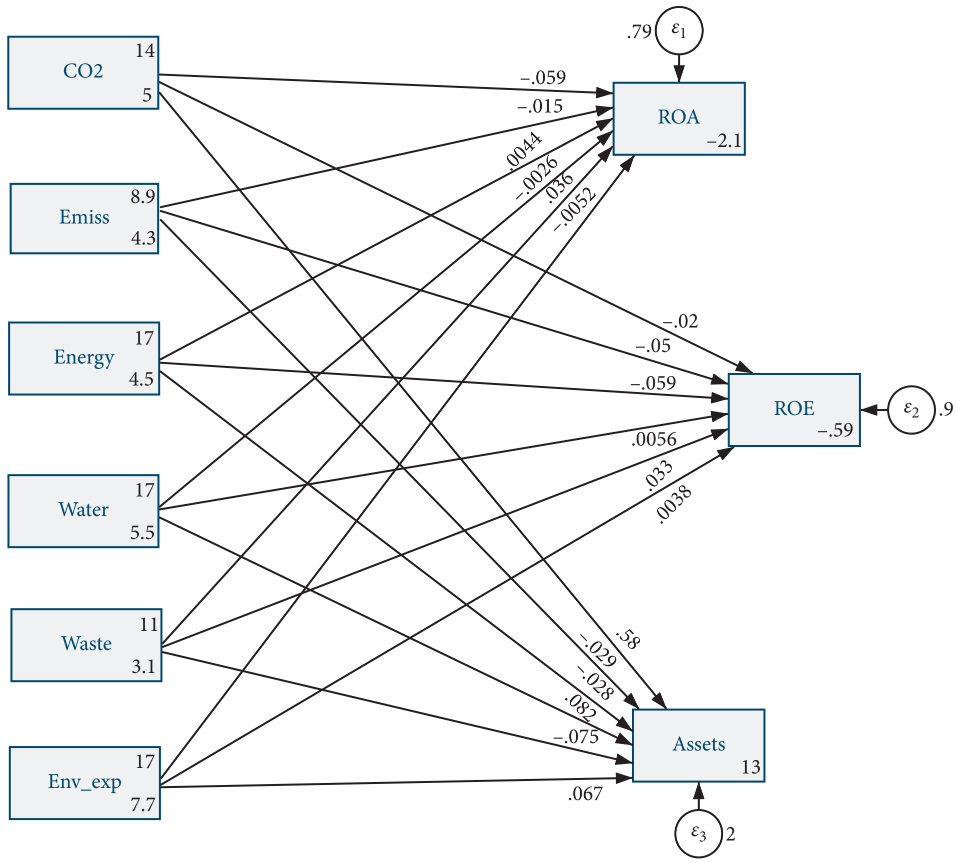

Figure 4: The association between concrete measures and the financial performance (SEM), for oil and gas companies from the EEA, 2009–2018. Source: own contribution in Stata 16.

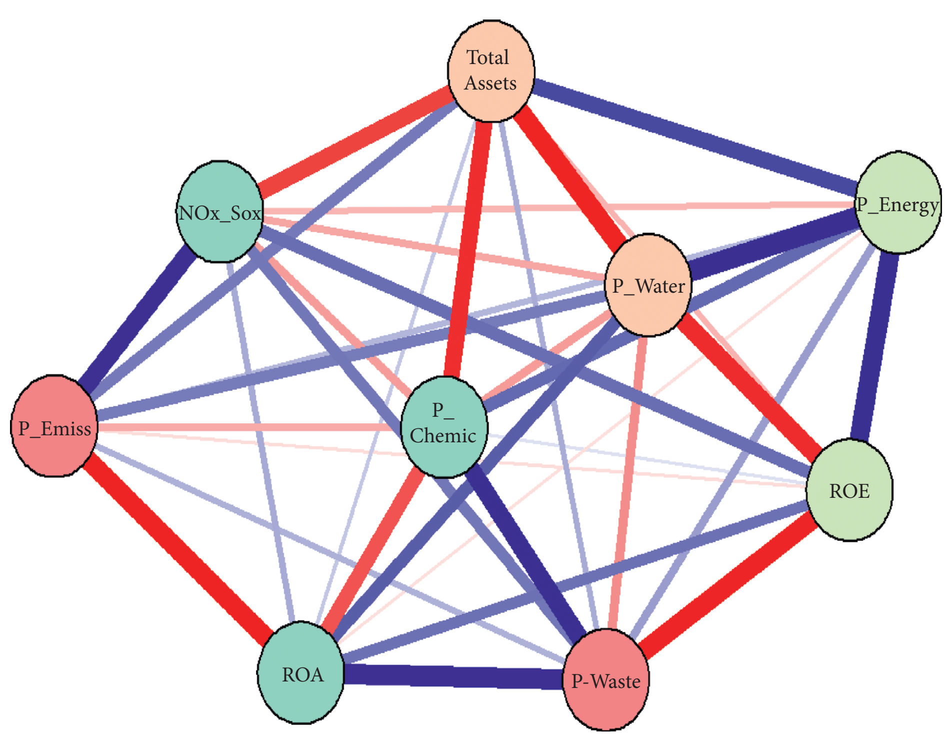

Figure 5: The association between policy measures and the financial performance (GGM), for the oil and gas companies from the EEA, 2009–2018. Source: own contribution in R program.

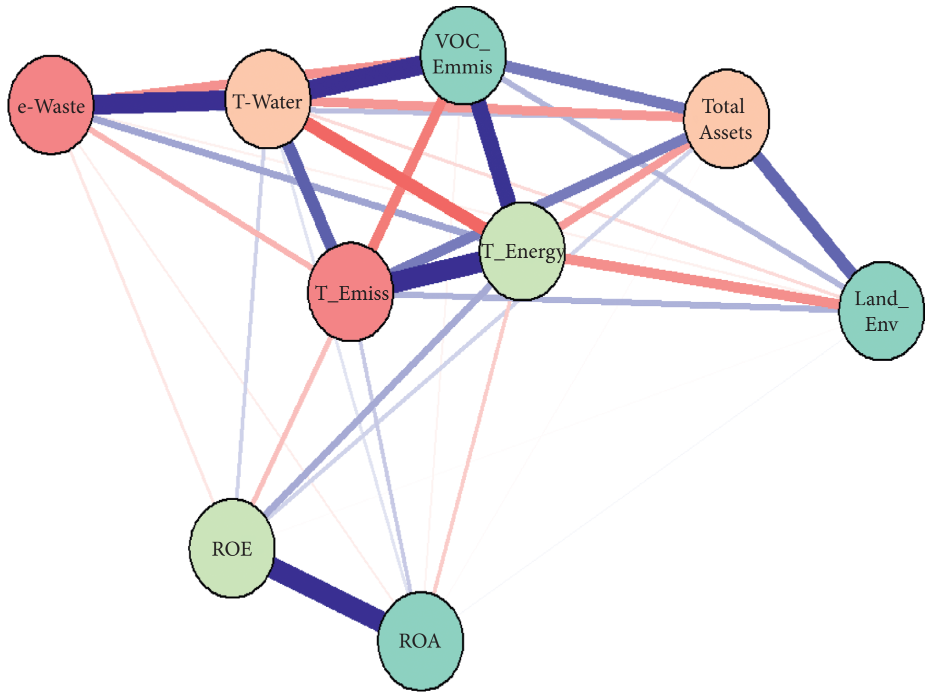

Figure 6: The association between the policy measures and the financial performance (GGM), for the oil and gas companies from the EEA, 2009–2018. Source: own contribution in R program.

connected to their financial performance. The SASB's materiality references are validated*, and our 1st Hypothesis: The policy environmental measures, belonging to SASB's Environmental Categories, are connected with the financial performance* is reinforced.

4.2.2. The Impact of Target Environmental Measures on the Financial Performance. The GGM estimated in the case of the environmental targets assumed by the oil and gas companies expresses, in a conclusive network visualization, the decrease of the intensity with which the materiality manifested within EP-FP relationship. The GGM findings (see Figure 6) reflect a lower connection between the financial performance (both the ROA and the ROE) and the environmental measures. A stronger connection can be seen between the control variable (Total Assets) and the variables that make up this category, supporting their economic implications.

Looking for more effective targets set out to preserve the environment, we have noticed that the materiality impacts of this type of measures are lower than the previous ones.

The opposite findings between the more-detailed information analyzed and the low predicting power of the financial performance evolution can be justified by the fact that the general policy covering environmental issues is not supported by the targets set out for environmentally sustainable growth. Similarly, to the SEM analysis, our 2nd Hypothesis: *The target environmental measures, belonging to SASB's Environmental Categories, are connected with the financial performance* is partially confirmed.

4.2.3. The Impact of the Concrete Environmental Measures on the Financial Performance. Going further, we have estimated the GGM in order to visualize the network between the financial performance and the measures with concrete content about the environmental footprint of a company (Figure 7).

The GGM findings support an even weaker association between the ROA and the ROE, on the one hand, and the environmental concrete measures, on the other hand. The controlling variable remains connected to the independent variables. According to both the SEM and the GGM outputs, the concrete panel of environmental measures has the lowest level of association with the financial performance. Thus, our 3rd Hypothesis: *The concrete environmental measures belonging to SASB's Environmental Categories are connected with the financial performance* is rejected.

A summary of the Gaussian Graphical Models provides a visual representation of a strong network interconnection only in the case of the policy environmental measures and the financial performance. The employment of a managerial policy regarding the ecological issues comprises financial and operational decisions. Based on the various financial implications from the policy-making stage, the measures belonging to this category have the most intense influences upon financial performance (the ROA and the ROE). As the environmental measures express a more particular content, namely, the targets set for the different environment issues or the concrete ecological achievements of a company, the intensity of the network interconnection with the financial performance is becoming weaker. The GGM outputs not only support the SEM conclusions but also provide a complementary analysis to its models. Similar to the remarks

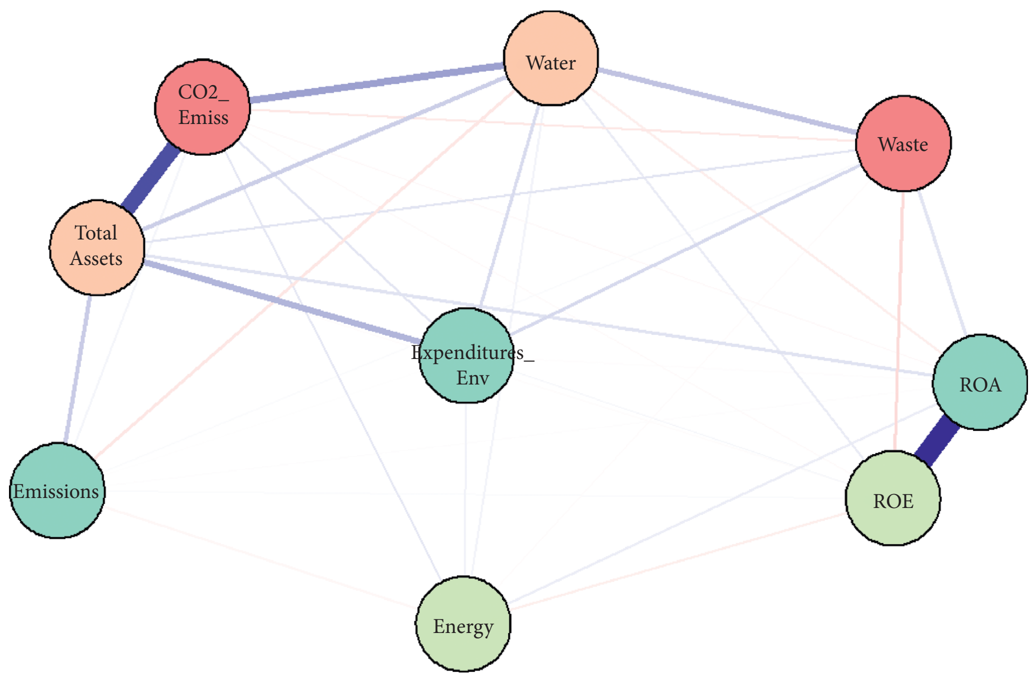

Figure 7: The association between the policy measures and the financial performance–GGM, for the oil and gas companies from the EEA, 2009–2018 *Source*: Own contribution in R program.

Table 3: Summary of the hypotheses and their results.

Hypothesis	Results	
	SEM	GGM
Hypothesis 1: the policy environmental measures, belonging to SASB's environmental categories, are connected with the financial performance.	Validated, with mixed findings (positive and negative links between EP-FP)	Validated, with mixed findings (positive and negative links between EP-FP)
Hypothesis 2: the target environmental measures, belonging to SASB's environmental categories, are connected with the financial performance.	Partially validated, with mixed findings (positive and negative links between EP-FP)	Partially validated, with mixed findings (positive and negative links between EP-FP)
Hypothesis 3: the concrete environmental measures, belonging to SASB's environmental categories, are connected with the financial performance is rejected.	Not validated	Not validated

Source: own contribution.

drawn from the SEM technique, the integrative role of the materiality theory is supported by the GGM outputs, while the new conditions assumed for such a materiality manifestation are partially validated.

5. Conclusions

Using the sample of the oil and gas companies from the EEA, this study brings to the fore the growing body of knowledge regarding the impact of environmental material issues on the financial performance. By applying two graphical integrative and complementary approaches (Structural Equations Modeling with latent class analysis and Gaussian Graphical Models) on the environmental-financial performance relationship, the research offers meaningful and robust evidences about the conditions of materiality's manifestation inside the network of variables.

Companies operating within the oil and gas industry are interested in achieving environmental footprint reduction and benefit from their green image, as "The European Green Deal" strategy set out for the year 2050 [3]. Strategically understanding the environmental-financial performance relationship represents a practical necessity, as it is an academic one. The research is relevant, robust, and extends the SASB's Map of Materiality recommendations to an integrative analysis, based on a different content range of the environmental measures. We have proposed a separation of the measures regarding the environmental behavior into three pillars, or informational levels (covering the general policy of the company, the targets set out, and its concrete footprint), as conditions of the materiality manifestation. Our empirical analysis relied on two approaches to modeling longitudinal and panel data, namely, the Gaussian graphical models (GGMs) and the structural equations (SEM). Both techniques imply a variance-covariance matrix, aiming to identify how variables are related to each other, namely, the direct and indirect effects of one variable on another, having their origin in path analysis. The SEM brings forward our research since it rejoins path analysis, factor analysis, and regression, thus allowing to specify multiple causal associations between our constructs, while the main advantage of the GGMs is the ability to handle different types of variables, as comprised in our dataset, since the variables included in the empirical analysis had different measurement units (e.g. binary, multi-category). The GGMs configured in our research were drawn as a network based on partial correlations (both positive and negative) graphically reflected through the absolute strengths (the width and the saturation of the edges between the nodes), thus being a network model of conditional associations. Therefore, we were able to model conditional associations, namely, the degree to which the variables are independent after conditioning on all other variables in the data set. This feature was essential in our empirical research endeavor since we focused on 18 environmental measures that capture, in a gradual frame, policies adopted by companies to achieve pollution reduction, targets set, and the deviations and the concrete measures as the final achievements. All of these credentials need to be assessed in their tight interdependence and sequential approach, as a complex network (performed in this paper through the GGMs) and through causal relationships (as enhanced by the SEM models designed to achieve the complicated model setup).

Based on a summary of the hypotheses and their results (Table 3), the overall research observation consists in the fact that the materiality manifestation varies both between individual environmental measures and the range of their informational content, just as Heijningen [22] also highlighted.

Based on the research outputs, we have noticed that materiality plays an active role in linking the financial performance with environmental, nonfinancial issues in the case of the oil and gas companies. The intensity of the connection reaches the highest point at the policy level and decreases as the informational content of the indicators evolves from general to particular. Considering the strong connection between the operational activity and the natural resources in the case of this industry, the presence of a clear environmental policy is appreciated as the core of the sustainable performance. Our findings support this affirmation.

The individual influences reveal both a positive and negative impact on the financial performance, and confirm the particularity of materiality theory as well as the conclusion of [12, 46]. However, mixed results can bring relevant observations. It is the case of the Water and Wastewater Management category, within which the measure disclosed as policy has a negative influence on the financial performance, while the target measures have a positive influence only on the ROA (according to the SEM outputs). The general information about the company policy to improve water efficiency can be appreciated by the stakeholders as a potential increase on costs volume, with a negative effect on the profitability. At the same time, the information about the concrete measures set out to achieve water efficiency (in the short term or the long term) seems to lead to operational efficiency and increased profitability. These findings have relevant practical implications for the policy-makers of the company, suitable to improve both its financial and environmental performance.

From all the six environmental categories identified by the SASB with a material impact, only the measure belonging to the GHG Emissions category has influenced the financial performance (the ROA and the ROE) at the level of all the three pillars (according to the SEM findings). The issues related to carbon dioxide (CO_2) and CO_2 equivalent emissions have a negative influence on the ROA and the ROE levels (even if they are disclosed as a general policy of the company, as targets set to achieve emission reduction or as the concrete amount of emissions). The negative relationship between the GHG emissions and the financial performance, in accordance with the findings of other scholars [16], suggests that all actions for becoming more environmentally friendly will increase the operational costs of the companies, leading to a decrease in their financial performance level.

The limits of our research may rely on the degree of certainty of the estimation of the binary data (subjective data), and the fact that the environmental performance is rather difficult to assess, since it can be influenced by a plethora of factors, "with unknown variables that cannot yet be captured as proxies in macro-econometric models (such as catastrophic events due to climate change)" [47] (p.20), or pandemic disease [2–4, 48]. Relying on the differences observed in the materiality manifestation, and having in mind their high importance for the oil and gas industry, we suggest that the future research should investigate the same environmental measures and the same organizations on the content range, but at the level of an industry with a lower environmental impact. Achieving the goal of an environmentally sustainable economy depends on the common efforts and the constant assessment of the implementation stages. In maintaining the correct direction, an important role is played by the relevance and the usefulness of the environmental measures within the decision process. A better understanding of these characteristics means a better understanding of the materiality and its impact on the financial performance.

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

China's Spatial Economic Network and Its Influencing Factors

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With the deepening of reform and opening-up, China's economy has been further developed, but there is still a problem of uneven development. It is of great significance to completely construct China's economic spatial correlation network, to clarify the role and status of each province in the whole network, and to study the influencing factors of the national spatial economic network. In this paper, we employ the network analysis method to analyze China's economic development in the past 20 years. Based on the modified gravity model, we construct China's spatial economic network and explore the network structure from three aspects: the whole network structure feature, characteristics of individual provinces in the network, and block model analysis. The results show that (1) China's spatial economic network has strong internal cohesion, and the hierarchy of the network is becoming less and less obvious. However, the network density is low, and the overall network relationship still needs to be strengthened. (2) The different levels in economic development illustrate the obvious economic unbalance among provinces. (3) The block model analysis results demonstrated that coastal areas are more attractive to other provinces and are playing an important role in driving China's economy. Finally, we employ Quadratic Assignment Procedure (QAP) regression analysis to analyze the influential factors on spatial economic network. Numerical results show that the geographic proximity and the differences in six factors (industrial structure, level of economic development, degree of opening to the outside world, medical level, size of labor market, and infrastructure) have significant impact on the spatial economic network. Moreover, the influence of these factors on the economic relation among provinces has been gradually strengthened in recent years.

1. Introduction

With the process of reform and opening-up, China's economic development has made great achievements. However, the diversity of region economy is an important problem in economic development. At present, China's economic development has entered the new normal, which means that we are facing both opportunities and challenges. It is important to promote coordinated development among regions.

In recent years, the issue of regional coordinated development has received attention. In March 2019, Chinese Premier Li Keqiang at the second session of the 13th National people's Congress of the Communist Party of China proposed to promote coordinated regional development, to improve the quality of new urbanization, to focus on solving the problem of unbalanced development, to reform and perfect relevant mechanisms and policies, and to promote the equalization of basic public services and the development of complementary regional advantages and urban-rural integration.

The national economic relationship directly affects the coordinated development of the regions. The flow of economic elements and differentiation of the industrial structure or other aspects are the basic forces to promote the establishment of economic links between provinces. Therefore, the purpose of this paper is to understand the structural characteristics of the spatial economic network and the influence of some factors on the spatial economic links, which is of great significance to improve the spatial economic network in order to realize the coordinated development of provinces.

Social network analysis is a useful method to study the relationship between social factors [1–3]. At first, it has been used in the study of social network structure and social relationship at home and abroad. Later, it was found that it has strong adaptability to complex economic network [4–6]. Network construction is a key part of social network analysis. At present, there are many methods to build spatial network, among which the one based on the gravity model is one of the most common used methods. This method is widely used in the construction of trade network, tourism network, population migration network, and so on. In the classical gravity model, the economic gravity between two cities is proportional to the total economic volume and inversely proportional to the geographical distance. Compared with other methods of network construction, the gravity model method takes into account the factor of economic geographical distance. The advantage of the method is that it is also flexible, and researchers can modify the model according to research needs to make it more reasonable to reflect the gravity between nodes. In 2020, Ao built the urban comprehensive quality index through six basic indexes and incorporated it and the intercity distance into the gravity model. They analyzed the strength of spatial economic connection in the eight regions of Xiangxi Autonomous Prefecture [7]; Yang introduced the concepts of urban quality and economic distance into the gravity model and measured the economic gravity between 11 cities in Inner Mongolia [8]. These studies added new ideas to the construction of gravity models and better complement the theoretical content in this field. In this paper, the gravity model used is modified based on the above research. And the QAP regression method is considered to study the influencing factors of spatial economic network structure of China. The advantage of this method is that it can study the relationship between relational matrices. And it has been widely used in trade network to study the influencing factors of network structure [9–12]. In recent years, this method has been gradually used to study the economic network of individual provinces or some urban agglomerations in China, but there are few literatures used to study the entire structure of China's spatial economic network. In 2019, Shao carried out QAP regression analysis on the influencing factors of the economic network of the urban agglomeration in the middle reaches of the Yangtze River, and they found that the influence of geographical proximity on the network structure is very significant, and the influence of the differences in traffic accessibility, labor market scale, opening to the outside word, infrastructure, industrial structure, and investment on the network is increasing [13]. In 2020, Liu used the QAP regression to explore the influencing factors of urban financial relations in the Yangtze River Delta region. The results showed that the three factors of economic development level, population scale, and government intervention are significant positive [14]. Based on the QAP regression analysis method, this paper intends to employ some of the influencing factors used in the above literature as a reference and some new variables. To observe the effect of these factors on China's spatial economic network, this paper assumes that the differences of industrial structure, infrastructure, opening to the outside world, economic development level, medical conditions, labor market scale, and geographical proximity between provinces have an impact on China's economic spatial network structure.

Based on the above literature, this paper will revise the gravity model and construct the network to observe the structural characteristics of China's spatial economic network. The influence factors of spatial economic network are analyzed by QAP regression, which is expected to provide decision basis for regional coordinated development in China.

2. Study Objects and Data Sources

In this paper, we select 31 provinces in China as the research object and observe the changes of China's spatial economic network in the past 20 years (2000–2019). The overall network structure characteristics and personal feature are explored. We only used the data of 2000–2018 to implement the QAP regression analysis because some data cannot be obtained. The bordered data in this study is obtained according to the map of China. Distance data are determined by distance between provincial capitals, while other raw data is obtained from the official website of China's State Bureau of Statistics. To eliminate inflation, we use the real GDP to reflect the gross domestic product of a province. Real GDP of provinces from 2000 to 2019 are shown in Figures 1 and 2. From the figures, China's economy is moving towards a positive trend, but there are still uneven developments between provinces.

3. Construction of Gravity Model

Spatial economic network can reveal the economic relations between provinces. The node of network represents one province, and the edge represents the economic gravity relationship established between two provinces. In this paper, the modified gravity model is employed which can make it more suitable for the research needs and can better measure the size of economic attraction between provinces. The modified gravity model is as follows:

$$T_{ij} = K_{ij}\frac{\sqrt{P_i G_i}\sqrt{P_j G_j}}{\left(D_{ij}/\left(g_i - g_j\right)\right)^b},$$
$$K_{ij} = \frac{G_i}{G_i + G_j}, \tag{1}$$

where G_i in the formula is the annual Gross Domestic Product (GDP) of the province i, g_i is the per capital GDP of the province i, P_i is the year-end population of the corresponding province i, D_{ij} is the distance between two provinces i and j, and b is the distance attenuation coefficient (here, we set $b = 2$).

The process of constructing correlation matrix is as follows. Firstly, we need to calculate the gravitation matrix T of economic relation between provinces by the modified gravity model (n is the number of provinces):

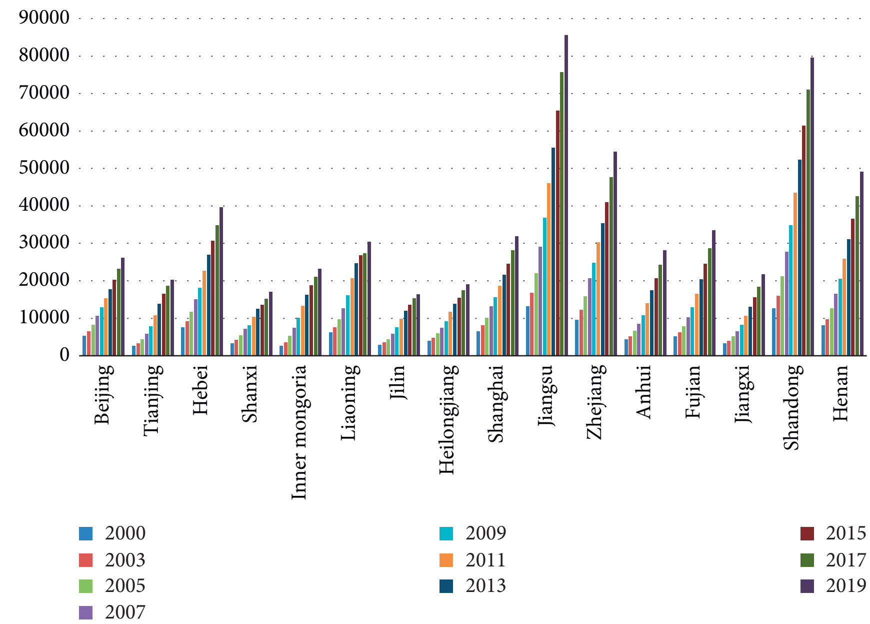

Figure 1: Real GDP of 16 provinces from 2000 to 2019.

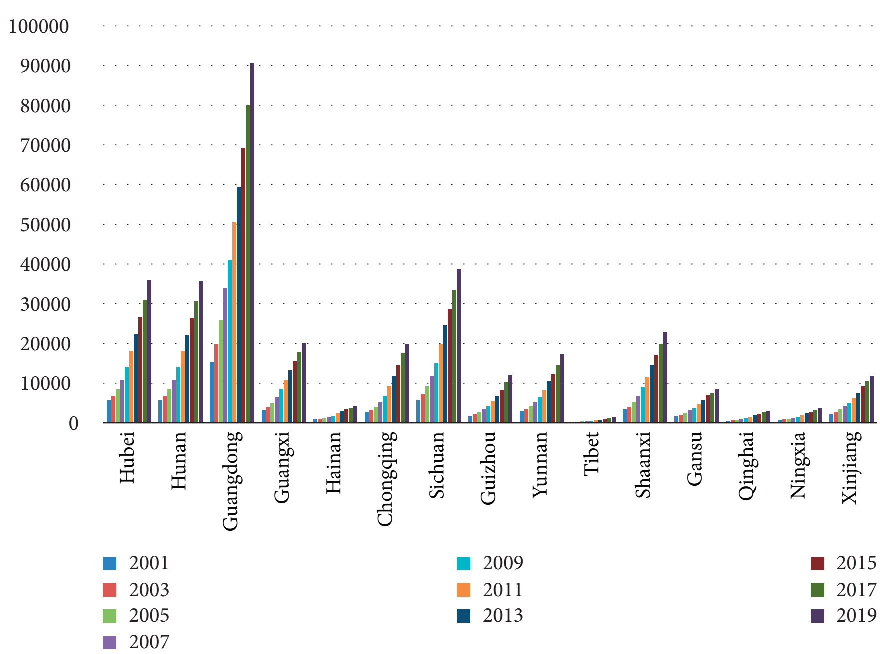

Figure 2: Real GDP of 15 provinces from 2000 to 2019.

$$\begin{bmatrix} T_{11} & T_{12} & \cdots & T_{1n} \\ T_{21} & T_{22} & \cdots & T_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ T_{n1} & T_{n2} & \cdots & T_{nn} \end{bmatrix}. \quad (2)$$

Secondly, we construct the adjacency matrix according to the gravitation matrix T. If $T_{ij} > \sum_{j=1}^{n} T_{ij}/31$, then $T_{ij} = 1$, which indicates that there is an economic connection between two provinces. Otherwise, $T_{ij} = 0$, which indicates that there is no economic connection between two provinces. Finally, we get an adjacency matrix with just the numbers 0 and 1; then, we construct the network according to the adjacency matrix.

4. Structural Analysis of Spatial Economic Network

In this section, we use the Ucinet tool to characterize the spatial economic network. We construct China's spatial economic network for eight years in Figure 3.

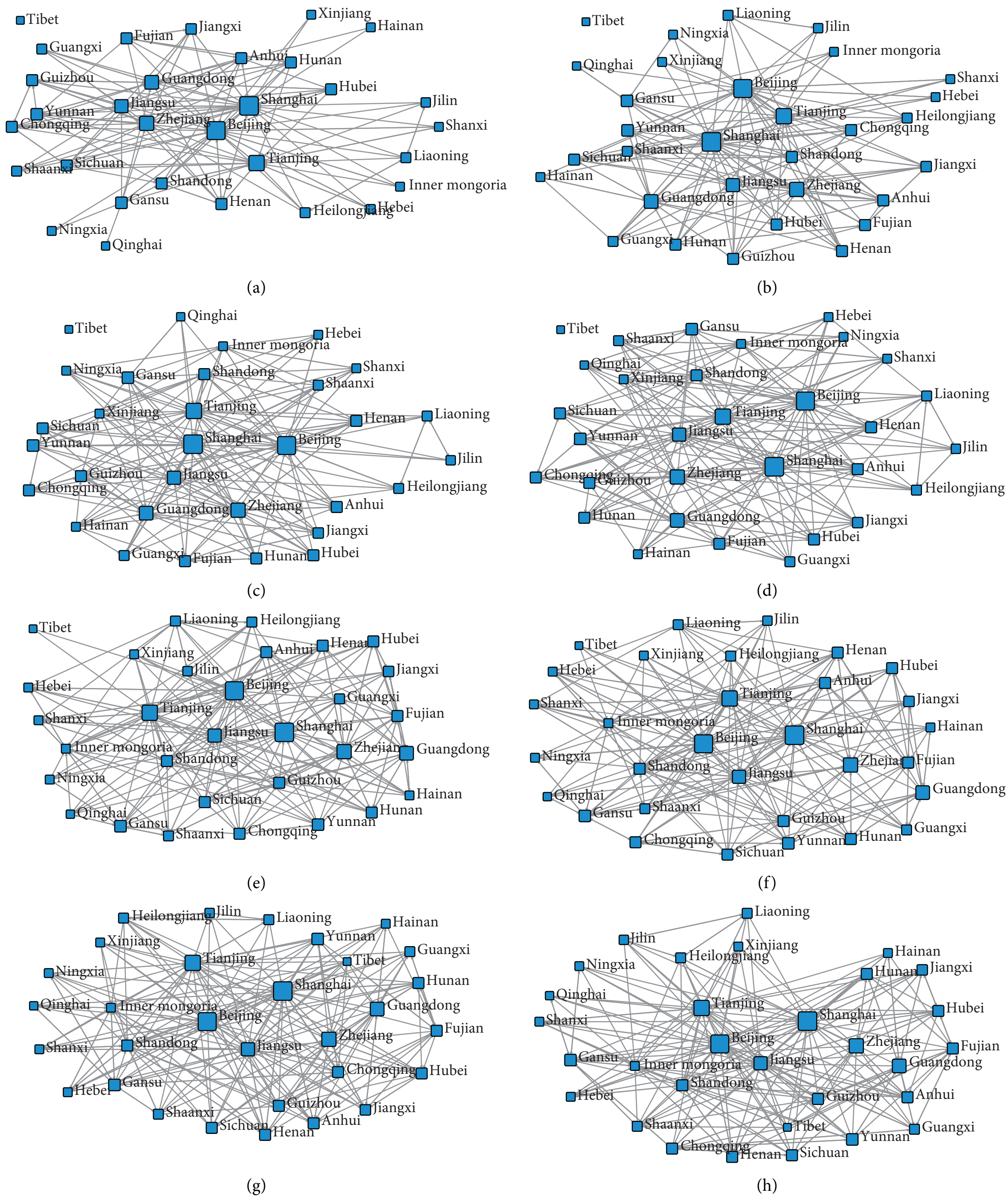

Figure 3: Visualization of China's spatial economic network. (a) Year 2000. (b) Year 2003. (c) Year 2006. (d) Year 2009. (e) Year 2012. (f) Year 2015. (g) Year 2018. (h) Year 2019.

From the structural changes of the network, we find the economic links between 31 provinces have increased in 20 years. Early, China's spatial economic network structure shows obvious marginalization of the central and western regions. However, the coastal areas play an essential role in the establishment of economic ties between provinces. This is closely related to the development strategy of the coastal area and the "three major zones" implemented by the country before 2000. As the problem of regional economic development becomes more pronounced, there have been growing calls to regional even development. In order to reduce interregional economic disparities, the development strategy of Western Development, revitalization of old industrial bases in northeast, and development of the central region in China were implemented in 2000, 2003, and 2006, respectively. From Figure 3, the economic links between provinces have increased since 2006.

4.1. Features of the Overall Network Structure. To explore the features of the overall network, we analyze three topological indices of spatial economic network including network density, cohesion, and hierarchy. Numerical results are shown in Figure 4.

The overall network density is the ratio of the actual numbers of associations in the network to the possible number, which reflects the degree of closeness of the relationship between the provinces. From Figure 4, China's spatial economic network density is increasing, but the increase is not large. The average of overall network density in the past 20 years is 0.22414. It indicates that the economic contact is weak between provinces, the cooperation between provinces need to be strengthened. The cohesion represents the degree of economic connection between three provinces. The average of overall network cohesion in the past 20 years is 0.45635, and it indicates that the cohesion of China's spatial economic network is stronger. The network hierarchy refers to the degree of unilateral connection between nodes. The higher the value of hierarchy is, the more obvious the hierarchical nature of the network structure is. It indicates the lack of bidirectional economic interaction between provinces. From Figure 4, we can find that the downward trend of the value of hierarchy is obvious. Between 2000 and 2006, the implementation of the three regional development strategies narrowed regional economic differences, the opening of China's high-speed rail in 2007 facilitated the flow of economic elements between provinces, and the approval of 18 free trade zones between 2014 and 2019 promoted the overall development of the eastern, central, and western regions.

The implementation of the economic development strategy and the improvement of transportation facilities in the past 20 years have led to a marked decrease in the level of China's economic network hierarchy. The concentration of economic development in the eastern region is gradually improving. At the same time, the economic links in regions have increased. Moreover, the cohesion and network density have also increased by a certain extent.

4.2. Characteristics of Individual Network Structure. Centrality is used to measure the function and status of network nodes in China's spatial economic network. In order to export the characteristics of each province in the spatial economic network, in this section, we study the importance of each province by means of UCINET in 2019, while the results in other years are shown in Tables 1–4. The study of the importance of network nodes from different angles corresponds to different methods. In this paper, the importance of nodes is judged by network structure information from the point of view of network topology. Based on the local properties of nodes, we select the index of degree centrality, which reflects the power and status of nodes in the network. The larger the value is, the more important the node is. Degree centrality can be divided into absolute degree centrality (the actual degree value of the point) and relative degree centrality (the ratio of absolute degree centrality to the maximum possible degree of the point in network). Equation (3) is the calculation method of relative degree centrality (n represents the absolute degree centrality and N represents the number of nodes in China's spatial economic network):

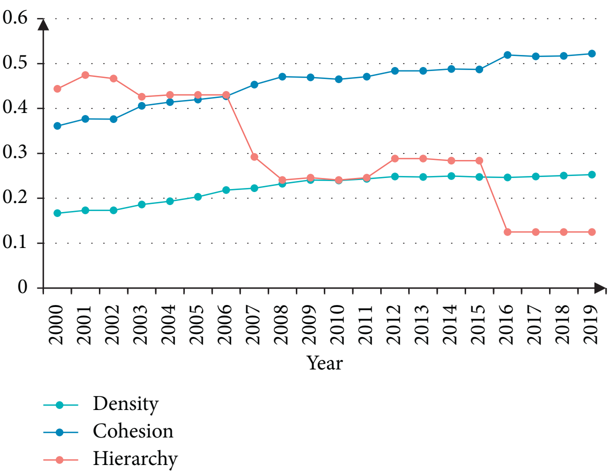

FIGURE 4: Topological indices analysis.

$$\mathrm{PC} = \frac{n}{N-1}. \tag{3}$$

Based on the global properties, we select the betweenness centrality index to measure the ability of the node to be evaluated to control the links between other nodes in the whole network. The larger the value is, the more important the node is. Equations (4)–(6) are the calculation method of betweenness centrality:

$$b_{jk}(i) = \frac{g_{jk}(i)}{g_{jk}}, \tag{4}$$

$$C_{\mathrm{AB}i} = \sum_{j}^{n} \sum_{k}^{n} b_{jk}(i), \tag{5}$$

$$\mathrm{BC} = \frac{2C_{\mathrm{AB}i}}{N^2 - 3N + 2}. \tag{6}$$

In Equation (4), g_{jk} is the number of shortest paths between nodes k and j, $g_{jk}(i)$ represents the number of shortest paths through node i between nodes k and j, and $b_{jk}(i)$ represents the probability that node i in the shortcut between nodes k and j. $N^2 - 3N + 2$ is the maximum number of shortest paths which through a node may exist.

In the directed network, the degree centrality of each node is divided into in-degree (the number of income associations of economy) and out-degree (the number of spillover associations of economy). The in-degree reflects the inflow of economic activities and the economic aggregation ability of provinces. The province is called the beneficiary of economic development if the in-degree is higher than the

Table 1: Degree centrality (in-degree).

Provinces	2000	2002	2004	2006	2008	2010	2012	2014	2016	2018
Beijing	24	24	25	25	24	22	23	24	23	23
Tianjing	17	18	22	23	23	22	23	24	24	23
Hebei	2	3	3	4	4	5	5	6	5	5
Shanxi	2	2	2	3	3	4	5	5	4	4
Inner Mongoria	1	2	2	6	9	11	12	13	14	13
Liaoning	2	2	2	2	2	2	3	2	3	3
Jilin	1	1	1	1	2	2	2	2	1	1
Heilongjiang	1	1	1	1	2	2	2	2	2	2
Shanghai	25	25	27	27	27	26	24	25	25	26
Jiangsu	13	13	14	19	20	22	23	24	25	26
Zhejiang	15	15	18	18	18	17	18	15	16	16
Anhui	7	7	7	8	11	11	11	11	10	10
Fujian	3	4	3	5	6	6	6	6	6	7
Jiangxi	4	4	4	5	5	6	6	6	6	6
Shandong	7	7	7	11	11	12	12	13	13	15
Henan	6	6	7	8	9	9	10	10	9	9
Hubei	2	2	4	4	5	6	6	6	6	7
Hunan	2	2	3	3	5	5	5	5	4	4
Guangdong	10	11	11	12	12	10	8	7	8	8
Guangxi	1	1	2	2	1	1	2	2	2	2
Hainan	0	0	1	1	1	1	1	1	1	1
Chongqing	2	2	2	2	3	3	3	4	5	6
Sichuan	2	2	2	2	2	2	3	3	2	2
Guizhou	3	2	4	4	2	6	7	5	4	4
Yunnan	1	1	1	2	2	2	2	2	2	2
Tibet	0	0	0	0	0	0	0	0	0	0
Shaanxi	0	1	0	0	2	2	2	2	2	1
Gansu	0	1	3	3	3	4	5	5	5	5
Qinghai	1	1	1	1	1	1	1	1	1	1
Ningxia	1	1	1	1	1	1	1	1	1	1
Xinjiang	0	0	0	0	0	0	0	0	0	0

Table 2: Degree centrality (out-degree).

Provinces	2000	2002	2004	2006	2008	2010	2012	2014	2016	2018
Beijing	6	6	6	7	7	5	5	6	6	5
Tianjing	5	5	6	6	6	5	5	6	7	6
Hebei	3	3	3	3	4	5	5	5	5	6
Shanxi	3	3	3	6	6	6	6	6	6	6
Inner Mongoria	3	3	3	6	9	8	8	8	7	7
Liaoning	5	5	5	5	7	8	9	9	5	5
Jilin	4	5	5	4	6	6	6	6	7	6
Heilongjiang	5	4	6	6	7	8	8	9	9	9
Shanghai	7	7	9	9	9	7	7	8	8	8
Jiangsu	3	3	4	5	5	5	4	4	4	4
Zhejiang	3	3	5	5	6	6	6	6	6	6
Anhui	4	4	4	4	3	3	3	3	3	3
Fujian	6	6	6	7	8	8	10	9	9	9
Jiangxi	6	6	7	7	7	8	8	8	8	8
Shandong	5	5	6	6	6	8	8	8	8	8
Henan	6	6	6	6	6	7	7	7	7	7
Hubei	7	7	6	6	7	8	7	7	7	7
Hunan	7	7	7	7	7	8	8	8	8	9
Guangdong	11	10	11	11	11	11	11	11	11	11
Guangxi	5	7	6	6	7	8	8	7	7	8
Hainan	2	2	6	9	6	8	8	7	7	7
Chongqing	8	8	8	8	9	9	10	8	8	8
Sichuan	8	8	8	8	9	10	10	10	9	9
Guizhou	7	8	7	9	10	10	12	12	10	11

Table 2: Continued.

Provinces	2000	2002	2004	2006	2008	2010	2012	2014	2016	2018
Yunnanv	9	6	6	7	10	10	10	10	10	10
Tibet	0	0	0	0	0	0	2	5	8	10
Shaanxi	5	7	7	8	8	8	9	9	9	9
Gansu	9	12	10	10	11	10	10	11	11	11
Qinghai	0	1	4	4	7	6	7	6	6	6
Ningxia	1	2	4	7	5	6	6	6	6	7
Xinjiang	0	2	6	11	7	8	8	7	7	7

Table 3: Relative degree centrality.

Provinces	2000	2002	2004	2006	2008	2010	2012	2014	2016	2018
Beijing	80	83.333	83.333	83.333	83.333	76.667	80	83.333	80	80
Tianjing	56.667	66.667	76.667	80	80	76.667	80	83.333	83.333	80
Hebei	10	10	13.333	16.667	16.667	20	20	23.333	20	20
Shanxi	10	10	10	20	20	20	23.333	23.333	20	20
Inner Mongoria	10	10	13.333	33.333	46.667	46.667	50	53.333	53.333	53.333
Liaoning	16.667	16.667	16.667	16.667	23.333	26.667	33.333	30	20	20
Jilin	13.333	13.333	16.667	13.333	20	20	20	20	23.333	20
Heilongjiang	16.667	20	20	20	23.333	26.667	26.667	30	30	30
Shanghai	83.333	86.667	90	90	90	86.667	83.333	90	90	90
Jiangsu	43.333	46.667	46.667	63.333	66.667	73.333	76.667	80	83.333	86.667
Zhejiang	50	50	60	60	60	56.667	60	50	53.333	53.333
Anhui	26.667	26.667	26.667	26.667	36.667	36.667	36.667	36.667	33.333	33.333
Fujian	23.333	26.667	20	30	36.667	36.667	40	36.667	36.667	40
Jiangxi	20	20	23.333	23.333	23.333	26.667	26.667	26.667	26.667	26.667
Shandong	26.667	20	30	43.333	40	50	50	53.333	53.333	60
Henan	23.333	23.333	23.333	26.667	30	30	33.333	33.333	30	30
Hubei	23.333	23.333	20	20	26.667	30	30	30	30	33.333
Hunan	23.333	23.333	23.333	23.333	26.667	30	30	30	26.667	30
Guangdong	46.667	40	46.667	50	50	43.333	40	36.667	40	40
Guangxi	16.667	23.333	23.333	23.333	23.333	26.667	26.667	23.333	23.333	26.667
Hainan	6.667	10	20	30	20	26.667	26.667	23.333	23.333	23.333
Chongqing	26.667	26.667	26.667	26.667	30	30	33.333	26.667	30	33.333
Sichuan	26.667	26.667	26.667	26.667	30	33.333	33.333	33.333	30	30
Guizhou	26.667	26.667	30	36.667	33.333	43.333	50	43.333	36.667	40
Yunnan	30	26.667	20	26.667	33.333	33.333	33.333	33.333	33.333	33.333
Tibet	0	0	0	0	0	0	6.667	16.667	26.667	33.333
Shaanxi	16.667	16.667	23.333	26.667	30	26.667	30	30	30	30
Gansu	30	23.333	36.667	36.667	36.667	33.333	36.667	36.667	36.667	36.667
Qinghai	3.333	6.667	13.333	13.333	23.333	20	23.333	20	20	20
Ningxia	6.667	13.333	13.333	23.333	16.667	20	20	20	20	23.333
Xinjiang	6.667	10	20	36.667	23.333	26.667	26.667	23.333	23.333	23.333

out-degree. The out-degree reflects the outflow of economic activities. The province is called the overflow side if the out-degree is higher than the in-degree.

The results in Table 5 show that the top provinces of the value of degree centrality are Shanghai, Jiangsu, Beijing, Tianjing, Inner Mongolia, Shandong, and Zhejiang, which are also economic beneficiaries in 31 provinces. This indicates that these provinces have the most economic relationships with other provinces. And they have strong economic agglomeration capacity compared with other provinces, more attractive to the inflow of funds, talents, and various economic resources. From the analysis of geographical distribution, it can be found that the vast majority of the beneficiary provinces are located in the coastal areas or the Yangtze River Delta region. These provinces are among the first to develop in the course of China's economic development due to their unique geographical advantages, so they have a relatively solid economic foundation and are at the core of China's spatial economic network. Most of the provinces that belong to the spillover are located in the northeast and the central and western regions. These provinces have fewer economic links with other provinces and lack economic attraction in the whole economic network, so they will make more talents and resources flow to the developed regions.

The index of betweenness centrality reflects the same problem. The provinces with high degree centrality values are also with high betweenness centrality values, indicating that they are on multiple shortest paths between provinces, and they not only have strong economic attraction to other

Table 4: Betweenness centrality.

Provinces	2000	2002	2004	2006	2008	2010	2012	2014	2016	2018
Beijing	21.79	22.814	16.311	13.294	11.895	10.074	12.603	10.69	9.763	10.172
Tianjing	7.743	10.615	12.836	11.949	10.805	10.074	12.603	10.69	10.946	10.172
Hebei	0.034	0.022	0.02	0.045	0.04	0.148	0.165	0.186	0.104	0.098
Shanxi	0.034	0.022	0.02	0.127	0.114	0.115	0.217	0.186	0.104	0.098
Inner Mongoria	0.034	0.022	0.02	0.759	2.087	2.46	2.747	3.221	3.784	3.046
Liaoning	0.091	0.08	0.066	0.077	0.214	0.394	0.905	0.514	0.04	0.05
Jilin	0.034	0.022	0.126	0.02	0.09	0.1	0.104	0.074	0.162	0.05
Heilongjiang	0.188	0.344	0.292	0.316	0.303	0.5	0.501	0.575	0.592	0.66
Shanghai	23.536	22.795	20.212	16.517	14.463	13.662	10.952	15.027	14.535	13.003
Jiangsu	3.005	3.178	2.916	5.693	6.477	8.014	8.957	10.146	11.195	11.975
Zhejiang	4.538	3.753	6.1	4.831	4.657	3.87	4.271	2.927	3.497	3.335
Anhui	0.468	0.583	0.536	0.358	1.012	1.147	1.115	1.025	0.693	0.607
Fujian	0.246	0.393	0.122	0.34	0.653	0.726	0.956	1.018	1.05	1.239
Jiangxi	0.186	0.219	0.344	0.227	0.206	0.255	0.355	0.274	0.262	0.288
Shandong	0.592	0.208	0.636	1.596	1.249	2.028	1.945	2.077	2.193	3.011
Henan	0.318	0.397	0.287	0.367	0.602	0.616	0.935	0.845	0.532	0.478
Hubei	0.285	0.302	0.172	0.15	0.206	0.283	0.384	0.303	0.291	0.322
Hunan	0.37	0.359	0.344	0.227	0.206	0.345	0.451	0.36	0.349	0.394
Guangdong	4.275	2.358	2.928	2.975	2.939	1.863	1.446	1.283	1.688	1.324
Guangxi	0.102	0.359	0.325	0.15	0.206	0.255	0.355	0.274	0.262	0.353
Hainan	0	0.05	0.09	0.305	0.149	0.255	0.355	0.274	0.262	0.249
Chongqing	0.242	0.258	0.204	0.179	0.228	0.223	0.502	0.172	0.316	0.464
Sichuan	0.376	0.455	0.344	0.27	0.414	0.526	0.519	0.523	0.496	0.44
Guizhou	0.242	0.258	0.628	0.652	0.502	0.852	1.757	1.287	0.97	1.045
Yunnan	0.652	0.417	0.172	0.224	0.613	0.732	0.755	0.768	0.741	0.64
Tibet	0	0	0	0	0	0	0.01	0.074	0.394	0.64
Shaanxi	0.136	0.114	0.287	0.367	0.33	0.211	0.274	0.212	0.219	0.21
Gansu	7.943	1.283	2.049	1.147	1.029	0.648	0.749	0.866	0.865	0.792
Qinghai	0	0	0.02	0.02	0.134	0.094	0.203	0.074	0.085	0.082
Ningxia	0	0.022	0.02	0.158	0.02	0.094	0.112	0.074	0.085	0.098
Xinjiang	0.01	0.022	0.082	0.568	0.226	0.359	0.384	0.186	0.193	0.185

Table 5: Centrality of China's spatial economic network in 2019.

Provinces	Degree centrality				Betweenness centrality
	Out-degree	In-degree	Benefit or not	Centrality	Centrality
Beijing	5	23	Benefit	80	10.061
Tianjing	6	23	Benefit	80	10.061
Hebei	6	5	Overflow	20	0.097
Shanxi	6	4	Overflow	20	0.097
Inner Mongoria	7	14	Benefit	56.667	3.704
Liaoning	6	3	Overflow	20	0.05
Jilin	7	2	Overflow	23.333	0.138
Heilongjiang	9	2	Overflow	30	0.563
Shanghai	8	26	Benefit	90	13.07
Jiangsu	4	26	Benefit	86.667	12.041
Zhejiang	6	16	Benefit	53.333	3.334
Anhui	3	10	Benefit	33.333	0.626
Fujian	9	7	Overflow	40	1.27
Jiangxi	8	6	Overflow	26.667	0.297
Shandong	8	14	Benefit	56.667	2.532
Henan	7	8	Benefit	26.667	0.325
Hubei	7	7	—	33.333	0.322
Hunan	9	4	Overflow	30	0.406
Guangdong	10	8	Overflow	36.667	1.064
Guangxi	8	3	Overflow	26.667	0.363
Hainan	7	1	Overflow	23.333	0.259
Chongqing	9	6	Overflow	33.333	0.459
Sichuan	9	2	Overflow	30	0.457

Table 5: Continued.

Provinces	Degree centrality				Betweenness centrality
	Out-degree	In-degree	Benefit or not	Centrality	Centrality
Guizhou	11	4	Overflow	40	1.02
Yunnan	10	2	Overflow	33.333	0.66
Tibet	11	0	Overflow	36.667	0.807
Shaanxi	9	2	Overflow	33.333	0.256
Gansu	11	5	Overflow	36.667	0.837
Qinghai	6	1	Overflow	20	0.08
Ningxia	6	1	Overflow	20	0.08
Xinjiang	7	0	Overflow	23.333	0.184

provinces but also have strong control over economic resources. The central and western regions are still at the edge of the spatial economic network and lack dominant role in the process of economic development.

The above results indicate that although China's previous regional development strategy (South-to-North Water Diversion and project of natural gas transmission from West to East China) has enabled backward areas to be development, the greater beneficiaries are developed regions.

4.3. Block Model Analysis. Block model analysis is a method to divide a large number of nodes into several blocks and then examine the correlation between each block. We use the Built-in CONCOR (convergent correlation) programs in the UCINET software to build the block model. The operation path in UCINET software is *Network* ⟶ *Roles/Positions* ⟶ *Structural* ⟶ *CONCOR* (set the maximum depth as 2 and the convergence criterion as 0.2).

After 2000, 15 years of economic ties between blocks are basically the same, and 2017 is one of them. So, this part takes 2017 to analyze the block model of China's spatial economic network. Finally, the network is divided into four blocks, and the results are shown in Table 6.

The density matrix of blocks is shown in Table 7. To get the image matrix, the overall network density is set to a threshold value as follows. If the block density is higher than the threshold, it is assigned to 1. Otherwise, it is assigned to 0. The image matrix in 2017 is shown in Table 7. In order to describe the relationship more intuitively, we draw a simplified graphic of image matrix, as shown in Figure 5.

The results show that the provinces in blocks I and II are roughly located in the coastal areas of the north and the south, respectively. And the provinces in blocks III and IV are roughly distributed in the north and south of the central and western part of China.

From the relationship between the four blocks, we find close economic connection between the provinces in block I, as well as between the provinces in block II. However, the economic relationship between these two blocks is less, which reflects the influence of the geographical location difference between the north and the south on the establishment of economic relationship between provinces. Blocks III and IV lack economic links, and the provinces within each block have few economic links. It means that the central and western provinces economic connection is not closely enough, which is related to their weak economic foundation and economic development ability. From Figure 5, we find the economic links between block III and blocks I and II and between block IV and block I are all unidirectional, which once again proves that the coastal areas have a strong economic attraction to the central and western regions. This phenomenon is mainly related to the developed economy of coastal areas. China's coastal areas have the geographical advantage of adjacent sea areas. The convenient shipping conditions make them essential areas for China to import and export to other countries, so its own economic development is good, and it can attract the inflow of talents in the undeveloped areas of the central and western regions.

There is a two-way link between blocks II and IV. This result reflects the central and western provinces of the south have some economic attraction to the southern coastal areas in recent years. They show that the economy of the central and western provinces in the south is developing rapidly, especially in the upper-middle reaches of Yangtze River in recent years. This is because the adjustment of industrial structure and the improvement of transportation conditions in the upper-middle reach Yangtze River, which has attracted a larger number of enterprises in the Pearl River and Yangtze River deltas. Therefore, the central and western provinces of the south have a good development momentum and have established two-way economic ties with the coastal areas.

5. Analysis of the Influencing Factors of Spatial Economic Network

The problem of collinearity may occur when analyzing the influencing factors of China's spatial economic network because of the adjacent relationship between provinces. QAP can avoid this problem as a specific method to study the relationship between relational data. QAP is a method of comparing the similarity of two square matrices and giving the correlation coefficient between the two matrices. The purpose of QAP regression analysis is to study the relationship between the influence matrix and spatial economic network.

5.1. Variable Selection and Model Construction. In the analysis of the block model of the spatial economic network, we found the geographical distance between provinces has a certain influence on the establishment of economic

Table 6: Result of regional partition in 2017.

Blocks	Provinces
I	Beijing, Tianjin, Jiangsu, Inner Mongoria, Shandong
II	Guangdong, Fujian, Shanghai, Zhejiang
III	Hebei, Shaanxi, Ningxia, Liaoning, Qinghai, Jilin, Heilongjiang XinJiang, Gansu, Shanxi, Chongqing
IV	Hunan, Yunnan, Tibet, Henan, Zhejiang, Anhui, Hubei, Jiangxi Guangxi, Hainan, Sichuan, Guizhou

Table 7: Density matrix and image matrix in 2017.

Blocks	Density matrix				Image matrix			
	1	2	3	4	1	2	3	4
I	0.450	0.050	0.182	0.218	1	0	0	0
II	0.100	0.333	0.023	0.591	0	1	0	1
III	0.873	0.318	0.118	0.033	1	1	0	0
IV	0.764	0.841	0.041	0.027	1	1	0	0

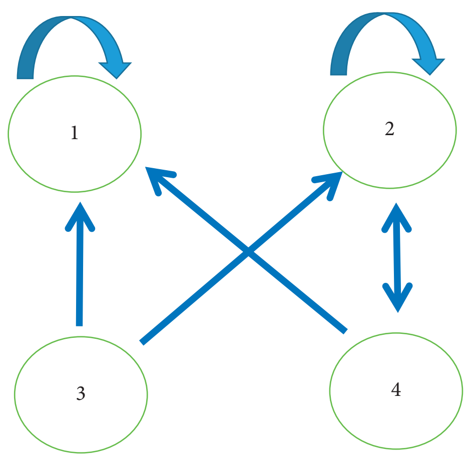

Figure 5: Simplified graphic of the image matrix.

relations. Therefore, we consider adding indicators of border or not (BOU) and urban geographical distance (UGD) into the model to reflect the impact of geographical distance on economic correlation. From the economic ties between coastal provinces, it seems easier to establish economic ties between provinces with similar levels of economic development. However, this is only a guess for the situation in developed regions. Is this a reasonable guess for the whole network? So, the index of per capita GDP (PAG) and foreign investment (FI) will be included in the QAP regression model as a reflection of the level of economic development. According to the previous literatures, it is found that population mobility, infrastructure differences, and urban industrial structure differences also affect the formation of spatial economic network. The larger the scale of the labor market, the more the employment opportunities. The region with more employment opportunities will attract more talent inflow and then promote the establishment of economic links between provinces. So, we establish the labor market scale (LMS) difference matrix to reflect the population flow between provinces. A similar industrial structure means that the two cities have similar stage and direction of development, and the two provinces are more likely to be linked. Therefore, the index of the added value of the secondary (PSI) and tertiary (PTI) industries are used to reflect the economic development model of the city. In addition, the difference in the proportion of road area (PRA) is used to reflect the difference in infrastructure between provinces. Moreover, the number of health personnel (NHW) reflects the medical conditions in a province. The number of foreign-invested enterprises (FIE) is used to present the extent of the province's opening to the outside world.

Before QAP regression analysis, we calculated the difference matrix of the corresponding indicators of each province in the spatial economic network. The above variables are appropriately treated with reference to the treatment methods in previous literatures, as shown in Table 8. The regression variables are shown by the relationship matrix of two provinces.

The spatial economic correlation matrix of provinces is used as the explained variable, and the index in Table 8 is used as the explanatory variable to construct the QAP regression model. The model is given as follows:

$$Y = f(\text{BOU}, \text{IDM}, \text{PAG}, \text{FI}, \text{FIE}, \text{PSI}, \text{PTI}, \text{PRA}, \text{LMS}, \text{NHW}). \tag{7}$$

The Y represents the spatial economic correlation matrix, BOU, IDM, PAG, FI, FIE, PSI, PTI, PRA, LMS, and NHW, are all relational matrices. The purpose of QAP regression is to study the effect of the above selected variables on China's spatial economic network.

5.2. QAP Regression Analysis. After determining the explanatory variables, we use UCINET software to QAP regression analysis. The operation path is $Tools-->TestingHypotheses-->QAP-->QAPcorrelation$. It is evident that the recent data can better reflect the current real economic development. So, we choose the data from

Table 8: Variable selection for QAP analysis.

Variables	Signification	Data processing
BOU	Whether provinces are adjacent	Build a binary matrix
IDM	Distance matrix between provinces	Take the distance between the provincial capitals as the standard
PAG	Per capita GDP	Calculate the difference between the provinces after standardized processing
FI	Foreign investment	
FIE	The number of foreign-invested enterprises	
PSI	The proportion of the added value of the secondary industry	
PTI	The proportion of added value of tertiary industry	
PRA	Proportion of road area	
LMS	Labor market size	After normalization and difference, the matrix is converted into a 0-1 matrix with the row mean value as the threshold
NHW	The number of health personnel	

2011 to 2018. The results of QAP regression analysis are shown in Table 9.

The purpose of QAP regression is to study the regression relationship between multiple matrices and one matrix, which requires that all variables must be square matrices. In the results of QAP regression analysis, the standardized regression coefficient of each explanatory variable and test of significance will be obtained. If the P value corresponding to the regression coefficient is less than the significant level (10%, 5%, and 1%), it is considered that the corresponding variable is significant in statistical sense, and the contribution of the corresponding variable to the explained variable is considered to be significant [15, 16].

From Table 9, the value of R^2 is between 0.35 and 0.43 in 2011–2018, which indicates that the influencing factors selected in this paper can explain 35% ~ 43% of the changes of China's spatial economic network. Compared with the existing literatures, the value of R^2 is already high [13, 14]. As shown in Table 9, the value of R^2 in 2018 among these eight years is the largest. This means that these 10 factors can better explain the formation of China's spatial economic network structure in 2018, which is related to the China's current economic development model.

The results showed that the regression coefficient of IDM is significant at 1% and BOU is significant at 5% between 2000 and 2018. The regression coefficient value of IDM is negative and the BOU is positive, indicating that the geographical proximity has a significant impact on the spatial economic association. The closer the two provinces are geographically, the easier it is to establish economic ties.

Per capital GDP is an important macroindex to measure the economic development of a region. Foreign investment refers to the total amount of funds invested by foreign investors and Chinese investors in cooperation in China. Both indicators can reflect the basic economic situation of a region. It can be found that the regression coefficients of the two indicators are negative and have passed the significance level test in 2011–2018. The results verify the hypothesis that it is easier to establish economic links among provinces with a similar level of economic development. According to official data, the provinces with high per capital GDP in 2018 are Beijing, Shanghai, Tianjing, and Jiangsu, while the ones with high foreign investment are Guangdong, Jiangsu, Shanghai, and Zhejiang. And the actual situation in China proves that there are indeed more economic links between these provinces.

The secondary and tertiary industries reflect the industrial structure of a province. From Table 9, the regression coefficients of the two indicators are negative and have passed significant test, which shows that the closer the industrial structure is, the easier it is to produce economic relationship between provinces. The absolute value of the coefficient corresponding to the PSI is larger than that of the PTI. According to the Chinese background, China's secondary industry mainly consists of various industrial categories and the tertiary industry mainly includes service and logistics industry. With the improvement of living standard, people pay more attention to the quality of public service. At the same time, the rapid development of transportation industry and the arrival of data era make people's consumption behavior change. A larger number of online consumption has made the logistics industry develop rapidly. This is the reason why the tertiary industry has a greater impact on China's spatial economic relations than the secondary industry in recent years.

The proportion of road area reflects the infrastructure situation of a province. The results show that the PRA has a significant impact on the establishment of economic relationships between provinces, indicating that the smaller the difference of infrastructure between provinces, the more economic correlation. Infrastructure is a public service system used to ensure the social and economic activities of a region. Only when a region has a sound public service system, it will be more focused on economic development. This shows that provinces with similar infrastructure backgrounds are more likely to have economic contacts.

Foreign-invested enterprises refer to those enterprises established within the territory of China and invested by foreign investors. The number of foreign-invested enterprises reflects the degree of opening to the outside world of a region and contributions to the expansion of its labor market. From Table 9, the regression coefficient of FIE is significant at 1%, indicating that the difference in the number of foreign-invested enterprises between provinces had led to the establishment of economic ties, which is related to the flow of labor force between provinces. Data

Table 9: The result of QAP regression analysis.

Variables	2011	2012	2013	2014	2015	2016	2017	2018
BOU	0.094***	0.071**	0.124***	0.114***	0.11***	0.092***	0.077**	0.08**
IDM	−0.304***	−0.315***	−0.267***	−0.27***	−0.241***	−0.231***	−0.231***	−0.218***
PAG	−0.272***	−0.261***	−0.287***	−0.288***	−0.356***	−0.308***	−0.278***	−0.25***
FI	−0.38***	−0.416**	−0.22*	−0.282**	−0.152**	−0.277**	−0.262**	−0.261***
FIE	0.50***	0.556***	0.417**	0.475***	0.346***	0.452***	0.408***	0.396***
PSI	−0.145**	−0.143**	−0.142**	−0.135**	−0.098	−0.093*	−0.105**	−0.1**
PTI	−0.24**	−0.275**	−0.25**	−0.098**	−0.196**	−0.19**	−0.214**	−0.222***
PRA	−0.151***	−0.166***	−0.155***	−0.161***	−0.164***	−0.165***	−0.174***	−0.163***
LMS	0.217***	0.292***	0.338***	0.386***	0.387***	0.367***	0.364***	0.394***
NHW	0.142***	0.071**	0.138***	0.083**	0.096***	0.067**	0.061**	0.07**
R^2	0.349	0.346	0.413	0.403	0.401	0.389	0.391	0.426

Note. *, **, and ***, respectively, represent the significance level of 0.1, 0.05, and 0.01.

released by China's Ministry of Commerce show that the eastern part of China has been the main concentration of foreign investment, and the number of investment enterprises in the eastern part of China is more than that in the central and western regions, which is also the reason for the flow of labor force to the eastern regions. Therefore, in order to reduce the difference, our country should actively encourage the transfer of foreign capital to the central and western regions, so as to fundamentally improve the economic base of central and western regions and promote economic relationships between provinces.

In addition, the LMS and NHW indicators have a significant positive impact on the formation of spatial economic network. It shows that the population mobility caused by the difference of employment opportunities and medical conditions among provinces promotes the economic correlation between provinces. From the change of regression coefficients in 2011–2018, we know that the LMS is exerting more and more influence on China's spatial economic network, which indicate the labor market scale between provinces still has great difference. The effect of NHW is becoming smaller and smaller, indicating the medical condition is gradually balanced in various regions of China.

6. Conclusion

China's spatial economic network based on the modified gravity model is constructed in this paper. We investigate the characteristics of overall network structure and its internal structure by the network analysis method. We employ the QAP regression analysis method to study the influencing factors of the spatial economic network. According to the numerical results, we derive the conclusion as follows. (1) In 2000–2019, the cohesion of every three provinces in China's spatial economic network has been strengthened year by year, the network density has increased year by year, and the network hierarchy has been weakened year by year. It shows that the implementation of the development strategies, such as the great development of the west, the revitalization of the old industrial base in the northeast, and the rise of the central region, has gradually improved China's spatial economic network structure. However, the network density is still low, indicating that the economic relationship between provinces needs to be strengthened. (2) The economic spillover and benefit of provinces present the unbalanced characteristics of economic development between provinces. The data in 2019 show that there are only seven beneficiary provinces, most of which are located in coastal areas, including Shanghai, Jiangsu, Beijing, Tianjing, Inner Mongolia, Shandong, and Zhejiang. The economic spillover provinces are mainly located in the central and western regions, including Qinghai, Ningxia, Guizhou, Yunnan, and Guangzi, which belong to the regions with relatively backward economy. According to the degree centrality and betweenness centrality of each provinces, Shanghai, Jiangsu, Beijing, and Tianjing are key nodes in China's spatial economic network, and they have strong ability to master economic resources. Hebei, Shanxi, Qinghai, and Ningxia are marginalized in the spatial economic network, and they play a small economic role and need to improve their own economic development ability. (3) The result of the block model analysis shows that the developed coastal areas have obvious economic attraction to the central and western regions. The reason is that the level of economic development in the central and western regions of China is relatively weak, so many central and western regions of the population to seek development to the coastal area flow. In addition, the economic strength of the central and western regions of the south has been increasing in recent years. (4) The QAP regression analysis results show that border or not, the geographical distance, per capita GDP differences, foreign investment differences, labor market scale differences, differences in the added value of the secondary and the tertiary, proportion of road area, number of health personnel, and number of foreign-invested enterprises significantly impact on China's spatial economic association. Among the indicators used in this paper, the regression coefficient corresponding to the number difference index of foreign-invested enterprises is the largest, which means that China's opening to the outside world policy has a strong influence on China's spatial economic network structure.

Based on the conclusion above, this study proposes the following policy recommendations. First, economic cooperation and interaction should be strengthened among neighboring provinces. The combination of countless such small cooperation circles can promote the increase of the density of the whole China's spatial economic network. In addition, the national policies need to consider how to improve the traffic conditions in different regions of the country and narrow the economic distance between provinces by reducing the time consumption of economic factor transportation. Second, the central government should not only stimulate the coastal provinces with strong ability to control economic resources, such as Shanghai, Jiangsu, Beijing, Tianjing, Shandong, and Zhejiang, to play an economic driving role, but also focus on strengthening the transmission function of the provinces that play the role of "intermediary" in China's spatial economic network. At the same time, some targeted regional development policies should be formulated. We should also carry out accurate control in view of the different positions and roles of provinces and blocks in the spatial network, so as to enhance the synergy of China's spatial economic network. Finally, with the arrival of big data era and the vigorous development of the high-speed rail industry, the provinces of central and western regions such as Hebei, Shanxi, Qinghai, and Ningxia, should seize the opportunity, actively adjust the local industrial structure, vigorously develop the local service and logistics industry, and respond positively to the policy of opening to the outside world. At the same time, it is necessary for provinces to control the large loss of labor force by improving health care and infrastructure and expanding the labor market. All provinces should fundamentally improve their economic development, so as to promote the formation of two-way cooperative links between underdeveloped and developed provinces, rather than forming one-way links through population flows caused by difference in resources and employment opportunities between provinces. Otherwise, it will deepen the degree of imbalance of China's regional economic development.

Data Availability

The data used to support the findings of this study may be released upon application to the China National Bureau of Statistics and can be checked at http://www.stats.gov.cn/tjsj/ndsj/.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

A Novel TODIM with Probabilistic Hesitant Fuzzy Information and Its Application in Green Supplier Selection

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TODIM is a well-known multiple-criteria decision-making (MCDM) which considers the bounded rationality of decision makers (DMs) based on prospect theory (PT). However, in the classical TODIM, the perceived probability weighting function and the difference of the risk attitudes for gains and losses are not consistent with the original idea of PT. Moreover, probabilistic hesitant fuzzy information shows its superiority in handling the situation that the DMs hesitate among several possible values with different possibilities. Hence, a novel TODIM with probabilistic hesitant fuzzy information is proposed in this paper to simulate the perceptions of the DMs in PT. To show the advantages of the proposed method, a novel TODIM is combined with hesitant fuzzy information. Finally, a case study is carried out to demonstrate the feasibility of the proposed method, and a series of comparative analyses and the sensitivity analyses are used to show the stability of the proposed method.

1. Introduction

Decision makers (DMs) are considered to be completely rational among the existing multiple-criteria decision-making (MCDM) methods based on expected utility theory. However, the DMs are naturally bounded rational in real world. They are not able to obtain every detail of decision-making alternatives and are limited by their cognitions. Therefore, TODIM (TOmada deDecisão Iterativa Multicritério), a well-known MCDM method considering the bounded rational behaviors based on prospect theory (PT) [1], was proposed by Gomes and Lima [2]. It handles the vagueness and bounded rationality of the DMs to make the optimal choices based on multiple criteria.

However, the classical TODIM is based on crisp number which makes it restricted to express the vague perceptions of the DMs. Thus, the fuzzy sets (FSs) were introduced, and the TODIM had been extended to various FSs to provide more accurate and detailed information. The existing extensions of the TODIM are summarized in Table 1.

The TODIM has been not only extended to various fuzzy circumstances but also applied to various ranges of applications. After analyzing the existing TODIM, the application fields are summarized from the following aspects: supplier selection [8, 10, 12, 15, 17, 18, 27, 29], manufacture [3, 7, 13, 19, 30, 31], investment problem [5, 16, 25, 26, 32], service evaluation [23, 24], personnel selection [6, 33], emergency plan selection [9, 14], site selection [20, 22], air quality [4], and power sources [21]. Undoubtedly, the TODIM has demonstrated its unparalleled advantages in solving the MCDM problems by considering the psychological factors of the DMs. However, according to our review, we find that most of the existing TODIMs ignore the importance of the transformed probability weight in the original PT. What is more, the risk attitudes shown in the classical TODIM are not inconsistent with PT which only works on the gains and losses. That is, the classical TODIM should be adjusted according to the original PT which permits a more scientific result in its application. Meanwhile, the DMs may be hesitant between several possible evaluation information under the highly uncertain circumstance. Hence, a hesitant fuzzy set (HFS) [34] is an effective tool to express the hesitant situation in decision-

Table 1: Extensions of TODIM with various FSs.

FSs	References
Interval number	[3, 4]
Intuitionistic fuzzy set	[5]
Pythagorean fuzzy set	[6, 7]
Q-rung orthopair fuzzy set	[8]
Trapezoidal fuzzy set	[4, 9]
Trapezoidal intuitionistic fuzzy set	[10]
Probabilistic interval-valued hesitant fuzzy set	[11]
Multiset hesitant fuzzy set	[12]
Probabilistic dual hesitant fuzzy set	[13]
Intervalued Pythagorean fuzzy linguistic term set	[14]
Unbalanced hesitant fuzzy linguistic term set	[15]
Neutrosophic number	[16]
Interval type-2 fuzzy set	[17, 18]
Interval-valued intuitionistic fuzzy set	[19, 20]
Triangular fuzzy set	[3, 9]
Triangular intuitionistic fuzzy set	[21, 22]
Hesitant fuzzy set	[23]
Hesitant trapezoidal fuzzy set	[24]
Probabilistic hesitant fuzzy set	[25]
Intuitionistic linguistic term set	[26]
Hesitant fuzzy linguistic term set	[27, 28]
Multiset hesitant fuzzy linguistic term set	[29]
Single-valued neutrosophic set	[30]

making processes. Besides, probabilistic hesitant fuzzy information is further proposed to depict the different probabilities of each hesitant fuzzy value in HFS [35]. Hence, this paper proposes the novel TODIM with probabilistic hesitant fuzzy information and hesitant fuzzy information, respectively, to fully illustrate the core idea of PT. Furthermore, according to the comparative analysis, we show the advantages of the novel TODIM with probabilistic hesitant fuzzy information.

The contributions of this paper are as follows: (i) a novel TODIM with probabilistic hesitant fuzzy information is proposed, which is fully aligned with the original idea of PT compared with the classical TODIM. (ii) The novel TODIM with hesitant fuzzy information also has been developed to show the advantages of probabilistic hesitant fuzzy information. (iii) In the novel TODIM, the different risk attitudes are considered and they only work on gains and losses instead of the consistent risk attitudes in the dominance function of the classical TODIM. Moreover, the transformed probability weight function is also included in the novel TODIM.

The outline of this paper is as follows: in Section 2, the basic concepts of PT, TODIM, and probabilistic hesitant fuzzy information are presented in detail. In Section 3, the existing researches about the TODIM are analyzed. And the novel TODIM is combined with probabilistic hesitant fuzzy information and hesitant fuzzy information according to the original PT from the perspective of dominance function. In Section 4, a case study about bus electric supplier selection problem is provided. Section 5 shows the superiority of the proposed methods by a series of comparative analyses, especially by comparing the novel TODIM under probabilistic hesitant fuzzy environment with the extension of TOPSIS. After that, the conclusions are presented in Section 6.

Table 2: Transformed probability weights.

Weights	Criteria			
	c_1	c_2	c_3	c_4
$\pi_{12j}(\omega_j')$	0.389	0.183	0.275	0.306
$\pi_{13j}(\omega_j')$	0.389	0.183	0.275	0.306
$\pi_{14j}(\omega_j')$	0.389	0.183	0.275	0.306
$\pi_{21j}(\omega_j')$	0.368	0.197	0.275	0.301
$\pi_{23j}(\omega_j')$	0.368	0.197	0.275	0.301
$\pi_{24j}(\omega_j')$	0.368	0.197	0.275	0.301
$\pi_{31j}(\omega_j')$	0.368	0.197	0.275	0.301
$\pi_{32j}(\omega_j')$	0.389	0.183	0.275	0.306
$\pi_{34j}(\omega_j')$	0.389	0.197	0.275	0.301
$\pi_{41j}(\omega_j')$	0.368	0.197	0.275	0.301
$\pi_{42j}(\omega_j')$	0.389	0.183	0.275	0.306
$\pi_{43j}(\omega_j')$	0.368	0.183	0.275	0.306

Table 3: Relative weights.

Relative weights	Criteria			
	c_1	c_2	c_3	c_4
π_{12j^*}	1	0.47	0.707	0.789
π_{13j^*}	1	0.47	0.707	0.789
π_{14j^*}	1	0.47	0.707	0.789
π_{21j^*}	1	0.537	0.749	0.82
π_{23j^*}	1	0.537	0.749	0.82
π_{24j^*}	1	0.537	0.749	0.82
π_{31j^*}	1	0.537	0.749	0.82
π_{32j^*}	1	0.47	0.707	0.789
π_{34j^*}	1	0.508	0.708	0.775
π_{41j^*}	1	0.537	0.749	0.82
π_{42j^*}	1	0.47	0.707	0.789
π_{43j^*}	1	0.497	0.747	0.834

Table 4: Relative prospect dominance degrees under each criterion.

Relative dominance degrees	Criterion			
	c_1	c_2	c_3	c_4
$\varphi_{j^*}(A_1, A_2)$	−37.23	−139.33	−36.21	−33.35
$\varphi_{j^*}(A_1, A_3)$	−9.25	−55.75	−32.14	−50.83
$\varphi_{j^*}(A_1, A_4)$	−36.46	−63.05	−25.14	−41.38
$\varphi_{j^*}(A_2, A_1)$	1.80	1.70	0.92	1.04
$\varphi_{j^*}(A_2, A_3)$	2.12	1.16	1.49	2.23
$\varphi_{j^*}(A_2, A_4)$	2.58	1.07	0.98	1.78
$\varphi_{j^*}(A_3, A_1)$	0.45	0.68	0.82	1.59
$\varphi_{j^*}(A_3, A_2)$	−43.89	−94.96	−58.35	−71.57
$\varphi_{j^*}(A_3, A_4)$	−40.28	0.40	0.62	0.84
$\varphi_{j^*}(A_4, A_1)$	1.76	0.77	0.64	1.29
$\varphi_{j^*}(A_4, A_2)$	−53.35	−88.08	−38.39	−57.11
$\varphi_{j^*}(A_4, A_3)$	1.95	−32.87	−24.37	−26.89

2. Some Concepts

In this section, some fundamental concepts are presented, including PT, TODIM, and the probabilistic hesitant fuzzy information. They are the essential parts of this paper.

Table 5: Prospect dominance degrees.

$\psi(A_1, A_2)$−246.12	$\psi(A_2, A_1)$5.46	$\psi(A_3, A_1)$3.53	$\psi(A_4, A_1)$4.46
$\psi(A_1, A_3)$−147.97	$\psi(A_2, A_3)$7.00	$\psi(A_3, A_2)$−268.77	$\psi(A_4, A_2)$−236.93
$\psi(A_1, A_4)$−166.03	$\psi(A_2, A_4)$6.41	$\psi(A_3, A_4)$−38.42	$\psi(A_4, A_3)$−82.19

Table 6: Overall prospect dominance degrees.

$\Omega(A_1)$	$\Omega(A_2)$	$\Omega(A_3)$	$\Omega(A_4)$
0	1	0.44	0.42

Table 7: Relative weights.

ω_{1r}	ω_{2r}	ω_{3r}	ω_{4r}
1	0.28	0.57	0.68

Table 8: Relative prospect dominance degrees.

Relative dominance degrees	Criteria			
	c_1	c_2	c_3	c_4
$\varphi_j(A_1, A_2)$	−1.88	−4.85	−2.02	−1.87
$\varphi_j(A_1, A_3)$	−0.85	−2.88	−1.89	−2.38
$\varphi_j(A_1, A_4)$	−1.86	−3.09	−1.64	−2.11
$\varphi_j(A_2, A_1)$	1.67	1.23	1.01	1.13
$\varphi_j(A_2, A_3)$	1.83	0.99	1.33	1.74
$\varphi_j(A_2, A_4)$	2.05	0.95	1.05	1.53
$\varphi_j(A_3, A_1)$	0.76	0.73	0.95	1.44
$\varphi_j(A_3, A_2)$	−2.06	−3.90	−2.65	−2.88
$\varphi_j(A_3, A_4)$	−1.95	0.55	0.82	1.01
$\varphi_j(A_4, A_1)$	1.65	0.78	0.82	1.28
$\varphi_j(A_4, A_2)$	−2.30	−3.74	−2.09	−2.54
$\varphi_j(A_4, A_3)$	1.74	−2.16	−1.63	−1.67

2.1. Prospect Theory. PT is a major innovation in describing the bounded behavior of the DMs. It makes choices by the prospect value $V(x_i)$, which is calculated by multiplying the values of the value function $v(x_{ij})$ and the weight function $w(p_j)$. Let $A = \{A_1, A_2, \ldots, A_n\}$ be a finite set of alternatives, $C = \{c_1, c_2, \ldots, c_m\}$ be a finite set of criteria, and $N = \{1, 2, \ldots, n\}$, $M = \{1, 2, \ldots, m\}$, $i \in N$, $j \in M$. The prospect value is obtained by the following equations:

$$V(x_i) = \sum_{j=1}^{m} v(x_{ij}) w(p_j), \tag{1}$$

$$v(x_{ij}) = \begin{cases} -\lambda (x_0 - x_{ij})^{\beta} & x_{ij} - x_0 < 0, \\ (x_{ij} - x_0)^{\alpha} & x_{ij} - x_0 \geq 0, \end{cases} \tag{2}$$

$$w(p_j) = \begin{cases} \dfrac{p_j^{\delta}}{\left[p_j^{\delta} + (1 - p_j)^{\delta}\right]^{1/\delta}}, & x_{ij} - x_0 < 0, \\ \dfrac{p_j^{\gamma}}{\left[p_j^{\gamma} + (1 - p_j)^{\gamma}\right]^{1/\gamma}}, & x_{ij} - x_0 \geq 0, \end{cases} \tag{3}$$

where x_{ij} denotes the evaluation value of the alternative A_i over c_j; x_0 represents the reference point; p_j is the weight of c_j; and α, β, λ, δ, and γ are the corresponding parameters acquired from the experiments. According to the experiment in the classical PT [31], $\alpha = \beta = 0.88$, $\lambda = 2.25$, $\delta = 0.69$, and $\gamma = 0.61$.

2.2. TODIM. The TODIM [2] is an effective MCDM method to simulate the behaviors of the DMs. It considers the risk attitudes of DMs during the decision-making processes and measures the alternative by comparing the relative dominance with other alternatives. The procedure of the classical TODIM is shown as follows:

Step 1: obtain the original decision-making information including the evaluation information $X = (x_{ij})_{n\times m}$ of the alternative A_i regarding the criterion c_j and the weighting vector of the criterion ω:

$$\begin{aligned} X &= \begin{pmatrix} x_{11} & \cdots & x_{1m} \\ \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{nm} \end{pmatrix} = (x_{ij})_{n\times m}, \\ \omega &= (\omega_1, \omega_2, \ldots, \omega_m), \\ \sum_{j=1}^{m} \omega_j &= 1. \end{aligned} \tag{4}$$

Step 2: normalize the decision matrix $X = [x_{ij}]_{n\times m}$ into $\breve{X} = (\breve{x}_{ij})_{n\times m}$ according to the cost criterion and benefit criterion:

$$\breve{x}_{ij} = \begin{cases} x_{ij}, & c_j \text{ is the benefit criterion}, \\ -x_{ij}, & c_j \text{ is the cost criterion}. \end{cases} \tag{5}$$

Step 3: obtain the relative weights ω_{jr} $(j = 1, 2, \ldots, m)$ of the criterion c_j $(j = 1, 2, \ldots, m)$:

$$\omega_{jr} = \frac{\omega_j}{\omega_r}, \tag{6}$$

where $r, j \in M$, $\omega_r = \max(\omega_j \mid j \in M)$ and c_r is called the reference criterion.

Table 9: Prospect dominance degrees.

$\psi_j(A_1, A_2)$−5.76	$\psi_j(A_2, A_1)$3.82	$\psi_j(A_3, A_1)$3.14	$\psi_j(A_4, A_1)$3.75
$\psi_j(A_1, A_3)$ −5.11	$\psi_j(A_2, A_3)$4.91	$\psi_j(A_3, A_2)$−7.59	$\psi_j(A_4, A_2)$−6.93
$\psi_j(A_1, A_4)$ −5.61	$\psi_j(A_2, A_4)$4.63	$\psi_j(A_3, A_4)$−0.12	$\psi_j(A_4, A_3)$−1.56

Table 10: Overall dominance degrees.

$\Omega(A_1)$	$\Omega(A_2)$	$\Omega(A_3)$	$\Omega(A_4)$
0	1	0.40	0.39

Table 11: Transformed probability weights.

Weights	Criteria			
	c_1	c_2	c_3	c_4
$\pi_{12j}(\omega_j')$	0.394	0.179	0.275	0.302
$\pi_{13j}(\omega_j')$	0.394	0.179	0.275	0.302
$\pi_{14j}(\omega_j')$	0.394	0.179	0.275	0.302
$\pi_{21j}(\omega_j')$	0.372	0.195	0.276	0.298
$\pi_{23j}(\omega_j')$	0.372	0.195	0.275	0.298
$\pi_{24j}(\omega_j')$	0.372	0.195	0.276	0.298
$\pi_{31j}(\omega_j')$	0.372	0.195	0.276	0.298
$\pi_{32j}(\omega_j')$	0.394	0.179	0.276	0.302
$\pi_{34j}(\omega_j')$	0.394	0.195	0.276	0.298
$\pi_{41j}(\omega_j')$	0.372	0.195	0.276	0.298
$\pi_{42j}(\omega_j')$	0.394	0.179	0.275	0.302
$\pi_{43j}(\omega_j')$	0.372	0.179	0.275	0.302

Table 12: Relative prospect dominance degrees.

Relative dominance degrees	Criteria			
	c_1	c_2	c_3	c_4
$\psi_j(A_1, A_2)$	−37.91	−106.24	−52.20	−68.83
$\psi_j(A_1, A_3)$	−27.06	−69.83	−50.00	−39.45
$\psi_j(A_1, A_4)$	−31.77	−37.94	−38.82	−18.07
$\psi_j(A_2, A_1)$	1.89	1.26	1.34	2.10
$\psi_j(A_2, A_3)$	0.86	0.54	−38.44	1.08
$\psi_j(A_2, A_4)$	1.27	0.91	1.05	1.69
$\psi_j(A_3, A_1)$	1.35	0.83	1.28	1.20
$\psi_j(A_3, A_2)$	−17.27	−45.29	0.99	−35.35
$\psi_j(A_3, A_4)$	−13.98	0.44	0.37	0.74
$\psi_j(A_4, A_1)$	1.58	0.45	1.00	0.55
$\psi_j(A_4, A_2)$	−25.47	−76.61	−41.09	−55.39
$\psi_j(A_4, A_3)$	0.70	−37.21	−14.48	−24.25

Table 13: Overall prospect dominance degrees.

$\Omega(A_1)$	$\Omega(A_2)$	$\Omega(A_3)$	$\Omega(A_4)$
0	1	0.86	0.56

Table 14: Relative weights.

ω_{1r}	ω_{2r}	ω_{3r}	ω_{4r}
1	0.27	0.55	0.65

Table 15: Relative prospect dominance degrees.

Relative dominance degrees	Criteria			
	c_1	c_2	c_3	c_4
$\varphi_j(A_1, A_2)$	−1.89	−4.18	−2.48	−2.83
$\varphi_j(A_1, A_3)$	−1.56	−3.29	−2.42	−2.07
$\varphi_j(A_1, A_4)$	−1.71	−2.33	−2.10	−1.33
$\varphi_j(A_2, A_1)$	1.72	1.03	1.25	1.67
$\varphi_j(A_2, A_3)$	1.10	0.63	−2.10	1.15
$\varphi_j(A_2, A_4)$	1.37	0.85	1.09	1.48
$\varphi_j(A_3, A_1)$	1.42	0.81	1.22	1.22
$\varphi_j(A_3, A_2)$	−1.21	−2.57	1.06	−1.94
$\varphi_j(A_3, A_4)$	−1.07	0.57	0.61	0.94
$\varphi_j(A_4, A_1)$	1.56	0.57	1.06	0.78
$\varphi_j(A_4, A_2)$	−1.51	−3.47	−2.17	−2.51
$\varphi_j(A_4, A_3)$	0.97	−2.33	−1.21	−1.58

Step 4: acquire the prospect dominance degree $\psi(A_i, A_k)$ of each alternative A_i over the rest of the alternatives A_k $(k = 1, 2, \ldots, n, k \neq i)$:

$$\psi(A_i, A_k) = \sum_{j=1}^{m} \varphi_j(A_i, A_k), \quad i, k \in N, \tag{7}$$

where the relative dominance degree $\varphi_j(A_i, A_k)$ over c_j is calculated by the following equation, and the parameter λ denotes the attenuation factor of the losses:

$$\varphi_j(A_i, A_k) = \begin{cases} \sqrt{\dfrac{\omega_{jr}}{\sum_{j=1}^{m}\omega_{jr}}\left(\breve{x}_{ij} - \breve{x}_{kj}\right)}, & \breve{x}_{ij} - \breve{x}_{kj} > 0, \\ 0, & \breve{x}_{ij} - \breve{x}_{kj} = 0, \\ \dfrac{-1}{\lambda}\sqrt{\dfrac{\sum_{j=1}^{m}\omega_{jr}}{\omega_{jr}}\left(\breve{x}_{kj} - \breve{x}_{ij}\right)}, & \breve{x}_{ij} - \breve{x}_{kj} < 0. \end{cases} \tag{8}$$

Table 16: The dominance degrees.

$\psi_j(A_1, A_2)$ −11.39	$\psi_j(A_2, A_1)$ 5.67	$\psi_j(A_3, A_1)$ 4.67	$\psi_j(A_4, A_1)$ 3.97
$\psi_j(A_1, A_3)$ −9.35	$\psi_j(A_2, A_3)$ 0.78	$\psi_j(A_3, A_2)$ −4.67	$\psi_j(A_4, A_2)$ −9.65
$\psi_j(A_1, A_4)$ −7.47	$\psi_j(A_2, A_4)$ 4.80	$\psi_j(A_3, A_4)$ 1.05	$\psi_j(A_4, A_3)$ −4.15

Table 17: Overall prospect dominance degrees.

$\Omega(A_1)$	$\Omega(A_2)$	$\Omega(A_3)$	$\Omega(A_4)$
0	1	0.74	0.47

Table 18: The results of 4 methods.

Methods	Overall prospect dominance degrees			
	$\Omega(A_1)$	$\Omega(A_2)$	$\Omega(A_3)$	$\Omega(A_4)$
Novel TODIM with probabilistic hesitant fuzzy information	0	1	0.44	0.42
Extended TODIM with probabilistic hesitant fuzzy information	0	1	0.40	0.39
Novel TODIM with hesitant fuzzy information	0	1	0.86	0.56
Extended TODIM with hesitant fuzzy information	0	1	0.74	0.47

Step 5: calculate the overall prospect dominance degree $\Omega(A_i)$:

$$\Omega(A_i) = \frac{\sum_{k=1}^{n} \psi(A_i, A_k) - \min_i\{\sum_{k=1}^{n} \psi(A_i, A_k)\}}{\max_i\left\{\sum_{k=1}^{n} \psi(A_i, A_k)\right\} - \min_i\left\{\sum_{k=1}^{n} \psi(A_i, A_k)\right\}}. \quad (9)$$

Step 6: rank the alternatives according to the overall dominance degree of each alternative $\Omega(A_i)$. The bigger $\Omega(A_i)$ is, the better the alternative A_i will be:

$$A_i \succ A_{i'} \Longleftrightarrow \Omega(A_i) > \Omega(A_{i'}). \quad (10)$$

2.3. Probabilistic Hesitant Fuzzy Information. Let X be a fixed set, and a probabilistic hesitant fuzzy set (P-HFS) on X is expressed by

$$H = \left\{ < x_i, h_{x_i}\left(p_{x_i}\right) > \middle| x_i \in X \right\}, \quad (11)$$

where $h_{x_i}(\cdot)$ is called the probabilistic hesitant fuzzy element (P-HFE). It represents all the possible membership degrees of $x_i \in X$ in [0, 1]. p_x is a set of probabilities associated with $h_{x_i}(\cdot)$ and $\sum p_{x_i} = 1$. To be more concise, we denote the P-HFE $h_{x_i}(p_{x_i})$ as $h(p) = \{h^t(p^t) \mid t = 1, 2, \ldots, \#h(p)\}$, where $\#h(p)$ is the number of all possible membership degrees, and $\sum_{t=1}^{\#h(p)} p^t = 1$. If $\sum_{t=1}^{\#h(p)} p^t < 1$ for a P-HFE $h(p)$, it can be transformed into $\dot{h}(p)$, which is defined as $\dot{h}(p) = \left\{h^t(\dot{p}^t) \mid t = 1, 2, \ldots, \#\dot{h}(p)\right\}$, where $\sum_{t=1}^{\#\dot{h}(p)} \dot{p}^t = 1$ and $\dot{p}^t = p^t / \sum_{t=1}^{\#h(p)} p^t, (t = 1, 2, \ldots, \#h(p))$ [35]. To compare two pieces of probabilistic hesitant fuzzy information, the score function $\rho(h(p))$ and the deviation function $\sigma(h(p))$ are defined as

$$\rho(h(p)) = \frac{\sum_{t=1}^{\#h(p)} p^t \times h^t(p^t)}{\sum_{t=1}^{\#h(p)} p^t}, \quad (12)$$

$$\sigma(h(p)) = \frac{\sum_{t=1}^{\#h(p)} \left(p^t \times \left(h^t(p^t) - \rho(h(p))\right)^2\right)}{\sum_{t=1}^{\#h(p)} p^t}. \quad (13)$$

The comparison rules of two P-HFEs are expressed as

(1) If $\rho(h_1(p)) > \rho(h_2(p))$, then $h_1(p) > h_2(p)$
(2) If $\rho(h_1(p)) < \rho(h_2(p))$, then $h_1(p) < h_2(p)$
(3) If $\rho(h_1(p)) = \rho(h_2(p))$, then
  (1) If $\sigma(h_1(p)) > \sigma(h_2(p))$, then $h_1(p) < h_2(p)$
  (2) If $\sigma(h_1(p)) < \sigma(h_2(p))$, then $h_1(p) > h_2(p)$
  (3) If $\sigma(h_1(p)) = \sigma(h_2(p))$, then $h_1(p) = h_2(p)$

Distance is also an important way to measure the relationship between two pieces of fuzzy information, and the same length of two P-HFEs is the premise for distance measurement. Therefore, probabilistic hesitant fuzzy values should be added to the shorter P-HFE. For example, let $h_1(p)$ and $h_2(p)$ be the two P-HFEs; if $\#h_1(p) < \#h_2(p)$, $\#h_2(p) - \#h_1(p)$ number of probabilistic hesitant fuzzy values should be added to $h_1(p)$. In this paper, the largest possible probabilistic hesitant fuzzy value is added to $h_1(p)$, and the corresponding probability is zero. In fact, there is no effect on the score function and the deviation function of the original P-HFE by adding a term with probability to be zero. Besides, the ordered P-HFE satisfies the following conditions:

(1) For an ascending ordered P-HFE, $p^t h^t(p^t) \leq p^{t+1} h^{t+1}(p^{t+1})$
(2) For a descending ordered P-HFE, $p^t h^t(p^t) \geq p^{t+1} h^{t+1}(p^{t+1})$
(3) If $p^t h^t(p^t) = p^{t+1} h^{t+1}(p^{t+1})$ and the orders are determined by p^t and p^{t+1}, then
  (1) For an ascending ordered P-HFE, $p^t < p^{t+1}$
  (2) For a descending ordered P-HFE, $p^t > p^{t+1}$
  (3) If $p^t = p^{t+1}$, the sequence of those two P-HFEs is random for both ascending ordered P-HFE and descending ordered P-HFE

Based on the ordered probabilistic hesitant fuzzy information, the Hamming distance is referred to [25] which is presented in the following equation:

$$d(h_1, h_2) = \frac{1}{\#h_1(p)} \sum_{t=1}^{\#h_1(p)} \left| p_1^t h_1^t\left(p_1^t\right) - p_2^t h_2^t\left(p_2^t\right) \right|. \quad (14)$$

For convenience, the below probabilistic hesitant fuzzy information satisfies: $\sum_{t=1}^{\#h'(p')} p'^t = 1$, and it is ordered and standardized.

3. A Novel TODIM with Probabilistic Hesitant Fuzzy Information

This section firstly goes through the existing researches of the TODIM based on various kinds of fuzzy information. From the perspective of dominance function, the necessity of improving TODIM is also presented. According to the detailed analysis, we figure out that the probabilistic hesitant fuzzy information has great superiority in expressing the different hesitation degrees of the DMs, and the novel TODIM is more reasonable which derives from the original PT considering the importance of the transformed probability weight function during the decision-making process. Subsequently, a novel TODIM with probabilistic hesitant fuzzy information is proposed in this section. For the sake of comparison, the novel TODIM with hesitant fuzzy information is also given in the following part.

3.1. Analysis of the Existing Researches about the TODIM with Fuzzy Information. The TODIM is known as an effective way to deal with the MCDM problems derived from PT, and it has advantages in expressing the behaviors of the DMs by using gains and losses. Actually, the crisp number is usually hard to access in the real world. Under this circumstance, the TODIM is applied to various FSs as analyzed in Table 1.

According to the review of extensions of the TODIM with fuzzy information, we find that most extensions are based on the classical TODIM, as shown in Section 2.2. That is, the risk attitudes work on the product of relative weight and the perceived gains or losses through the square root in the dominance function (equation (8)) which is inconsistent with the original PT (equation (2)). Besides, the existing TODIM calculates the relative weight by using objective probability instead of using the transformed probability weight function shown in equation (3). Actually, the dominance function is the main part to express the idea of PT. Hence, this section will show the model of the dominance function with fuzzy information.

Krohling and Souza [9] developed a TODIM by adjusting dominance function with trapezoidal fuzzy number as shown in the following equation:

$$\varphi_j(A_i, A_k) = \begin{cases} \sqrt{\dfrac{\omega_{jk}}{\sum_{j=1}^m \omega_{jk}}} d\left(r_{ij}, r_{kj}\right), & r_{ij} > r_{kj}, \\ 0, & r_{ij} = r_{kj}, \\ \dfrac{-1}{\theta} \sqrt{\dfrac{\sum_{j=1}^m \omega_{jk}}{\omega_{jk}}} d\left(r_{kj}, r_{ij}\right), & r_{ij} < r_{kj}, \end{cases} \quad (15)$$

where ω_{jk} is the relative weight calculated from the original weight; θ is the attenuation factor of the losses; r_{ij} and r_{kj} are two FSs; and $d(\cdot)$ is the distance between r_{ij} and r_{kj}.

According to equation (15), the dominance function excludes the distance outside the square root. However, some researchers hold the view that the above dominance function (equation (15)) is far more deviating from the original PT. Hence, there is another progress proposed by Peng et al. [12] through adjusting the square number k as shown in equation (16). The distance of fuzzy evaluation information is included in the square root, which is similar to the classical TODIM:

$$\varphi_j(A_i, A_k) = \begin{cases} \sqrt[k]{\dfrac{\omega_{jr}}{\sum_{j=1}^m \omega_{jr}} d\left(r_{ij}, r_{kj}\right)}, & r_{ij} > r_{kj}, \\ 0, & r_{ij} = r_{kj}, \\ \dfrac{-1}{\lambda} \sqrt[k]{\dfrac{\sum_{j=1}^m \omega_{jr}}{\omega_k} d\left(r_{ij}, r_{kj}\right)}, & r_{ij} < r_{kj}, \end{cases} \quad (16)$$

where k is the regulating variable that is determined by the preference of the DMs, and when $k = 2$, the dominance function perfectly agrees with the classical TODIM.

Tan et al. [36] thought that the square root or k used in the former dominance functions does not reflect the core idea of PT. The parameters could be different, which is shown in the experiments, while the square root or k is the same value all the time. Based on this, the dominance function was modified as follows where risk attitudes work on the product of the relative weight and distances:

$$\varphi_j(A_i, A_k) = \begin{cases} \left(\frac{\omega_{jr}}{\sum_{j=1}^{m}\omega_{jr}} d(r_{ij}, r_{kj})\right)^{\alpha}, & r_{ij} > r_{kj}, \\ 0, & r_{ij} = r_{kj}, \\ \frac{-1}{\theta}\left(\frac{\sum_{j=1}^{m}\omega_{jr}}{\omega_k} d(r_{ij}, r_{kj})\right)^{\beta}, & r_{ij} < r_{kj}. \end{cases} \quad (17)$$

Li et al. [28] insisted that in original PT, weight should be the form of weight function rather than the original weight. Hence, the original weight was replaced with the weight function based on (17) in their work. However, Tian et al. [32] thought that the risk attitudes only work on the gains or losses according to the value function based on PT and do not work on the weight. Then, the dominance function was adjusted as

$$\varphi_j(A_i, A_k) = \begin{cases} \frac{w_{ijk}(x_{ij} - x_{kj})^{\alpha}}{\sum_{j^*=1}^{m} w_{ijk}}, & x_{ij} > x_{kj}, \\ 0, & x_{ij} = x_{kj}, \\ \frac{-\lambda\left(\sum_{j=1}^{m} w_{ijk}\right)(x_{kj} - x_{kj})^{\beta}}{w_{ijk}}, & x_{ij} < x_{kj}, \end{cases} \quad (18)$$

where α, β, and λ are the parameters obtained by experiments. In their work, the transformed probability weight is considered in the decision-making process instead of the original weight. The different preferences of the DMs on gains and losses are well described in this way. More importantly, the core idea of PT is fully illustrated by the risk attitudes which work on the gains or the losses. However, this TODIM has not been extended to various FSs. Therefore, in this paper, we are dedicated to adopting the framework of this novel TODIM, which comprehensively explains the idea of PT, and combining it with probabilistic hesitant fuzzy information.

3.2. Procedure of the Novel TODIM with Probabilistic Hesitant Fuzzy Information. Based on the above analysis, this section presents a new procedure of the novel TODIM with probabilistic hesitant fuzzy information, which is based on the idea of the original PT. The procedure is given as follows:

Step 1: obtain the original evaluation information matrix $Y = (h_{ij}(p_{ij}))_{n\times m}$ according to equation (4) and the weight of the corresponding criterion. Both the evaluation information and the weight satisfy the characteristic of the P-HFE:

$$Y = \begin{pmatrix} h_{11}(p_{11}) & \cdots & h_{1m}(p_{1m}) \\ \vdots & \ddots & \vdots \\ h_{n1}(p_{n1}) & \cdots & h_{nm}(p_{nm}) \end{pmatrix} = \left(h_{ij}(p_{ij})\right)_{n\times m}, \quad (19)$$

$$\omega = \left(h_{\omega_1}(p_{\omega_1}), h_{\omega_2}(p_{\omega_2}), \ldots, h_{\omega_m}(p_{\omega_m})\right), \quad (20)$$

where $i \in N$, $j \in M$; $h_{ij}(p_{ij})$ is the evaluation information of the alternative A_i over the criterion c_j; and $h_{\omega_j}(p_{\omega_j})$ is the weighting information of c_j.

Step 2: normalize the evaluation information matrix according to Section 2.3:

$$Y' = \begin{pmatrix} h'_{11}(p'_{11}) & \cdots & h'_{1m}(p'_{1m}) \\ \vdots & \ddots & \vdots \\ h'_{n1}(p'_{n1}) & \cdots & h'_{nm}(p'_{nm}) \end{pmatrix} = \left(h'_{ij}(p'_{ij})\right)_{n\times m}, \quad (21)$$

$$\omega' = (\omega'_1, \omega'_2, \ldots, \omega'_m), \quad (22)$$

where $\sum_{j=1}^{m} p'_{ij} = 1 \quad (i \in N)$, $\sum_{j=1}^{m}\omega'_j = 1$; $\omega'_j = \omega_j / \sum_{j=1}^{m}\omega_j$; and $\omega_j = \sum_{t=1}^{\#h_{\omega_j}(p_{\omega_j})} p^t_{\omega_j} h^t_{\omega_j}(p^t_{\omega_j})$.

Step 3: work out the transformed probability weight function $\pi_{ikj}(\omega'_j)$ according to the weighting function of PT:

$$\pi_{ikj}(\omega'_j) = \begin{cases} \pi^{+}_{ikj}(\omega'_j) = \frac{\omega'^{\gamma}_j}{\left(\left(\omega'^{\gamma}_j\right) + \left(1 - \omega'_j\right)^{\gamma}\right)^{1/\gamma}}, & h'_{ij}(p'_{ij}) \geq h'_{kj}(p'_{kj}), \\ \pi^{-}_{ikj}(\omega'_j) = \frac{\omega'^{\delta}_j}{\left(\omega'^{\delta}_j + \left(1 - \omega'_j\right)^{\delta}\right)^{1/\delta}}, & h'_{ij}(p'_{ij}) < h'_{kj}(p'_{kj}), \end{cases} \quad (23)$$

where the comparison between $h'_{ij}(p'_{ij})$ and $h'_{kj}(p'_{kj})$ is determined by using equations (12) and (13).

Step 4: acquire the relative weight π_{ikj^*} of A_i over A_k:

$$\pi_{ikj^*} = \frac{\pi_{ikj}(\omega'_j)}{\pi_{ikr}(\omega'_r)}, \quad r, j \in M, \forall (i,k), \tag{24}$$

where $\pi_{ikr}(\omega'_r) = \max(\pi_{ikj}(\omega'_j) \mid j \in M)$ and $\pi_{ikr}(\omega'_r)$ is named as the reference criterion.

Step 5: calculate the relative prospect dominance degrees $\varphi_{j^*}(A_i, A_k)$ of the alternative A_i over A_k under the criterion c_j as follows:

When c_j is the benefit criterion, the relative prospect dominance degree is $\varphi^B_{j^*}(A_i, A_k)$:

$$\varphi^B_{j^*}(A_i, A_k) = \begin{cases} \dfrac{\pi_{ikj^*}\left(d\left(h'_{ij^*}\left(p'_{ij^*}\right), h'_{kj^*}\left(p'_{kj^*}\right)\right)\right)^{\alpha}}{\sum_{j^*=1}^{m}\pi_{ikj^*}}, & h'_{ij^*}\left(p'_{ij^*}\right) > h'_{kj^*}\left(p'_{kj^*}\right), \\ 0, & h'_{ij^*}\left(p'_{ij^*}\right) = h'_{kj^*}\left(p'_{kj^*}\right), \\ \dfrac{-\lambda\left(\sum_{j^*=1}^{m}\pi_{ikj^*}\right)\left(d\left(h'_{ij^*}\left(p'_{ij^*}\right), h'_{kj^*}\left(p'_{kj^*}\right)\right)\right)^{\beta}}{\pi_{ikj^*}}, & h'_{ij^*}\left(p'_{ij^*}\right) < h'_{kj^*}\left(p'_{kj^*}\right). \end{cases} \tag{25}$$

When c_j is the cost criterion, the relative prospect dominance degree is $\varphi^C_{j^*}(A_i, A_k)$:

$$\varphi^C_{j^*}(A_i, A_k) = \begin{cases} \dfrac{-\lambda\left(\sum_{j^*=1}^{m}\pi_{ikj^*}\right)\left(d\left(h'_{ij^*}\left(p'_{ij^*}\right), h'_{kj^*}\left(p'_{kj^*}\right)\right)\right)^{\beta}}{\pi_{ikj^*}}, & h'_{ij^*}\left(p'_{ij^*}\right) > h'_{kj^*}\left(p'_{kj^*}\right), \\ 0, & h'_{ij^*}\left(p'_{ij^*}\right) = h'_{kj^*}\left(p'_{kj^*}\right), \\ \dfrac{\pi_{ikj^*}\left(d\left(h'_{ij^*}\left(p'_{ij^*}\right), h'_{kj^*}\left(p'_{kj^*}\right)\right)\right)^{\alpha}}{\sum_{j^*=1}^{m}\pi_{ikj^*}}, & h'_{ij^*}\left(p'_{ij^*}\right) < h'_{kj^*}\left(p'_{kj^*}\right), \end{cases} \tag{26}$$

where α, β, and λ are the parameters of PT; $d(h'_{ij^*}(p'_{ij^*}), h'_{kj^*}(p'_{kj^*}))$ is the corresponding distance calculated by using equation (14).

Step 6: obtain the prospect dominance degrees based on equation (7):

$$\psi(A_i, A_k) = \sum_{j^*=1}^{m} \varphi_j^*(A_i, A_k), \quad \forall (i,k). \tag{27}$$

Step 7: calculate the overall prospect dominance degrees from equation (9):

$$\Omega(A_i) = \frac{\sum_{k=1}^{n}\psi(A_i, A_k) - \min_i\left\{\sum_{k=1}^{n}\psi(A_i, A_k)\right\}}{\max_i\left\{\sum_{k=1}^{n}\psi(A_i, A_k)\right\} - \min_i\left\{\sum_{k=1}^{n}\psi(A_i, A_k)\right\}}, \quad \forall i, k \in N. \tag{28}$$

The bigger the $\Omega(A_i)$ is, the better the alternative A_i will be.

3.3. Procedure of the Novel TODIM with Hesitant Fuzzy Information. Hesitant fuzzy information is represented by HFS [34] and is used to describe the situation that the DMs hesitate between several different values, and each hesitation value is equally important. In fact, it also can be expressed as a special form of probabilistic hesitant fuzzy information. When the probabilities are equal, probabilistic hesitant fuzzy information turns into hesitant fuzzy information. The HFS can be denoted as $H = \left\{ < x_i, h_{x_i} > \mid x_i \in X \right\}$, and $h_{x_i} = \left\{ h_{x_i}^t \mid t = 1, 2, \ldots, \#h_{x_i} \right\}$ is called a hesitant fuzzy element (HFE). To demonstrate the effectiveness of the proposed method in Section 3.2, we further combine the novel TODIM with hesitant fuzzy information in this section. The process is shown as follows:

Step 1: obtain the original information matrix and weight information:

$$Y = \begin{pmatrix} h_{11} & \cdots & h_{1m} \\ \vdots & \ddots & \vdots \\ h_{n1} & \cdots & h_{nm} \end{pmatrix} = \left(h_{ij}\right)_{n\times m}, \tag{29}$$

$$\omega = \left(h_{\omega_1}, h_{\omega_2}, \ldots, h_{\omega_m}\right), \tag{30}$$

where $i \in N$, $j \in M$; h_{ij} is the evaluation information of the alternative A_i over the criterion c_j; and h_{ω_j} is the weighting information of c_j.

Step 2: normalize the weight information based on the following equation:

$$\omega_j' = \frac{\omega_j}{\sum_{j=1}^{m} \omega_j}, \tag{31}$$

where $\omega_j = \rho(h_{\omega_j})$ and $\rho(h_{\omega_j})$ is the score function (32) of the HFE h_{ω_j}:

$$\rho(h) = \frac{1}{\#h} \sum_{t=1}^{\#h} h^t. \tag{32}$$

Step 3: obtain the transformed probability weight function $\pi_{ikj}(\omega_j')$ according to the following equation:

$$\pi_{ikj}\left(\omega_j'\right) = \begin{cases} \pi_{ikj}^{+}\left(\omega_j'\right) = \dfrac{\omega_j'^{\gamma}}{\left(\omega_j'^{\gamma} + \left(1 - \omega_j'\right)^{\gamma}\right)^{1/\gamma}}, & h_{ij}' \geq h_{kj}', \\ \pi_{ikj}^{-}\left(\omega_j'\right) = \dfrac{\omega_j'^{\delta}}{\left(\omega_j'^{\delta} + \left(1 - \omega_j'\right)^{\delta}\right)^{1/\delta}}, & h_{ij}' < h_{kj}', \end{cases} \tag{33}$$

where the comparison of the HFEs h_{ij}' and h_{kj}' is decided by the score function (equation (32)) and the deviation function (the following equation) of the HFEs:

$$\sigma(h) = \frac{1}{\#h} \sqrt{\sum_{\forall_{h^t} \in h} \left(h^t - \rho(h)\right)^2}. \tag{34}$$

The detailed rules are represented as follows:

(1) If $\rho(h_{ij}') > \rho(h_{kj}')$, then $h_{ij}' > h_{kj}'$

(2) If $\rho(h_{ij}') < \rho(h_{kj}')$, then $h_{ij}' < h_{kj}'$

(3) If $\rho(h_{ij}') = \rho(h_{kj}')$, then

  (1) If $\sigma(h_{ij}') > \sigma(h_{kj}')$, then $h_{ij}' < h_{kj}'$
  (2) If $\sigma(h_{ij}') < \sigma(h_{kj}')$, then $h_{ij}' > h_{kj}'$
  (3) If $\sigma(h_{ij}') = \sigma(h_{kj}')$, then $h_{ij}' = h_{kj}'$

Step 4: calculate the relative weight $\pi_{ikj'}$ based on equation (24) and the transformed probability weight $\pi_{ikj}(\omega_j')$

Step 5: work out the relative prospect dominance degrees $\varphi_{j'}(A_i, A_k)$ of the alternatives A_i over A_k under the criterion c_j as follows:

When c_j is the benefit criterion, the relative prospect dominance degree is $\varphi_{j'}^{B}(A_i, A_k)$:

$$\varphi_{j'}^{B}(A_i, A_k) = \begin{cases} \dfrac{\pi_{ikj'}\left(d\left(h_{ij'}', h_{kj'}'\right)\right)^{\alpha}}{\sum_{j'=1}^{m} \pi_{ikj'}}, & h_{ij'}' > h_{kj'}', \\ 0, & h_{ij'}' = h_{kj'}', \\ -\dfrac{\lambda\left(\sum_{j'=1}^{m} \pi_{ikj'}\right)\left(d\left(h_{ij'}', h_{kj'}'\right)\right)^{\beta}}{\pi_{ikj'}}, & h_{ij'}' < h_{kj'}'. \end{cases} \tag{35}$$

When c_j is the cost criterion, the relative prospect dominance degree is $\varphi_{j'}^{C}(A_i, A_k)$:

$$\vartheta_{j'}^{C}(A_i, A_k) = \begin{cases} -\dfrac{\lambda\left(\sum_{j'=1}^{m}\pi_{ikj'}\right)\left(d\left(h'_{ij'}, h'_{kj'}\right)\right)^{\beta}}{\pi_{ikj'}}, & h'_{ij'} > h'_{kj'}, \\ 0, & h'_{ij'} = h'_{kj'}, \\ \dfrac{\pi_{ikj'}\left(d\left(h'_{ij'}, h'_{kj'}\right)\right)^{\alpha}}{\sum_{j'=1}^{m}\pi_{ikj'}}, & h'_{ij'} < h'_{kj'}, \end{cases} \tag{36}$$

where λ denotes the attenuation factor of the losses and $d(h'_{ij'}, h'_{kj'})$ is the corresponding distance calculated by

$$d\left(h_{ij}, h_{kj}\right) = \frac{1}{\#h_{ij}}\sum_{t=1}^{\#h_{ij}}\left|h_{ij}^{t} - h_{kj}^{t}\right|, \quad \#h_{ij} = \#h_{kj}. \tag{37}$$

Step 5: acquire the prospect dominance degrees based on equation (27).

Step 6: calculate the overall dominance degrees according to equation (28), and the bigger the $\Omega(A_i)$ is, the better the alternative A_i will be.

From the procedures above, the novel TODIM with probabilistic hesitant fuzzy information and the novel TODIM with hesitant fuzzy information are given in Sections 3.2 and 3.3, respectively. It is worth noting that in the proposed methods, the original weight information is represented by P-HFE and HFE according to (20) and (30) respectively. Moreover, the score function is used to represent the weight information of (22) and (31), which is inspired from [37]. Indeed, the score function is an excellent tool that reflects the comprehensive information of a piece of the evaluation for the alternative, and it is also good at grasping the basic information. Therefore, we also use the score function to complete the weight transformation in this paper. Besides, both these methods conform to the original PT by modifying the perceived probability weighting function and the difference of the risk attitudes for gains and losses. Concerning the ability to express the information of DMs, the novel TODIM with probabilistic hesitant fuzzy information has more advantages in describing different hesitant degrees of the hesitant values by using possibilities. The novel TODIM with hesitant fuzzy information is used to carry out a series of convincing comparisons. Actually, it is regarded as a particular form of the former method when the probability is equal. Hence, the novel TODIM with probabilistic hesitant fuzzy information is our main focus in this paper, and we believe that it can reflect more evaluation information than the novel TODIM with hesitant fuzzy information. Then, a case study is carried out to show the application of the proposed methods.

3.4. Theoretical Analysis of the Proposed Method. It is critical to know the advantages of the proposed method which helps us to understand the MCDM process and at the same time contributes to analyzing the ranking results reasonably. The theoretical superiority of combining the novel TODIM with probabilistic hesitant fuzzy information can be concluded from the two aspects: information distortion and information attenuation. In terms of information distortion, the proposed method has modified three inconsistencies of classical TODIM with PT. First, this method reflects the actual meaning of parameters compared with the method proposed by Krohling and Souza [9] and Peng et al. [12], and their dominance functions are equations (15) and (16), respectively. Although the values of α and β are equal under this circumstance, their meanings are completely different, and their values may be different in different experiments. α indicates the concavity of the power function for gains, while β represents the convexity case for losses. It is improper to depict those two different states with only one uniform parameter k, which may lead to information distortion. The proposed method has also made the second measure to avoid information distortion, and it is the use of weight function compared with the method proposed in [36] and its dominance function shown as equation (17). The weight function is important in PT because it modifies an easily overlooked situation that people tend to overestimate low probability events and underestimate high probability events. Third, the most important point revealed by the proposed method and neglected by most existing studies is that the α and β only appear in the value function and work on gains and losses according to the original PT.

The novel TODIM does compensate for some shortcomings of the traditional TODIM by reflecting the actual meaning of parameters, considering the transformed weight function and modifying its core idea referring to the original PT. However, the information attenuation is inevitable when the novel TODIM is explained by crisp number [32]. In some practical situations, the DMs could not give an accurate assessment and usually hesitant in several assessments. This situation can be well simulated by hesitant fuzzy information. But hesitant fuzzy information could not reflect the different preferences for every possible value. Probabilistic hesitant fuzzy information can describe different preferences for each possible value with probabilities, so the performance of the novel TODIM with probabilistic hesitant fuzzy information will be superior to the one with scrip number and the one with hesitant fuzzy information. For example, if a person is invited to evaluate a suitable supplier of electric vehicle charging piles in the urban planning, he/she is not very sure about the score and hesitates between several values 81, 85, and 90. Furthermore, among those three values, he/she prefers 81, and he/she thinks there is 0.7 probability of 81 and 0.2 and 0.1 probabilities of 85 and 90, respectively. In this situation, the evaluation information can be interpreted as {81(0.7), 85(0.2), 90(0.1)} by probabilistic hesitant fuzzy information. While using hesitant fuzzy information, this situation is only interpreted as {81, 85, 90}, which could not reflect the preference of DM. In addition, probabilistic hesitant fuzzy information can reflect the opinions of DMs in group decision-making. For instance, when five experts were invited, they need to give their opinions. If one expert gives 70, the other three of them assign 83, and only one expert gives 91; the evaluation information will be expressed as {70(0.2),83(0.6),91(0.2)} in the form of probabilistic hesitant fuzzy information. If hesitant fuzzy information is used, the evaluation information will be {70, 83, 91}. Obviously, the use of hesitant fuzzy information sometimes leads to information loss. Furthermore, the information attenuation will be amplified when the gap between these evaluation values is large. Hence, considering the limitations of hesitant fuzzy information in expressing the idea of individuals and in collecting ideas of a group, probabilistic hesitant fuzzy information is more suitable to describe the uncertainties of DMs.

From the theoretical analysis above, the novel TODIM with probabilistic hesitant fuzzy information has more advantages than the one with crisp number or the one with hesitant fuzzy information. It eases information distortion by adjusting itself to the original PT and avoids information attenuation by using probabilistic hesitant fuzzy information. The superiority of the proposed method is theoretically illustrated. Then, an illustrative example is given to show its advantages in further detail and to enhance the understanding of the proposed method.

4. Illustrative Example

This section presents an electric bus bid case with four different methods. They are the extension of two types of different fuzzy information including probabilistic hesitant fuzzy information and hesitant fuzzy information.

4.1. Background of the Case. With the development of new energy technologies, electric buses have become one of the most mature areas of new energy vehicle applications. Electric bus is clean, low noise, and environmental protection, which greatly enhances the user's experience. It has been reported by Bloomberg that the U.S. has a fleet of 300 electric buses, while China has 421,000 by the end of 2018 [38]. Besides, it has been estimated that more than 385,000 electric buses have been put into services, accounting for 17% of the total national bus fleet [39].

With the promotion of ecological civilization strategy, the Chinese government has put forward higher requirements for the application of green energy. It is estimated that by 2020, the number of new energy vehicles used in urban public transportation will reach 600,000. In other words, more electric clean buses are needed to deploy sustainable development strategy in more cities. Evidently, the most important step is to select a dependent new energy vehicle supplier. Investment [40, 41] plays an important role in this process. As a well-known public transportation company in Shanghai, China, Shanghai Pudong New Area Public Transport Investment Development Company mainly engaged in urban transportation and vehicle maintenance. It has announced a procurement project to purchase more electric public transportation buses in September 6, 2019 [41]. After the preliminary bid screening, there are four qualified suppliers left: A_1, A_2, A_3, and A_4. The final round of bidding aims to select the most appropriate green supplier. Selection experts concern the following aspects: safety (c_1), environment (c_2), economy (c_3), and convenience cost (c_4), and all the four criteria belong to the benefit ones.

4.2. Screening Process of the Novel TODIM with Probabilistic Hesitant Fuzzy Information

Step 1: to better distinguish the probability in the evaluation information from the membership degree, it is magnified by 100 times. Then, the evaluation information is given as follows:

$$Y = \begin{array}{c} \\ A_1 \\ A_2 \\ A_3 \\ A_4 \end{array} \begin{array}{c} \begin{array}{cccc} c_1 & c_2 & c_3 & c_4 \end{array} \\ \begin{pmatrix} \{55(0.22), 68(0.51), 73(0.27)\} & \{60(0.45), 66(0.39), 70(0.16)\} & \{62(0.69), 68(0.21), 71(0.1)\} & \{64(0.66), 72(0.32), 77(0.02)\} \\ \{62(0.28), 77(0.63), 79(0.09)\} & \{68(0.29), 77(0.68), 80(0.03)\} & \{60(0.18), 73(0.21), 85(0.61)\} & \{77(0.6), 88(0.36), 80(0.04)\} \\ \{63(0.32), 71(0.48), 77(0.2)\} & \{66(0.39), 71(0.52), 77(0.09)\} & \{68(0.59), 74(0.32), 79(0.09)\} & \{71(0.53), 78(0.22), 81(0.25)\} \\ \{67(0.49), 72(0.44), 75(0.07)\} & \{62(0.58), 69(0.3), 74(0.12)\} & \{67(0.61), 71(0.26), 78(0.13)\} & \{68(0.36), 73(0.49), 79(0.15)\} \end{pmatrix} \end{array}, \tag{38}$$

$$\omega = (\{0.34(0.68), 0.40(0.32)\}, \{0.09(0.39), 0.11(0.61)\}, \{0.19(0.56), 0.22(0.44)\}, \{0.21(0.43), 0.27(0.57)\}).$$

Step 2: normalize the evaluation matrix of the four green suppliers and get the normalized weight information at the same time:

$$Y = \begin{array}{c} \\ A_1 \\ A_2 \\ A_3 \\ A_4 \end{array} \begin{array}{c} \begin{array}{cccc} c_1 & c_2 & c_3 & c_4 \end{array} \\ \begin{pmatrix} \{55(0.22), 73(0.27), 68(0.51)\} & \{70(0.16), 66(0.39), 60(0.45)\} & \{71(0.1), 68(0.21), 62(0.69)\} & \{77(0.02), 72(0.32), 64(0.66)\} \\ \{79(0.09), 62(0.28), 77(0.63)\} & \{80(0.03), 68(0.29), 77(0.68)\} & \{60(0.18), 73(0.21), 85(0.61)\} & \{80(0.04), 88(0.36), 77(0.60)\} \\ \{77(0.2), 63(0.32), 71(0.48)\} & \{77(0.09), 66(0.39), 71(0.52)\} & \{79(0.09), 74(0.32), 68(0.59)\} & \{78(0.22), 81(0.25), 71(0.53)\} \\ \{75(0.07), 72(0.44), 67(0.49)\} & \{74(0.12), 69(0.3), 62(0.58)\} & \{78(0.13), 71(0.26), 67(0.61)\} & \{79(0.15), 68(0.36), 73(0.49)\} \end{pmatrix} \end{array}, \tag{39}$$

$$\omega' = (0.395, 0.112, 0.224, 0.269)$$

Step 3: calculate the transformed probability weights according to equation (23), and the results are shown in Table 2.

Step 4: obtain the relative weights according to equation (24), and the results are shown in Table 3.

Step 5: work out the relative prospect dominance degrees of the alternative A_1 over the others under each criterion, which is determined by using equations (25) and (26), shown in Table 4.

Step 6: obtain the prospect dominance degrees of the alternative A_i over the others by using equation (27), shown in Table 5.

Step 7: the overall prospect dominance degrees of each alternative is calculated by using equation (28), and the results are exhibited in Table 6.

Step 8: since $\Omega(A_2) > \Omega(A_3) > \Omega(A_4) > \Omega(A_1)$, there exists $A_2 \succ A_3 \succ A_4 \succ A_1$. The company A_2 should be selected in this bid.

4.3. Screening Process of the Extended TODIM with Probabilistic Hesitant Fuzzy Information

Step 1: the normalized evaluation matrix is transformed in the same way as shown in Step 1 and Step 2 in Section 4.2.

Step 2: calculate the relative weight of each criterion based on (6), shown in Table 7.

Step 3: obtain the relative dominance degrees $\varphi_j(A_i, A_k)$ of the alternative A_i over A_k under the criterion c_j as follows, and the result is exhibited in Table 8, and $\varphi_j(A_i, A_i) = 0$ is not shown in this table:

When c_j is the benefit criterion, the relative prospect dominance degree is

$$\varphi_j^B(A_i, A_k) = \begin{cases} \sqrt{\dfrac{\omega_{jr}'}{\sum_{j=1}^{m}\omega_{jr}'} d\left(h_{ij}'\left(p_{ij}'\right), h_{kj}'\left(p_{kj}'\right)\right)}, & h_{ij}'\left(p_{ij}'\right) > h_{kj}'\left(p_{kj}'\right), \\ 0, & h_{ij}'\left(p_{ij}'\right) = h_{kj}'\left(p_{kj}'\right), \\ -\dfrac{1}{\lambda}\sqrt{\dfrac{\sum_{j=1}^{m}\omega_{jr}'}{\omega_{jr}'} d\left(h_{ij}'\left(p_{ij}'\right), h_{kj}'\left(p_{kj}'\right)\right)}, & h_{ij}'\left(p_{ij}'\right) < h_{kj}'\left(p_{kj}'\right). \end{cases} \tag{40}$$

When c_j is the cost criterion, the relative prospect dominance degree is

$$\varphi_j^C(A_i, A_k) = \begin{cases} -\dfrac{1}{\lambda}\sqrt{\dfrac{\sum_{j=1}^{m}\omega_{jr}'}{\omega_{jr}'} d\left(h_{ij}'\left(p_{ij}'\right), h_{kj}'\left(p_{kj}'\right)\right)}, & h_{ij}'\left(p_{ij}'\right) > h_{kj}'\left(p_{kj}'\right), \\ 0, & h_{ij}'\left(p_{ij}'\right) = h_{kj}'\left(p_{kj}'\right), \\ \sqrt{\dfrac{\omega_{jr}'}{\sum_{j=1}^{m}\omega_{jr}'} d\left(h_{ij}'\left(p_{ij}'\right), h_{kj}'\left(p_{kj}'\right)\right)}, & h_{ij}'\left(p_{ij}'\right) < h_{kj}'\left(p_{kj}'\right), \end{cases} \tag{41}$$

where $d(h_{ij}'(p_{ij}'), h_{kj}'(p_{kj}'))$ is the distance of $h_{ij}'(p_{ij}')$ and $h_{kj}'(p_{kj}')$.

Step 4: the prospect dominance degrees of the alternative A_i over the others under each criterion are determined by using equation (27). The result is exhibited in Table 9, and $\psi_j(A_i, A_i) = 0$ is not shown in this table.

Step 5: the overall dominance degrees of each alternative are calculated by using equation (28), and the results are exhibited in Table 10.

Step 6: since $\Omega(A_2) > \Omega(A_3) > \Omega(A_4) > \Omega(A_1)$, we can get $A_2 \succ A_3 \succ A_4 \succ A_1$. The company A_2 should be selected in this bid.

4.4. Screening Process of the Novel TODIM with Hesitant Fuzzy Information

Step 1: obtain the evaluation matrix and the weight information as hesitant fuzzy information:

$$Y = \begin{array}{c} \\ x_1 \\ x_2 \\ x_3 \\ x_4 \end{array} \begin{array}{c} \begin{array}{cccc} c_1 & c_2 & c_3 & c_4 \end{array} \\ \begin{pmatrix} \{55,68,73\} & \{60,66,70\} & \{62,68,71\} & \{64,72,77\} \\ \{62,77,79\} & \{68,77,80\} & \{60,73,85\} & \{77,80,88\} \\ \{63,71,77\} & \{66,71,77\} & \{68,74,79\} & \{71,78,81\} \\ \{67,72,75\} & \{62,69,74\} & \{67,71,78\} & \{68,73,79\} \end{pmatrix} \end{array}, \quad (42)$$

$$\omega = (\{0.34, 0.40\}, \{0.09, 0.11\}, \{0.19, 0.22\}, \{.21, 0.27\}). \quad (43)$$

Step 2: normalize the evaluation matrix. The normalized evaluation information matrix is the same as (42). Besides, the normalized weight information is based on equation (31).

Step 3: obtain the transformed probability weights by using equation (33), and the results are shown in Table 11. The comparison of the two HFEs h'_{ij} and h'_{kj} is determined by the score function (equation (32)) and the deviation function (equation (34)).

Step 4: obtain the relative weight of A_i over A_k based on equation (24).

Step 5: calculate the relative prospect dominance degrees $\varphi_j^*(A_i, A_k)$ of the alternative A_i over A_k under the criterion c_j. When c_j is the benefit criterion, the relative prospect dominance degree is calculated by using equation (35). Otherwise, the relative prospect dominance degree is calculated by using equation (36). The results are exhibited in Table 12.

Step 6: obtain the dominance degrees of the alternative A_i over the others by using equation (27).

Step 7: obtain the overall dominance degrees according to equation (28), shown in Table 13.

Step 8: since $\Omega(A_2) > \Omega(A_3) > \Omega(A_4) > \Omega(A_1)$, we can get $A_2 \succ A_3 \succ A_4 \succ A_1$. Thus, the company A_2 should be selected in this bid.

4.5. Screening Process of the Extended TODIM with Hesitant Fuzzy Information

Step 1: obtain the evaluation matrix and the weight information as hesitant fuzzy information. They are the same as the information shown in (42) and (43), respectively.

Step 2: calculate relative weights, and the results are shown in Table 14:

$$\omega_{jr} = \frac{\omega_j}{\omega_r} = \frac{\rho\left(h_{\omega_j}\right)}{\rho\left(h_{\omega_r}\right)}, \quad (44)$$

where $j, r \in M$, $\rho(h_{\omega_j})$ is the score function shown in (32).

Step 3: calculate the relative dominance degrees $\varphi_j(A_i, A_k)$ of the alternative A_i over A_k under the criterion c_j as follows, and the results are exhibited in Table 15:

When c_j is the benefit criterion, the relative dominance degree is

$$\varphi_j^B(A_i, A_k) = \begin{cases} \sqrt{\dfrac{\omega_{jr}}{\sum_{j=1}^m \omega_{jr}} d\left(h_{ij}, h_{kj}\right)}, & h_{ij} > h_{kj}, \\ 0, & h_{ij} = h_{kj}, \\ -\dfrac{1}{\lambda}\sqrt{\dfrac{\sum_{j=1}^m \omega_{jr}}{\omega_{jr}} d\left(h_{ij}, h_{kj}\right)}, & h_{ij} < h_{kj}. \end{cases} \quad (45)$$

When c_j is the cost criterion, the relative dominance degree is

$$\varphi_j^C(A_i, A_k) = \begin{cases} -\dfrac{1}{\lambda}\sqrt{\dfrac{\sum_{j=1}^m \omega_{jr}}{\omega_{jr}} d\left(h_{ij}, h_{kj}\right)}, & h_{ij} > h_{kj}, \\ 0, & h_{ij} = h_{kj}, \\ \sqrt{\dfrac{\omega_{jr}}{\sum_{j=1}^m \omega_{jr}} d\left(h_{ij}, h_{kj}\right)}, & h_{ij} < h_{kj}, \end{cases} \quad (46)$$

where $d(h_{ij}, h_{kj})$ is the distance of hesitant fuzzy information h_{ij} and h_{kj}.

Step 4: obtain the dominance degrees of the alternative A_i over the others by using equation (27), shown in Table 16.

Step 5: obtain the overall dominance degrees by using equation (28), shown in Table 17.

Step 6: since $\Omega(A_2) > \Omega(A_3) > \Omega(A_4) > \Omega(A_1)$, we can get $A_2 \succ A_3 \succ A_4 \succ A_1$. Thus, the company A_2 should be selected in this bid.

4.6. Analysis. In this section, we summarize the results of the above decision-making processes and display them in Table 18. By comparing the results of these four methods, the preponderance of combining the novel TODIM with probabilistic hesitant fuzzy information is fully illustrated.

From Table 18, the same ranking results ($A_2 \succ A_3 \succ A_4 \succ A_1$) are presented from the four kinds of methods. Obviously, the company A_2 is considered to be the optimal choice, and the company A_1 is the worst choice. However, there are huge differences in the value of overall prospect dominance degrees obtained by the four methods.

Based on Table 18 and Figure 1, compared with Method 1 and Method 2, as well as Method 3 and Method 4, the difference of overall prospect dominance degrees between the alternatives A_3 and A_4, which use the novel TODIM based on PT, is greater than the extended one. We attribute this phenomenon to the different risk attitudes of the DMs concerning about gains and losses which are considered in PT. Compared with Method 1 and Method 3, as well as Method 2 and Method 4, we can discover that the overall prospect dominance degrees obtained from the methods, which adopt probabilistic hesitant fuzzy information and concern different preference degrees of hesitant values, are smaller than those obtained from hesitant fuzzy information. We contribute this phenomenon in reflecting more details of DMs are produced by using the probabilistic fuzzy information. The result also illustrates that probabilistic hesitant fuzzy information is good at expressing the DMs' evaluation information and different preferences for hesitant fuzzy values. Therefore, we believe the novel TODIM with probabilistic hesitant fuzzy information is more comprehensive and effective in decision-making.

5. Comparative Analysis

To better illustrate the effectiveness of the proposed method, we carry out the comparative analysis with TOPSIS, sensitivity analysis, and simulation analysis. The results of the analyses strongly support the superiority of the developed method.

5.1. Comparative Analysis with TOPSIS. Analysis in Section 4.6 focuses on comparing the different extensions of TODIM with different fuzzy information. In this section, to illustrate the advantages of TODIM with probabilistic hesitant fuzzy information, we compare it with TOPSIS under probabilistic hesitant fuzzy environment. It offers a more convincing analysis because this does not focus on the psychological factor of DMs. Motivated by He and Xu [43] and Dagdeviren et al. [44], probabilistic hesitant fuzzy information is extended to TOPSIS. By applying the example in Section 4, we use this method to obtain the best alternative.

First, we obtain the normalized evaluation matrix which is the same as the matrix of Step 2 in Section 4.2. Second, we find the positive ideal alternative A^+ which is the alternative with the closest distance to ideal solution and the negative ideal alternative A^- which is farthest to the ideal solution by using equations (49) and (50) based on each criterion. The results are presented in Table 19:

$$A^+ = \left\{h_1^+, h_2^+, \ldots, h_j^+\right\} = \left\{\max_i h_{ij} \,\middle|\, i = 1, 2, \ldots, n\right\}, \quad (47)$$

$$A^- = \left\{h_1^-, h_2^-, \ldots, h_j^-\right\} = \left\{\max_i h_{ij} \,\middle|\, i = 1, 2, \ldots, n\right\}. \quad (48)$$

Then, we use equations (49) and (50) to compute the distances between the alternative and the ideal solution, where the distance measures are obtained by using equation (14), and the results are shown in Table 20:

$$D_i^+ = \sum_{j=1}^{m} w_j d\left(h_{ij}\left(p_{ij}\right), h_i^+\right), \quad (49)$$

$$D_i^- = \sum_{j=1}^{m} w_j d\left(h_{ij}\left(p_{ij}\right), h_i^-\right). \quad (50)$$

We can easily obtain the relative closeness coefficients of each alternative by using equation (51). They are listed in Table 21. Hence, the ranking of the alternatives obtained from TOPSIS with probabilistic hesitant fuzzy information is $A_2 \succ A_4 \succ A_3 \succ A_1$:

$$C_i^* = \frac{D_i^-}{D_i^+ + D_i^-}, \quad i = 1, 2, \ldots, n. \quad (51)$$

The superiority of the proposed method can be seen from the results shown in Tables 18 and 21. The ranking result obtained from the TOPSIS method is different from the one obtained from the novel TODIM with probabilistic hesitant fuzzy information, and the ranking result of the middle two alternatives (A_3 and A_4) is different in those two methods. This distinction can be attributed to the following reasons, which are also the advantages of the proposed method. First, the novel TODIM has identified more information on DMs. It not only involves the transformed probability weight but also considers the difference between every two alternatives, instead of focusing on the difference between the alternative and the positive ideal solution or the negative ideal solution shown in TOPSIS. In addition, TOPSIS with probabilistic hesitant fuzzy information does not reflect the psychological factors of DMs, while probabilistic hesitant fuzzy information describes the uncertain evaluation information, and all participants usually are bounded rational in real decision-making situations. This defect is fully compensated in the TODIM by considering the risk attitudes for gains and losses, which makes the results more accurate, objective, and more consistent with practical experience.

By addressing the comparison of the existing method, the demand for combining probabilistic hesitant fuzzy information with TODIM has also been fully demonstrated. The overall prospect dominance degrees of TODIM and the relative closeness coefficients of the TOPSIS with probabilistic hesitant fuzzy environment are much smaller than the results of TODIM with hesitant fuzzy information. It is strongly proven that the probabilistic hesitant fuzzy information has discerned and reflected more information of DMs. Therefore, probabilistic hesitant fuzzy information is an effective tool to express a wider range of uncertain information in the decision-making process.

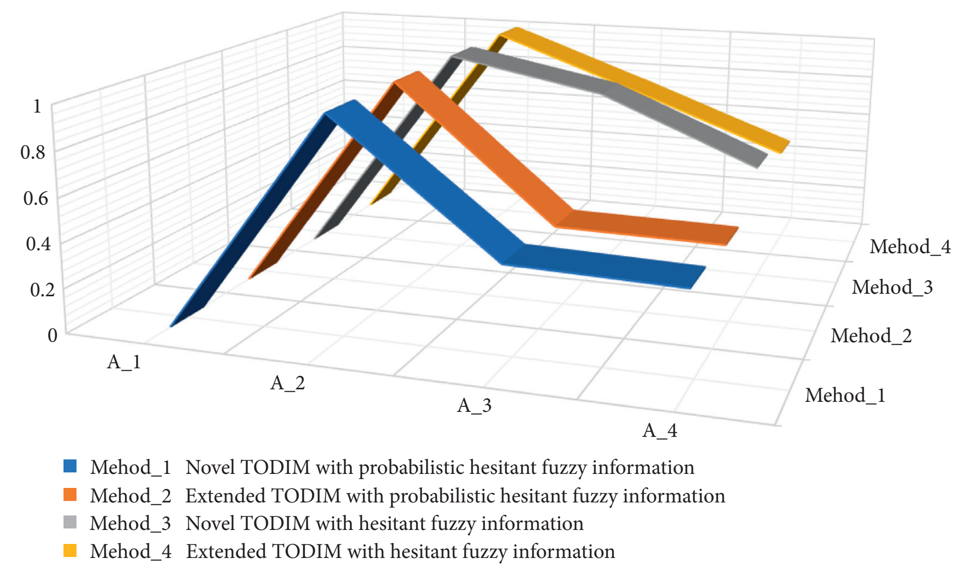

Figure 1: Overall prospect dominance degrees.

Table 19: The positive ideal solution and negative ideal solution.

	c_1	c_2	c_3	c_4
A^+	{79 (0.09), 62 (0.28), 77 (0.63)}	{80 (0.03), 68 (0.29), 77 (0.68)}	{60 (0.18), 73 (0.21), 85 (0.61)}	{80 (0.04), 88 (0.36), 77 (0.60)}
A^-	{55 (0.22), 73 (0.27), 68 (0.51)}	{70 (0.16), 66 (0.39), 60 (0.45)}	{71 (0.1), 68 (0.21), 62 (0.69)}	{77 (0.02), 72 (0.32), 64 (0.66)}

Table 20: Distances between the alternatives and the idea solution.

	A_1	A_2	A_3	A_4
D_i^+	6.5980	0.0000	9.1503	8.5449
D_i^-	0.0000	6.5980	4.0679	5.6463

Table 21: The relative closeness coefficients.

	A_1	A_2	A_3	A_4
C_i^*	0.00	1.00	0.31	0.40

5.2. Sensitivity Analysis Based on the Parameter Values. To better illustrate the advantages of the novel TODIM with probabilistic hesitant fuzzy information, this part conducts a sensitivity analysis of the novel TODIM and the extended TODIM with probabilistic hesitant fuzzy information and hesitant fuzzy information, respectively. Both comparative analyses fully illustrate the advantages of the novel TODIM based on PT. Moreover, this paper presents the comparative analysis to illustrate the superiority of probabilistic hesitant fuzzy information in reflecting more evaluation information of DMs by comparing it with hesitant fuzzy information in a fixed method.

5.2.1. Sensitivity Analysis of the Novel TODIM and the Extended TODIM with the Same Fuzzy Information. In the beginning, we analyze the difference of sensitivity between the novel TODIM and the extended TODIM with the same fuzzy information. According to the results, we recognize that no matter how the parameter λ changes, there are no significant changes for the ranking results from each method. Therefore, we use the overall prospect dominance degrees to show the strength of the novel TODIM.

(1) Sensitivity Analysis of the Novel TODIM and the Extended TODIM with Probabilistic Hesitant Fuzzy Information. Since λ is the only common parameter both in the novel TODIM and in the extended TODIM with probabilistic hesitant fuzzy information, the fluctuation of the overall prospect dominance degree can be easily observed by changing the value of λ $(1.25 \leq \lambda \leq 2.25)$ which is shown in Figure 2.

The overall prospect dominance degrees of the first and the last alternative remain unchanged which is naturally determined by the TODIM itself, and they are 1 and 0 separately when the ranking result is unchanged. Subsequently, making the alternatives A_3 and A_4 as an analysis group, when λ varies, the fluctuation range of the overall prospect dominance degree from the novel TODIM is smaller than the one obtained from the extended TODIM, which indicates that the novel TODIM is stable. Besides, the overall prospect dominance value obtained from the two methods shows a reverse trend. The main reason is that λ is proportional to the dominance function in the novel TODIM, and it is also proportional to the overall prospect dominance degree. In the extended TODIM, the dominance function is affected by the reciprocal form of λ, so λ is inversely proportional to the dominant function. This kind of reverse trend also can be found in the following analysis under the hesitant fuzzy environment.

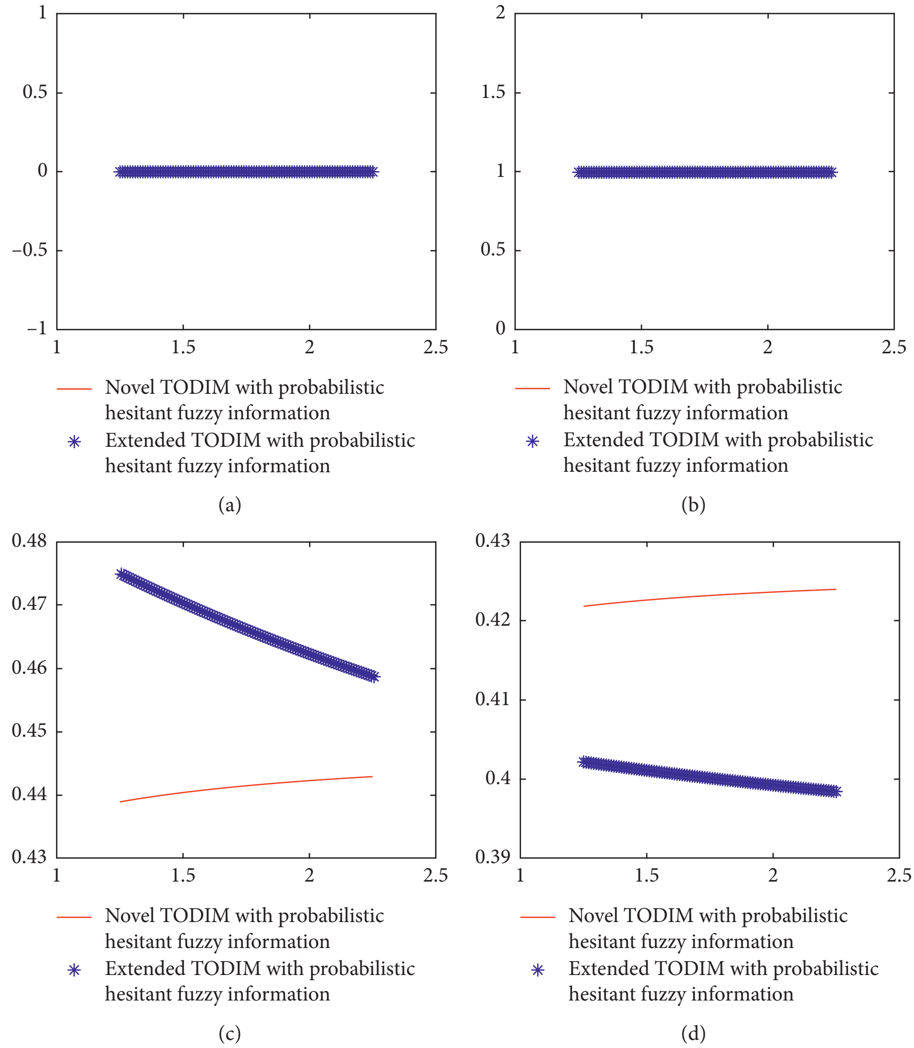

Figure 2: Sensitivity analysis with probabilistic hesitant fuzzy information. $1.25 \leq \lambda \leq 2.25$, $\alpha = \beta = 0.88$, $\delta = 0.69$, and $\gamma = 0.61$. (a) A_1; (b) A_2; (c) A_3; (d) A_4.

(2) Sensitivity Analysis of the Novel TODIM and the Extended TODIM with Hesitant Fuzzy Information. The changes of the overall prospect dominance degree in Figure 3 are obtained by altering the value of λ $(1.25 \leq \lambda \leq 2.25)$ in the novel TODIM and the extended TODIM with hesitant fuzzy information. According to Figure 3, it is apparent that the overall prospect dominance degrees of the alternatives A_1 and A_2 stay constant when the parameter λ varies. At the same time, the fluctuation of the overall prospect dominance degree from the novel TODIM is smaller than that from the extended TODIM which also demonstrates that the novel TODIM is stable.

5.2.2. Sensitivity Analysis of the Novel TODIM and the Extended TODIM Based on Different Types of Fuzzy Information. This section presents two sets of comparative analyses to illustrate the advantages of probabilistic hesitant fuzzy information in expressing the perceptions of the DMs. The first one is the novel TODIM with probabilistic hesitant fuzzy information and with hesitant fuzzy information. The second one is the extended TODIM with probabilistic hesitant fuzzy information and with hesitant fuzzy information. We find that the ranking results of each alternative keep unchanged when the parameters change. Subsequently, the overall prospect dominance degrees are used to show the advantages of probabilistic hesitant fuzzy information.

(1) Sensitivity Analysis of the Novel TODIM with Probabilistic Hesitant Fuzzy Information and Compared with Hesitant Fuzzy Information. Since many parameters are used in the novel TODIM, this part presents the changes of overall prospect dominance degree of each alternative when the parameters change, which are shown in Figures 4–8.

Figure 4 presents the fluctuation of the overall prospect dominance degree from the novel TODIM with probabilistic hesitant fuzzy information and with hesitant fuzzy information separately by changing the parameter λ $(1.25 \leq \lambda \leq 2.25)$. We can clearly see that for the alternatives A_3 and A_4, the changes of overall prospect dominance degree obtained by probabilistic hesitant fuzzy information are smaller than the one obtained by hesitant fuzzy

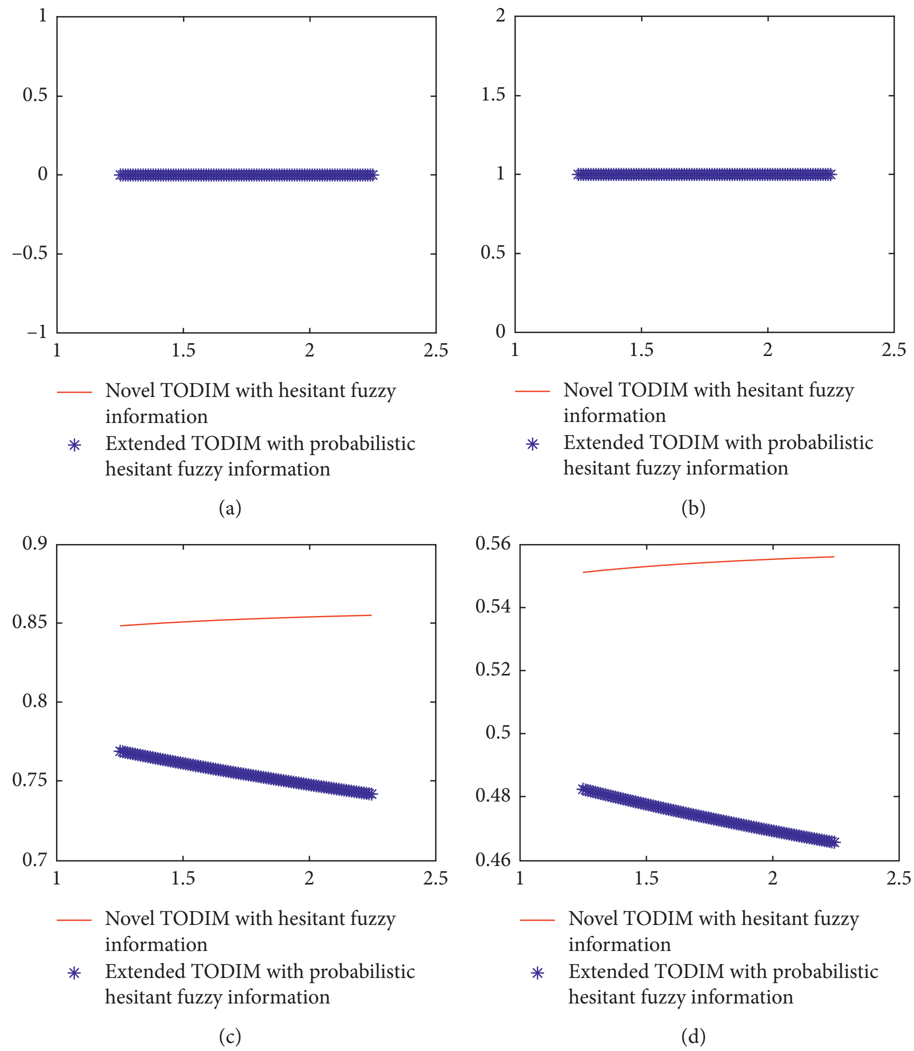

FIGURE 3: Sensitivity analysis with hesitant fuzzy information. $1.25 \le \lambda \le 2.25$, $\alpha = \beta = 0.88$, $\delta = 0.69$, and $\gamma = 0.61$. (a) A_1; (b) A_2; (c) A_3; (d) A_4.

information, which indicates the stability of probabilistic hesitant fuzzy information.

Figure 5 presents the fluctuation of the overall prospect dominance degree from the novel TODIM with probabilistic hesitant fuzzy information and with hesitant fuzzy information separately by changing the parameter α ($0.68 \le \alpha \le 1.21$). It is obvious that for the alternatives A_3 and A_4, the changes of overall prospect dominance degree obtained by probabilistic hesitant fuzzy information are smaller than the one obtained by hesitant fuzzy information, which also indicates that the probabilistic hesitant fuzzy information is stable.

Figure 6 presents the fluctuation of the overall prospect dominance degree from the novel TODIM with probabilistic hesitant fuzzy information and with hesitant fuzzy information separately by changing the parameter β ($0.68 \le \beta \le 1.02$). We can see that for the alternatives A_3 and A_4, the changes of overall prospect dominance degree obtained by probabilistic hesitant fuzzy information and by hesitant fuzzy information have obvious differences. For the alternative A_4, the change trend of the methods with two different types of information goes in the same direction; however, the greater fluctuation occurs in the method with hesitant fuzzy information. For the alternative A_3, the change trend of the two methods goes in the opposite direction.

Figure 7 presents the fluctuation of the overall prospect dominance degree from the novel TODIM with probabilistic hesitant fuzzy information and with hesitant fuzzy information separately by changing the parameter δ ($0.36 \le \delta \le 0.84$). For the alternatives A_3 and A_4, significant fluctuation can be observed in the overall prospect dominance degree which is obtained by probabilistic hesitant fuzzy information, while small changes happen to the one obtained from hesitant fuzzy information. For both the alternatives A_3 and A_4, the overall prospect dominance degrees obtained from the two methods tend to change in the same direction.

Figure 8 presents the fluctuation of the overall prospect dominance degree obtained from the novel TODIM with

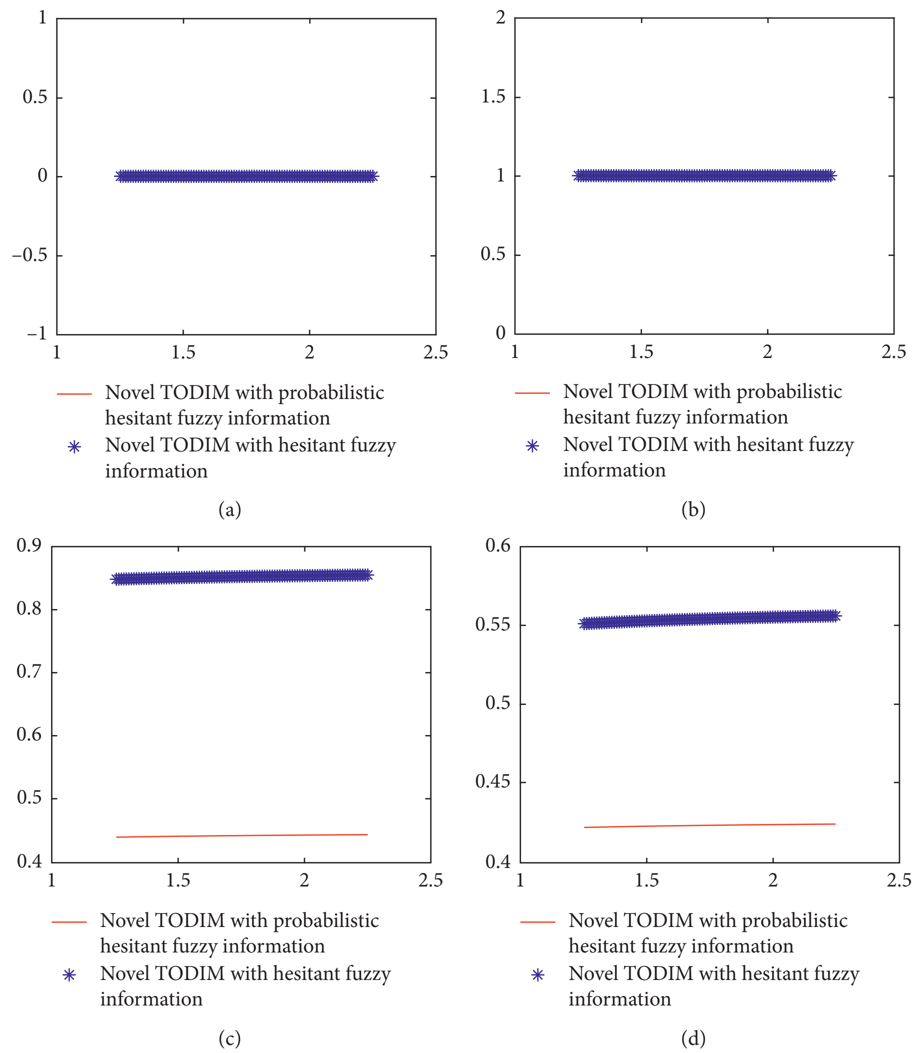

Figure 4: Sensitivity analysis of the novel TODIM by changing λ. $1.25 \le \lambda \le 2.25$, $\alpha = \beta = 0.88$, $\delta = 0.69$, and $\gamma = 0.61$. (a) A_1; (b) A_2; (c) A_3; (d) A_4.

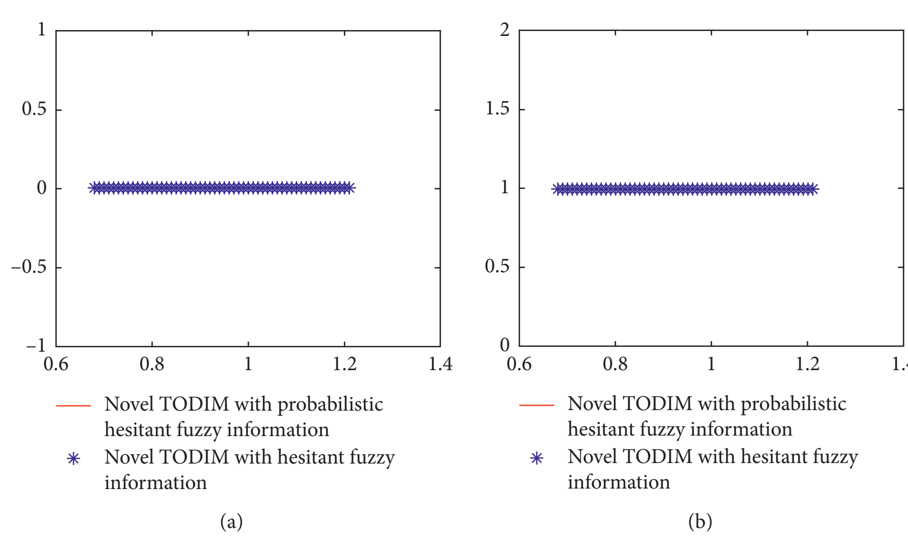

Figure 5: Continued.

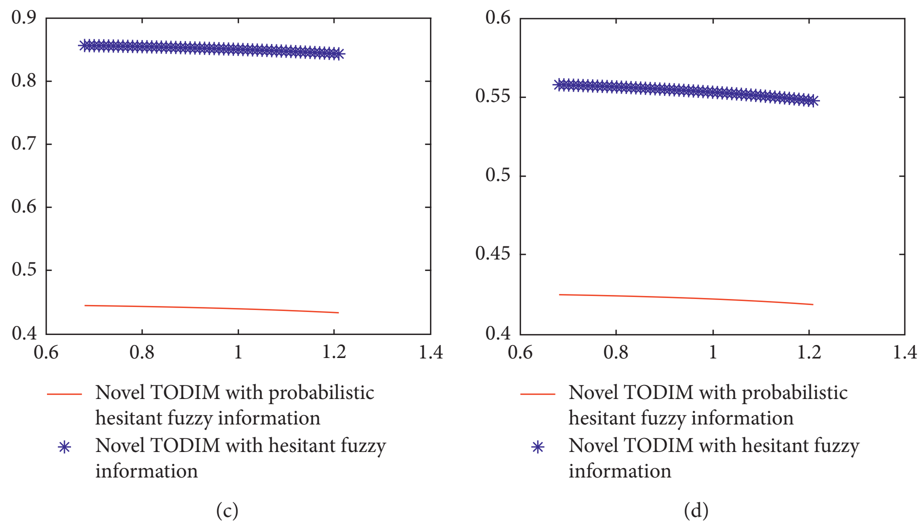

Figure 5: Sensitivity analysis of novel TODIM by changing α. $0.68 \leq \alpha \leq 1.21$, $\beta = 0.88$, $\delta = 0.69$, $\gamma = 0.61$, and $\lambda = 2.25$. (a) A_1; (b) A_2; (c) A_3; (d) A_4.

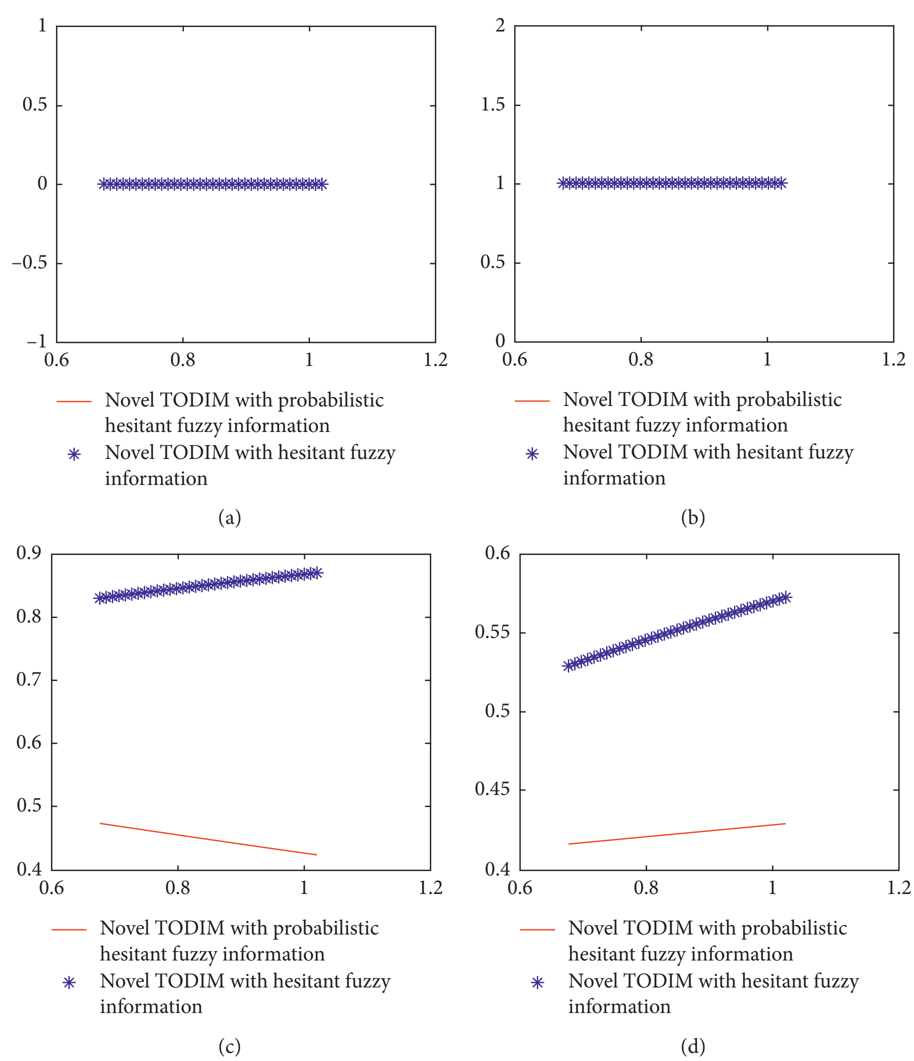

Figure 6: Sensitivity analysis of novel TODIM by changing β. $0.68 \leq \beta \leq 1.02$, $\alpha = 0.88$, $\delta = 0.69$, $\gamma = 0.61$, and $\lambda = 2.25$. (a) A_1; (b) A_2; (c) A_3; (d) A_4.

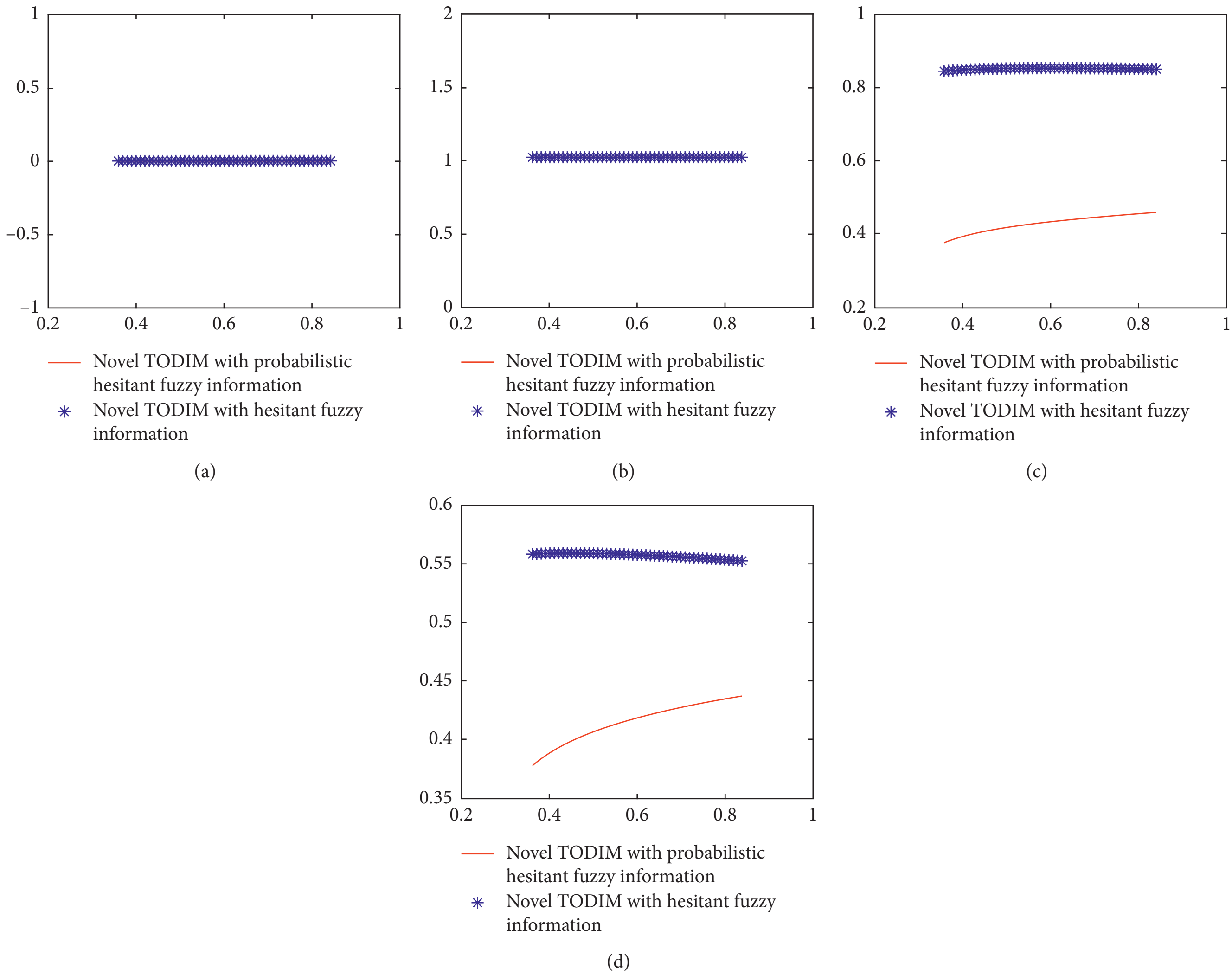

Figure 7: Sensitivity analysis of the novel TODIM by changing δ. $0.36 \le \delta \le 0.84$, $\alpha = \beta = 0.88$, $\gamma = 0.61$, and $\lambda = 2.25$. (a) A_1; (b) A_2; (c) A_3; (d) A_4.

probabilistic hesitant fuzzy information and with hesitant fuzzy information separately by changing the parameter γ ($0.55 \le \gamma \le 0.721$). For the alternatives A_3 and A_4, the overall prospect dominance degrees obtained from these two kinds of methods are almost unchanged. No matter how A_3 or A_4 alters, the overall prospects tend to change in the same direction.

(2) Sensitivity Analysis of the Extended TODIM with Probabilistic Hesitant Fuzzy Information and Compared with Hesitant Fuzzy Information. Since there is only one mutual parameter λ in the extended TODIM, this section considers the changes of the overall prospect dominance degree by changing it.

Figure 9 presents the fluctuation of the overall prospect dominance degree by changing the parameter λ ($1.25 \le \lambda \le 2.25$) in the extended TODIM with probabilistic hesitant fuzzy information and with hesitant fuzzy information. For the alternatives A_3 and A_4, the overall prospect dominance degree obtained by hesitant fuzzy information changes significantly, while the one obtained by probabilistic hesitant fuzzy information is nearly unchanged, and it also continues to decrease when increasing the value of the parameter λ. Besides, regardless of the alternative A_3 or A_4, the overall prospect dominance degrees obtained from the two methods tend to change in the same direction.

In summary, the novel TODIM is stable and effective (Figures 2 and 3) with the same type of fuzzy information. The overall prospect dominance degree obtained by probabilistic hesitant fuzzy information changes slightly than the one obtained by hesitant fuzzy information (Figures 4 and 9).

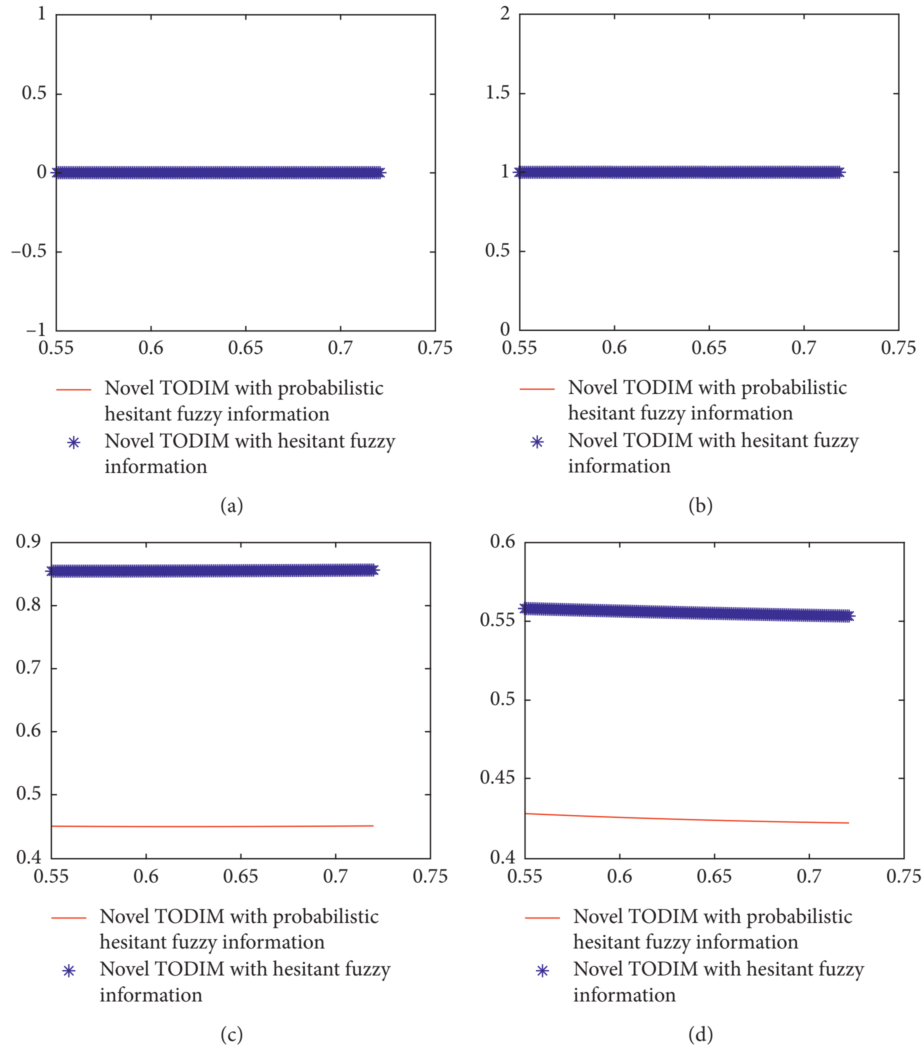

Figure 8: Sensitivity analysis of the novel TODIM by changing γ. $0.55 \le \gamma \le 0.721$, $\alpha = \beta = 0.88$, $\delta = 0.69$, and $\lambda = 2.25$. (a) A_1; (b) A_2; (c) A_3; (d) A_4.

The results illustrate that the probabilistic hesitant fuzzy information is steadier and contains more information from DMs. Figures 5–9 present the changes in the overall prospect dominance degree when changing other parameters with different types of fuzzy information from the novel TODIM.

5.3. Simulation Analysis. After sensitivity analysis of the parameters based on one sample, we present the analysis results of 1000 sets of data which are randomly generated by MATLAB software. The ranking results are shown in Table 22 and Figures 10–13.

From Table 22, the ranking results of 1000 sets of random data by using different kinds of methods are presented. 393 sets of data have the same ranking results in these four methods. With probabilistic hesitant fuzzy information, 633 sets of data have the same ranking results by using the novel TODIM and the extended TODIM. However, with hesitant fuzzy information, 654 sets of data are observed to have the same ranking results by using the novel TODIM and the extended TODIM. The number of ranking results with hesitant fuzzy information is bigger than that of the ranking results with probabilistic hesitant fuzzy information because the latter one includes more information and it is more difficult to get the same ranking result. 622 sets of data have the same ranking results by using the novel TODIM with probabilistic hesitant fuzzy information and the novel TODIM with hesitant fuzzy information. 679 sets of data have the same ranking results by using the extended TODIM with probabilistic hesitant fuzzy information and the extended TODIM with hesitant fuzzy information.

According to the results, there are large numbers of random data with the same ranking results, which shows the feasibility and applicability of the proposed method. On

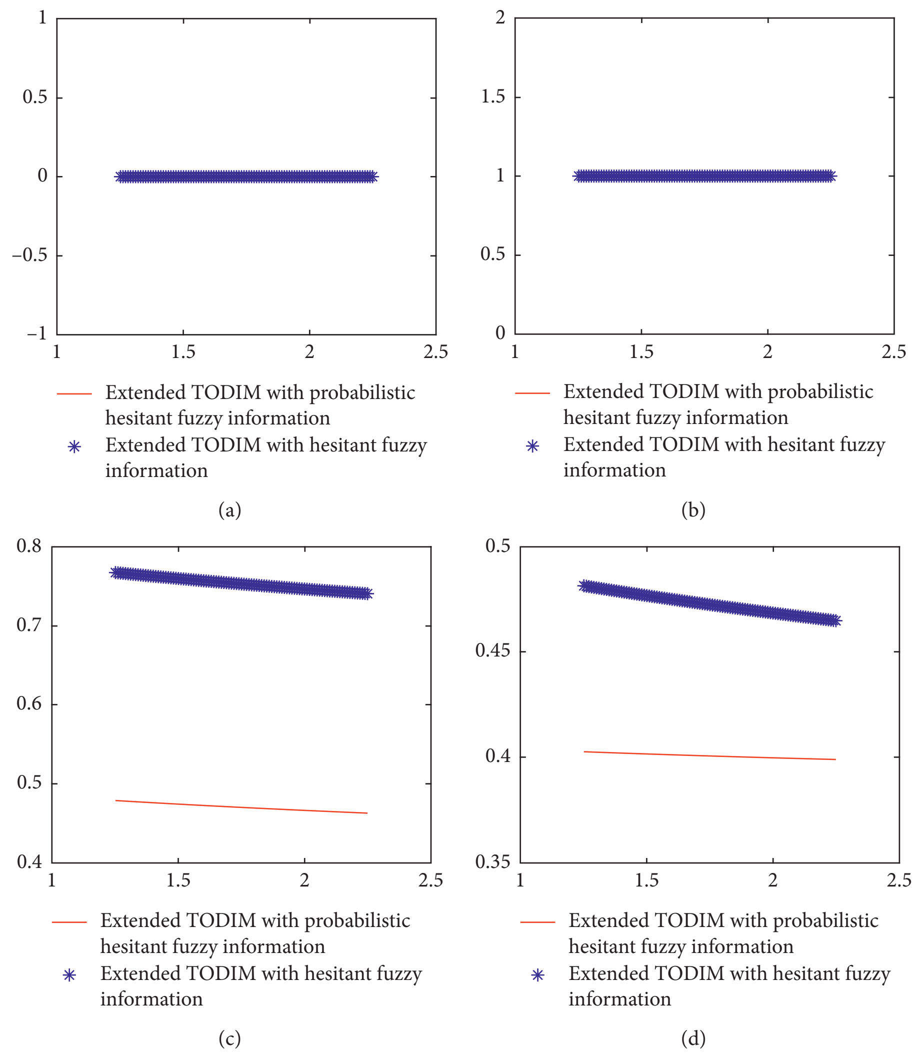

Figure 9: Sensitivity analysis of extended TODIM by changing λ. $1.25 \leq \lambda \leq 2.25$, $\alpha = \beta = 0.88$, $\gamma = 0.61$, and $\delta = 0.69$. (a) A_1; (b) A_2; (c) A_3; (d) A_4.

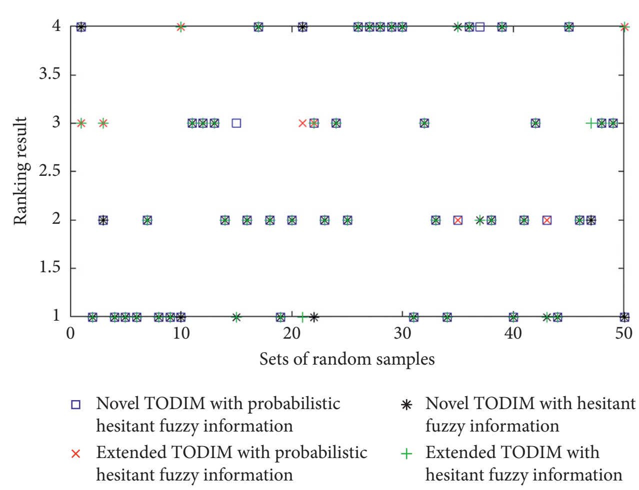

Figure 10: Ranking results of the alternative A_1 (50 sets of random samples).

Table 22: Ranking results of each method with 1000 sets of random samples.

Methods	Results: The number of the same ranking result	Results: The number of the different ranking result
Novel TODIM with probabilistic hesitant fuzzy information Extended TODIM with probabilistic hesitant fuzzy information Novel TODIM with hesitant fuzzy information Extended TODIM with hesitant fuzzy information	393	607
Novel TODIM with probabilistic hesitant fuzzy information Extended TODIM with probabilistic hesitant fuzzy information	633	367
Novel TODIM with hesitant fuzzy information Extended TODIM with hesitant fuzzy information	654	346
Novel TODIM with probabilistic hesitant fuzzy information Novel TODIM with hesitant fuzzy information	622	378
Extended TODIM with probabilistic hesitant fuzzy information Extended TODIM with hesitant fuzzy information	679	321

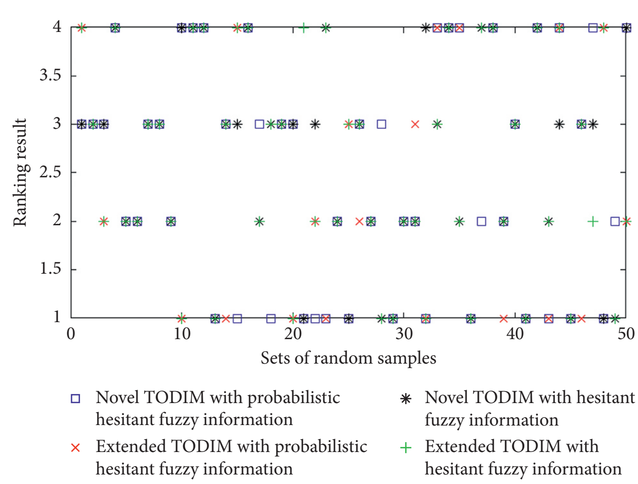

Figure 11: Ranking results of the alternative A_2 (50 sets of random samples).

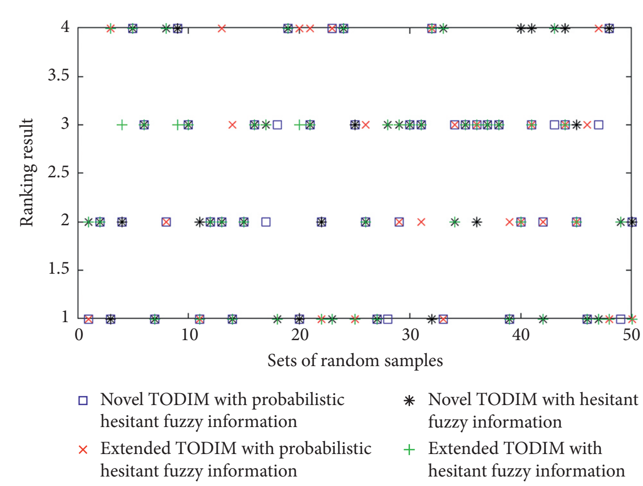

Figure 12: Ranking results of the alternative A_3 (50 sets of random samples).

the contrary, there are still some existing sets of data samples with different ranking results which indicates the differences between these methods. We attribute this difference to the following two points: (1) Compared with hesitant fuzzy information, probabilistic hesitant fuzzy information contains more original decision information. The former one is just a special form of probabilistic hesitant fuzzy information when the probability is equal, and the latter one is more general. (2) Compared with the extended TODIM, the novel TODIM based on PT rewrites the dominance function of TODIM and makes it more in line with the actual decision-making environment, which contains more details about risk attitudes for gains and losses of DMs. Based on Table 22, the ranking results are presented in the form of numbers. To observe the ranking results of each alternative more intuitively, Figures 10–13 present the ranking results of the first 50 sets of random data in detail.

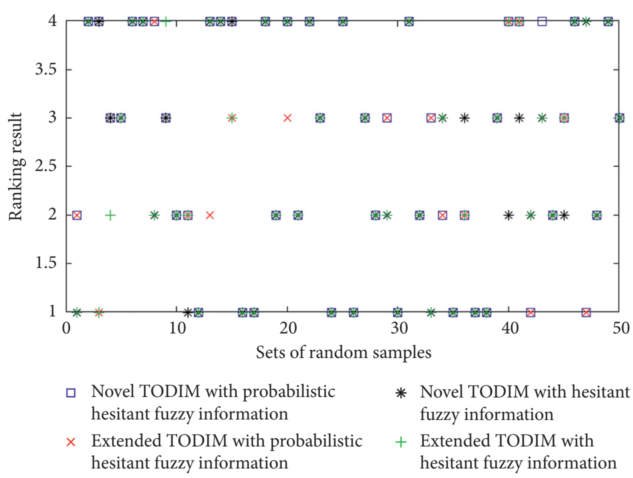

FIGURE 13: Ranking results of the alternative A_4 (50 sets of random samples).

6. Conclusions

The TODIM is a MCDM method based on PT which shows the risk aversion attitude through the dominance function. Based on equation (6) of the classical TODIM, the relative weight is calculated by the one-dimensional probability weight; however, according to equation (3), the original PT considers that the DMs adopt the nonlinear transformed probability weight function in the decision-making process. Without a doubt, the classical TODIM ignores the effect of the transformed probability weighting function on decision-making results. Besides, it is easy to recognize from equation (8) that the multiply value of relative probability weight and the perceived gain or loss value are regarded as the overall preferences of the DMs in the classic TODIM. However, the different risk attitudes for gains and losses are mainly reflected by the value function in the classic PT according to equation (2), and it takes the product of the value function and the weight function as a decision reference. Such a phenomenon has not been well proclaimed in the classical TODIM.

At the same time, it is considered that the DMs are more likely to express their perceptions as the form of probabilistic hesitant fuzzy information under the highly uncertain circumstance because they can express their preference for the hesitant fuzzy values by probabilistic hesitant fuzzy information. That is the reason why we propose a probabilistic hesitant fuzzy TODIM based on a new perspective of PT. To illustrate the feasibility and effectiveness of the proposed method, this paper also presents the novel TODIM with hesitant fuzzy information and TOPSIS with probabilistic hesitant fuzzy information.

The most important innovation of this paper is that an improved TODIM based on PT with probabilistic hesitant fuzzy information is proposed. This paper realizes the reconstruction of the relative dominance function of the classical TODIM based on PT and integrates probabilistic hesitant fuzzy information into the improved TODIM. Moreover, this paper combines the novel TODIM with the hesitant fuzzy information. Furthermore, a case study, parameter sensitivity analysis, and simulation analysis are all carried out to show the advantages of the proposed methods and the differences between these methods and the existing ones.

The proposed method has some certain advantages in expressing fuzzy information of the DMs. For example, probabilistic hesitant fuzzy information can express the degree of hesitation by using different probabilities for hesitant values. On the contrary, probability can also represent the proportion that the DMs give the same hesitation value in group decision-making. There is no doubt that group decision-making has become an effective way to solve complicated problems and consensus is the precondition to make a reasonable decision. Hence, more concentration should be put into consensus problems based on PT in the future.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Effect of Capital Constraint in a Dual-Channel Supply Chain

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Capital constraint is a significant factor that mainly restricts the development of small- and medium-sized enterprises. This paper explores the channel strategy and pricing decision in a dual-channel supply chain, which consists of one supplier and one retailer. Adequate and inadequate capital constraints for the supplier are distinguished by determining whether open the retail channel to sell. The observations offer managerial insights into supply chain member. First, the results indicate that the capital constraint is a key factor affecting channel strategies and pricing decisions. With the increased value of capital constraint, the wholesale price of offline channel and the selling price of online channel firstly decrease and then remain constant. Second, the results demonstrate that, with capital constraint, the supplier pays more attention to consumers' brand loyalty if it chooses to open the online channel only. Additionally, the price-sensitivity parameter has no effect on the strategy of opening only the offline channel. Moreover, when the channel competition is too intense, the supplier will choose to only open the online channel strategy and increase the online selling price if the capital is insufficient.

1. Introduction

The foundation for daily operation activities for an enterprise is working capital. It can be said that capital is the prerequisite and decisive factor for enterprise to carry out production and operation activities [1, 2]. However, the small- and medium-sized enterprises account for over half of the world's gross domestic product and employment in major economy, yet there is a widespread shortage of capital liquidity. For example, during the 2008 global financial crisis, a large number of companies ran into financial difficulties as production expanded and raw material prices and labor costs rose. In addition, the capital shortage will not only restrict the production and operation of enterprises but also bring the inventory and shortage risks to the upstream and downstream, thus affecting the stable development of the entire supply chain. At the same time, with the development of e-commerce and Internet technology, many manufacturers win customers and increase market share by opening online channels [3, 4]. In addition, opening an online channel increases the operating cost, which causes capital constraint to become a significant factor affecting the opening of online channel. With the rapid development of economic globalization and consumer demand, as a new sales channel, the demand of online channel is rapidly increasing, and opening the online channel needs to burden the certain risks, so the degree of risk aversion of firms has an important impact on channel selection strategy and pricing decisions [5].

Under the background, we investigate the following questions: Compared to the case without capital constraint, how does the supplier adjust the operational strategies and pricing decisions and maximize the profit? How does capital constraint affect the members' decision-making in a dual-channel supply chain? Is there a threshold of capital constraint that can achieve a supply chain, the condition on which sale channel to be opened?

To address these questions, we analyze the channel choice in a one-supplier-one-retailer supply chain, where the supplier is capital-constrained. The optimal pricing strategies are discussed under different scenarios and the profits of supplier and retailer are compared. Further, we investigate the condition for opening dual-channel supply chain and explore the effects of capital constraint. The main contributions of our research are summarized in the following respects. First, it describes how capital constraint affects channel strategies and pricing decisions in a multi-dual supply chain. Second, it identifies the relationships among the pricing decisions, consumer behavior, and price-sensitivity parameter. Third, it compares the optimal decisions and profits of members under the different scenarios of capital constraint.

The remainder of the paper is organized as follows. We review the related literature in Section 2. The problem description and model assumption are introduced in Section 3. Section 4 investigates and compares the optimal decision under different capital constraints. We conduct the numerical analysis in Section 5. Finally, the conclusion is given in Section 6.

2. Literature Review

In this section, we give an overview of closely relevant literature on channel selection strategy, consumer behavior across channel, and capital constraints in operational management.

2.1. Channel Selection Strategy in Supply Chain. Channel selection strategy is a hot issue in marketing research and operational research. This work in this stream is mainly on sale channel selection [6–8], recycling channel selection [9–12], distribution channel selection [12–14], and return channel selection [15–17]. Furthermore, several scholars investigated the conditions for the case where opening an additional online channel is optimal [18–22] and found that the channel selection was dependent on the substitutable coefficient between online and offline channels. In addition, some interesting researches explore the multidecision optimization problem under dual-channel structure, such as low-carbon supply chain [23–26] and remanufacturing supply chain [26–28]. Moreover, Zhou et al. [29] analyzed the impact of asymmetric information in the presence of channel choice and pricing strategy and found that the downstream weakens the service provider's advantage via channel selection. Under the multichannel competition, Wang et al. [30] proposed the model of channel choice and pricing decisions and found that the difference among multiple channels' operational costs was a critical factor in the downstream's selection. Considering the demand uncertainties in online channel and offline channel, Modak and Kelle [31] demonstrated the pricing decision and ordering decision in a delivery-time supply chain to examine the impact of consumer channel loyalty on members' profits. Most of above literature considered a supply chain in which the manufacturer opened an online channel and found primarily the effect of channel difference on channel selection strategy. However, none of these scholars involved the situation of retailer's encroachment in online channel. This paper combines the ignored issue to investigate the conditions and boundaries on three scenarios of channels, i.e., online channel, offline channel, and dual channel.

2.2. Consumer Behavior across Purchasing Selection. Obviously, the consumers are influenced by different types of preferences including price and quality. For monitoring the environmental performance of green product in consumers' awareness, some scholars found more environmental factors in choosing the product, such as low-carbon product [32, 33] and remanufactured product [34–37]. Furthermore, some scholars have made an analysis from the empirical perspective; these include Aguilar and Vlosky [38] and Ma et al. [39]. In particular, some scholars have also studied the influence of consumer preference on the performances of dual channel and multichannel. Liu et al. [40] discussed the different dynamic network structure of supply chain members via a two-stage game model to analyze the effect of consumer environmental awareness on the equilibriums. The above studies showed that the increase of consumer environmental awareness is beneficial to environment-friendly manufacturer and retailer. Ji et al. [41] considered cap-and-trade regulation to study the condition whether opening a direct channel is affected by low-carbon preference and found that when the degree of consumer's preference is in a certain interval, dual channel is advantageous to the manufacturer. Additionally, some researches focus on the effects of low-carbon preference on channel selection. Khouja et al. [42] introduced consumer behavior into the channel strategies of different structures and observed that the combination of channel option and consumer behavior is the important factor to affect channel selection.

Accordingly, consumers' selection of purchase channel is mainly depending on their preference. In the existing research, most scholars focused on only one preference. Although many studied the multifactor analysis in consumer behavior, they subdivided the market based on consumers' preference and concentrated on a special market to discuss their strategies. Actually, we attempt to subdivide the different brand loyalty between online channel and offline channel. Hence, in such situation, considering consumer behavior in channel selection is necessary for operational management.

2.3. Capital Constraint in Operational Management. There has been limited research on the influences of capital constraint in operational management [43] (https://www.sciencedirect.com/science/article/pii/S0925527319300994) [44–46]. Ding et al. [43] considered the interaction and influence of capital constraint on decision from the perspective of risk management. Xu and Birge [46] analyzed the single cycle newsboy problem and explained how capital constraints and capital structure affect the inventory decisions of enterprises. On this basis, Xu and Birge [47] established a model to study the optimal operation decision under the conditions of capital constraint and management incentive. Ma et al. [45] analyzed the optimal inventory strategy when retailers face the risk attitude of capital shortage and loss aversion. Dada and Hu [44] studied the impact of the constraint of the enterprise's own capital on its procurement decision under the condition of uncertain demand. In terms of supply chain coordination, Jin et al. [48] established a supply chain model consisting of a supplier, a capital-constrained retailer, and consumers and analyzed contract type under sales promotion in supply chain coordination. Feng et al. [49] assumed that the members are constrained by budgets and proposed a gain-sharing contract to coordinate supply chains. Wang and Zhang [50] studied a remanufacturer's production strategy with capital constraints and differentiated demand in a closed-loop supply chain.

The literature mainly analyzes channel selection strategy in supply chain, consumer behavior across purchasing selection, and capital constraint in operational management, which can be summarized in Table 1. However, most of the above studies consider the decision-making behavior of retailers under capital constraint and do not consider the decision-making of suppliers under capital constraint. The transformation to "specialized and innovative" is the direction of the development of small- and medium-sized suppliers, which means that solving financial constraints is crucial to the development of small- and medium-sized suppliers. On this basis, this paper proposes the impact of capital constraint on pricing strategy of suppliers' online and offline channels under different scenarios and compares the equilibrium under different scenarios.

3. Problem Description and Assumption

In this paper, we explore the channel selection and pricing decision in a dual-channel supply chain, where the supplier determines the wholesale price to retailer in the offline channel and selling price in the online channel under the capital constraint K. Further, the retailer investigates the retail price. Owing to the price difference between online and offline channels, we consider that the consumers are of two types: physical loyalty and brand loyalty. The consumers with physical loyalty buy products via retailer, whereas those with brand loyalty buy products through supplier and retailer. In other words, the former will use offline channels to buy products, while the latter will use online channels. Moreover, similar to Cai et al. [54] and Xu et al. [55], we assume that the proportions of brand loyalty and physical loyalty are θ and $1-\theta$. Further, the potential market demands and selling prices of online channel and offline channel are, respectively, d_i and p_i, where $i = s$ or r. In addition, we assume that c_s and c_r are the operational costs of the two channels. To model the profit and obtain the equilibrium, we consider the linear demand function [1]. Therefore, before the supplier or the retailer enters the direct channel, we find the online demand $D_s^0 = 0$ and the offline demand $D_r^0 = d_r(1-p_r)$. After the retailer enters the direct channel but the supplier does not, the online demand is $D_s^0 = 0$ and the offline demand is $D_r^0 = (d_r + d_s)(1-p_r)$. However, if both the supplier and retailer enter, the selling prices of the two channels are inconsistent, and consumers may switch the original channel to the other channels as the channel substitution η of price gap affects the consumer's choice. Therefore, the demand functions for online channel and offline channel can be depicted as follows:

$$D_s = d_s[\theta(1-p_s) - \eta(p_s - p_r)], \quad (1)$$

$$D_r = d_r(1-p_r) + d_s[(1-\theta)(1-p_r) + \eta(p_s - p_r)]. \quad (2)$$

4. Model Equilibriums

In this section, we investigate the channel strategies and pricing decisions for supply chain, in which the supplier's capital is restricted. In order to have more concise results, we denote $\psi = (Ac_r - \eta c_s d_s)^2 + 2Bc_s^2 d_s > 0$, where $A = d_r + (1 + \eta - \theta)d_s > 0$ and $B = (n+\theta)d_r + (\eta + \theta - \theta^2)d_s > 0$.

4.1. Pricing Decision for Retailer

4.1. Pricing Decision for Retailer. According to the Stackelberg game, we consider that the supplier is the leader and the retailer is the follower. Based on the selling price of online channel and wholesale price of offline channel made by the supplier, the retailer decides the selling price of offline channel to maximize its own profit, so the expression is as follows:

$$\max \pi_r = (p_r - w)D_r. \quad (3)$$

Based on the backward induction, given p_s and w, the retailer determines the selling price of offline channel to maximize profit. The second derivate with respect to the selling price of offline channel is $\partial^2\pi_r/\partial p_r^2 = -2A < 0$, which means that the retailer's profit is a jointly concave function in the selling price. Hence, we have the optimal selling price $p_r^* = [d_r + d_s(1-\theta+\eta p_s) + Aw]/2A$. Therefore, the above means that retailer's response of selling price needs to consider the impact of demand market and pricing strategies, so next we discuss the supplier's equilibrium.

4.2. Pricing Decisions for Supplier

4.2.1. Supplier's Capital Is Adequate. Under this case, the supplier's capital being adequate indicates that costs of the supplier operating online channel and offline channel do not exceed the constraint K. Considering the demands between the two channels are nonnegative, the optimization problem for supplier if the capital is adequate is the solution to

$$\max \pi_s = (p_s - c_s)D_s + (w - c_r)D_r$$
$$\text{s.t.} \begin{cases} D_s \geq 0, \\ D_r \geq 0, \\ c_s D_s + c_r D_r < K. \end{cases} \quad (4)$$

Proposition 1. *The optimal channel strategy and pricing decisions for supplier with adequate capital constraint are shown in Table 2.*

Here, we use A to indicate that the supplier's capital is adequate and O/C to indicate the opening/closing of online and offline channels.

Table 1: The gap between existing literature and our research.

	Channel selection	Consumer behavior	Capital constraint
[15, 18, 20, 23, 28, 50, 51]	√		
[2, 20, 24, 34, 47, 48, 52]	√	√	
[4, 14, 15, 28, 49, 53]	√		√
[1, 10, 22, 30, 33, 40, 41]			√
Our research	√	√	√

Table 2: The optimal strategy and pricing decisions with adequate capital constraint.

The channel strategy	The pricing decisions
A-C-C	$p_s = 1$, $w = 1$
A-O-C	$p_s = (1 + c_s)/2$, $w = 2A - (1 - c_s)\eta d_s/2A$
A-C-O	$p_s = ([2\theta + (1 + c_r)\eta]A + 2B)/(2[(\eta + \theta)A + B])$, $w = (1 + c_r)/2$
A-O-O	$p_s = (1 + c_s)/2$, $w = (1 + c_r)/2$

Proof. Substituting the response of p_r^* into Formula (3), we obtain the Hessian matrix with respect to the selling price of online channel and wholesale price of offline channel is

$$H^s = \begin{bmatrix} \dfrac{\partial^2 \pi_s}{\partial p_s^2} & \dfrac{\partial^2 \pi_s}{\partial p_s \partial w} \\ \dfrac{\partial^2 \pi_s}{\partial w \partial p_s} & \dfrac{\partial^2 \pi_s}{\partial w^2} \end{bmatrix} = \begin{bmatrix} -\dfrac{d_s\left(2B + \eta^2 d_s\right)}{A} & \eta d_s \\ \eta d_s & -A \end{bmatrix}. \quad (5)$$

Obviously, it is easy to have $|H_1^s| = -d_s(2B + \eta^2 d_s)/A < 0$ and $|H_2^s| = 2Bd_s > 0$. Therefore, the Hessian matrix of supplier's profit function is negatively defined. In addition, we introduce Karush-Kuhn-Tucker conditions to characterize the optimality condition and model a Lagrangian function of optimization problem expressed as $L_s = \pi_s + \lambda_1[K - (c_s D_s + c_r D_r)] + \lambda_2 D_s + \lambda_3 D_r$, where λ_1, λ_2, and λ_3 are the multipliers corresponding to the slack variables [56]. For ensuring that the supplier's capital is adequate, we have $\lambda_1 = 0$. Hence, the channel choice and pricing strategies are discussed as follows:

(i) Case 1: $\lambda_1 = 0$, $\lambda_2 > 0$, and $\lambda_3 > 0$ mean that the supplier will not open both online channel and offline channel if the capital is adequate (A-C-C Strategy). Equating the first-order conditions to zero and solving the KKT conditions, we have the optimal decisions $p_s = 1$ and $w = 1$. Meanwhile, the solutions satisfy the conditions $c_s > 1$ and $c_r > 1$, so $c_s > p_s$ and $c_s > w$, which show that the margin profits of the supplier's online channel and offline channel are negative. Therefore, the supplier will not choose to open dual channels, which will not be discussed too much later because the situation is not common in practice.

(ii) Case 2: $\lambda_1 = 0$, $\lambda_2 = 0$, and $\lambda_3 > 0$ mean that the supplier will open online channel but not offline channel if the capital is adequate (A-O-C Strategy). Equating the first-order conditions to zero and solving the KKT conditions, we have $p_s = (1 + c_s)/2$ and $w = [2A - (1 - c_s)\eta d_s]/2A$.

(iii) Case 3: $\lambda_1 = 0$, $\lambda_2 = 0$, and $\lambda_3 = 0$ mean that the supplier will open offline channel but not online channel if the capital is adequate (A-C-O Strategy). Equating the first-order conditions to zero and solving the KKT conditions, we have $p_s = (\{[2\theta + (1 + c_r)\eta]A + 2B\})/(2[(\eta + \theta)A + B])$ and $w = (1 + c_r)/2$.

(iv) Case 4: $\lambda_1 = 0$, $\lambda_2 > 0$, and $\lambda_3 > 0$ mean that the supplier will open dual channels if the capital is adequate (A-O-O Strategy). Equating the first-order conditions to zero and solving the KKT conditions, we have $p_s = (1 + c_s)/2$ and $w = (1 + c_r)/2$.

From Proposition 1, we find that there are four optimal channel strategies when the supplier's capital is adequate. Moreover, although optimal wholesale and selling price are not affected by the capital constraint in Table 1, the supplier's channel strategies also need to consider capital in order to maintain the capital adequate. Specifically, when $K > B(1 - c_s)c_s d_s/2A$, the supplier will choose to open online channel but not offline channel owing to high cost of retailing. When the threshold $K > ABc_r(1 - c_r)/2[(\eta + \theta)A + B]$, the supplier will choose to open the offline channel but not online channel because of high investment of offline channel. Further, when the threshold $K > [c_s d_s(A\theta + Bc_s) + Ac_r(A - \eta d_s) - \psi]/4A$, the supplier will choose to open dual channels. □

4.2.2. Supplier's Capital Is Fully Used. When the supplier's capital is fully used, it means that the channel selection is influnced by the constraint K. Similarly, the demands of online channel and offline channel are nonnegative. Therefore, the optimization problem of supplier's profit can be expressed as follows:

$$\max \pi_s = (p_s - c_s)D_s + (w - c_r)D_r$$
$$\text{s.t.} \begin{cases} D_s \geq 0, \\ D_r \geq 0, \\ c_s D_s + c_r D_r < K. \end{cases} \quad (6)$$

Proposition 2. *The optimal channel strategy and pricing decisions when supplier's capital is fully used are shown in Table 3.*

Here, we use F to indicate that the supplier's capital is fully used and O/C to indicate the opening/closing of online and offline channels.

Proof. From the above, we get the Lagrangian function $L_s = \pi_s + \lambda_1 [K - (c_s D_s + c_r D_r)] + \lambda_2 D_s + \lambda_3 D_r$, where $\lambda_1 > 0$ to ensure that the supplier's capital is fully used. We can calculate the optimal decisions as follows:

(i) Case 1: $\lambda_1 > 0$, $\lambda_2 = 0$, and $\lambda_3 > 0$ mean that the supplier will open online channel but not offline channel if the capital is fully used (F-O-C Strategy). Equating the first-order conditions to zero and solving the KKT conditions, we have $p_s = 1 - AK/Bc_s d_s$ and $w = 1 - (\eta K)/(Bc_s)$.

(ii) Case 2: $\lambda_1 > 0$, $\lambda_2 > 0$, and $\lambda_3 = 0$ mean that the supplier will open offline channel but not online channel if the capital is fully used (F-C-O Strategy). Equating the first-order conditions to zero and solving the KKT conditions, we have $p_s = 1 - (\eta K)/(c_r B)$ and $w = 1 - (K[(\eta + \theta)A + B])/(AB)c_r$.

(iii) Case 3: $\lambda_1 > 0$, $\lambda_2 > 0$, and $\lambda_3 = 0$ mean that the supplier will produce both the online channel and offline channel if the capital is fully used (F-O-O Strategy). Equating the first-order conditions to zero and solving the KKT conditions, we have $p_s = \{\psi + c_s^2 d_s(\theta A + B) + c_s A[c_r(A - \eta d_s) - 4K]\}/2\psi$ and $w = \{\psi + c_s c_r d_s(\theta A + B) + c_r A[c_r(A - \eta d_s) - 4K]\}/2\Psi$.

Proposition 2 illustrates that three optimal channel strategies exist when the supplier's capital is fully used, and the optimal wholesale of offline channel and selling price of online channel are correlated with the capital constraint at this time. Further, if $K < (1 - c_s)c_s d_s B/2A$ or $K < (c_r - c_s)c_s d_s B/2(c_r A - \eta c_s d_s)$, the supplier will use all capitals to open online channel but not offline channel. Similarly, if the threshold $K < (1 - c_r)c_r AB/2[(\eta + \theta)A + B]$, the supplier will use all of the capitals to open offline channel but not online channel. Meanwhile, if the threshold satisfies $(1 - c_r)c_r AB/2[(\eta + \theta)A + B] < K < [c_s d_s \quad (\theta A + c_s B) + c_r A (A - \eta d_s) - \psi]/4A$, the supplier will use all of the capitals in opening both online channel and offline channel. □

4.3. Comparison of Different Strategies under Capital Constraints. This subsection first analyzes the impact of parameters and capital constraint under different channel strategies and then compares the optimal pricing and profits of different channel strategies when the supplier's capital is sufficient and fully utilized.

Proposition 3. *The thresholds of c_s and K defined seven channel selection regions as shown in Table 4.*

Proof

(1) *A-O-C Strategy*. According to $\lambda_1 = 0$, $\lambda_2 = 0$, and $\lambda_3 \geq 0$, we can get $K - (c_s D_s + c_r D_r) \geq 0$, $D_s = ((1 - c_s)d_s B)/2A \geq 0$, and $[c_r A - d_r - (1 - \theta + \eta c_s)d_s]/A \geq 0$. Combining the three inequalities, we know that $K^* \geq ((1- c_s)c_s d_s B)/2A$ and $c_s^* < [\eta d_s - (1 - c_r)A]/\eta d_s$. Similarly, according to the inequality, we can get $\theta^* \geq [1 - c_r + \eta(c_s - c_r)]/((1 - c_r) + d_r/d_s)$ and $\eta^* \geq (1 - c_r)[d_r + (1 - \theta)d_s]/(c_r - c_s)d_s$. For the sake of simplicity, we set $\theta_2 = [1 - c_r + \eta(c_s - c_r)]/(1 - c_r) + d_r/d_s$ and $\eta_2 = ((1- c_r)[d_r + (1 - \theta)d_s])/(c_r - c_s)d_s$.

(2) *A-C-O Strategy*. According to $\lambda_1 = 0$, $\lambda_2 \geq 0$, and $\lambda_3 = 0$, we can get $K - (c_s D_s + c_r D_r) \geq 0$, $D_r = ((1 - c_r)c_r AB)/2[(\eta + \theta)A + B] \geq 0$, and $\lambda_2 \geq 0$. Combining the three inequalities, we know that $K^* \geq ((1 - c_r)c_r AB)/2[(\eta + \theta)A + B]$ and $c_s^* > (\eta c_r + \theta)A + B/[(\eta + \theta)A + B]$. Similarly, for the sake of simplicity, we can also get the range of values for θ and η as follows:

$$\begin{aligned}
\theta^* < \theta_1 &= \frac{1}{4(1 - c_s)d_s}\{2(1 - c_s)d_r + [2(1 - c_s) + \eta(1 - c_r)]d_s \\
&\quad + \sqrt{[2(1 - c_s)d_r - (2 + \eta - \eta c_r - 2c_s)d_s]^2 - 8\eta(1 - c_s)d_s\{(1 + c_r - 2c_s)d_r + [1 + (1 + \eta)c_r - (2 + \eta)c_s]\}}, \\
\eta^* < \eta_1 &= \frac{1}{2(c_r - c_s)d_s} - \{(1 + c_r - 2c_s)d_r - [1 + \theta + (1 - \theta)c_r - 2c_s]d_s \\
&\quad + \sqrt{[(1 + c_r - 2c_s)d_r + (1 + \theta + (1 - \theta)c_r - 2c_s)d_s]^2 - 8\theta(c_r - c_s)(1 - c_s)d_s[d_r + (1 - \theta)d_s]}\Big\}.
\end{aligned} \tag{7}$$

(3) *A-O-O Strategy*. According to $\lambda_1 = 0$, $\lambda_2 = 0$, and $\lambda_3 = 0$, we can get $K - (c_s D_s + c_r D_r) \geq 0$, $D_s = \{(\theta + \eta c_r)A + B - c_s[(\eta + \theta)A + B]\}/4A \geq 0$, and $D_r = [(1 - c_r)A - (1 - c_s)\eta d_s]/4 \geq 0$. Combining the three inequalities, we know that $K^* \geq [c_s d_s(\theta A + c_s B) + c_r A(A - \eta d_s) - \psi]/4A$ and

Table 3: The optimal channel strategy and pricing decisions when supplier's capital is fully used.

The channel strategy	The pricing decisions
F-O-C	$p_s = 1 - (KA)/(c_s d_s B)$, $w = 1 - (K\eta)/(c_s B)$
F-C-O	$p_s = 1 - (K\eta)/(c_r B)$, $w = 1 - (K([\eta+\theta]A + B))/(c_r AB)$
F-O-O	$p_s = (\psi + c_s^2 d_s(\theta A + B) + Ac_s[c_r(A - \eta d_s) - 4K])/(2\psi)$, $w = (\psi + c_s c_r d_s(\theta A + B)) + (Ac_r[c_r(A - \eta d_s) - 4K])/2\psi$

$([\eta d_s - (1 - c_r) \quad A]/ \quad \eta d_s) \le c_s^* < ([(\eta c_r + \theta)A + B]/[(\eta + \theta)A + B])$.

(4) *F-O-C Strategy*. According to $\lambda_1 = 0$, $\lambda_2 = 0$, and $\lambda_3 = 0$, we can get $[(1 - c_s)c_s d_s B - 2AK]/(c_s^2 d_s B) \ge 0$, $D_s = (K/c_s) \ge 0$ and $[(c_r - c_s)c_s d_s B - 2K \quad (c_r A - \eta c_s d_s)]/(c_s^2 d_s B) \ge 0$. Combining the three inequalities, we know that $K_1 < ((1 - c_s)c_s d_s B)/2A$ and $K_2 < (c_r - c_s)c_s d_s B/2(c_r A - \eta c_s d_s)$. By subtracting these two thresholds, we can get $K^* < ((1 - c_s)c_s d_s B)/2A$ when $c_s^* < [\eta d_s - (1 - c_r)A]/\eta d_s$ and $K^* < ((c_r - c_s)c_s d_s B)/2(c_r A - \eta c_s d_s)$ when $[\eta d_s - (1 - c_r)A]/\eta d_s \le c_s^* < ([(\eta c_r + \theta)A + B]/[(\eta + \theta)A + B])$.

(5) *F-C-O Strategy*. According to $\lambda_1 = 0$, $\lambda_2 = 0$, and $\lambda_3 = 0$, we can get the following three expressions about supplier's capital constraint $\{(1 - c_r)c_r AB - 2K[(\eta + \theta)A + B]\}/(c_r^2 AB) \ge 0$, $\{2K[(c_r - c_s)\eta A - c_s (\theta A + B)] - c_r \quad (c_r - c_s)AB\}/ \quad (c_r^2 AB) \ge 0$, and $D_r = (K/c_r) \ge 0$. Combining the above inequalities, we obtain $(c_r(c_r - c_s)AB)/2[(c_r - c_s)\eta A - c_s \quad (\theta A + B)] < K < ((1 - c_r)c_r AB)/ \quad 2[(\eta + \theta)A + B]$. Meanwhile, the conditions $(1 - c_r)c_r AB/(2[(\eta + \theta)A + B]) > c_r(c_r - c_s)AB/2 \quad [(c_r - c_s)\eta A - c_s(\theta A + B)]$ if $c_s > [(\eta c_r + \theta)A + B]/[(\eta + \theta)A + B]$ and $(c_r(c_r - c_s)AB)/2[(c_r - c_s)\eta A - c_s(\theta A + B)] > 0$ if $c_s < A^{\eta c_r}/[(\eta + \theta)A + B]$ must be satisfied; therefore, $K^* < ((1 - c_r)c_r AB)/2[(\eta + \theta)A + B]$ and $c_s^* > [(\eta c_r + \theta)A + B]/[(\eta + \theta)A + B]$.

(6) *F-O-O Strategy*. According to $\lambda_1 = 0$, $\lambda_2 = 0$, and $\lambda_3 = 0$, we can obtain the following three inequalities: $\{[c_s d_s(\theta A + c_s B) + c_r A(A - \eta d_s) - \psi] - 4AK\}/\Psi \ge 0$, the demand of online channel $D_s = \{c_r(c_r - c_s) AB - 2K\eta c_r A + 2c_s K \quad [(\eta + \theta)A + B]\}/2\Psi \ge 0$, and the demand of offline channel $D_r = \{2K(c_r A - \eta c_s d_s) - (c_r - c_s)c_s d_s B\}/2\Psi \ge 0$. Combining the three inequalities, we can calculate the results that $K_1 < [c_s d_s(\theta A + c_s B) + c_r A(A - \eta d_s) - \psi]/4A$ and $K_2 < (c_r(c_r - c_s)AB)/2\{\eta c_r A - c_s[(\eta + \theta)A + B]\}$ if $c_s > ([\eta d_s - (1 - c_r)A]/\eta d_s)$ and $K_3 \ge ((c_r - c_s) c_s d_s B)/2(c_r A - \eta c_s d_s)$. By subtracting the two thresholds of K_1 and K_2, we can get $K_1 - K_2 < 0$; thus $K_1 < K_2$ and $K^* < [c_s d_s(\theta A + c_s B) + c_r A(A - \eta d_s) - \psi]/4A$. In addition, in order to ensure the thresholds $([c_s d_s(\theta A + c_s B) + c_r A(A - \eta d_s) - \psi]/4A) \ge ((c_r - c_s)c_s d_s B)/2(c_r A - \eta c_s d_s)$, the following condition must be satisfied: $\{[(\eta c_r + \theta)A + B] - [(\eta + \theta)A + B]c_s\}/4A(c_r A - \eta c_s d_s) \ge 0$. Therefore, we can obtain $((c_r - c_s)c_s d_s B)/2(c_r A - \eta c_s d_s) \le K^* < [c_s d_s (\theta A + c_s B) + c_r A(A - \eta d_s) - \psi]/4A$ and $([\eta d_s - (1 - c_r)A]/\eta d_s) \le c_s^* < ([(\eta c_r + \theta)A + B]/[(\eta + \theta) A + B])$.

Based on the results in Table 3, we derive the following corollaries for management reference. □

Corollary 1. *The channel decisions are significantly affected by the cost of online channel c_s and the capital constraint K and the thresholds of them define seven channel decision regions.*

Proof. The corollary shows that the supplier has seven channel strategies to choose from, as well as which ones need to consider capital constraint, consumers' brand loyalty, price-sensitivity coefficient, and production costs. In addition, the above parameters can also have an influence on supplier's judgment as to whether its capital is sufficient. □

Corollary 2. *For any given c_s, the supplier will be more inclined to use all capitals as K decreases.*

Proof. It is easy to see from Table 3 that, regardless of the value range of c_s, the K result is sufficient for the supplier when it is greater than the threshold, and the supplier will use the capital completely if the capital constraint K is less than the threshold. As K decreases, capital will be more likely to be fully utilized, and Corollary 2 is proven. Therefore, the supplier needs to pay special attention to the threshold of capital in the actual operations. Once they are lower than this threshold, the supplier needs to make full use of capitals to maximize their effectiveness. □

Corollary 3. *The maximum value of K when the supplier chooses to use all capitals decreases as c_s increases.*

Proof. For conveniences, we first define the equations $K_1 = ((1 - c_s)c_s d_s B)/2A$, $K_2 = [c_s d_s(\theta A + c_s B) + c_r A(A - \eta d_s) - \psi]/4A$, and $K_3 = (1 - c_r)c_r AB/2[(\eta + \theta)A + B]$. Comparing the threshold of K, we find $K_1 - K_2 = (A - \eta d_s + Ac_r + \eta c_s d_s)(Ac_r + \eta c_s d_s)/4A > 0$ and $K_2 - K_3 = [(B + \theta Ac_s) + A\eta(c_r - c_s)] \quad [(B + \theta A)(1 - c_s) + A\eta(c_r - c_s)]d_s/4A \quad [(\eta + \theta)A + B] > 0$; thus, it is easily derived that $K_1 > K_2 > K_3$. From Table 3, we can see that when K result is less than the threshold, the supplier will choose to use all capitals. Moreover, since the threshold of K takes K_1, K_2, and K_3 in turn as c_s increases, Corollary 3 is proven. This shows that as cost of online channel increases, the threshold of capital that supplier needs to open channels is lower. Therefore, the supplier should carefully investigate changes in market demands to minimize the cost of investment when selecting a channel strategy.

Furthermore, based on the equilibrium results in Table 1 and Table 2, we can obtain additional propositions as follows. □

Proposition 4. *Whether the supplier's capital is adequate or fully used, (i) the selling price of offline channel is always higher than that of online channel under the dual channel*

Table 4: The impact of c_s and K on channel strategies under capital constraint.

Threshold of c_s	Threshold of K	Optimal strategy
$[0, (\eta d_s - (1-c_r)A)/\eta d_s)$	$[((1-c_s)c_s d_s B)/2A, t+n\infty)$	A-O-C
	$[0, ((1-c_s)c_s d_s B)/2A)$	F-O-C
$[(\eta d_s - (1-c_r)A/\eta d_s), ((\theta+\eta c_r)A+B)/((\eta+\theta)A+B))$	$[(c_s d_s(\theta A + c_s B) + c_r A(A-\eta d_s) - \psi)/4A, t+n\infty)$	A-O-O
	$[(((c_r - c_s)c_s d_s B)/(2c_r A - 2\eta c_s d_s)), (c_s d_s(\theta A + c_s B) + c_r A(A-\eta d_s) - \psi)/4A)$	F-O-O
	$K < ((c_r - c_s)c_s d_s B)/(2c_r A - 2\eta c_s d_s)$	F-O-C
$[((\theta+\eta c_r)A+B)/((\eta+\theta)A+B), 1)$	$[((1-c_r)c_r AB)/2[(\eta+\theta)A+B], t+n\infty)$	A-C-O
	$[0, (1-c_r)c_r AB/2[(\eta+\theta)A+B])$	F-C-C

strategy; (ii) if other conditions remain the same, the selling price of opening an online channel is always lower than that of closing online channel, and the opposite is true for an offline channel.

Proof. The above results can be easily obtained by making a difference. Conclusion (i) can be explained by the fact that the offline channel requires other extended services such as physical stores and manual services, which makes the channel costs more expensive, so the corresponding selling price is higher to maintain the profit of the supplier. Conclusion (ii) indicates that suppliers should reduce selling price to attract consumers when they choose to open online channel, but the retail price of retailer in the physical store is higher, which is also due to the large initial costs of opening the store. □

Proposition 5. *For any c_s and K values, the profit of supplier with adequate capitals is always higher than that when capital is fully used under the same channel strategy, namely, O-O strategy, O-C strategy, and C-O strategy.*

Proof. When the supplier chooses to open online channel but not offline channel, the total profits of the supplier are reduced when the capital is sufficient and the capital is fully utilized; then, we easily have $\pi_m^A - \pi_m^F = [2AK + (1-c_s)c_s d_s B]^2/(4c_s^2 d_s AB) \geq 0$; thus, $\pi_m^A - \pi_m^F$ is obtained. Similarly, when the supplier chooses to open offline channel but not online channel, the difference of supplier's profits under different capital constraint can be calculated as $\pi_m^A - \pi_m^F = \{2K[(\eta+\theta)A + B] + (1-c_r)c_r AB\}^2/4c_r^2 AB[(\eta+\theta)A + B] \geq 0$, and if the supplier chooses to open dual channels, the difference of profits is $\pi_m^A - \pi_m^F \geq 0$, seen in the numerical analysis because the formula is too complicated; thus, the profit of supplier with adequate capitals is always higher than that when capital is fully used under the same choice. This indicates that no matter which channel strategy the supplier chooses, the greater the capital investment, the greater the profit, so it is advisable for the supplier to keep its available capital sufficient during the course of its operations. □

5. Numerical Analysis

In this section, we use a numerical example to analyze the threshold of capital constraint on the supplier's channel strategy first and then discuss the impacts of capital constraint, consumers' brand loyalty, and price-sensitivity parameter on optimal prices and profits in detail. Considering the coefficient values used in the existing literature [4, 20, 57], the parameters of this paper are set as follows: $d_r = 10$, $d_s = 50$, $c_r = 0.55$, $c_s = 0.15$, $\theta = 0.8$, $\eta = 0.5$, and $K = 5$.

5.1. Impact of Parameters on Channel Strategies. The impact of consumers' brand loyalty and price-sensitivity parameter on the threshold of capital constraint is described in Table 5. From the previous theoretical analysis, the price-sensitivity parameter and consumers' brand loyalty correspond to three strategies in the different intervals. Therefore, in order to analyze the impact more specifically, we consider that the price-sensitivity coefficient is in three different intervals.

Based on the above, we observe that, with the increasing consumers' brand loyalty, the threshold of capital constraint for the supplier to only open offline channel decreases, while it increases if only opening online channel. This shows that, regardless of the adequacy of capital, as consumers' brand loyalty increases, the capital expenditure should be reduced in the offline channel strategy, while the large-scale investment in online channel strategy should be implemented to obtain higher profit. Moreover, the threshold of capital to open dual channels keeps decreasing as consumers' brand loyalty increases when the capital is adequate, and the opposite is if the capital is fully used. This highlights the importance of adequate capitals for supplier, since, with the increase in consumers' brand loyalty, the decline in the threshold of capital constraint for opening dual channels when the capital is sufficient means less difficulty.

Moreover, with increasing the price sensitivity, the threshold of capital constraint to open only online channel or offline channel will increase. Therefore, the supplier needs to pay more attention to consumers' price sensitivity and replenish capitals in a timely manner when considering opening the corresponding channel. Similar to consumers' brand loyalty, under the dual-channel strategy, as consumer price sensitivity increases, the supplier will invest less and less if it keeps sufficient capital, while if capital is used fully, the investment will increase. Further, the threshold of capital constraint required to open dual channels if capital is adequate is always higher than that when capital is fully utilized. This means that the strategy of full using capitals by the supplier will make it easier to open dual channels.

5.2. Impact of Supplier's Capital on Decisions and Profits. Figure 1 describes the impact of supplier's capital on optimal decisions and profits under different channel strategies.

From these four figures, we observe that the optimal decisions and profits change first and then remain constant as capital increases. This means that the supplier's capital will affect its decisions and profits if it is fully used, while it will not affect these results when the capital is adequate. Regardless of the value of θ, the supplier tends to use full capital as the constraint decreases. Hence, the supplier should adjust the decision according to the market in real time when the capital is unstable initially and keep the price constant after the capitals are adequate in the later stage. Specifically, when the supplier moves from offline channel to dual-channel strategy, all participants will attract consumers through reducing prices, and the supplier's effort is significantly greater from Figure 1(b). If the supplier's channel strategy is changed from dual channels to single channel, the price of the corresponding channel should be increased, which is caused by shortening the channel source. Moreover, we can realize that the retail price is higher than the online price when the dual channels are opened, owing to the fact that the physical store will generate costs such as rental and service, which confirms Proposition 4. In addition, regardless of whether the capitals are sufficient, only opening

Table 5: The impact of θ and η on K under different channel strategies.

θ	$\eta \in [0, \eta_1]$	Threshold of K		$\eta \in [\eta_1, \eta_2]$	Threshold of K		$\eta \in [\eta_{2,1}]$	Threshold of K	
		A	F		A	F		A	F
	0.00	3.40	3.40	0.20	3.80	3.80	0.50	4.21	4.21
0.1	0.05	3.53	3.53	0.30	3.95	3.95	0.60	4.32	4.32
	0.10	3.63	3.63	0.40	4.09	4.09	0.70	4.43	4.43
	0.00	2.78	2.78	0.20	3.27	3.27	0.50	3.79	3.79
0.3	0.05	2.93	2.93	0.30	3.47	3.47	0.60	3.93	3.93
	0.10	3.05	3.05	0.40	3.63	3.63	0.70	4.05	4.05
	0.00	3.76	1.36	0.20	3.61	1.90	0.50	3.22	2.44
0.5	0.05	3.73	1.52	0.30	3.49	2.11	0.60	3.07	2.57
	0.10	3.70	1.66	0.40	3.37	2.28	0.70	2.92	2.68
	0.00	3.78	1.91	0.20	3.60	2.49	0.50	3.18	3.00
0.7	0.05	3.75	2.08	0.30	3.48	2.70	0.60	3.10	3.10
	0.10	3.71	2.24	0.40	3.33	2.86	0.70	3.16	3.16
	0.00	3.80	2.45	0.20	3.59	3.12	0.50	3.47	3.47
0.9	0.05	3.77	2.68	0.30	3.44	3.32	0.60	3.51	3.51
	0.10	3.72	2.85	0.40	3.42	3.42	0.70	3.54	3.54

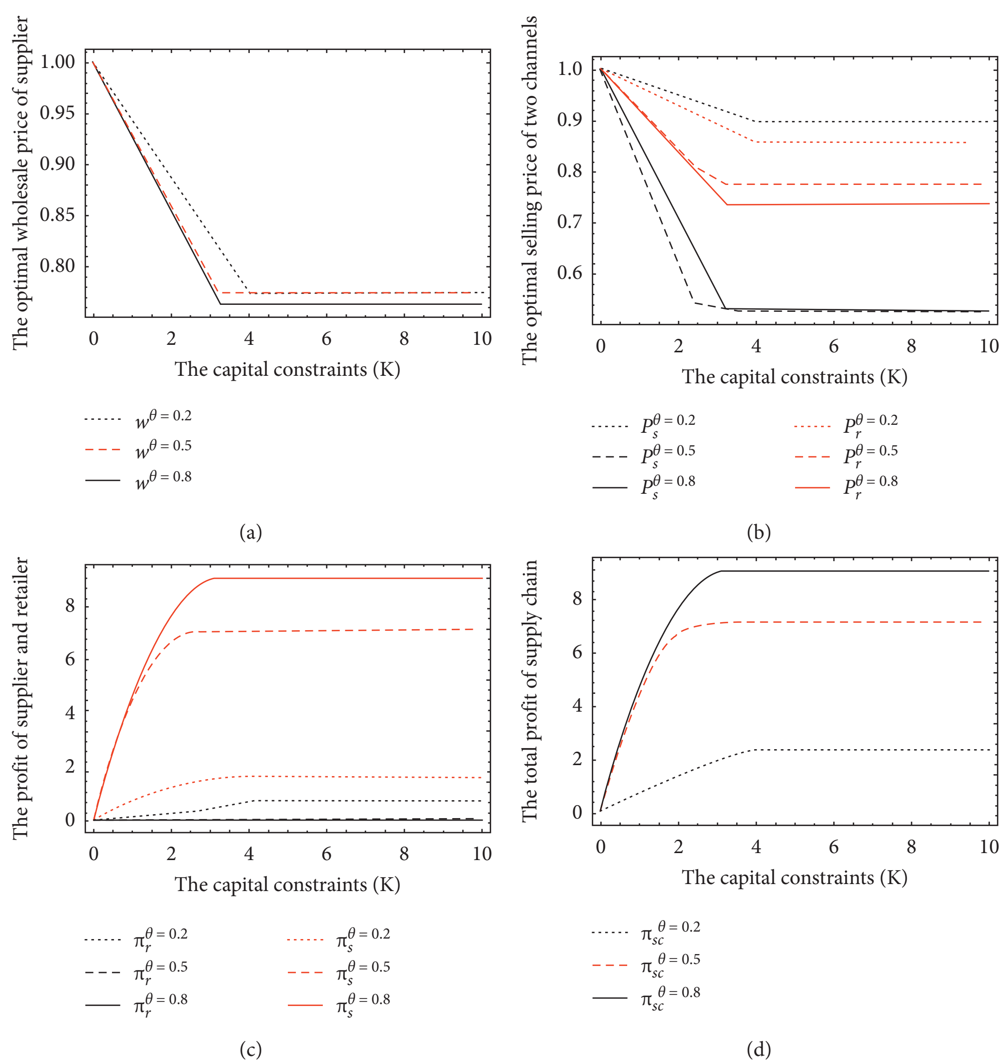

Figure 1: The impact of supplier's capital on decisions and profits. (a) The impact of K on channel prices. (b) The impact of K on channel quantities. (c) The impact of K on channel profits. (d) The impact of K on supplier's profit.

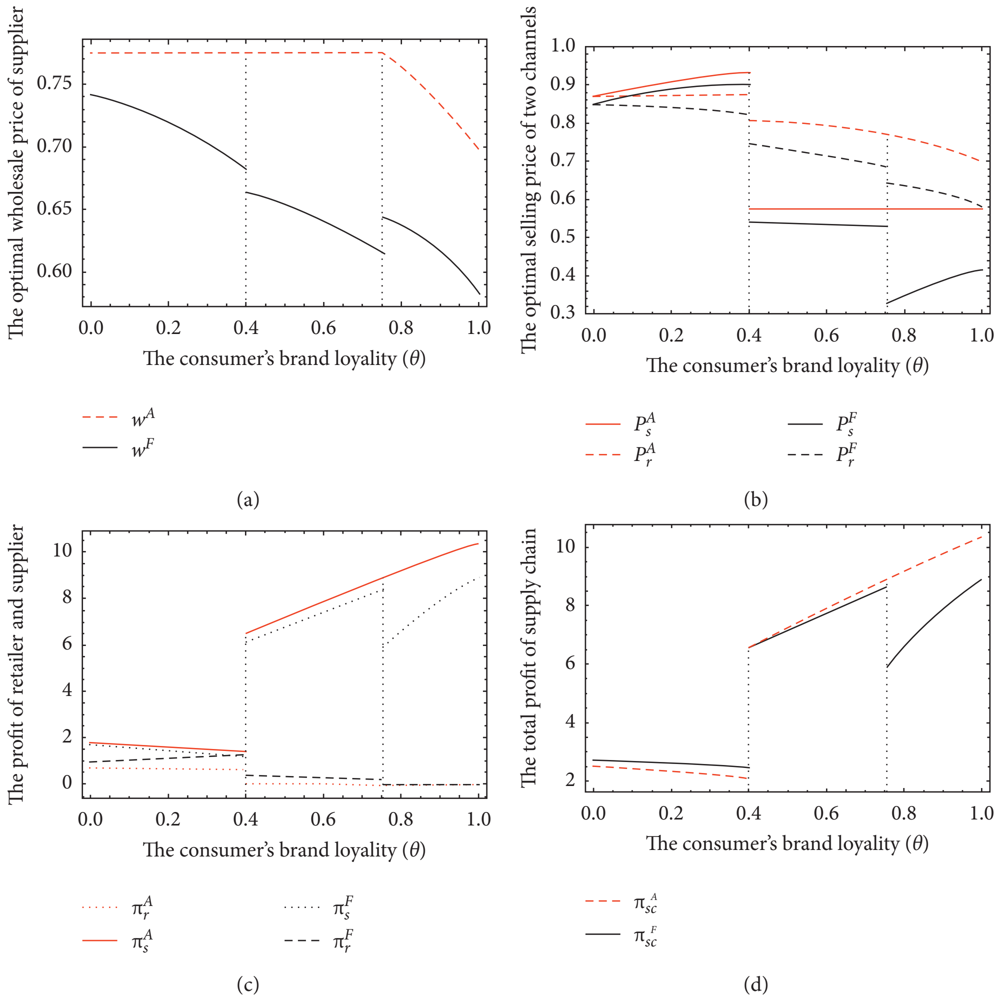

Figure 2: The impact of consumers' brand loyalty on decisions and profits. (a) The impact of θ on wholesale price. (b) The impact of θ on online price. (c) The impact of θ on participants' profits. (d) The impact of θ on total profit of supply chain.

online channel is most beneficial to the supplier, while only opening offline channel is more beneficial to the retailer. From here, we can see the important value of brand loyalty to the enterprises.

5.3. Impact of Consumers' Brand Loyalty on Decisions and Profits. Figure 2 demonstrates the impacts of consumers' brand loyalty on the optimal price decisions and profits of supply chain.

Obviously, when the other parameters remain the same, the supplier and the retailer will face three different situations as θ changes from Figure 2. (i) When consumers' brand loyalty is low, the supplier will choose only offline channel strategy. Meanwhile, the profits of all participants will decrease as θ increases if the supplier's capitals are adequate, implying that increasing retail price when consumers' brand loyalty is weak will reduce consumer purchases. However, if the supplier's capital is fully used, the supplier will lower the wholesale price, which will lead to an increase in the retailer's profit. This means that inadequate capitals from the supplier have given the retailer more power. (ii) With the increase of consumers' brand loyalty, the supplier will choose to open dual channels. We can see from Figure 2(b) that both the supplier and the retailer will cut selling prices when entering dual channels, but the benefits from supplier are enough to offset the cost of opening online channel. Therefore, it is profitable for the supplier to strive to increase consumers' brand loyalty and wait for opportunities to enter dual channels. However, the retailer's profit is much smaller than that when only offline channel is opened, especially when the supplier has adequate capitals, owing to the fact that it will not easily adjust the wholesale price. (iii) When consumers' brand loyalty is high enough, the supplier will choose only online channel strategy. It is clear that the supplier's profit will continue to increase at this time because it has an absolute brand advantage. In particular, the supplier who wants to open only online channel also needs to make certain price cuts to attract customers if its capitals are inadequate, while it can use other means such as advertising if capitals are adequate. In addition, the total profit of supply chain is higher with inadequate capitals when the offline channel is opened only, and in other cases the results are exactly the opposite as in Figure 2(d). It also reflects that

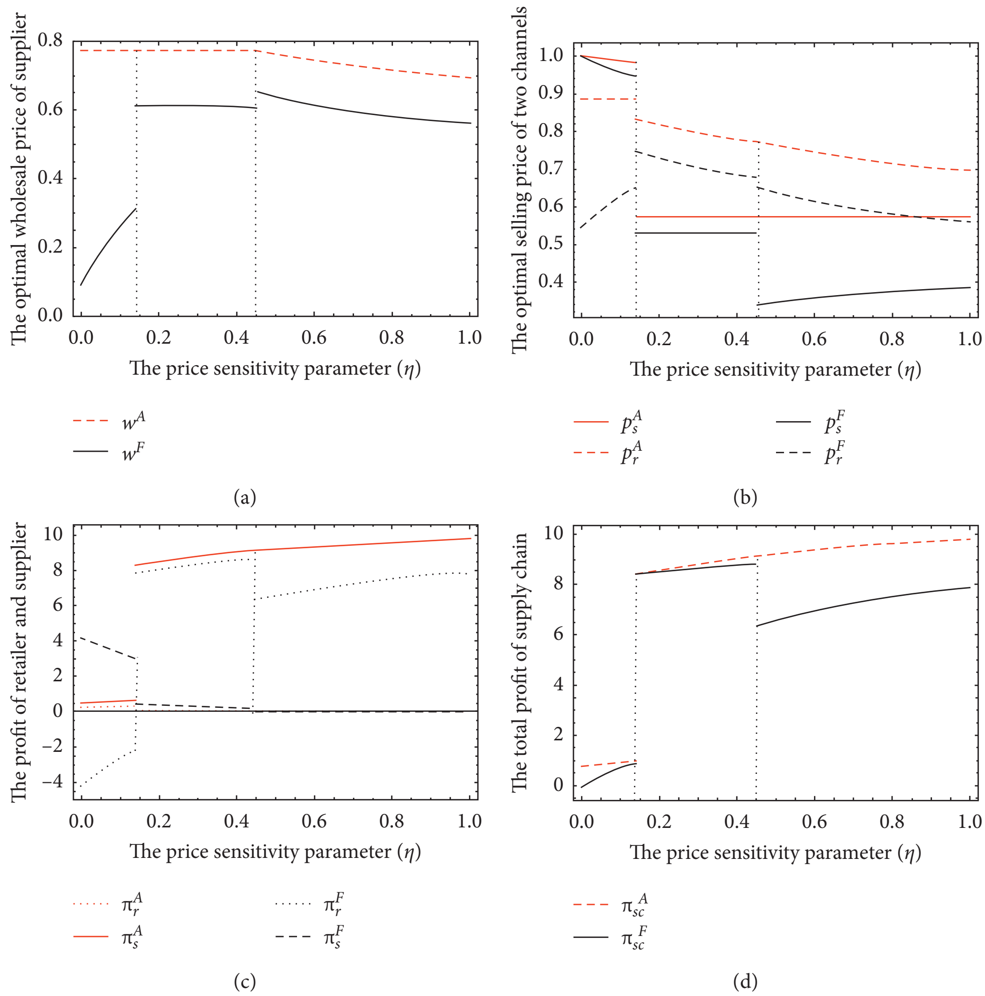

FIGURE 3: The impact of price-sensitivity parameter on decisions and profits. (a) The impact of η on wholesale price. (b) The impact of η on online price. (c) The impact of η on participants' profits. (d) The impact of η on total profit of supply chain.

inadequate capitals of the supplier are more beneficial to the retailer, while sufficient capitals can promote the supplier to change channel strategies to obtain greater profit.

5.4. Impact of Price-Sensitivity Parameter on Decisions and Profits. This subsection analyzes the influences of price-sensitivity parameter on the optimal channel strategies and profits.

It is not difficult to find from Figure 3 that, with the change of η, the supplier also faces three different channel strategies. (i) When the price sensitivity of the market is not obvious, the supplier will only open the offline channel. Moreover, neither the supplier nor the retailer will adjust the price, which will result in no significant change in their profits if the supplier's capitals are adequate. However, if the supplier's capital is inadequate, the profit of the supplier is negative, implying that the benefits from the increase in the wholesale price are not sufficient to support the capital flow, and the retailer can obtain higher profit by appropriately raising the retail price due to the price insensitivity of consumers. (ii) As the price sensitivity of the market increases, the supplier should open dual channels to implement price competition. We can find that appropriately reducing the selling price to attract customers to the online channel will bring considerable benefits to the supplier when entering the dual channels. Similarly, owing to no adjustment of wholesale price if the supplier has adequate capitals, the retailer can also achieve considerable profit by appropriately adjusting the retail price and its own loyal customers, which is a win-win situation. However, the huge increase of wholesale price will seriously damage the retailer's income if the supplier's capitals are insufficient. (iii) If the price sensitivity is too high, the supplier should only open online channel in order to avoid price wars with the retailer and maintain customers through consistently lower selling price. In addition, when the capitals are insufficient, it should try to reduce price to attract customers to online channel. Therefore, the supplier can promote price competition when consumers are sensitive to prices and maintain sufficient capital to maximize its profit, but increased price competition is not good for the retailer.

6. Conclusions

With the rapid development of e-commerce, the online transactions are simple, efficient, and costly, attracting more and more suppliers to open online channel. Additionally, capital constraint is an important factor that the suppliers cannot ignore when formulating channel strategies. Therefore, if the capital constraint of the supplier is considered, this paper explores how the factors will affect the supplier's channel selection and the impacts of different strategies on the profits of the supplier and the retailer. Meanwhile, we obtain some managerial insights as follows. First, the impact of capital constraints on the supplier's channel selection and price decisions is significant. The supplier should adjust prices in a timely manner according to channel strategy when capitals are inadequate and only open online channel to obtain the highest return when capitals are adequate. Second, when the consumer's brand loyalty or market price sensitivity is low, the supplier should only open offline channel and keep the wholesale price unchanged if the capitals are adequate. Meanwhile, if capitals are inadequate, the price needs to be adjusted, implying that the retailer gains more benefits by mastering more channel resources. Finally, when a supplier first enters an online channel (whether in dual channels or an online channel only), it needs to cut prices significantly to attract customers. However, with the increase of brand loyalty or price sensitivity, the supplier can obtain rich profit without adjusting the price if capitals are adequate, but the inadequate capitals of the supplier are more favourable to retailer.

There are also some issues for future research. For example, this paper only analyzes the effect of financial constraints on decisions from the perspective of the supplier, while the situation considering both the supplier and the retailer facing financial constraints remains to be explored. Furthermore, the extension with the uncertain demand is also an interesting topic.

Data Availability

All data are included within the paper.

Conflicts of Interest

The authors declare no conflicts of interest.

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Research Article

A Bayesian Best-Worst Method-Based Multicriteria Competence Analysis of Crowdsourcing Delivery Personnel

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Crowdsourcing delivery is becoming a prevalent tool for tackling delivery problems by building a large labor-intensive service network. In this network, the delivery personnel consist of a large number of people with a complex composition and high level of mobility, creating enormous challenges for the quality of service and the management of a crowdsourcing platform. Hence, we attempt to conduct a competence analysis to determine whether they can provide promised services with high quality, i.e., they are competent for their job. To this end, the competence theory is introduced, and a multicriteria competence analysis (MCCA) approach is developed. To illustrate the MCCA approach, a real-world case study is conducted involving a Chinese takeaway delivery platform, where the Bayesian best-worst method is used to determine the weights of the criteria based on the data collected from managers of the platform company. Also, the competence scores of the personnel involved are collected through surveys and data sources of the company. Given the weights and the competence scores, we use additive value function to identify the overall competence scores of them, which reflects the level of competence for their job. The results show that Skills is the most important competence, while Knowledge is the least important of the four competence dimensions. In subcriteria, four core elements are identified such as punctuality, customer service awareness, responsible, and goods intact. In addition to the importance of criteria, a ranking of a sample of personnel is provided, and almost half of the crowdsourcing delivery personnel's competence is below the average and vary significantly, while the relationship between the competence level and some other variables is also discussed. Moreover, the developed MCCA approach in this paper can be applied to analyze the competence of personnel in many other industries as well.

1. Introduction

The prosperity of E-commerce and omnichannel retail stimulates the surge of individual packages and delivery vehicles [1] and brings great challenges to logistics operation. With the rise of the sharing economy and crowdsourcing, it is possible to reconstruct logistics operation scenarios [2]. Crowdsourcing delivery, as a successful combination of traditional logistics activities and innovative crowd resources sharing, is becoming a prevalent tool in practice. More possibilities for solving delivery problems have been provided by using the resources of the crowds [3] including maximizing crowds' utility [4], reducing infrastructure expenses, enhancing efficiency in parcel turnaround time and failure rate [5], and optimizing loading capacity [6], as well as reducing traffic congestions and pollution using spare capacity [7, 8].

Crowdsourcing delivery plays an increasingly important role in the logistics sector, and the crowdsourcing delivery personnel are an important link between the crowdsourcing platform and the end customers. Crowdsourcing delivery platforms embrace a large number of public and distributed delivery resources and build a complex labor-intensive service network to meet customer requests [9]. In this case, the resources involved are utilized optimally by the crowdsourcing platform. Despite the certain benefits it brings to the platform and customer, this kind of delivery also may prove precarious, since the people making up the crowds are with a complex composition and previously unknown [10]. Even so, the crowdsourcing platform has lowered the entry barrier and simplified registration procedures to encourage users to register [11]. Also, there are potential risks, such as package damage, loss, and privacy violations, which may affect the level of service quality and subsequently customer satisfaction and end up jeopardizing the reputation of the platform [9, 12]. Moreover, most of the crowdsourcing delivery personnel only work part-time and usually flexibly manage their schedules [11]. Accordingly, their availability, service awareness, and service level for upcoming orders are less clear, creating the uncertainty concerning the operation process [13], which may, in turn, affect the platform's steady operation.

For the crowdsourcing delivery personnel, providing services with promised quality is a concrete manifestation of competence. The importance of them being competent and then achieving predetermined outcomes in their professionals is beyond doubt [14] that they are competent for the crowdsourcing delivery job is a critical factor when it comes to sustaining the platform's health [11]. As such, we attempt to connect the competence analysis to the new environment of crowdsourcing delivery since it provides a way to determine whether individuals meet the specified performance criteria, that is, whether they demonstrate the professional competence required [15].

Looking at the practical operations, we find that some crowdsourcing delivery platforms have made endeavors to boost the performance of the crowdsourcing delivery personnel. According to our survey, some crowdsourcing delivery platforms in China release the rider ranking and offer monetary (cash) or nonmonetary (level up) incentives based on the ranking. However, this ranking is not set for each individual, and people below a certain level are excluded. Besides, it is also simplistic to considering only the number of orders being delivered, punctuality, and platform score, as well as a certain period. Some other factors that may affect personnel's competence are not taken into account, such as the necessary skills and knowledge [16], certain work experience [17], strong customer service awareness [9], average delivery time [18], guaranteed goods condition [12], effective customer feedback [19], and innate individual traits [20]. It shows that not enough attention has been paid by practitioners to those aspects, and, as yet, a comprehensive competence analysis of crowdsourcing delivery personnel is still lacking.

Consequently, both the theoretical backgrounds and practical operations motivate us to conduct a comprehensive competence analysis of crowdsourcing delivery personnel, which is the main contribution of this study. To this end, the competence theory is introduced, and on this basis, we develop a multicriteria competence analysis (MCCA) approach, which is the generic framework and also another contribution of this study. To further illustrate the proposed MCCA approach, a real-world case study is conducted involving a Chinese takeaway delivery platform, where we use the Bayesian best-worst method to identify the weights of criteria, and the key elements contributing to crowdsourcing delivery personnel's competence are identified as well. Combining the acquired weights and collected data, we use the additive value function to calculate the overall competence scores of the crowdsourcing delivery personnel.

The remainder of the paper is organized as follows. Section 2 provides an overview of the literature on crowdsourcing delivery and competence analysis. The developed MCCA methodology and the Bayesian BWM is presented in Section 3. Section 4 contains a real-world case study where a Chinese takeaway delivery platform is involved. In Section 5, we analyze the weights of criteria and the ranking of a sample of personnel and discuss the results of the MCCA involving crowdsourcing delivery personnel. Finally, the conclusions and suggestions for future research are provided in Section 6.

2. Related Works

2.1. Crowdsourcing Delivery. Crowdsourcing is a shift of work patterns that the work normally performed by designated agents is outsourced to an undefined and large pool of people with an open structure [10]. Currently, it is gaining increasing popularity, and different types of online crowdsourcing platforms have emerged such as Didi Chuxing and Uber (transport), iStockPhoto (picture), Amazon Mechanical Turk (online staffing), Threadless (apparel design), and UberEATS, Meituan takeaway, and Ele.me (online food delivery). In the crowdsourcing environment, their functions are fully tapped for consumer engagement, value acquisition, and information gathering, as well as idea generation [12].

The integration of traditional logistical activities with the concept of crowdsourcing has given rise to the concept of "crowdsourcing logistics." In addition to the term "crowd logistics," other terms, like "crowdsourcing delivery," "crowd shipping," "cargo hitching," and "collaborative logistics" are also used. In this paper, we use the term "crowdsourcing delivery." It is defined as an information network-empowered center that coordinates logistics service demand with the supply of crowd resources with free time or space and a willingness to provide the necessary services and be compensated accordingly [21]. To illustrate the concept, we use the Meituan takeaway delivery as an example and divide the entire process into seven phases: (i) a customer initiates an order request to the platform and pays; (ii) the platform releases the order online; (iii) the registered crowdsourcing delivery person receives the order; (iv) the crowdsourcing delivery person goes to the merchant to wait for the order to be prepared and then picks the order up; (v) the crowdsourcing delivery person delivers the order to the customer and clicks "Takeaway delivered" on the mobile app; (vi) the customer receives the goods and evaluates the crowdsourcing delivery person; (vii) the crowdsourcing delivery person is paid by the platform. In this case, it is possible to reconstruct logistical operation scenarios by matching growth in consumer demand with underused individual supplies via mobile applications and online platforms [22].

Since the emergence of crowdsourcing delivery, it has been the subject of various studies. At an individual level, Chandra et al. [3] pointed out that the resources of the crowd, including people, objects, and entities, provided more possibilities to solve delivery problems arising from the surge of individual packages and delivery vehicles. In this context, cyclists and pedestrians become temporary deliverers due to their own delivery needs [6], and most of them can switch between the roles of the deliverer and recipient. By transporting parcels on the final leg of the delivery process, their utility is maximized [4]. However, the most direct factor that motivates people to register on a crowdsourcing platform is the potential economic advantage [23]. They are paid per order, and as such are rewarded for each order they have completed.

As an intermediary, the crowdsourcing delivery platform uses technological capabilities and information sharing to enable crowds and customers to interact with each other [12]. Bauer et al. [23] described information and communications technology (ICT) as an enabler and connector in the entire value chain, including initiating crowdsourcing requests, communicating, processing tasks, reporting solutions and problems, and paying people. With the enormous growth of ICT, paying people working in a crowdsourcing environment has become more convenient than ever [24], which has attracted many people to join the crowdsourcing delivery sector. According to the report released by the Meituan Research Institute, more than 2.7 million people registered on the Meituan Crowdsourcing Delivery Platform in 2018 [25]. Mladenow et al. [12] pointed out that crowdsourcing delivery was essentially location-based crowdsourcing (LBCS), and people could receive a wide range of information and services for a better crowdsourcing experience with GPS or WLAN positioning techniques. Consequently, people who have registered on crowdsourcing platforms in China such as Meituan Crowdsourcing Delivery, Dada Express, and JD Crowdsourcing Delivery have free access to smartphones and location-based services to receive (delivery) orders.

Crowdsourcing delivery plays an increasingly important part in the last mile delivery. More specifically on the performance of crowdsourcing delivery, Castillo et al. [13] have examined the impact of uncertainty related to crowdsourcing delivery on the effectiveness of the logistical process and suggested that the variables of time windows and daily demand variability would be detrimental to the logistical effectiveness of a crowdsourcing fleet compared to that of a dedicated one. In contrast to Castillo et al. [13], Devari et al. [26] demonstrated the broad application prospects of the social network in the last mile delivery in terms of reducing costs and emissions, while maintaining delivery reliability. Also, Behrend and Meisel [27] integrated item-sharing with crowd shipping on the same platform and included three transfer modes, and the optimization solution showed that a platform's profits could increase dramatically through crowd shipping in all three modes.

Concerning the exploration of an intelligent approach in crowdsourcing delivery, Wang et al. [5] proposed an optimization model that utilized a pool of urban crowds to complete the delivery tasks, and the corresponding solution could well optimize real-time delivery in the context of large-scale mobile crowdsourcing. Kafle et al. [4] designed a cyclist- and pedestrian-based system to relay parcels from a truck carrier using a tabu search-based algorithm, and the final result showed a reduction in both delivery miles and involved costs. Giret et al. [6] used multiagent system techniques and complex network-based algorithms to design an intelligent crowd-based approach to sustainable last mile delivery, and the test showed that the approach significantly reduced CO_2 emissions and the use of trucks. Similarly, Chandra et al. [3] developed a simulation framework by leveraging crowdsourced big data to improve truck mobility and realize a "smart freight" solution by avoiding downstream congestion in the delivery route.

Existing studies indicate the broad application prospects of crowdsourcing delivery. Much attention has been paid to the topics of individual utility, ICT, application effectiveness, and intelligent approach. In most cases, the management of the crowds or individuals, in particular about competence analysis, is not included, even though it is vital for crowdsourcing delivery personnel to be competent in their jobs, simply because the quality of crowdsourcing delivery service depends on it [5]. As a result, we attempt to connect the individual competence with the crowdsourcing delivery environment. To this end, the competence theory is introduced.

2.2. Competence Analysis. The concept of the competence analysis was developed by McClelland [28], who argued that traditional academic aptitude and knowledge tests did not fully evaluate job performance or real-life outcomes and were often biased against minorities, suggesting using research methods that could identify unbiased "competency" variables and elicit job performance instead. The concept of competence is a topic of ongoing discussion. Messick [29] defined competence as what a person knew and could do while embracing the structure of knowledge and abilities under ideal circumstances, while Gonczi et al. [30] viewed competence as a set of attributes related to professional knowledge, skills, and attitudes, and Beaumont [31] stated that competence was the ability to apply knowledge, understanding, and skills in performing the tasks and roles required by a set of performance standards. Similarly, Kurz and Bartram [32] argued that competence referred to an individual's specific attainment under the constraint of multiple performance criteria, while also pointing out that although the two words "competence" and "competency" may be very similar, they conveyed different meanings: the former was much related to the performance and attainments, while the latter exhibited the antecedents underpinning outstanding performance. In the context of O2O, Cheng et al. [11] defined competence as an offline entity's ability to provide services and complete the desired task at the quality required. Based on these various definitions, it may be clear that the concept of competence is multidimensional and work environment-related [14].

As with the various attempts to define the concept of competence, its connotation and extension are constantly expanding and evolving. During this course, we have searched for articles in the databases of Web of Science, Elsevier, Springer, and Wiley with the keywords "competence," "individual competence," and "competence framework" and made a summary of the existing competence frameworks (see Table 1).

Although the first three dimensions in Table 1 (cognitive competence, functional/behavioral competence, and social/ethical competence) are defined as different terms, they have the same meaning as Knowledge, Skills, and Abilities (KSA) [36]. As such, KSA provides the basic elements of competence. Other dimensions of competence, such as metacompetence, qualification, motor skills, social skills, and information, can still be attributed to the KSA classification indicated above according to their components, while discretion, attitudes, and standards can be assigned to the dimension of traits.

Based on the frameworks for individual competence, there have been useful studies on competence assessment. Gonczi [40] pointed out that competence cannot be observed directly, but it can only be inferred from people's performance. Kurz and Bartram [32] also believed that measuring competence in the workplace involves assessing people's performance using predefined occupational or work-related standards. Therefore, under the performance-based evaluation, the evaluator will assess whether an individual meets the criteria specified in the competence standard based on that individual's performance [14]. Wass et al. [41] pointed out that multiple-choice questions, short essays, and oral examinations can be applied to assess clinical competence, which was following the pyramid framework for clinical competence proposed by Miller [42]. McRobbi et al. [43] designed a competence grid for junior pharmacists by inviting a steering group of clinical pharmacists, academics, and clinical pharmacy managers to develop three competency clusters, using a four-point scale to assess the performance of junior pharmacists. They also pointed out that this grid could be integrated into competence measures in other areas of practice and disciplines. Concerning educational competence, Hartig et al. [44] developed a new service structure for technology-based assessment, which as such provided strong support for research projects by using IT tools to test and assess learning competence and educational quality, while Shavelson [38] proposed an assessment triangle (construct, observation, and inference), in which the generalizability theory and statistical theory were adopted for modeling, and applications were applied in education, business, and military to assess people's competence, and finally the dependability of competence scores was verified. Safadi et al. [45] conducted a cross-sectional survey to assess the level of competence of nursing graduates in five competence dimensions (management, professionalism, problem-solving, nursing process, and the knowledge of basic skills) and concluded that nurse recruitment policies should consider individual competence rather than innate characteristics. As a set of valuable assessment instruments, some well-known competence assessment frameworks, such as European Qualifications Framework, European e-Competence Framework, Competence Assessment Information System MyCompetence, Occupational Information Network (O ∗ NET), and European Skills/Competences, Qualifications, and Occupations (ESCO), were developed and applied to a broad range of users to provide general and comprehensive competence reference and outcome assessment [46].

The abovementioned studies reveal that there has been considerable and varied research, often with good results, especially in terms of establishing some mature competence assessment frameworks. However, the existing theoretical research of individual competence focuses predominantly on clinical, medical, psychological, educational, and other areas. We also find that research in the area of logistics is relatively scarce, which is why we apply competence frameworks to that domain and conduct competence analysis of crowdsourcing delivery personnel. Moreover, there is no multicriteria approach provided for using these frameworks in real-world situations, which is why, in the next section, we present an MCCA methodology that helps both researchers and managers to use these frameworks in a practical setting.

3. Methodology

3.1. MCCA Methodology. The previous section shows that the existing frameworks consist of several main dimensions and subdimensions, while each dimension describes the specific job standards or performance criteria for the personnel involved. This means that the frameworks include several criteria that are used to evaluate a certain number of personnel (alternatives), which implies that we could formulate an analysis as a multicriteria decision analysis (MCDA). If we take the dimensions as criteria (with some subcriteria) and the personnel as alternatives, this type of competence analysis can be viewed as a multicriteria competence analysis (MCCA) and therefore provides a new approach to evaluating the competence of personnel. MCDA methods can be employed to implement the MCCA approach. In this case, in the MCCA approach, the main components are the criteria and their weights and the personnel and their competence scores. For MCCA, one could select a framework from the previous section, in which the occupations, the opinion of the managers, and the other factors could play a role.

As a generic framework for evaluating the competence of personnel, the steps of the MCCA approach are described as follows.

3.1.1. Step 1. Determining the Objective of the Competence Analysis and Defining the Scope of the Problem. The MCCA aims to identify the competence level of personnel. As such, the first step is to define the goal of the analysis. Generally, there are four different goals: (i) evaluation, where the aim simply is to identify the level of competence of each individual; (ii) selection, where the goal is to select personnel based on their competence level; (iii) ranking, where the aim is to rank several personnel members in a given work environment; and (iv) classification or sorting, where the aim is to differentiate between different classes of personnel. It is, of

Table 1: Frameworks for individual competence.

Framework	Dimensions and their meanings
KSMTSS [33]	Knowledge: a usable body of facts and concepts, retention of information, whether technical, or a method of communication Skill: the ability to state a goal, list the action sequence, and think logically and systematically; problem-solving ability, accurate self-assessment, interpersonal ability to manage or orchestrate the work of a team Motive: a desire to achieve goals as a reflection of improving one's performance Trait: physical control, a disposition to take an initiative, risk orientation Self-image: a person's self-assessment of the values and personal characteristics Social role: a person's perception of a set of social norms, fit in the expectation of social groups
CFBE [34]	Cognitive competence: formal professional knowledge, tacit-practical knowledge, procedural knowledge, and contextual knowledge as well as knowledge application Functional competence: occupation-specific function, process management, mental and physical skills Behavioral competence: confidence, persistence, independent thinking, emotional and stress control, listening skills, task-centered awareness, interpersonal skills Ethical competence: abide by the laws, the rule of morality, be sensitive to the needs of others and value, adopt appropriate attitudes, abide by the professional code of conduct, self-regulation, environmental sensitivity, customer-centeredness, moral judgment, acknowledge boundaries of own competence, keep up to date
KSEQ [32]	Knowledge: use data, facts, and information about things and processes and understand the rationale and why in professional practice Skills: identify problems, coordinate conflicting information, make a judgment in time and apply techniques and procedures to the job Experience: the history of accumulated job experience Qualifications: requirements for individuals to engage in certain occupations such as professional license and organization-specific training
CFPSM [35, 36]	Cognitive competence: technical/theoretical knowledge, procedural knowledge, informal tacit/practical knowledge, contextual/background knowledge Functional competence: "know how" things that an individual who works in a particular career field should be able to do and demonstrate, such as directing subordinates, goal and action management, human resource management, focus on others Personal competence: Decisive action, ethical behavior, communication, focusing on results, influence others, self-management, information searching Social competence: ability and willingness to cooperate, interact responsibly with others, act in a team and relationship-oriented manner Meta-competence: ability to facilitate the acquisition of the other substantive competences or skills
KSAOs [37]	Knowledge: a body of various professional knowledge such as law, business, manufacturing, communications, arts, health services engineering, and mathematics Skills: content skills, process skills, resource management, social skills, technical skills, systems skills, and complex problem-solving skills Abilities: physical abilities like flexibility, balance, and coordination; cognitive abilities like verbal, memory, and perceptual; psychomotor abilities like control movement, reaction time, and fine manipulative; and sensory abilities like auditory and speech Other characteristics: achievement orientation, interpersonal orientation, conscientiousness, adjustment, social influence, and practical intelligence
APSRSI [38]	Ability: task performance, the potential for performance under certain situational supports and constraints Performance: know-how ability to perform physically or mentally, or both Standardization: required tasks or responses to elicit performance are identical, identical working conditions, same administration for all test participants Real-life: performance has to be observed in real-life situations Standards: some level or standard of performance, such as "adequate," "sufficient," "proper," "suitable," or "qualified" Improvement: competence is malleable, deliberate practice, education or some other environmental intervention can be used as tools for improvement
KSA [14]	Knowledge: disciplinary knowledge, specific professional knowledge Skills: working with artifacts, multitasking, processing information, instant decision-making Attitudes: accuracy, coping with pressure, integrity, stress tolerance, feeling for specific jobs
KSASPDICL [39]	Knowledge: disciplinary knowledge, knowledge base and cognitive competence Skills: working with artifacts, functional competence, and perceptual motor skills Attitudes: affective factors and meta-competence Sociality: social skills, social interaction, and social role Personal traits: individual merit Discretion: mode of behavior, intuition, and revelation Information: information processing and methodology Context: specific situation and task, background, and culture Learning: mode of learning, professional learning

course, necessary to specify the work environment and occupational attributes of the personnel involved before conducting the following analysis because the MCCA approach is closely associated with the work environment. In this step, for instance, the work environment could be a logistics company, and personnel's occupational attributes could be defined by logistics managers. The work environment is a key factor in defining relevant criteria (Step 2).

3.1.2. Step 2. Determining the Evaluation Criteria for Competence Analysis of the Personnel through Competence Analysis Frameworks and Experts' Opinions. In this step, different occupational attributes determine the variation in the criteria for evaluating the competence of personnel. For example, evaluation criterion C for logisticians P could involve several aspects: technology skills, transportation knowledge, customer and personal service, coordination skills, information ordering, deductive reasoning, communicating abilities, professional ethics, and work styles. The criteria present multidimensional attributes, which can increase the difficulty of the determination process. Thus, based on the theoretical competence analysis frameworks, it is also important to include the experts' opinions of the company in question to determine the evaluation criteria [47]. Generally, an MCCA problem can be formulated as a matrix as follows:

$$S = \begin{array}{c} \\ p_1 \\ p_2 \\ \vdots \\ p_m \end{array} \begin{array}{c} \begin{matrix} c_1 & c_2 & \cdots & c_n \end{matrix} \\ \begin{pmatrix} s_{11} & s_{12} & \cdots & s_{1n} \\ s_{21} & s_{22} & \cdots & s_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ s_{m1} & s_{m2} & \cdots & s_{mn} \end{pmatrix} \end{array}, \quad (1)$$

where $C = \{c_1, c_2, \ldots, c_n\}$ denotes a set of evaluation criteria for competence analysis, $P = \{p_1, p_2, \ldots, p_m\}$ indicates a group of personnel, and s_{ij} represents the corresponding competence score of each individual i for criterion j.

3.1.3. Step 3. Collecting Competence Scores of Each Individual for All Criteria from Various Data Sources. Competence scores s_{ij} need to be collected from the department where personnel are employed in various ways, like internal statistics, questionnaires, and interviews. Due to the variety of data sources, for all criteria C, the competence scores s_{ij} may use scales, like minutes, miles, money, and rates. To ensure the criteria can be compared to each other and further perform the MCCA [48], the competence scores need to be normalized, for instance, using the following normalization method:

$$s_{kj}^{\text{norm}} = \begin{cases} \dfrac{s_{kj}}{\max\{s_{ij}\}}, & \text{for a positive criterion,} \\ \\ 1 - \dfrac{s_{kj}}{\max\{s_{ij}\}}, & \text{for a negative criterion.} \end{cases} \quad (2)$$

3.1.4. Step 4. Finding the Optimal Weights of All Criteria That Have Been Identified for the Competence Analysis. Given all the predetermined criteria for competence analysis of personnel, finding the weight $w^* = \{w_1, w_2, \ldots, w_j\}$ of all criteria C is an essential part, for which, in this step, a multicriteria weighting method can be applied, including SMART (simple multiattribute rating technique) [49], AHP (analytic hierarchy process) [50], ANP (analytic network process) [51], and BWM (best-worst method) [52].

This is an important part of MCCA, as the decision makers could differentiate among the evaluation criteria. While in particular cases, Knowledge may be a very important dimension of personnel competence, in other situations, Skills may be a more relevant dimension. This step incorporates the opinions of managers regarding the importance of the criteria into MCCA.

3.1.5. Step 5. Finding an Overall Level of the Personnel Competence with Aggregating the Scores. Determining the overall competence level of the personnel is the final part of MCCA. After determining the weights of the criteria, the aggregated score for each individual i can be calculated. In this step, the aggregation process can also assume different forms, for instance, as an additive value function [53]. As shown in (3), the aggregated score v_i can be based on the weight w_j and s_{ij}^{norm}:

$$v_i = \sum_{j=1}^{n} w_j s_{ij}^{\text{norm}}, \quad \forall i = 1, 2, \ldots, m, \quad (3)$$

where $w_j \geq 0$ and $\sum_{j=1}^{n} w_j = 1$.

Then, for any occupation, the competence level of individual i is better than of i' if and only if v_i is greater than $v_{i'}$ or

$$i \succ i' \Longleftrightarrow v_i > v_{i'}. \quad (4)$$

The MCCA approach developed here indicates a new direction for assessing the competence level of personnel, which integrates the comprehensive impact of multiple criteria with an MCDA method. As such, the resulting competence level is a more comprehensive measure of how competent people are for their particular jobs. In addition to the final scores of the personnel involved, the MCCA approach also shows the path to identify the key elements of the criteria that have been identified on personnel competence level. With the help of the weights that have been assigned to the criteria, the core requirements for the competence of personnel can be determined. As a generic framework, the MCCA approach can be applied to a variety of occupations.

3.2. Bayesian Best-Worst Method. Given the MCCA methodology, we need to select an appropriate method to implement it. For our case study, we use BWM [52, 54] because of its several attractive features: (i) BWM requires the DM identifying the best and worst criteria (or alternatives) at the very first before conducting a pairwise comparison, and it enables the DM to have a more explicit vision of the range of the evaluation. Consequently, this allows for more reliable comparisons, as well as better consistency of the comparisons [52]. (ii) It is possible to mitigate the anchoring bias that arises during the DM's pairwise comparisons in a single optimization model by using two opposing references, the best and the worst [55]. BWM is highly consistent with this procedure, and this kind of consider-the-opposite-strategy have been proven effective [56]. (iii) BWM better balances the data and time efficiency in the structured pairwise comparison-based method [55]. On the one hand, BWM offers the possibility to check the consistency of the pairwise comparisons provided. Compared to methods using a single vector such as the Swing and SMART family, BWM bridges the gap where pairwise comparison consistency check is not available, despite the high data (and time) efficiency of such single vector input-only methods. On the other hand, BWM enhances data efficiency compared to full-matrix methods such as AHP. While pairwise comparisons under the full-matrix method offer the possibility of checking consistency, it poses too many questions to the DM, which may lead to confusion and inconsistency.

The method has been applied to many real-world problems, including logistics [57], IoT [58], water security sustainability evaluation [59], energy technology selection [60], manufacturing [61], supplier selection [62], airport evaluation [63], and many more, see [64].

There are several extended versions of BWM [52, 54, 65, 66], and in this paper, we use the Bayesian BWM. Considering the decision makers (DMs) are a group, it offers an ideal approach from a probabilistic angle to determine the overall weights. The Bayesian BWM is based on the original BWM, so the input, i.e., the pairwise comparisons, is the same. However, as for the output, there is a difference between the two methods. In the original BWM, the final output is a concrete value of the weight, while the Bayesian BWM provides a probability distribution. Specifically, the Bayesian BWM includes the following steps:

Step 1. Determining a set of decision criteria $C = \{c_1, c_2, \ldots, c_n\}$.

Step 2. Determining the best (c_B) and the worst (c_W) criteria from C. In this step, no pairwise comparison of the DMs is required, and they only identify the best or most important criterion and the worst or least important criterion.

Step 3. Conducting the pairwise comparison between the best criterion and the other criteria using a number between 1 and 9. The higher the number, the stronger the relative importance between the criteria. The resulting Best-to-Others vector is $A_B = (a_{B1}, a_{B2}, \ldots, a_{Bn})$, where a_{Bj} denotes the preference of the best criterion c_B over other criteria $c_j \in C$.

Step 4. Conducting the pairwise comparison between the other criteria and the worst criterion using a number between 1 and 9. The resulting Others-to-Worst vector is $A_W = (a_{1W}, a_{2W}, \ldots, a_{nW})^T$, where a_{jW} indicates the preference of the criterion $c_j \in C$ over the worst criterion c_W.

Step 5. Estimating the probability distribution of each individual optimal weight $w^{1:K}$ and the overall optimal weight w^{agg} given $A_B^{1:K}$ and $A_W^{1:K}$, where k represents the DM and $k = 1, \ldots, K$.

To this end, the joint probability distribution is used:

$$P\left(w^{\text{agg}}, w^{1:K} \middle| A_B^{1:K}, A_W^{1:K}\right). \tag{5}$$

Based on (5), the probability of each variable then can be computed with the sum rule:

$$P(x) = \sum_y P(x, y), \tag{6}$$

where x and y denote two arbitrary random variables.

To build a Bayesian model, a probabilistic hierarchical model is plotted, as shown in Figure 1, to clarify the relationship between the different variables.

It is clear that the variable w^k depends on both A_B^k and A_W^k, while w^{agg}, in turn, depends on w^k, while either A_B^k or A_W^k is independent of w^{agg} according to the direction of the arrow. This independence feature can be described as follows:

$$P\left(A_W^K \,\|\, w^{\text{agg}}, w^K\right) = P\left(A_W^K \,\|\, w^K\right). \tag{7}$$

Combining Bayes theorem with (5) provides the following equation:

$$P\left(w^{agg}, w^{1:K} \,\|\, A_B^{1:K}, A_W^{1:K}\right) \propto P\left(A_B^{1:K}, A_W^{1:K} \,\|\, w^{agg}, w^{1:K}\right) P\left(w^{\text{agg}}, w^{1:K}\right) = P\left(w^{\text{agg}}\right) \prod_1^K P\left(A_W^K \,\|\, w^K\right) P\left(A_B^K \,\|\, w^K\right) P\left(w^K \,\|\, w^{\text{agg}}\right). \tag{8}$$

To further compute the posterior distribution, the variables in (8) have to be specified. As the input of BWM, A_B^k and A_W^k can be modeled by multinomial distribution due to the property of the integer, resulting in

$$A_W^k | w^k \sim \text{multinomial}\left(w^k\right), \quad \forall k = 1, \ldots, K. \tag{9}$$

Although it also applies to the vector A_B^k, the difference between A_B^k and A_W^k yields the reverse weight, as follows:

$$A_B^k | w^k \sim \text{multinomial}\left(\frac{1}{w^k}\right), \quad \forall k = 1, \ldots, K. \tag{10}$$

We then need to determine the weight w in the multinomial distribution, and the Dirichlet distribution will act

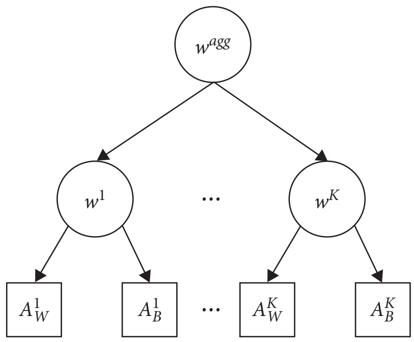

Figure 1: Probabilistic hierarchical model of the Bayesian BWM.

as the prior distribution to model w because of its nonnegativity and sum-to-one properties:

$$\mathrm{Dir}\,(w \parallel \alpha) \sim \frac{1}{B(\alpha)} \prod_{j=1}^{n} w_j^{\alpha_j - 1}, \quad \alpha \in \mathbb{R}^n. \tag{11}$$

Equation (11) depicts the probability density function of the continuous random variable w when it obeys the Dirichlet distribution. Therein, $B(\alpha)$ is a multivariate beta function, and $B(\alpha) = \prod_{j=1}^{n} \Gamma(\alpha_j)/\Gamma(\alpha_0)$. $\Gamma(\alpha)$ is the gamma distribution; α_j is the dimensionless distribution parameter, and $\alpha_j > 0$, $j = 1, 2, \ldots, n$; α_0 is the sum of the distribution parameters, i.e., $\alpha_0 = \sum_{j=1}^{n} \alpha_j$ [67].

Then, for every individual weight w^k in (9) or (10), when w^{agg} is given, it is expected to be in the proximity of w^{agg}. For this purpose, the Dirichlet distribution has to be reparametrized regarding its mean and concentration parameter:

$$w^k \parallel w^{agg} \sim \mathrm{Dir}\,(\gamma \times w^{agg}), \quad \forall k = 1, \ldots, K, \tag{12}$$

where w^{agg} indicates the mean of the distribution and the nonnegative parameter γ denotes the closeness between w^k and w^{agg}, i.e., concentration parameter. Also, γ needs to be modeled and the gamma distribution can be adopted:

$$\gamma \sim \Gamma(a, b), \tag{13}$$

where a and b are the shape parameters of the gamma distribution, and the values are both set to 0.1 [68] because with such settings, the gamma distribution is similar to the uniform distribution, thus it has minimum effect on the posterior distribution [65]. Moreover, Bayesian BWM uses estimation to get the weights of the probability distribution. As such, when we do not know the valid values of certain parameters, we use uniform-like distributions and let the data skew the values. This means that when only partial knowledge about the unknown distribution is available, the probability distribution that conforms to this knowledge but has the maximum entropy value should be selected, which is also the idea underlying the maximum entropy principle [69].

Finally, we employ an uninformative Dirichlet distribution to provide a prior distribution of w^{agg} with the setting of the parameter α to 1 [65]. Then, the aggregated weights w^{agg} can be can be described as

$$w^{agg} \sim \mathrm{Dir}\,(1). \tag{14}$$

The Bayesian model defined by the above equations does not output a closed-form solution. Therefore, the Markov chain Monte Carlo (MCMC) [70] is required to compute the posterior distribution in equation (8) where the "just another Gibbs sampler" (JAGS) [71] is used to generate the random sample.

4. Case Study

To illustrate the MCCA approach, we conducted a real-world case study where the goal is to analyze the competence of the crowdsourcing delivery personnel in Chongqing, China. To this end, a survey and the Bayesian BWM are adopted to assist in the data collection and weight acquisition, respectively. The overall steps of the case study are outlined in Figure 2.

4.1. Criteria Determination. Competence measurement involves the evaluation of workplace performance against a number of predetermined occupational or job-related multiple criteria [32]. Of the multiple criteria that are listed in the competence analysis framework in Section 2, this paper does not include the dimension of Qualification, mainly because certain formal knowledge thresholds may be required, but not all of them require initial qualifications [72]. It is also in accordance with the actual situation where some Chinese crowdsourcing delivery platforms do not set a high entry barrier or require strict qualifications for people who want to register as crowdsourcing delivery personnel, as long as they have a valid ID and health certificate (https://peisong.meituan.com/).

Combined with the competence analysis framework, the main criteria involved are Knowledge, Skills, Abilities, and Traits (KSAT). The subcriteria are based on the interpretation of KSAT's components and the views of different scholars in literature because they are rarely included in any studies into competence in the area of crowdsourcing delivery. In addition, we consult with experts and include their opinions to identify the final subcriteria. The resulting MCCA framework for crowdsourcing delivery personnel is shown in Table 2.

4.2. Data Collection. In line with the MCCA approach, we need to obtain the competence scores. In this instance, we collected data regarding the crowdsourcing delivery personnel from the Meituan takeaway platform in Chongqing, China, combining the platform's statistical data with telephone interviews. First, the basic statistic data, like average delivery time, total delivery mileage, and customer ratings, were collected through the takeaway platform's mobile app from different users. However, some data, like total order quantity, registration time, relevant work experience, etc., were still not directly accessible, which meant that, in the second step, using the work telephone number displayed in the mobile phone app, we conducted a 30-minute telephone interview to collect the data from crowdsourcing delivery personnel of the same platform. Based on the principle of data availability and usefulness, we finally were able to collect the data of 81 different people.

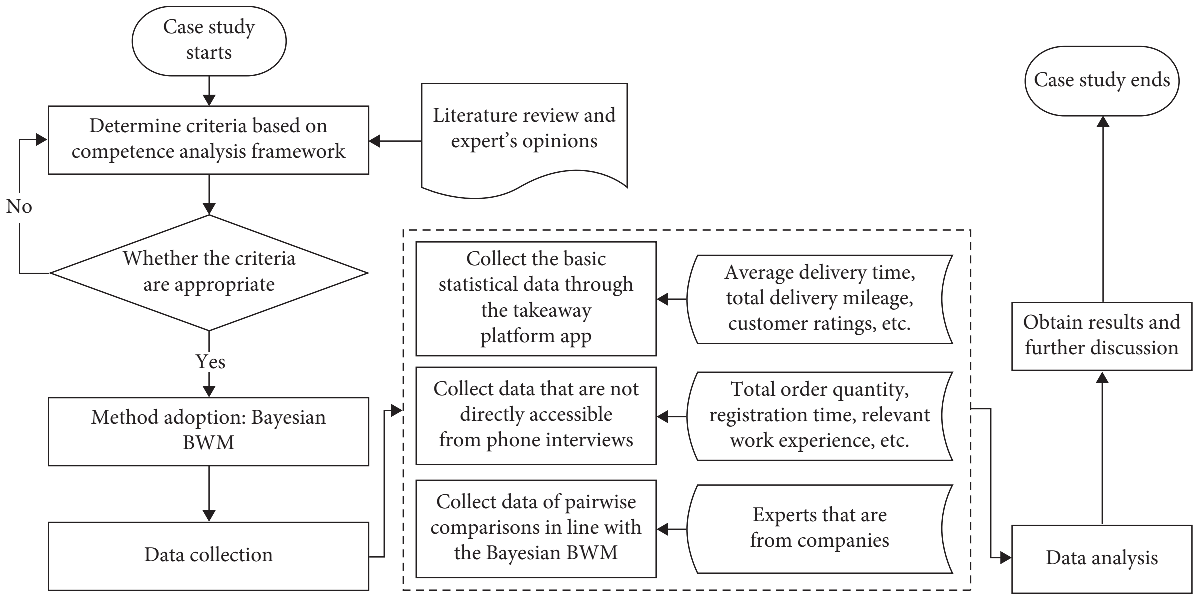

Figure 2: Case study flowchart.

As for the data processing, the data of subcriteria "Knowledge of crowdsourcing delivery," "Previous job experience," and "Customer service awareness" mainly reflect the richness of knowledge and experience, and a 5-point Likert scale (from very low 1 to very high (5)) [75] was used to process the linguistics information acquired from the self-reports by the crowdsourcing delivery personnel, after which the method in (2) is used for data normalization.

Following the steps in the Bayesian BWM, questionnaires were sent to 15 site managers of the Meituan takeaway platform. Based on their input, the daily duties of the site manager can be summarized as follows: recruitment and management of riders; statistics and analysis of site data; promotion of site scale; organization of rider activities; routine training of riders; management training and relationship management of cooperative merchants; supervising service quality; and properly handling customer complaints and various contradictions from delivery service. Of the managers involved, two managers are from Kaizhou District, Chongqing, two managers are from Nan'an District, Chongqing, two managers are from Jiangbei District, Chongqing, two managers are from Wanzhou District, Chongqing, and three managers from Shapingba District, Chongqing. In addition to Chongqing, the rest of the site managers are from Zhengzhou, Henan Province, two are from Zhongyuan District, and the other two managers are from Jinshui District. To ensure that all the site managers have adequate information to conduct the comparisons, some documents describing the Bayesian BWM and the competence criteria of the crowdsourcing delivery personnel are also provided.

5. Results and Discussion

In this section, we first present the weights of the criteria, after which we discuss the credal ranking, which elaborates the confidence of the rankings. Finally, we present a ranking of the personnel based on the weights and competence scores.

5.1. Criteria Weights. The output of the aggregated weights is a Dirichlet distribution in the Bayesian BWM. Prior to obtaining the final weights and calculating the competence scores, the average of the Dirichlet distribution of aggregated weights needs to be computed [65]. The average weights of the main criteria and subcriteria, as well as the overall weights, are listed in Table 3.

Table 3 reveals that "Total mileage" has the lowest priority of all the 14 subcriteria, while "Punctuality" and "Customer service awareness" are the most important. For the crowdsourcing delivery personnel, the delivery radius is about 4 km, while the delivery radius of dedicated delivery personnel is 2.5 to 3 kilometers. The delivery radius directly affects their delivery mileage. Even with the same number of orders per day, there can be a significant difference in delivery miles between the two groups. Therefore, the competence or effective performance for the crowdsourcing delivery personnel does not necessarily depend on the length of the delivery miles, but more on the time within which the order is delivered [7]. Crowdsourcing delivery is real-time delivery, and unlike normal express delivery, goods have to be delivered to customers within a very short period, so timeliness and customer service awareness are particularly important competence criteria. In addition to "Punctuality" and "Customer service awareness," the subcriteria "Responsible" and "Goods intact" rank very high as well. These four subcriteria make up the basic requirements for the competence of the crowdsourcing delivery personnel, which means that they need to have a certain awareness of customer service and deliver the customer's goods intact and on time in a responsible manner.

Table 2: MCCA framework for the crowdsourcing delivery personnel.

Main criteria	Meaning	Subcriteria	Measurement	Source
Knowledge (C_1)	Accumulated relevant delivery knowledge and experience of the crowdsourcing delivery personnel through postentry training and previous experience in the logistics field as well as appropriate self-assessment of their service awareness	Knowledge of crowdsourcing delivery (C_{11})	Level of knowledge of crowdsourcing delivery after training since entering into the crowdsourcing delivery platform	[16]
		Previous job experience (C_{12})	Level of previous related work and accumulated experience in the field of logistics owned by the crowdsourcing delivery personnel	[17, 73]
		Customer service awareness (C_{13})	Degree of customer service awareness self-reported by the crowdsourcing delivery personnel	[9]
Skills (C_2)	In a certain delivery environment, the delivery personnel use certain transport means (motorcycle, electric motorcycle, balance vehicle, and on foot), complete the order received from the takeaway platform with smartphones within a certain period while keeping the customer's goods intact	Total mileage (C_{21})	Crowdsourcing delivery personnel's total delivery mileage as of the date of statistics	[74]
		Delivery order quantity (C_{22})	Crowdsourcing delivery personnel's total delivery order quantity as of the date of statistics	[37]
		Average delivery time (C_{23})	The ratio of total delivery time to the total number of deliveries	[18]
		Goods intact (C_{24})	The ratio of all the customers who rate the goods intact to all the customers who have given their ratings to the crowdsourcing delivery personnel	[12]
Abilities (C_3)	Job performance or the effective outcomes achieved by the order completeness during each delivery of the personnel and is mostly manifested by the various feedbacks from the customers	Negative ratings (C_{31})	The ratio of all the customers who give negative reviews like "slow delivery," "mismatched meals," "overtime delivery," "poor attitude," and "unfamiliar with routes" to all the customers who have given their ratings to the crowdsourcing delivery personnel	[18, 19]
		Punctuality (C_{32})	The ratio of the number of orders delivered on time (the early or late orders are excluded) to the total number of orders delivered	[18]
		Extra reward (C_{33})	Numbers of all the customers who give extra money reward to the delivery personnel	Our team
Traits (C_4)	Internal or external characteristics or qualities displayed by the crowdsourcing delivery personnel via completing each customer's order	Politeness and warmth (C_{41})	The ratio of all the customers who rate the delivery personnel as being polite and warm to all the customers who have given their ratings	[39]
		Instrument neat (C_{42})	The ratio of all the customers who rate the delivery personnel as being clean and tidy to all the customers who have given their ratings	[33, 37]
		Responsible (C_{43})	The ratio of all the customers who appraise delivery personnel delivering the goods even in bad weather to all the customers who have given their ratings	[20]
		Neatly dressed (C_{44})	The ratio of all the customers who indicate the delivery personnel are neatly dressed to all the customers who have given their ratings	[33, 37]

For the measurement of the relationship between a pair of criteria, the Bayesian BWM introduces the concept of credal ranking [65]. Compared to the traditional way, which merely uses two figures to determine the confidence superiority, it devises a Bayesian test to compute the confidence of each credal ranking. By applying this principle to the real-world case, the confidence superiority between different pairs of competence criteria can be computed.

As shown in Figure 3, "Skills" is the most important of all the main criteria. This is mainly because for a specific job or profession, the skill reflects people's ability to perform the tasks and roles according to the expected standards or requirements [12]. They are required to be prequalified to make sure that they have the necessary skills to perform at the required quality [16]. Essentially, crowdsourcing delivery personnel provide a more convenient service to various

Table 3: Weights of main criteria and subcriteria.

Main criteria	Weight	Subcriteria	Local weight	Global weight
Knowledge (C_1)	0.104	Knowledge of crowdsourcing delivery (C_{11})	0.197	0.049
		Previous job experience (C_{12})	0.214	0.053
		Customer service awareness (C_{13})	0.589	0.147
Skills (C_2)	0.396	Total mileage (C_{21})	0.107	0.027
		Delivery order quantity (C_{22})	0.244	0.061
		Average delivery time (C_{23})	0.307	0.077
		Goods intact (C_{24})	0.342	0.086
Abilities (C_3)	0.366	Negative ratings (C_{31})	0.289	0.072
		Punctuality (C_{32})	0.588	0.147
		Extra reward (C_{33})	0.123	0.031
Traits (C_4)	0.133	Politeness and warmth (C_{41})	0.153	0.038
		Instrument neat (C_{42})	0.178	0.044
		Responsible (C_{43})	0.466	0.117
		Neatly dressed (C_{44})	0.204	0.051

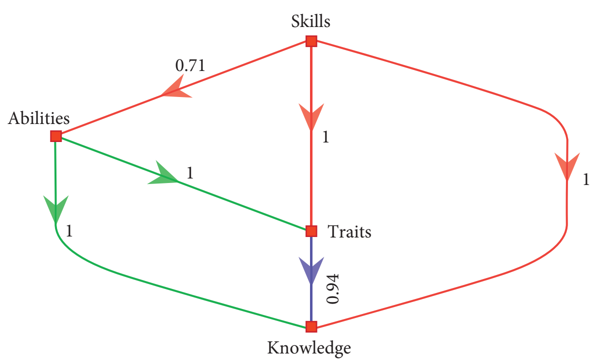

Figure 3: Credal ranking for the main criteria.

customers. Therefore, the first and most important criterion to assess whether they are competent as service providers is for them to deliver goods to the right address at the right time [76]. Although "Skills" is considered more important than the other three criteria, a confidence of 0.71 between it and the dimension of "Abilities" implies that some managers believe abilities play a more important role, since the ability is a powerful manifestation of individual performance [38], with skill being a necessary tool to achieve it. The dimension of "Abilities" ranks in second place, which means that, in absolute terms, it is still more important than "Knowledge" and "Traits," with a confidence of 1. Among the four main criteria, it is not surprising to see that "Knowledge" is considered to be the least important criterion, with even "Traits" ranking higher with a confidence of 0.94. This is in line with the actual situation involving crowdsourcing delivery personnel in China because to attract more people to the crowdsourcing delivery platform the entry barrier is kept relatively low. Besides, the fact that "Traits" is not ranked the lowest implies that personal qualities or characteristics are also considered by experts to be essential elements in ensuring the quality of service demonstrating personnel's competence.

As for the Knowledge dimension, Figure 4 shows that the criterion "Service awareness" is considered the most important one, with a confidence of 1, which once again confirms the importance of customer service awareness for crowdsourcing delivery personnel, since customer demand is met by the delivery service, and their service awareness to a large extent determines the level of quality of the service being provided [12]. Between previous experience and training knowledge, the former is considered to be more important than the latter, with a confidence of 0.67, which indicates that the managers believe that people who have previously worked similar jobs are more likely to perform better in their new environment.

The credal ranking for the "Skills" dimension in Figure 5 shows that the criterion of "Goods intact" is considered the most important, with a confidence of 1 against "Total mileage," with a confidence of 0.99 against "Order quantity," and with a confidence of 0.76 against "Average delivery time." The confidence level between "Goods intact" and "Average delivery time" is the lowest, indicating that both time and goods are highly valued by experts in assessing the competence of crowdsourcing delivery personnel. Also, "Average delivery time" is almost as important as "Order quantity" and "Total mileage."

Concerning the "Abilities" dimension, the criterion of "Punctuality" appears to be the most important, as shown in Figure 6, which is also reflected between the "Negative ratings" and the "Extra reward" with a confidence of 1. This is in line with reality, as the additional reward shows the customer's superior satisfaction with the crowdsourcing delivery service although this will not apply to every single delivery. The frequency with which it occurs will, in turn, affect its importance in assessing the competence of the crowdsourcing delivery personnel.

With respect to the "Traits" dimension, Figure 7 explicitly shows that the criterion of "Responsible" is superior to the other three criteria, with a confidence of 1, because the delivery time of crowdsourcing delivery personnel is more flexible and the constraints are more relaxed, compared to dedicated delivery personnel [11]. Therefore, the ability to deliver goods to customers in extreme conditions reflects a responsible attitude and professional dedication. Of all the criteria, "Politeness and warmth" is considered to be the least important.

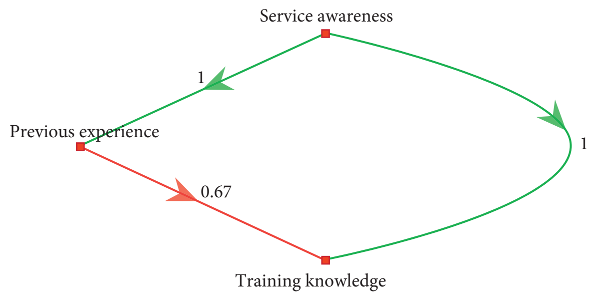

Figure 4: Credal ranking for the “Knowledge” dimension.

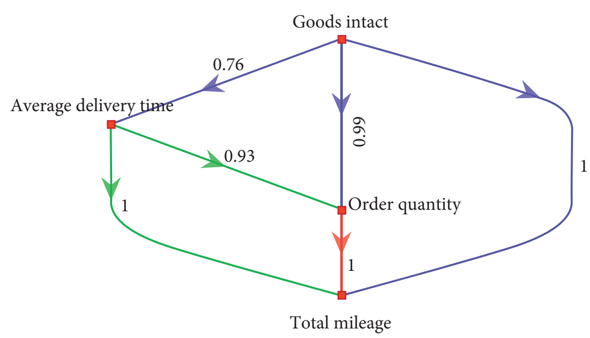

Figure 5: Credal ranking for the “Skills” dimension.

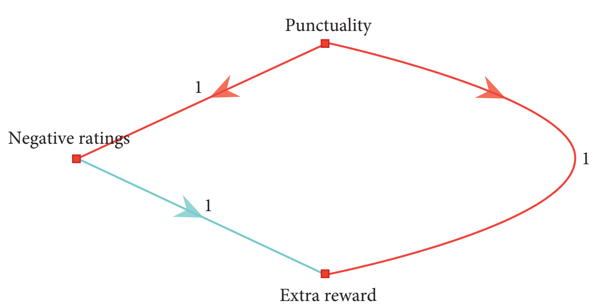

Figure 6: Credal ranking for the “Abilities” dimension.

However, the relative importance between the criterion of “Neatly dressed” and “Instrument neat” is not very significant, with a confidence level of 0.78, which is the lowest of all confidence levels.

5.2. Competence Analysis of Crowdsourcing Delivery Personnel. Combining the weights and data discussed above, the competence scores for crowdsourcing delivery personnel (CDP) are calculated as shown in Table 4. To guarantee the privacy of the crowdsourcing delivery personnel, their names are replaced with numbers.

Based on the competence scores for crowdsourcing delivery personnel in Table 4, some statistic results can be derived, as shown in Table 5.

Table 5 shows that, among all the crowdsourcing delivery personnel, the highest competence score is assigned to CDP 2, while the lowest score is assigned to CDP 75. CDP 2’s competence score is more than twice that of CDP 75. The significant difference between them is

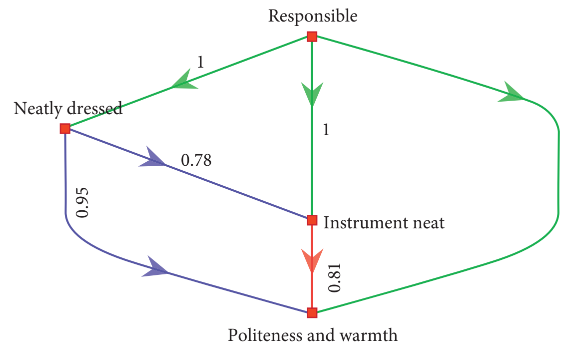

Figure 7: Credal ranking for the “Traits” dimension.

also reflected in the standard deviation, which is relatively high, which also clearly illustrates the fact that the competence of 81 crowdsourcing delivery personnel varies significantly.

Moreover, we attempt to explore the impact of varying length of registration time on the competence of crowdsourcing delivery personnel, dividing them into four groups based on a three-month boundary: Group A (1 to 3 months), Group B (3 to 6 months), Group C (6 to 9 months), and Group D (more than 9 months). The personnel numbers are arranged in descending order accordingly. Similarly, some basic statistical results can be obtained from different groups.

Among the four groups in Table 6, the average competence score of Group A is the highest and Group D is the lowest, with Groups B and C somewhere in between. Together with the overall average score, it can be concluded that of the nearly half of the undercompetent crowdsourcing delivery personnel, 42.5% are in Group A, 37.5% in Group B, 15% in Group C, and 5% in Group D. In this light, Group A continues to be at the bottom of the competence ranking, while Group D holds the top position, with the value of the standard deviation distributing in the same order. The standard deviation of Group D is the highest and close to that of the overall level in Table 5. By contrast, the standard deviation of Group A is the lowest. There is a considerable difference between the competence scores of the two groups, with the competence of the personnel in Group A being significantly higher and more stable than that of group D. The people in Group D have all worked for the platform for less than 3 months, and most of them joined fairly recently. As such, they do not have the time to gain the proper experience, skills, and training, which explains the difference. On the other hand, there is much less of a difference between the standard deviation of Groups B and C, who represent the people that have worked for the platform for more than 3 months, but less than 9 months, and their overall competence is relatively stable compared with Group D. Of these two groups, the people in Group C perform better than those in Group B, as indicated by the four statistical indicators presented in Table 6.

The group comparison proves the positive impact of registration time on crowdsourcing delivery personnel, which means that, over time, they become more competent, a conclusion that is also supported by Figure 8.

Table 4: Competence scores for crowdsourcing delivery personnel.

Number	Competence scores	Number	Competence scores	Number	Competence scores
CDP 1	0.666	CDP 28	0.608	CDP 55	0.402
CDP 2	0.733	CDP 29	0.586	CDP 56	0.579
CDP 3	0.650	CDP 30	0.709	CDP 57	0.558
CDP 4	0.625	CDP 31	0.546	CDP 58	0.527
CDP 5	0.586	CDP 32	0.565	CDP 59	0.450
CDP 6	0.682	CDP 33	0.626	CDP 60	0.668
CDP 7	0.659	CDP 34	0.663	CDP 61	0.563
CDP 8	0.669	CDP 35	0.703	CDP 62	0.521
CDP 9	0.668	CDP 36	0.681	CDP 63	0.487
CDP 10	0.650	CDP 37	0.473	CDP 64	0.541
CDP 11	0.684	CDP 38	0.577	CDP 65	0.609
CDP 12	0.584	CDP 39	0.724	CDP 66	0.504
CDP 13	0.692	CDP 40	0.562	CDP 67	0.565
CDP 14	0.715	CDP 41	0.599	CDP 68	0.595
CDP 15	0.691	CDP 42	0.482	CDP 69	0.569
CDP 16	0.550	CDP 43	0.557	CDP 70	0.542
CDP 17	0.673	CDP 44	0.544	CDP 71	0.517
CDP 18	0.652	CDP 45	0.594	CDP 72	0.530
CDP 19	0.564	CDP 46	0.439	CDP 73	0.431
CDP 20	0.603	CDP 47	0.670	CDP 74	0.537
CDP 21	0.650	CDP 48	0.463	CDP 75	0.314
CDP 22	0.600	CDP 49	0.492	CDP 76	0.600
CDP 23	0.562	CDP 50	0.534	CDP 77	0.542
CDP 24	0.707	CDP 51	0.538	CDP 78	0.520
CDP 25	0.601	CDP 52	0.525	CDP 79	0.386
CDP 26	0.536	CDP 53	0.587	CDP 80	0.368
CDP 27	0.626	CDP 54	0.490	CDP 81	0.366

Table 5: Statistical results for overall competence scores.

Personnel	*N*	Mean	Max	Min	SD
Overall	81	0.575	0.733	0.314	0.089

Table 6: Statistical results for different groups' competence scores.

Group	*N*	Mean	Max	Min	SD
Group A	20	0.502	0.609	0.314	0.082
Group B	21	0.536	0.670	0.402	0.068
Group C	21	0.615	0.724	0.473	0.064
Group D	19	0.652	0.733	0.550	0.049

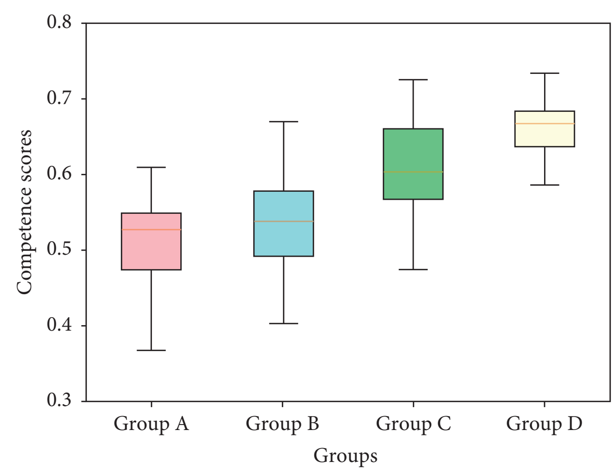

Figure 8: Competence scores of different groups.

It is clear from Figure 8 that there is an upward trend when it comes to competence levels. As time progresses, the median of the competence scores of the four groups increases, and the gap between the upper and lower limits narrows. Especially, the fluctuation of the competence scores of Group A is the most obvious, while Group D has minimal fluctuation. This intuitively demonstrates that the more experienced crowdsourcing delivery personnel are not only more competent but that their performance is the most stable as well, with the highest competence score in the other three groups being higher than the lowest score in Group D, which indicates that there are some excellent performers among the crowdsourcing delivery personnel who joined the platform more recently and that they clearly have the competence required. There are some implications for the platform managers. They need to establish a comprehensive competence evaluation system for the crowdsourcing delivery personnel and then identify the outstanding ones, especially among those who joined recently. Apart from that, because of the relatively large turnover in crowdsourcing delivery personnel, some monetary and nonmonetary incentive plans need to be formulated to encourage the outperformers to stay longer and provide better service quality.

6. Conclusions

In this paper, we conducted a comprehensive competence analysis of crowdsourcing delivery personnel. During this process, we developed a multicriteria competence analysis (MCCA) approach as a new way to assess the competence of personnel with the MCDA method embedded to implement the MCCA approach. To illustrate the MCCA approach, we conducted a real-world case study of a Chinese takeaway delivery platform to perform the competence analysis of crowdsourcing delivery personnel and applied the Bayesian best-worst method to identify the weights of the criteria in MCCA. Once the weights were obtained and the competence scores collected, the additive value function was used to generate the overall competence level of the crowdsourcing delivery personnel. The relationship between their competence level and some other variables was also discussed, allowing us to draw the following conclusions.

6.1. Theoretical Implications

(1) Combining the crowdsourcing delivery environment with competence evaluation expands the extension of the competence theory. To the best of our knowledge, this is the first time that the competence theory is applied in the field of crowdsourcing delivery. Besides, the developed MCCA approach provides a new approach to the competence analysis of personnel by considering the comprehensive impact of multicriteria from an MCDA perspective. As such, both the comprehensive competence analysis of crowdsourcing delivery personnel and the proposed MCCA approach enrich existing research in the areas of competence, crowdsourcing, and logistics.

(2) The MCCA approach builds a generic analysis framework to assess the competence of personnel, while the real-world case study provides a solid validation of its applicability. Furthermore, it is not limited to the area of crowdsourcing delivery: as long as the multiple criteria and corresponding scores for the personnel are determined within a specific working environment, the MCCA approach can always provide reasonable results, which means it can be used in other industries as well.

(3) Bayesian BWM serves as an effective tool for implementing the MCCA approach. Given the predetermined criteria in MCCA, it produces more colorful results that reflect the preferences of DMs and the relative relationships between the criteria from a probabilistic angle. For instance, if we look at the main dimensions of the proposed KSAT framework, “Skills” is the most important criterion, with a confidence of 1 over “Traits” and “Knowledge,” in which case DMs’ preference of a criterion could be confirmed explicitly with a certain confidence level.

6.2. Managerial Implications

(1) In the tailored MCCA framework, “Skills” is considered the most important and “Knowledge” is the least important, which indicates that it is important for managers to consider certain job skills, not only when hiring and promoting personnel, but also in terms of job training, entry setting, and post-screening for personnel. As for the dimension of “Knowledge,” although it is considered the least important in this particular case, it may be more important in other scenarios. Moreover, there are four critical criteria identified from the 14 subcriteria, indicating that a comprehensive competence evaluation system needs to be established in which core elements need to be prioritized when analyzing the competence of the personnel involved.

(2) In the crowdsourcing delivery market, the delivery personnel consist of a large number of people with a complex composition and high level of mobility, creating enormous challenges for the management of a crowdsourcing platform. To keep the organization healthy, the managers have to develop standardized operating procedures, management systems, and incentive plans to retain personnel, including the use of ICT and social welfare policies. Also, the MCCA can be seen as a learning tool rather than as a mere grading system. It can help crowdsourcing delivery personnel understand their strengths and weaknesses and allow them to improve in areas where they are weaker, in a structured and targeted manner.

(3) How long crowdsourcing delivery personnel have been on the job has a significant impact on their competence level and stability. A comparison of the four groups shows that their competence levels improve over time, while more pronounced fluctuations reflect a shorter time on the job. At an individual level, this provides some indication that competence is an individual’s accumulated performance in many aspects during a certain period, which means that every dimension in the proposed KSAT framework is indispensable when it comes to the development of competence. Meanwhile, it motivates platform managers to formulate attractive human resource policies, provide convenient equipment and facilities, and create a better working environment for the crowdsourcing delivery personnel, persuading them to stay and thus sustain the platform’s long-term development.

6.3. Future Research. In this paper, we performed the competence analysis of crowdsourcing delivery personnel by using the data collected from Chongqing, while the sample size was also limited. Future research could collect more data from different regions, possibly integrating big data analysis techniques into the MCCA approach. Furthermore, the developed MCCA approach was illustrated by a real-world case study set within a specific crowdsourcing delivery scenario. There are other delivery modes as well, like dedicated delivery and merchant’s taking care of the delivery themselves, and future studies could compare these different alternatives using the method set out in this paper. Finally, while we used additive value function as an aggregation method, there are alternative methods as well, including outranking methods, to aggregate the data being collected.

Data Availability

The data used in this paper consists of two parts. For the internal statistical data of the crowdsourcing delivery platform such as average delivery time, total delivery mileage, and customer ratings as well as the data obtained by conducting telephone interviews with crowdsourcing delivery personnel working on this platform such as total order quantity, registration time, and relevant work experience, they have not yet made available because these data belong to the right of a third party, the crowdsourcing delivery platform, so the authors can only use these data for academic research, but have no right to publish data sources. For another part of the data, the Bayesian BWM questionnaires that were sent to the site managers are available by sending an e-mail to the corresponding author at wx921@163.com.

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 Volatility Forecasting Power of Financial Network Analysis

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This investigation connects two crucial economic and financial fields, financial networks, and forecasting. From the financial network's perspective, it is possible to enhance forecasting tools, since econometrics does not incorporate into standard economic models, second-order effects, nonlinearities, and systemic structural factors. Using daily returns from July 2001 to September 2019, we used minimum spanning tree and planar maximally filtered graph techniques to forecast the stock market realized volatility of 26 countries. We test the predictive power of our core models versus forecasting benchmarks models in and out of the sample. Our results show that the length of the minimum spanning tree is relevant to forecast volatility in European and Asian stock markets, improving forecasting models' performance. As a new contribution, the evidence from this work establishes a road map to deepening the understanding of how financial networks can improve the quality of prediction of financial variables, being the latter, a crucial factor during financial shocks, where uncertainty and volatility skyrocket.

1. Introduction

In this paper, we used minimum spanning tree length (MSTL) and maximally filtered graph length (PMFGL) methodologies to improve the forecasting of volatility in financial markets. In times of crisis, uncertainty soars, and capital markets evolve quickly and wildly, generating a surge in the volatility of financial assets (a metric for measuring the uncertainty in financial markets is the Chicago Board Options Exchange Volatility Index (CBOE VIX). Since its inception, this index exhibits an average history value of nearly 20, but during the subprime crisis of 2008-2009 reached its maximum historical level of 89.53. Similarly, nowadays, during the COVID-19 crisis, the index reached a second historic maximum level of 85.47 units), affecting the price behavior, risk management, and asset pricing, also consumption, savings, and investment decisions in the economy, that weakening the economic growth and well-being in the short and long run [1]. Consequently, improving the forecasting of volatility is a priority for its role in portfolio selection, risk management, and derivatives pricing, helping policymakers, institutions, and people to minimize better adverse effects in the postcrisis stage [2, 3].

During the past two decades, forecasting models' performance has improved with the incorporation of more data, where the results of the predictions are very reliable on weekly, monthly, and even quarterly horizons [4]. New approaches emerged, from high-frequency models [5] to multivariate ARCH, stochastic volatility models for time-varying return volatilities, and conditional distributions [6, 7], and long memory models [8]. Despite these broad advances, volatility models continue to be of very little dimensionality and univariate, which do not manage to incorporate second-order effects and nonlinear relationships typical of complex systems [5].

Complexity is a crucial element for understanding the behavior of financial markets and its reaction to disturbances. An example of a complex system is capital markets characterized by the presence of multiple economic agents interacting simultaneously (complex systems in opposition to linear systems are characterized among other factors, by being nonlinear. In other words, in a nonlinear system, the change in the outputs is nonproportional to the change in the inputs, causing the system to appear chaotic, unpredictable, or even contradictory). The existence of multiple entities and various interaction rules (on several degrees and nonlinearities), among other characteristics, generates collective effects that hinder the understanding and modeling of the whole system [9].

One way to improve the understanding of complex systems' behavior is through the use of network methods (they allow modeling the indirect effects in the interconnections of its components or entities. The traditional econometric methods study the direct effects on the relationships of the entities of a system; when using networks, it is feasible to estimate, for example, the distance between two entities or nodes and how likely an indirect effect is between them. These kinds of computations are not feasible using only traditional statistics. This advantage is one of the reasons because network approaches have been used in economics and financial markets). The literature that examines networks in financial markets focuses on the implications of network properties and their relationships with the stability and fragility of financial systems [10, 11]. The literature also explored how the distribution of the links affects the systemic reaction to shocks and how the connectivity of critical nodes or hub nodes could destabilize and even cause the entire network to collapse [12–15]. Likewise, other relevant topics are related to transaction networks of financial assets, portfolio selection, risk management, overlapped portfolios, integration of financial markets, and financial crises [16–22].

Network methodologies apply correlation networks to analyze the synchronization of returns. For the case of interconnectedness risk, planar maximally filtered graph (PMFG) and minimum spanning trees (MST) are used to study the increase in cointegration between financial markets (this phenomenon not only negatively affects investors' possibilities to diversify but is also evidence of an increase in the influence of regional and global economic phenomena on the economies and financial markets that comprise it. For example, Onnela et al. [18] study correlation networks of the S&P 500, finding the presence of dynamic clusters whose existence is not exclusively due by the industrial sector, but to psychological and economic factors captured in the asset network. They also find that the normalized tree length of the MST (MSTL) is dynamic and reaches minimums during financial crises and that the potential for diversification is related to the evolution of the MSTL of the asset network. During crises, the topology of an MST becomes more star-like and compact, being this network less resilient to shocks and more prone to systemic risk [23]) [24]. We applied minimum spanning tree length (MSTL) and maximally filtered graph length (PMFGL) to measure the synchronization of returns of global stock markets (Granger causality refers to temporary anticipation of an effect (called forecasting power), which may be due to a black box of explanations. We evaluate the predictive power of equity markets via Granger-causality and forecasting regressions, which are useful to assess whether a variable has the predictive ability, not whether it "causes" other variables to change. The latter question can only be answered by using a structural model. However, we can study whether PMFGL and MSTL have predictive ability above and beyond that contained in other variables, such as global demand pressures and interest rates, used as a proxy for the world business cycle, and we undertake such analysis [25]) because both are parsimonious representations of the complex network of interrelationships, and its connections are useful for obtaining direct and indirect information [26]. The ability to represent a dynamic system is a second reason for measuring cointegration with these methodologies. This topic is particularly useful when it is required to represent the phenomenon incorporating a large number of markets under examination [24]. Despite the differences between MSTL and PMFGL, the advantage of reducing the complexity of networks is that it represents nonredundant and the essential connections in a graphical way.

We intend to explore the possibilities of using the MSTL and PMFGL methodologies to improve the forecasting of volatility in financial markets. We hypothesize that there is Granger causality (Granger causality refers to temporary anticipation of an effect (called forecasting power), which may be due to a black box of explanations. We evaluate the predictive power of equity markets via Granger causality and forecasting regressions, which are useful to assess whether a variable has the predictive ability, not whether it "causes" other variables to change. The latter question can only be answered by using a structural model. However, we can study whether PMFGL and MSTL have predictive ability above and beyond that contained in other variables, such as global demand pressures and interest rates, used as a proxy for the world business cycle, and we undertake such analysis [25]) between the global MSTL and global PMFGL and the realized stock market volatility. We think that the global network correlations between the stock markets have relevant information to forecasting realized volatility of stock indices. It is vital to notice that our paper does not study "causality effects," and in other words, we do not study the structural link between the length of MSTL (and PMFGL) and the realized volatility of stock markets.

We contribute to the extant financial network literature in two ways. First, we study an application of the PMFGL and MSTL in the field of forecasting, defining a methodology for testing the predictive power of these two network measures. Second, we connect to relevant fields that, to our best knowledge, have not been linked, network analysis and forecasting. We believe that there is an excellent possibility of contributing financial networks to the field of financial forecasting. Many papers forecast stock market volatility, but none have used financial network metrics that incorporate correlations' asset trees as independent factors [27–29].

To analyze our hypothesis, we test the predictive power of the global MSTL and global PMFGL on the stock market of 26 countries of North America, Latin America, Europe, Asia, and Oceania. For this, we collected daily returns from July 2001 to September 2019 for the main stock indices of these countries and calculated their monthly realized volatility. We then apply finance network methodologies to estimate the PMFGL and MSTL metrics to represent the global correlation structure and to observe it dynamically over time. Finally, we tested the predictive power of such network metrics using in-the-sample and out-of-sample tests. Finally, we applied robustness tests to our results.

Our main finding is that MSTL helps to predict the realized volatility of stock markets. Specifically, results indicate that there is Granger causality of the MSTL on the volatility performed in most Asian and European markets. Nevertheless, there is no evidence for the case of North and Latin American markets. This finding would mean that the global correlation network behind the MSTL contains useful information that helps to predict the realized volatility of stock markets. Another relevant result relates to the predictive power of PMFGL. There is evidence that compared to the MSTL, its ability is more limited. One explanation could be that compared with MSTL, this network measure captures more information from the entire asset's correlation network. This would appear to be counterproductive to its volatility predictive power. These results are robust in out-of-sample tests adding benchmark models with six lags, but the effect disappears when we add the variation of the VIX lagged in one month. The previous is preliminary evidence that the MSTL would be an efficient indicator to represent information of the global volatility of the stock markets, with similar predictive power to VIX. However, we think that MSTL has more advantage than the VIX. First, MSTL considers information of all stock markets in comparison with VIX that is elaborated only with the North American stock market. Secondly, MSTL is calculated with realized correlations, and VIX is estimated with expected volatility that is more sensible at market sentiments.

The main conclusion of this paper is that the global correlation connections add useful information that helps to predict the realized volatility in a relevant segment of global stock markets. These results imply that policymakers and practitioners could improve their estimations of future volatility in financial markets and, consequently, improve their forecasting and decision-making regarding asset pricing and risk management. From an economic policy point of view, this work could help policymakers to improve financial stability frameworks and design models that consider the underlying structure of the global network of stock indices. Finally, a possible extension of this work is the development of new methods that deepen the study of the connection between correlations' assets networks and the influence of volatility gauges as the VIX.

This paper is organized as follows. In Section 2, we present the possibilities of expanding the realized volatility forecasting methodologies. In Section 3, we indicate the methodology and the data used in the study. Section 4 shows the results of the in-the-sample and out-of-sample and robustness tests. Section 4 concludes and provides some future research extensions.

2. Realized Volatility Forecasting Methodologies

Financial crises have attracted considerable attention from the literature of financial networks. During the financial crisis of 2008-2009, the synchronization of returns, defined as the tendency of stock markets to display significant comovements [30], has a negative impact on the contribution of diversification to risk minimization. This high interconnectedness risk (network centrality measures quantify the interconnectedness risk. The network is built from some measure of dependence between financial assets (e.g., correlations)) phenomenon is an element that becomes a contagion channel for financial shocks in times of crisis.

Evidence indicates that in high-volatility environments, such as that of financial crises, the network topology of equities markets changes, and the correlation among financial assets rises, diminishing in consequence, the effectiveness of diversification as a risk management tool. This issue is critical for strategies applied in portfolio management, where tactical and strategic asset allocation decisions are based on modeling the correlations of returns of financial assets [22, 23, 31, 32].

Nevertheless, the returns of financial assets, especially stocks, are particularly difficult to predict (see [33] for a review); however, the volatility of their returns seems to be relatively easier to forecast. The stylized fact about volatility is that it is low, but slowly decaying persistency. In this sense, it is not surprising the growing literature focused on modeling and forecasting financial volatility, due to its implications for asset pricing, portfolio management, and risk management.

One of the main problems of volatility measures is that the conditional variance is a "latent" variable. Therefore, it is not directly observable (see [34] for a discussion). There is a wide range of models to estimate this latent variable, such as autoregressive conditional heteroskedasticity (ARCH or GARCH type models) and stochastic volatility (SV) models. However, as pointed out in [35, 36], these models tend to fail to correctly accommodate some stylized facts regarding financial time series such as high excess kurtosis.

A novel and increasingly popular method is the quantification of realized volatility. The main advantage of this approach is that the ex-post volatility becomes necessarily observable rather than being treated as a latent variable. In this sense, it becomes straightforward to evaluate the out-of-sample forecasting accuracy of different models when predicting realized volatility, as it can be modeled directly (see [37, 38] for a discussion)

While our out-of-sample forecasting approach using financial networks is somewhat novel, there are recent attempts to establish relationships between local market volatilities and the international financial interlinkages. For instance, Bouri et al. [39] examine the predictive ability of commodity and significant developed stock markets forecasting the implied volatility (IV) of each one of the individuals BRICS (Brazil, Russia, India, China, and South Africa) stock markets. Using a Bayesian graphical SVAR approach (BGSVAR, see [40]), they find some evidence of Granger causality mainly from the global stock markets (and some individual markets) IV over the BRICS IV (notably, they find that the commodity market is important exclusively in South Africa. One possible explanation for this result is the strong relationship between major exporting economies and global commodity prices, extensively reported in [41–45]). This result is somewhat consistent with previous evidence relating to global factors and BRICS stock markets [46].

In related work, Ji et al. [47] model a dynamic network for the IV transmission among US equities, commodities, and BRICS equities. In general, they show that the integration structure of the information transmission network is somewhat unstable, with changes over time. Their results suggest that the impact of the analyzed events is heterogeneous, e.g., some events have an impact exclusively on the IV of local markets, but others impact global volatility.

In the same line, Ji et al. [48] use a directed acyclic graph to study the contemporaneous and lagged relationships between bitcoins and other financial assets as commodities, stock markets, and fixed income indices. Notably, they find little evidence of contemporaneous relations between bitcoins and other financial assets, although they find some evidence of predictability in the bear market states of bitcoins.

Respect to market volatility linkages, Aggarwal and Raja [49] study the cointegration among the stock markets of BRIC economies. Additionally, they examine the IV transmission between the Indian IV index and three international indices; in particular, they study how shocks in the IV of one market may affect other markets' volatility. Similarly, Ewing et al. [50] study the effects of the NAFTA agreement on volatility transmissions of each market. Other empirical papers exploring the linkages among financial markets include [51, 52] for NAFTA economies, [53] for linkages between the US and European markets, and [54] for Latin American markets.

Finally, Hussain Shahzad et al. [55] study spillovers in the Eurozone credit market sector. Using network theory and daily data on 14 sector-level credit default swaps (CDS) indices in the Eurozone, they identify the main sectors transmitting (and receiving) spillovers during regular periods and crisis. In particular, they find that many CDS sectors became strongly interconnected in crisis periods, and this linkage remains for some later periods, suggesting some evidence of contagion.

3. Method

3.1. The Minimum Spanning Tree Length (MSTL). We follow the standard procedure to obtain the return correlations and dynamic asset trees based on price market indexes [18, 56]. The closure prices index i at time date τ is $P_i(\tau)$. The return of index i is given by $r_i(\tau) = \ln P_i(\tau) - \ln P_i(\tau - 1)$, for a consecutive sequence of trading days. For each index i, daily returns are calculated within a time window of 1 month. Let be $\mathbf{r}_i^t$ the return vector of the index i of the month t, then

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

where ρ_{ij}^t is the correlation coefficient between the indices i and j where $\langle \ldots \rangle$ indicates the average over all the trading days of the month t. In this way, a $N \times N$ symmetrical matrix $\mathbf{C}^t$ of correlations between market indexes (N is the number of financial indices) with values $-1 \leq \rho_{ij} \leq 1$.

Then, the correlations of $\mathbf{C}^t$ are converted to distances $d_{ij} = (2(1 - \rho_{ij}))^{(1/2)}$, which represents the distance between the market index i and j. Thus, a correlation $\rho_{ij} = -1$ indicates a maximum distance of $d_{ij} = 2$, whilst $\rho_{ij} = 1$ indicates a minimum distance of $d_{ij} = 0$.

The minimum spanning tree (hereafter, MST) is a tree structure graph that connects the N indexes through $N - 1$ edges avoiding loops and clicks, and where the path to connect all the nodes is minimal. The MST is constructed using the Prim algorithm [46]. In this way, MST reduces the information space of the entire network by connecting all nodes with $N(N - 1)/2$ edges, to a tree with $N - 1$ edges [57].

The sum of the edges of the resulting tree $\mathbf{T}^t$ calculated for each month t forms a time series. We define the normalized length of the MST (MSTL) as follows:

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

So, for every month, we have an MSTL. The variation in the MSTL is calculated as $\Delta L(t) = \ln L(t) - \ln L(t - 1)$, which allows us to work with a stationary time series.

3.2. The Planar Maximally Filtered Graph Length (PMFGL). The planar maximally filtered graph (PMFG) also filters out the complete graph based on the distance matrix $\mathbf{D}^t$ by keeping only the main representative links by varying the genus of the graph [58, 59]. In this case, the PMFG retains a bit more information. The MST keeps $N - 1$ edges, while the PMFG keeps $3N - 6$ edges compared to the $N(N - 1)/2$ edges of the complete graph [60]. In addition, the PMFG also contains the MST.

The length of the PMFG (therefore, PMFGL) is simply defined as the sum of all distances d_{ij}^t of the resulting distance matrix for the PMFG. Since the PMFG retains a greater number of edges (thus a greater number of correlations), it is possible that this network can better express the level of synchronization in the market. For this reason, it is included in the core models.

Since the PMFG supports cycles in the network and may include negatively correlated stocks, the PMFG length will always be greater than that of the MST. Precisely because of this feature of including more information, it is interesting to be able to compare the models that explain the risk of interconnectivity as a measure of robustness. It is worth mentioning that we do not calculate the PMFG length for regions. The PMFG includes the MST and the edges used to join the nodes in the PMFG are of minimum distance; therefore, the length of the regional PMFG is the same as the length of the MST.

3.3. Realized Variance. We measured volatility with the daily variance of stock market using the realized variance model ($\mathrm{RV}_{i,t}$) [4]:

$$\mathrm{RV}_{i,t} = \sum_{j=1}^{N} r_{i,j,t}^{2}. \tag{3}$$

The realized volatility is our dependent variable, where $r_{i,j,t}$ is the daily return for the day j on the month t for the market index i. We used daily data provided by Bloomberg from July 2001 to September 2019, totaling 216 months, for a total of 26 market indexes in America, Europe, Asia, and Oceania. These market indices are part of the benchmarks published by Bloomberg for each stock market at the country and region level. We included the VOX CBOE in our robustness out-of-sample test following [20] that incorporated with a control for the monthly volatility of each region and monthly variation of VIX index.

3.4. Forecasting Model and Evaluation. We used two types of forecasting models to evaluate the predictive power of the MSTL and PMFGL. First, we named "core models" at forecasting models for our in-the-sample and out-of-sample tests that include the natural logarithm variation of the MSTL (therefore, VMSTL) and include the natural logarithm variation of PMFGL (therefore, VPMFGL) (see Table 1 panels A and B). Second, for our out-of-sample tests, we named "benchmark models" at forecasting models that are inspired in a vast literature that has shown that AR(p) models are usually difficult benchmarks to beat when forecasting realized volatility [4, 8]. In this sense, we use a heterogeneous autoregressive (HAR) model as our main benchmark (see Table 1 panel C).

In the table, $\mathrm{RV}_{i,t}$ is the realized variance in the month t for the market index i, VMSTL_{t-1} is the global minimal spin tree length in the month $t-1$, VPMFGL_{t-1} is the global planar maximally filtered graph in the month $t-1$, $\mathrm{RV}_{i,t-1}$, $\mathrm{RV}_{i,t-2}$, and $\mathrm{RV}_{i,t-3}$ are the first, second, and third lags of the realized volatility, respectively, for the market index i, and e_i is the disturbance error.

Our main goal in this paper is to test the existence of Granger causality from the structure of the network to the realized volatility. For this, we focus on testing the following null hypothesis H_0: $\beta_i = 0$; this means that we are comparing our core models to benchmark models (see Table 1). Our null hypothesis both in sample and out of sample posits that the VMSTL_{t-1} and VPMFGL_{t-1} have no role in predicting the market index realized volatility. We test these hypotheses both in sample and out of sample focusing on one-step-ahead forecasts only, leaving the analysis of multistep-ahead forecasts as an extension for future research.

In-sample evaluations are carried out using the t-statistic associated with the coefficient of the minimal spin tree length. For covariance stationary processes, the central limit theorem requires a proper estimation of the long-run variance; in this sense, we use HAC standard errors as suggested in [61, 62] (Newey and West [61] propose a Barlett kernel to ensure a positive definite variance matrix. Additionally, Newey and West [62] propose an automatic lag selection method for the covariance matrix estimation). In-sample estimates, however, are usually criticized because they are relatively different from a real-time forecasting exercise and also because there are prone to data mining-induced overfitting. To mitigate these shortcomings, we also consider out-of-sample analysis.

For out-of-sample evaluations, as we are working in an environment with nested models, we use the ENCNEW test proposed in [63] (other tests for nested models such as [64–66] were also considered with similar messages, and they are available upon request). Again, for out-of-sample analysis, we are considering the null hypothesis H_0: $\beta_i = 0$. In the context of linear models estimated by OLS, Clark and McCracken [63] derive the correct asymptotic distribution of this test. While the distribution is not standard, critical values for one-step-ahead forecasts are available in their paper. Under general conditions, the asymptotic distribution of the ENCNEW test is a functional of Brownian motions depending on the number of excess parameters of the nesting model, which is 1 in our specifications, and on the parameter π defined as the limit of the ratio P/R, where P is the number of one-step-ahead forecasts and R is the size of the first expanding window used in the out-of-sample analysis (π is defined as the limit P/R when P, $R \longrightarrow \infty$. Clark and McCracken [63] show that the asymptotic distribution of the ENCNEW depends, among other parameters, on π. In this sense, $\pi = 0.4$ can be interpreted as the estimation window being approximate twice the prediction window's length). The asymptotic distribution of the test varies also with the scheme used to update the estimates of the parameters: either rolling, recursive, or fixed. Additionally, we emphasize that this test is one-sided, and in other words, rejection of the null occurs only when the statistic is greater than a critical value located at the right tail of the distribution (see [67, 68] for wonderful reviews and further details about the implementation of out-of-sample tests of predictive ability in nested model environments).

For in-sample analysis, we estimate our models with all the available observations. For the case of out-of-sample analysis, we split the sample in three different ways, as suggested in [69]. For each splitting, we consider two windows: an initial estimation window of size R and an evaluation window of size P such that $T = P + R$, where T is the total number of observations. We split the samples in three different ways. First, we use the first half for the initial estimations and the second half to make our predictions. Second, we use approximately the first third of observations for initial estimations and two thirds for evaluation. Third, we use approximately 70% of initial observations for estimation and 30% for evaluation. Finally, we update our parameters using recursive windows, although results with rolling windows are very similar. We only report the results for the third division ($\pi = 0.4$) for saving space; however, the message of predictability is very similar in all divisions and they are available upon request.

3.5. The Data. We used daily data provided by Bloomberg from July 2001 to September 2019, totaling 223 months, for a total of 26 market indexes in North America, Latin America, Europe, Asia, and Oceania (see Table 2 for details). These indices belong to regional stock indices published by

Table 1: The main econometric models for both the core and benchmark models.

Panel A: *in-the-sample core models*
(1) $RV_{i,t} = c + \beta_i * VPMFGL_{t-1} + \gamma_{i,1} * RV_{i,t-1} + \gamma_{i,2} * RV_{i,t-2} + \gamma_{i,3} * RV_{i,t-3} + e_i$
(2) $RV_{i,t} = c + \beta_i * VMSTL_{t-1} + \gamma_{i,1} * RV_{i,t-1} + \gamma_{i,2} * RV_{i,t-2} + \gamma_{i,3} * RV_{i,t-3} + e_i$
Panel B: *out-of-sample core models*
(3) $RV_{i,t} = c + \beta_i * VPMFGL_{t-1} + \gamma_{i,1} * RV_{i,t-1} + \gamma_{i,2} * RV_{i,t-2} + \gamma_{i,3} * RV_{i,t-3} + \gamma_{i,4} * RV_{i,t-4} + \gamma_{i,5} * RV_{i,t-5} + \gamma_{i,6} * RV_{i,t-6} + e_i$
(4) $RV_{i,t} = c + \beta_i * VMSTL_{t-1} + \gamma_{i,1} * RV_{i,t-1} + \gamma_{i,2} * RV_{i,t-2} + \gamma_{i,3} * RV_{i,t-3} + \gamma_{i,4} * RV_{i,t-4} + \gamma_{i,5} * RV_{i,t-5} + \gamma_{i,6} * RV_{i,t-6} + e_i$
(5) $RV_{i,t} = c + \beta_i * VPMFGL_{t-1} + \gamma_{i,1} * RV_{i,t-1} + \gamma_{i,2} * RV_{i,t-2} + \gamma_{i,3} * RV_{i,t-3} + e_i$
(6) $RV_{i,t} = c + \beta_i * VMSTL_{t-1} + \gamma_{i,1} * RV_{i,t-1} + \gamma_{i,2} * RV_{i,t-2} + \gamma_{i,3} * RV_{i,t-3} + e_i$
(7) $RV_{i,t} = c + \beta_i * VPMFGL_{t-1} + \gamma_{i,1} * RV_{i,t-1} + \gamma_{i,2} * RV_{i,t-2} + \gamma_{i,3} * RV_{i,t-3} + \delta_i * VVIX_{t-1} + e_i$
(8) $RV_{i,t} = c + \beta_i * VMSTL_{t-1} + \gamma_{i,1} * RV_{i,t-1} + \gamma_{i,2} * RV_{i,t-2} + \gamma_{i,3} * RV_{i,t-3} + \delta_i * VVIX_{t-1} + e_i$
Panel C: *out-of-sample benchmark models*
(9) $RV_{i,t} = c + \gamma_{i,1} * RV_{i,t-1} + \gamma_{i,2} * RV_{i,t-2} + \gamma_{i,3} * RV_{i,t-3} + \gamma_{i,4} * RV_{i,t-4} + \gamma_{i,5} * RV_{i,t-5} + \gamma_{i,6} * RV_{i,t-6} + e_i$
(10) $RV_{i,t} = c + \gamma_{i,1} * RV_{i,t-1} + \gamma_{i,2} * RV_{i,t-2} + \gamma_{i,3} * RV_{i,t-3} + e_i$
(11) $RV_{i,t} = c + \gamma_{i,1} * RV_{i,t-1} + \gamma_{i,2} * RV_{i,t-2} + \gamma_{i,3} * RV_{i,t-3} + \delta_i * VVIX_{t-1} + e_i$

Source: authors' elaboration.

Table 2: Stock country indices by region.

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

Source: authors' elaboration.

Bloomberg for each stock market at the country and region level. As mentioned above, we included the CBOE VIX index in our robustness section as part of an out-of-sample test following Lavin et al. [20], who incorporated the monthly variation of the VIX index as a control for the monthly volatility of each regional market.

4. Empirical Results

In this section, we first report the estimation results of 26 market indices of our core models (Table 1 panel A) using in-sample data. Secondly, we evaluate the forecasting performance with our benchmark models (Table 1 panel B). Finally, we check the robustness of models adding in the out-of-sample test a lag of variation of VIX (VVIX). We calculate the ENCNEW out-of-sample test of Clark and McCracken [63].

Figure 1 shows a representation of the financial indices' MSTs in three different periods: before, during, and after the financial crisis of 2008. The proximity of the assets about their origin geographical location remains an unalterable property through time. This phenomenon produces clusters based on geographical location. For example, Asian market indices tend to cluster together. The same is true of European indices. Only the two Oceania indices (Australia and New Zealand) appear to be accommodating regardless of geographic location. However, the lengths of the MSTs are different. The MST length was 10.97 in precrisis, and it decreased to 10.23 in crisis and then increased again to 11.68 in the postcrisis period. In times of financial crisis, markets synchronize, increasing the intercorrelations between financial assets. Consequently, the distances represented on each edge of the network shorten [18].

4.1. In-Sample Analysis. Tables 3–5 report estimates of core models in Table 1 panel A. In all Tables 3–5, we consider monthly frequencies and use HAC standard errors according to [61, 62]. Generally speaking, the VMSTL coefficients are more significant than the PMFG coefficients. This evidence shows that the MSTL is a more efficient measure because the additional information included in the PMFGL does not represent a higher statistical significance. When comparing the significance of the core models (1) and (2)fd2 presented in Table 1 panel A, we observed that the MSTL has greater predictive power, presenting statistical significance in 11 markets out of 26 in total to the PMFG that shows statistical significance in 7 markets out of 26 in total, consistent with the idea that the MSTL is more efficient by not considering correlations of lesser magnitude.

However, the predictive power of VMSTL varies by geographic area. In specific, the VMSTL coefficient is significant at least at a 10% level in most European and Asian stock markets (see Tables 4 and 5), but we did not find significance in the VMSTL coefficient in the models that represent the American equity markets (see Table 3). These results imply the existence of causality to the Granger between the dynamics of the network of correlations formed

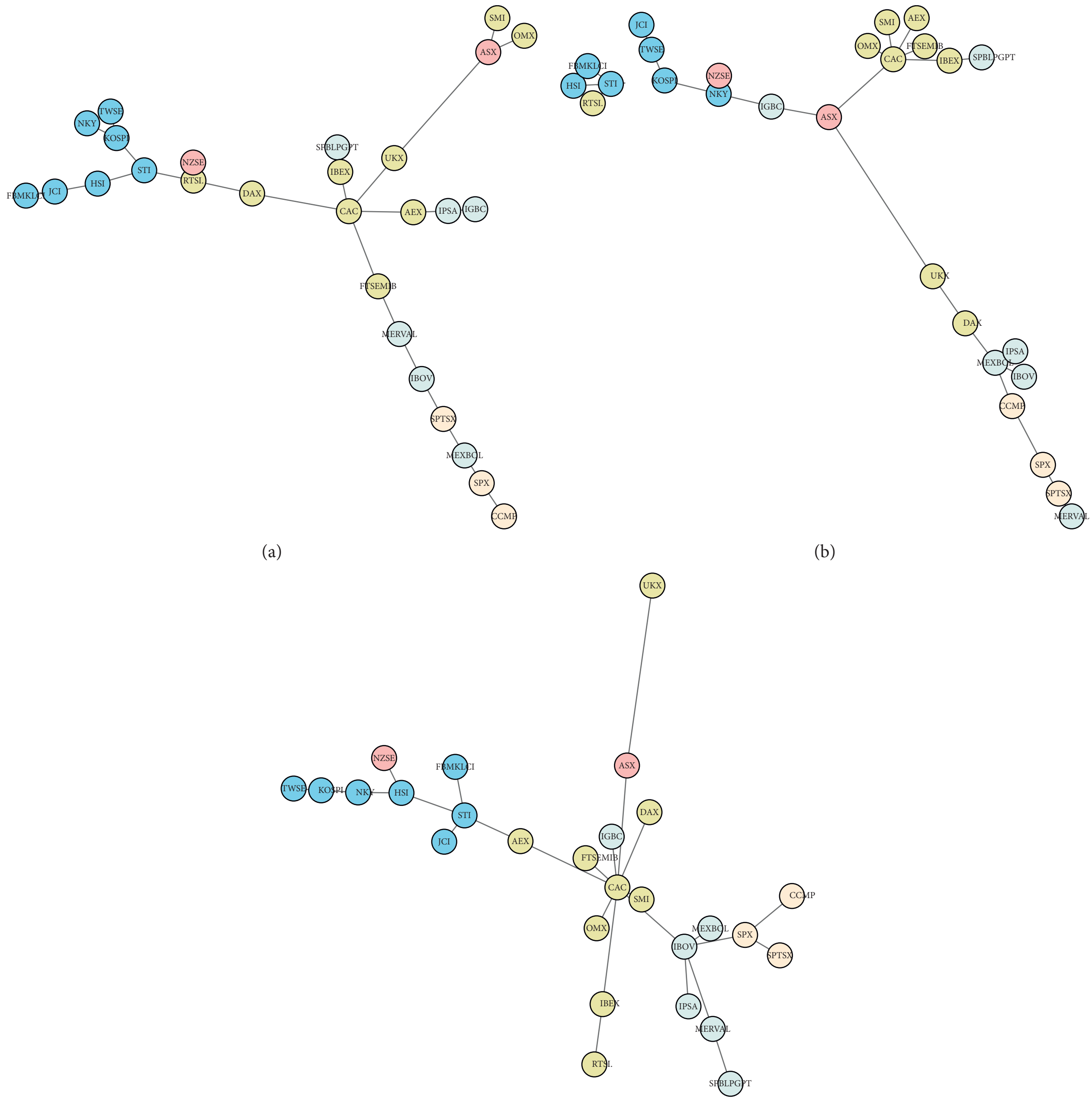

Figure 1: The resulting MSTs for three different periods. (a) Precrisis (January, February, and March 2008), (b) crisis (September, October, and November 2008), and (c) postcrisis (March, April, and May 2009). The color of the vertex represents different regions: blue: Asia, light blue: Latin America, light yellow: Europe, light Salmon: North America, and pink: Oceania.

between global stock markets and the volatility of the European and Asian stock markets.

Regarding Europe, Table 4 shows that the volatility of the stock markets in France ($\beta = -0.672$, $p = 0.015$), Spain ($\beta = -0.700$, $p = 0.0.044$), Italy ($\beta = -0.838$, $p = 0.0124$), and Sweden ($\beta = -0.822$, $p = 0.0214$) has the highest relationship with the global network of correlations lagging in one month. Regarding Asia, Table 5 indicates that the volatility realized in the markets of Taiwan ($\beta = -1.083$, $p = 0.001$), Korea ($\beta = -0.829$, $p = 0.0188$), and Hong Kong ($\beta = -0.672$, $p = 0.0476$) shows the relationship with the global network of correlations lagging in a month of greater magnitude of statistical significance. Regarding Oceania, Table 5 shows that only the volatility of the New Zealand stock market ($\beta = -0.623$, $p = 0.0474$) shows statistical significance with the global network of correlations with one month of lag.

Several additional features are worth noticing from our in-sample core models. First, the term of the constant and the coefficient of the first volatility lag are statistically significant in all markets (see Tables 3–5), consistent with the strong autocorrelation of the volatility of the equity indices. Second, the coefficient of the three lags is positive in all

Table 3: The forecasting realized volatility of North and Latin America stock market indices using in-sample analysis with monthly data and core econometric specifications shown in Table 1.

(1) Variable	(2) SPX	(3)	(4) CCMP	(5)	(6) SPTSX	(7)	(8) MEXBOL	(9)	(10) IBOV	(11)	(12) IPSA	(13)	(14) MERVAL	(15)	(16) IGBVL	(17)
C	**−1.438*****	**−1.444*****	**−1.346*****	**−1.351*****	**−1.392*****	**−1.393*****	**−1.783*****	**−1.784*****	**−1.866*****	**−1.863*****	**−2.952*****	**−2.947*****	**−1.664*****	**−1.665*****	**−1.540*****	**−1.541*****
	0.470	*0.471*	*0.414*	*0.414*	*0.455*	*0.454*	*0.398*	*0.399*	*0.401*	*0.400*	*0.492*	*0.492*	*0.309*	*0.308*	*0.356*	*0.357*
VMSTL (−1)	−0.271		−0.247		−0.323		0.094		0.278		−0.328		0.350		0.017	
	0.371		*0.300*		*0.402*		*0.362*		*0.327*		*0.374*		*0.395*		*0.436*	
VPMFGL (−1)		0.145		−0.041		−0.212		0.113		0.339		−0.322		0.349		−0.017
		0.340		*0.294*		*0.367*		*0.340*		*0.308*		*0.344*		*0.376*		*0.394*
AR (−1)	**0.492*****	**0.547*****	**0.452*****	**0.477*****	**0.489*****	**0.502*****	**0.583*****	**0.585*****	**0.442*****	**0.450*****	**0.467*****	**0.468*****	**0.498*****	**0.497*****	**0.501*****	**0.500*****
	0.104	*0.102*	*0.096*	*0.099*	*0.081*	*0.081*	*0.075*	*0.074*	*0.083*	*0.085*	*0.065*	*0.064*	*0.069*	*0.067*	*0.065*	*0.065*
AR (−2)	**0.167***	0.113	**0.172***	0.146	**0.264*****	**0.253*****	0.005	0.003	**0.152****	**0.144****	**0.046****	0.044	0.041	0.042	**0.191****	**0.193****
	0.089	*0.090*	*0.088*	*0.092*	*0.086*	*0.086*	*0.085*	*0.082*	*0.071*	*0.072*	*0.086*	*0.084*	*0.099*	*0.099*	*0.085*	*0.085*
AR (−3)	**0.120***	**0.119***	**0.157****	**0.157****	0.042	0.040	**0.129***	**0.129***	0.061	0.061	0.047	0.048	0.133	0.132	0.061	0.061
	0.072	*0.071*	*0.077*	*0.077*	*0.060*	*0.060*	*0.069*	*0.069*	*0.055*	*0.055*	*0.075*	*0.075*	*0.086*	*0.086*	*0.088*	*0.089*
R-squared	0.504	0.504	0.500	0.499	0.539	0.538	0.429	0.429	0.327	0.329	0.276	0.276	0.349	0.349	0.457	0.457
Prob (Wald F-statistic)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Note: AR stands for lag monthly volatility realized. AR (−1) and AR (−2) represent the first and second lags of volatility realized. SPX, CCMP, SPTX, MEXBOL, and IGBVL Lmex denote one-month volatility realized returns of the respective indices. The estimations from the first equation in Table 1 are presented here. $^{*}p < 10\%$, $^{**}p < 5\%$, and $^{***}p < 1\%$. Source: authors' elaboration.

Table 4: The forecasting realized volatility of European stock market indices using in-sample analysis with monthly data and core econometric specifications shown in Table 1.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)
Variable		FTSE				CAC				DAX		IBEX						FTSEMIB
AEX		OMX		RTS		SMI												
C	−1.479***	−1.482***	−1.392***	−1.392***	−1.277***	−1.278***	−1.342***	−1.342***	−1.127***			−1.129***						−1.247***
	−1.249***	−1.234***		−1.235***		−1.754***		−1.758***				−2.023***						−2.029***
0.323	0.323	0.278	0.279	0.312	0.312	0.275	0.277	0.237	0.235	0.284		0.284	0.326	0.325	0.343	0.343	0.368	0.369
VMSTL (−1)	−0.566		0.974**		−0.721*		0.700**		−0.838**		−0.783*		0.822**		−0.158		−0.857*	
	0.365		0.397		0.367		0.346		0.332		0.445		0.354		0.389		0.515	
VPMFGL (−1)		−0.310		−0.691*		−0.519		−0.516		0.681**		−0.460		−0.568*		−0.051		−0.547
		0.355		0.386		0.375		0.332		0.318		0.428		0.335		0.367		0.462
AR (−1)	0.474	0.508	0.436***	0.474***	0.508***	0.534***	0.505***	0.527***	0.476***			0.496***						0.458***
	0.502***	0.407***		0.440***		0.504***		0.513***				0.394***						0.429***
0.092	0.091	0.097	0.096	0.081	0.083	0.065	0.067	0.082	0.083	0.108		0.105	0.075	0.074	0.092	0.092	0.112	0.109
AR (−2)	0.164**	0.130*	0.288***	0.246***	0.205**	0.177**	0.210***	0.183**	0.298***			0.277***						0.283***
	0.235***	0.320***		0.284***		0.139**		0.133*				0.224***						0.188**
0.067	0.067	0.092	0.088	0.083	0.084	0.072	0.070	0.091	0.090	0.088		0.084	0.073	0.068	0.074	0.074	0.083	0.080
AR (−3)	0.134**	0.134**	0.045	0.049	0.072	0.075	0.060	0.064	0.034	0.035	0.058	0.061	0.068	0.072	0.022	0.020	0.069	0.069
	0.058	0.058	0.056	0.055	0.061	0.060	0.052	0.052	0.059	0.059	0.051	0.050	0.056	0.056	0.076	0.076	0.061	0.060
Adjusted R-squared	0.494	0.491	0.523	0.518	0.547	0.544	0.525	0.522	0.586	0.584	0.564	0.560	0.545	0.541	0.362	0.361	0.379	0.374
Prob (Wald F-statistic)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Note: AR stands for lag monthly volatility realized, and AR (−1) and AR (−2) represent the first and second lags of volatility realized. SPX, CCMP, SPTX, MEXBOL, and IGBVL Lmex denote one-month volatility realized returns of the respective indices. The estimations from the first equation in Table 1 are presented here. $^{*}p < 10\%$, $^{**}p < 5\%$, and $^{***}p < 1\%$. Source: authors' elaboration.

Table 5: The forecasting realized volatility of Asian and Oceania stock market indices using in-sample analysis with monthly data and core econometric specifications shown in Table 1.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)
Variable	NKY					HSI				KOSPI		TWSE	JCI	FBMKLCI	STI	ASX		NZSE
C	−2.021***	−2.041***	−1.182***	−1.179***	−1.041***	−1.038***	−1.256***	−1.256***	−2.091***	−2.090***	−2.077***	−2.078***	−1.290***	−1.293***	−1.228***	−1.232***	−2.557***	−2.569***
	0.413	0.416	0.316	0.316	0.236	0.237	0.281	0.284	0.391	0.392	0.465	0.464	0.317	0.317	0.344	0.341	0.720	0.718
VMSTL (−1)	−0.913*		0.672**		0.829**		1.083***		−0.218		−0.476		−0.480		−0.472		0.623**	
	0.470		0.337		0.350		0.339		0.357		0.396		0.434		0.351		0.312	
VPMFGL (−1)		−0.660		0.655**		0.658**		0.948***		−0.175		−0.264		−0.359		−0.315		−0.498*
		0.430		0.322		0.333		0.324		0.334		0.374		0.396		0.334		0.291
AR (−1)	0.396***	0.418***	0.481***	0.484***	0.436***	0.458***	0.302***	0.313***	0.459***	0.462***	0.360***	0.377***	0.502***	0.515***	0.565*	0.585***	0.327***	0.334***
	0.080	0.080	0.066	0.067	0.070	0.070	0.073	0.073	0.071	0.072	0.073	0.071	0.059	0.057	0.072	0.070	0.069	0.068
AR (−2)	0.266***	0.237***	0.224**	0.222**	0.231***	0.208***	0.379***	0.369***	0.104	0.101	0.253***	0.238***	0.204***	0.191***	0.127***	0.106	0.222***	0.216***
	0.078	0.078	0.109	0.103	0.065	0.066	0.072	0.073	0.078	0.078	0.086	0.086	0.074	0.071	0.094	0.092	0.058	0.057
AR (−3)	−0.009	−0.006	0.099	0.098	0.165***	0.167***	0.119**	0.119**	0.096	0.096	0.102	0.100	0.098**	0.098**	0.124*	0.126*	0.105	0.103
	0.047	0.046	0.079	0.078	0.057	0.057	0.047	0.046	0.061	0.061	0.072	0.072	0.043	0.043	0.069	0.069	0.074	0.074
Adjusted R-squared	0.357	0.349	0.567	0.568	0.592	0.589	0.527	0.523	0.322	0.322	0.383	0.379	0.549	0.548	0.576	0.574	0.316	0.311
Prob (Wald F-statistic)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Notes: AR stands for lag monthly volatility realized, and AR (−1) and AR (−2) represent the first and second lags of volatility realized. SPX, CCMP, SPTX, MEXBOL, and IGBVL Lmex denote one-month volatility realized returns of the respective indices. The estimations from the first equation in Table 1 are presented here $^{*}p < 10\%$, $^{**}p < 5\%$, and $^{***}p < 1\%$. Source: authors' elaboration.

Table 6: Forecasts of realized volatility of North and Latin American stock market indices using out-of-sample analysis with monthly data ($\pi \equiv P/R = 0.4$).

(1) Benchmark model	(2) S&P 500—USA	(3) Nasdaq—USA	(4) Toronto composite—Canada	(5) BMV IPC—Mexico	(6) IBOVESPA—Brazil	(7) IPSA—Chile	(8) MERVAL—Argentina	(9) IGBVL—Peru
Panel A VPMFGL model								
AR (3)	−0.401	−0.435	−0.147	−0.567	0.053	−0.250	0.132	−0.814
AR (6)	−0.425	−0.517	−0.201	−0.441	0.046	−0.580	−0.030	−0.816
AR (3) VVIX(1)	0.358	0.284	−0.152	**0.766***	**3.278*****	−0.708	**0.738***	−0.215
AR(6) VVIX(1)	0.631	**0.732***	−0.020	**1.577****	**2.922*****	−0.916	**1.513****	−0.118
Panel B VMSTL model								
AR(3)	−0.330	−0.330	−0.036	−0.641	−0.081	−0.479	−0.002	−0.891
AR(6)	−0.294	−0.439	−0.102	−0.494	−0.020	−0.843	−0.154	−0.880
AR(3) VVIX(1)	−0.442	−0.327	−0.286	0.470	**2.794*****	−0.894	**0.763***	−0.202
AR(6) VVIX(1)	−0.270	0.041	−0.207	**1.265****	**2.695*****	−1.100	**1.448***	−0.205

10%, 5%, and 1% critical values are 0.685, 1.079, and 2.098, respectively, when there is only one excess parameter. P represents the number of one-step-ahead forecasts and R the sample size of the first estimation window. The AR (3)-VVIX (1) benchmark corresponds to model 1. $^{*}p < 10\%$, $^{**}p < 5\%$, and $^{***}p < 1\%$. Source: authors' elaboration.

Table 7: Forecasts of European realized stock market indices volatility using out-of-sample analysis with monthly data ($\pi \equiv P/R = 0.4$).

(1) Benchmark model	(2) FTSE—UK	(3) CAC—France	(4) DAX—Germany	(5) IBEX—Spain	(6) FTSEMIB—Italy	(7) AEX—Holland	(8) OMX—Sweden	(9) RTS—Russia	(10) SMI—Swiss
Panel A VPMFGL model									
AR(3)	0.107	**1.159****	0.218	**0.708***	**3.079*****	−0.907	**1.240****	−0.601	**1.208****
AR(6)	−0.104	**0.976***	0.100	0.460	**2.766*****	−1.086	0.360	−0.647	**1.172****
AR(3) VVIX(1)	−0.533	−0.049	−0.941	−0.353	0.602	−1.828	−0.411	−0.282	−0.543
AR(6) VVIX(1)	−0.667	−0.425	−1.071	−0.732	−0.004	−2.025	−0.866	−0.332	−0.730
Panel B VMSTL model									
AR(3)	**0.883***	**2.743*****	**1.394****	**2.151*****	**4.371*****	0.672	**2.747*****	−0.623	**2.617*****
AR(6)	0.608	**2.609*****	**1.260****	**2.150*****	**4.213*****	0.526	**1.872****	−0.733	**2.522*****
AR(3) VVIX(1)	−0.325	**1.048***	−0.233	**0.747***	**1.333****	−0.886	0.034	−0.722	0.043
AR(6) VVIX(1)	−0.531	0.682	−0.310	0.468	**0.718***	−1.090	−0.516	−0.871	−0.135

10%, 5%, and 1% critical values are 0.685, 1.079, and 2.098, respectively, when there is only one excess parameter. P represents the number of one-step-ahead forecasts and R the sample size of the first estimation window. The AR(3)-VVIX(1) benchmark corresponds to model 1. $^{*}p < 10\%$, $^{**}p < 5\%$, and $^{***}p < 1\%$. Source: authors' elaboration.

Table 8: Forecasts of realized volatility of Asian and Oceania stock market indices using out-of-sample analysis with monthly data ($\pi \equiv P/R = 0.4$).

(1) Benchmark model	(2) NIKKEI—Japan	(3) HANG-SENG—Hong Kong	(4) KOSPI—Korea	(5) TSE—Taiwan	(6) Jakarta stock exchange—Indonesia	(7) KLCI—Malaysia	(8) Strait Times—Singapore	(9) ASX—Australia	(10) NZSE—New Zealand
Panel A VPMFGL model									
AR(3)	**2.284*****	**3.221*****	**2.478*****	**4.994*****	−0.467	**1.038****	**1.818****	**1.938****	**2.322*****
AR(6)	**1.599****	**2.691*****	**2.002****	**5.929*****	−0.778	**1.008****	**1.649****	**2.344*****	**3.042*****
AR(3) VVIX(1)	−0.353	−0.529	−0.374	0.005	−0.282	−0.081	−0.062	−0.268	−0.394
AR(6) VVIX(1)	−0.738	−1.050	−0.607	0.135	0.357	−0.354	−0.152	−0.284	−0.504
Panel B VMSTL model									
AR(3)	**4.630*****	**3.063*****	**3.268*****	**5.946*****	−0.484	**2.135*****	**2.638*****	**2.958*****	**3.625*****
AR(6)	**3.977*****	**2.469*****	**2.541*****	**6.841*****	−0.815	**2.008****	**2.268*****	**3.319*****	**4.343*****
AR(3) VVIX(1)	**0.774***	−0.621	−0.110	0.104	−0.409	−0.304	0.259	−0.107	−0.447
AR(6) VVIX(1)	0.329	−1.045	−0.515	0.147	0.158	−0.474	0.087	−0.189	−0.538

10%, 5%, and 1% critical values are 0.685, 1.079, and 2.098, respectively, when there is only one excess parameter. P represents the number of one-step-ahead forecasts and R the sample size of the first estimation window. The AR(3)-VVIX(1) benchmark corresponds to model 1. $^{*}p < 10\%$, $^{**}p < 5\%$, and $^{***}p < 1\%$. Source: authors' elaboration.

markets, consistent with the persistence of financial markets: an increase in volatility is an indicator of an increase in volatility in the following period. This relationship is consistent with the first lag in all markets except the UK, but statistical significance decreases for the second and third lags. Finally, the adjusted determination coefficients are between 27.6% and 59.2%, the highest being the KOSPI in Korea and the lowest the SPIPSA in Chile.

4.2. Out-of-Sample. Tables 6–8 show the ENCNEW test results [63] in out-of-sample exercise for the Americas, Europe, and Asia-Oceanic. These tables focus on the core models described in Table 1 panel B, and the results correspond to the statistical difference between the core models presented in Table 1 panel B (with VMSTL and VPMFGL) versus the benchmark models presented in Table 1 panel C when the number of observations to make the forecast is 40% of the total sample ($P/R = 0.4$).

In Tables 6–8, we use the following notation to describe specifications in Table 1: AR (3) and AR (6) denote an autoregressive process of orders 3 and 6, respectively, for the one-period return in realized volatility stock indices. VVIX (1) denotes a lag effect of the monthly variation of the VIX, in order to add a robustness test to the results. Additionally, we separate Tables 6–8 into two panels: panel A in Tables 6–8 reports the comparison of the core model (Table 1 panel B) that includes the lagged variation of the PMFGL in one month with our benchmark models (Table 1 panel C); panel B in Tables 6–8 reports the comparison of the core model (Table 1 panel B) that includes the lagged variation in a period of the MSTL with the benchmark models (Table 1 panel C)

In the case of America (Table 6), only the markets of Mexico, Brazil, and Argentina reject the null hypothesis for the VVIX benchmark models. In Brazil's case, the probability of rejecting the null hypothesis is greater than 1%, which means that the forecast model incorporates the lag of the variation of the MSTL, and the lag of the variation of the PMFGL is statistically better than the VVIX benchmarks models. This result is repeated for Mexico and Argentina, although with a significance level that fluctuates between 5% and 10%.

Regarding Europe, the core models (incorporating the one-month lag variation of the MSTL and PMFGL) obtain better results compared to all the benchmark models. In general terms, we observe that the MSTL has greater predictive power than the PMFGL, which turns out to be significant in 7 out of 9 European markets considered, while the model that considers the PMFGL only turns out to be significant in 5 out of 9 markets. Panel B of Table 7 shows the results of the model comparison that includes the lagged variation of the MSTL.

We present similar results in Asia and Oceania. Table 8 shows that 8/9 market indices reject the null hypothesis, all over the 5% levels, indicating that both the variation of the PMFGL lagging in one period and the variation of the MSTL lagging in a period add useful information for improving the forecast of benchmark models. However, when comparing with a benchmark model that incorporates the VVIX lagging in a period, the significance of the proposed models disappears, indicating a strong influence of the VIX on the volatility of the Asian and Oceania economies.

5. Conclusions

The interconnectedness among financial institutions plays a crucial role in terms of the systemic risk of financial markets. This issue is especially critical during financial turmoil when uncertainty and volatility spur. The recent financial network literature has been studying this phenomenon, focusing mainly on situations where a shock over a single or a group of critical nodes could destabilize the entire system [70]. Independently of the nature of the shocks, its consequences are clear in terms of volatility on financial markets, especially on stock markets and their time-varying dependence structure [71].

In this research, we explore a different view. As the economic and financial literature states, uncertainty provokes a negative impact on economic growth, expectations, investment, consumption, and future returns on stock markets. For this reason, we analyze network theory's application as a tool to forecast the volatility of stock markets. In this sense, improving the actual forecasting models in terms of performance and accuracy will benefit practitioners, regulators, and academics in their tasks.

We contribute to the extant literature in two ways. On the first hand, we help to improve the actual forecasting models in terms of performance and accuracy, which will benefit practitioners, regulators, and academics in the task of financial market regulation, crisis monitoring, portfolio management, risk strategies, and asset pricing, among other roles. On the other hand, we establish a bridge between two important fields: financial network and forecasting literature. This paper could generate more significant developments in both areas, enhancing the quality of empirical analysis of financial markets and gaining a broad view of complex systems.

Our results evidence that it is possible to improve actual forecasting volatility models through network metrics for many stock indices. Using assets' correlation networks, we show that the forecasting accuracy and performance of realized volatility standard models enhance, even including volatility gauges such as CBOE VIX index as a control variable. This outcome is a novel contribution from the financial networks' literature to the economic and financial areas to develop future contributions and connections between these two relevant fields.

These results have two implications. From a practitioner's point of view, it is possible to use these network measures to assess current and future diversification possibilities and forecast the portfolios' expected volatilities, improving consequently, delegated investment services. Secondly, these results are useful for regulatory agents, who monitor the state of the financial system, its stability, and its systemic risk.

Our research contributes to enhancing the forecasting capabilities of volatility in financial markets based on market data. From a policy point of view, it is highly desirable that Central Banks, Stocks Exchanges, and the investment community, in general, advance in the task of improving the estimations of volatility. For instance, whether an independent institution monitors and publishes future volatility prospects, the evolution of asset synchronization, and asset diversification capabilities will help agents better assess risk and return relationships in the financial markets, with its consequently positive impact on the financial efficiency. In this sense, this work would help policymakers improve financial stability frameworks and design models that consider financial markets a complex system, i.e., their underlying structure, their correlations, and their interactions.

We built the edges of the complete network based on Pearson correlations between returns of different stock indices. These correlations measure the linear association between them, leaving aside a more complex nonlinear component that determines the covariation between different elements of this system. A possible extension of this work is to capture these nonlinearities through more sophisticated methods inferring the network's structural connectivity [72].

Likewise, the presence of high-frequency cross-correlations between synchronous time evolution of stock markets is known. It is also known that when considering higher frequencies (not only across one day-trading), there are changes in the stocks' hierarchical structures [25]. This idea makes us think that the realized volatility can be expressed differently according to the frequency used in the analysis, and consequently, it would be necessary to study the behavior of our volatility models proposed in these scenarios.

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

High-Frequency Trading and Its Impact on Exogenous Liquidity Risk of China's Stock Index Futures Market before and after Trading Restrictions

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Since China's first stock index futures, China Securities Index 300 (CSI300) stock index futures were published in 2010, and China's stock index futures market is now in a period of rapid development and play a key role in price discovery. During 2014 to 2015, China's stock index futures market fluctuated abnormally, and the overuse of high-frequency trading (HFT) strategies in the stock index futures market was blamed as the main reason of the abnormal volatility. To lower down market fluctuation, the regulatory institute then announced a series of trade restriction policy to prevent the overuse of HFT behaviour. However, until now, the impact of such trade restriction policy for HFT remains uncertain. To tackle this issue, based on minute-level HFT data from the CSI 300 index futures market, this paper aims to investigate the relationship between HFT and the exogenous liquidity risk and how HFT affects China's stock index futures market on its liquidity using the liquidity-adjusted value at risk (LVaR) model. The findings indicate that HFT improves the return of the liquidity provider and reduces the exogenous liquidity risk significantly.

1. Introduction

Stock index futures are an important financial derivative, and their main function is to maintain capital values and avoid systematic risk in the stock market. Since the stock index futures market is closely related to its stock spot market, coupled with the principle of leveraged trading of futures, the marginal risk of the stock index futures market may cause risks in the spot market through the risk transmission mechanism. Nowadays, with the rapid development of trading technology in recent years, high-frequency trading, a kind of programmatic trading, based on low latency between order submission and execution or cancellation, is booming in the China stock index futures market. However, HFT may make bid-ask spread in low level, and hence it could easily cause liquidity risk and pose new challenges to the risk management of the China stock index futures market. In this circumstance, investors may bear huge liquidity risk leading to huge losses, and the market will lose its function [1].

On June 12, 2015, the Shanghai Stock Exchange Composite Index (SH index) reached 5178, a new peak in recent years. After that, the spot market fluctuated violently, over a thousand stocks went through stock suspension during that period, trading volume dropped sharply, and market liquidity hit the freezing point. Some scholars think that the overuse of HFT in the stock index futures market is the key factor of the sharp fluctuation of the spot market. From August to September in 2015, the China Financial Futures Exchange (CFFEX) issued a series of stock index futures trading restriction measures to lower the sharp fluctuations of the stock market and reduce the excessive speculation behaviour in the market. The policies aim to regulate the trading behaviour of the stock index futures market through lifting the HFT cost in order to promote the healthy development of the China stock index futures market. However, it is reported that these regulatory measures such as increasing margin and limiting opening positions have a series of negative effects on the futures market and the spot market, respectively, especially for the liquidity level on both markets. Liquidity refers to the possibility that investors can trade a certain asset with less trading time, lower transaction cost, reasonable price level, and smaller price fluctuation, while liquidity risk means all kinds of risks such as sharp rise in transaction costs, extended trading time, and difficulty in realizing due to the loss of investors' confidence. Lack of liquidity in the market may make it hard for investors to complete the transaction.

In the existing research studies on liquidity risk, many researchers have expounded the importance of the liquidity risk. Jorion [2] pointed out that liquidity is the most important issue in risk management. The vast majority of unforeseeable losses are caused by the sudden disappearance of liquidity due to the lack of liquidity in the market or by increased clearing costs due to the market moving in the opposite direction to the traders' positions. Amihud and Mendelson [3] described liquidity as "everything in the market." Lawrence and Robinson [4] mentioned that ignoring liquidity risk is much likely to lead to undervaluation of the market risk, which could be about 15 percent. Dowd [5] thought that losses caused by liquidity risks may even be as large as those caused by market risks. Pastor and Stambaugh [6] proved in their empirical study that the market shock cost in the direction of buying or selling is used as the state variable to measure the market liquidity risk.

Because of the characteristics of the liquidity risk as an indispensable systemic risk and its important position in risk management, researchers have been trying to conduct in-depth research on liquidity risk for decades, in order to find a more suitable liquidity risk measurement model for the capital market, so as to better understand the market where they are located. As to the measurement of the liquidity risk, Bangia, Diebold, and Stroughair [7] divide liquidity into exogenous and endogenous components.

Exogenous liquidity is determined by market characteristics and has the same impact on each market participant, independent of the individual trading behaviour of individual market participants [8]. Markets with good exogenous liquidity tend to have much trading volume and more stable bid-ask spread. On the contrary, bid-ask spread in the market with poor exogenous liquidity fluctuates greatly, while the depth of declaration and trading volume is relatively small. Endogenous liquidity is related to the positions held by investors. Generally speaking, the larger the positions held by investors, the worse the endogenous liquidity. However, the measurement of endogenous liquidity needs to be based on the assumption of positions, and the data of investors' positions are often not easy to obtain. Therefore, the computation in this paper takes only the risk of exogenous liquidity that will affect any investor into account and ignores the possible impact of endogenous liquidity.

With the development of financial theory and financial engineering, financial market risk measurement technology has become more comprehensive. At present, the main methods of financial market risk measurement include the sensitivity analysis method, volatility analysis method, VaR method [2], stress test [9], extreme value theory [10], and Copula [11]. Among the above methods, the value at risk model (VaR) is one of the mainstream methods on risk measurement in the financial market. Since the 1990s, it has been introduced into risk management and gradually widely used in the field of market risk measurement and supervision. However, the traditional VaR model still has some limitations. For instance, traditional VaR models do not take the impact of investors' trading behaviors on market prices (or market shocks) into account. The traditional VaR model is based on the assumption that investors can clear in a short time, so it ignores the possible losses caused by price fluctuations. Furthermore, the impact of clearing on bid-ask spreads in market makers' markets is also not taken into account.

However, the VaR model ignores that the big deals may lead to market price and price fluctuation; in order to improve the deficiency of the VaR model, Hisata and Yamai [12] argure that the uncertainty of bid-ask spread can be regarded as an indicator of liquidity risk, so the volatility of bid-ask spread is introduced into exogenous cost of liquidity (ECL), and they propose the LVaR model (liquidity-adjusted value at risk). As for domestic research studies in China on the liquidity risk study, Hu and Song [13] took the stock price of 16 listed commercial banks in China as samples to establish the VaR model after liquidity risk adjustment. Based on the day-level trading data of Shanghai stock exchange, Zhu [14] defined the measure index of liquidity risk from the perspective of the price shock faced by investors in actual investment. Xu et al. [15] used the VaR model to verify the liquidity risks of enterprises with different liquidity in the NEEQ (National Equities Exchange and Quotations) market under different market conditions and proposed the corresponding regulation policy. Tong et al. [16] theoretically analyzed day-level liquidity risk, studied the relationship between regulatory indexes and day-level liquidity risk, and explored the deficiencies of regulatory framework indexes.

1.1. Highlights. Despite considerable research results on liquidity risk, they are mainly concentrated in the spot market such as the stock market. At present, due to the complexity of the liquidity risk formation mechanism in the futures market, relevant research on HFT in China's stock index futures market is still scarce, and systematic research work has not yet been carried out, not to speak at intraday level. The above detail illustrates the importance of liquidity risk measurement of the stock index futures market and the lack of relevant theoretical research in China. Given the importance of that, research on the stock index futures market in China based on the financial market microstructure theory is carried out in this paper. Specifically, the LVaR model is used to quantify the liquidity risk using minute-level HFT data of CSI 300 index futures.

The main contribution of this study includes the following:

(1) The experimental data used in this paper are based on minute-level HFT data ranging from 2014 to 2016 which spans the entire stock index futures market turbulent period containing the period under trading restrictions, which is beneficial to systematically study the relationship between HFT and liquidity risk in the stock index futures market, and has an extremely valuable research value.

(2) The liquidity risk model is illustrated by LVaR to demonstrate how HFT affects liquidity on the CSI 300 index futures market. The research results and conclusions are of great significance to the market risk management of other financial futures, such as providing reference for the risk monitoring of other stock index futures products, treasury futures products, and other financial derivatives that may be launched in the future.

The rest of the paper is organized as follows. Section 2 briefly describes the problem statement including the basic concepts of liquidity risk and why the specific range of data is selected for the experiment. In Section 3, the relationship between HFT and liquidity is demonstrated by the VAR model. In Section 4, the LVaR model is introduced to model exogenous liquidity risk, and the impact of HFT is deeply analyzed. Section 5 concludes the paper.

2. Problem Statement

Regarding if HFT is beneficial to the liquidity risk in the stock index futures or not, the research community has been controversial. Besides, to the best of our knowledge, the impact of HFT on China's stock index futures market has not been deeply analyzed before. In this context, the study of HFT on China's stock index futures market has both theoretical and practical meanings.

In this section, the definition of liquidity risk is first introduced. And, the range of experimental data used in this paper and why we choose that to demonstrate the liquidity risk brought by HFT are then presented.

2.1. Concepts of Liquidity. Liquidity was first proposed by Keynes in 1936 and is now broadly defined as "liquidity is a price-balanced ability to buy and sell large amounts of certain financial assets without fluctuating their prices."

Bangia et al. [7] think liquidity should be classified into two parts: endogenous liquidity and exogenous liquidity. Exogenous liquidity is determined by market characteristics and is not affected by the individual trading behaviour of individual market participants and is the same for each market participant.

The market trade volume with good exogenous liquidity is very large, the bid-ask spread is small and stable, and the quotation depth (the possible trading volume under the existing bid-ask price level of the market maker) is high. In this case, the realization cost is relatively small and can even be ignored. Conversely, a market with poor exogenous liquidity would be characterized by a large fluctuation in bid-ask spreads and a very small quotation depth and trading volume.

As can be seen from Figure 1, the relationship between position size and liquidation value is as follows: when the quantity of the buy order (sold) is less than the depth of the buy order, the transaction can be traded at the current quotation level. At this time, only the exogenous liquidity risk exists, and there is no endogenous liquidity risk. On the contrary, when the amount of buying (selling) is higher than the quotation depth, the realized cost of the asset will exceed the current quotation level, which will cause the exogenous liquidity risk and the endogenous liquidity risk to exist at the same time. The portion of the cost is reflected as the endogenous liquidity risk.

Endogenous liquidity, on the other hand, is related to positions held by market participants. Generally speaking, the larger the position held by market participants, the worse the endogenous liquidity. Figure 1 shows the relationship between position and the realized value. The measurement of endogenous liquidity needs to be based on the assumption of the position volume, which is not available. Therefore, in the following liquidity risk calculation, only the risk brought by the exogenous liquidity is considered.

2.2. Trade Regulation Change and Its Impact on CSI 300 Index Futures. Since the CSI 300 index future was published in April in 2010, the trade regulation underwent a series of change, and it is summarized in Table 1.

As can be seen from Table 1, the trade restriction policy introduced in September 2015 was the most severe one, in which the transaction fee rose from 0.115‰ to 2.3‰ which greatly increased the cost of speculative transactions, which obviously has a tremendous impact on the market structure and market liquidity.

Figure 2 illustrates the trend of the closing price of CSI 300 index futures. It can be clearly seen that the market has experienced different market stages such as rising and plunging, spanning the entire turbulent period before and after the stock market crash, which indicated that the trading restriction policy has had a tremendous impact on the stock index future.

Figure 3 presents the trading volume of the CSI 300 index futures (logarithm). Compared with the trading volume before trade restriction (blue part), after the restriction policy was implemented on September 7 in 2015, due to the increase in margin, the cost of high-frequency transaction increased significantly, and the trading volume of the CSI 300 stock index futures (red part) was significantly reduced, indicating that the trading restriction policy has had a tremendous impact on stock index futures.

In order to effectively compare the impact of HFT on the liquidity of China's stock index futures market, this paper adopts an event-driven approach, taking the strictest trading restriction measures implemented in September in 2015 as the divided point. The experimental data samples are divided into two parts (see Table 2). The first part is from July 1, 2014, to September 2, 2015, and the second part ranges from September 7, 2015, to December 31, 2015. The first part can be simply thought as the active period of HFT, and the second part is nonactive because of the extreme expensive rate of the transaction fee, which is 20 times higher than before, and limited opening hands. Therefore, the first part of this period can be used to analyze how HFT affects the

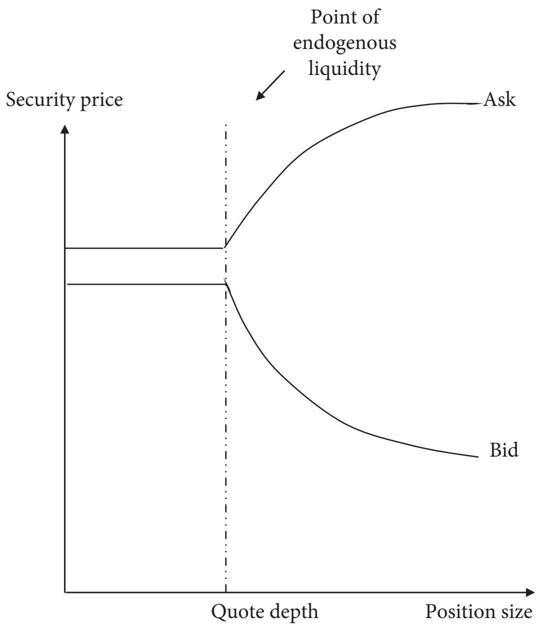

Figure 1: Relationship between position size and security size.

liquidity risk in the stock index future market, while the second part is used for comparison.

3. Correlation of HFT and Market Liquidity

In this section, the basic explanation of the VAR model will be given, followed by experiments on how HFT is correlated with market liquidity. The purpose of this section is to explore the relationship between HFT behaviour and market liquidity in the China stock index futures market using the trading agent index and liquidity indicators.

3.1. Correlation of HFT with Market Liquidity Based on VAR Model. Vector autoregression model (VAR) proposed by Sims in 1980 that has been widely used in the international finance and capital market is used in our study. The VAR model decomposes the variable y into linear combinations of other variables and performs similar equation relations for other variables. It uses multiple simultaneous equations for modeling the relationship between variables. In each equation, endogenous variables will carry out regression of the lag value of all endogenous variables contained in the model, so as to estimate the dynamic relationship between all endogenous variables and make predictions. The specific formula is as follows:

$$y_{1t} = c_1 + A_1 y_{1.t-1} + \cdots + A_k y_{1.t-k} + +B_1 y_{2.t-1} + \cdots + B_k y_{2.t-k} + u_{1t}, \tag{1}$$

where y_{1t} and y_{2t} are the k vectors of endogenous variables. Based on the VAR model shown in equation (1), the correlation between y_{1t} and y_{2t} is established. u_t is the random disturbance term of each equation, c is the constant constraint term, and A and B are the coefficients of the lagging variable to be estimated.

Based on the VAR model introduced above, the correlation analysis between HFT and liquidity is given as follows:

$$\text{algo}_t = c_1 + \sum_{j=1}^{3} \delta^j \text{algo}_{t-j} + \alpha_1 \text{sprd}_t + \sum_{n=1}^{3} \Pi_n \text{sprd}_{t-n} + \nu_{1,t}\text{Size}_t + \psi_{1,t}\text{Vol}_t + u_{1t}, \tag{2}$$

$$\text{sprd}_t = c_2 + \sum_{k=1}^{3} \Pi_k \text{sprd}_{t-k} + \beta_1 \text{algo}_t + \sum_{m=1}^{3} \theta_m \text{algo}_{t-m} + \nu_{2,t}\text{Size}_t + \psi_{2,t}\text{Vol}_t + u_{2t}, \tag{3}$$

where algo_t represents the trading amount of AT, which indicates the activeness of HFT behaviour; sprd_t as bid-ask spread is a collection of the liquidity measurement index including itself and the other two indicators as follows: $eSprd_t$ represents the effective spread and $r\text{Sprd}_t$ represents the realization spread, which indicates the income and net compensation of the liquidity provider like HF traders. Besides, advSel_t represents the adverse selection cost. There are also two control variables, $Size_t$ is the transaction size and Vol_t is the volatility, which is determined by calculating historical volatility at the midpoint of the buy-sell price. Other variables including δ, α, β, Π, θ, ψ, and ν are coefficients to be estimated.

For determining lag length k, we use two popular methods, the Akaike Information Criteria (AIC) [17] and the Schwartz Information Criteria (SIC) [18], to determine an appropriate lag period. Both AIC and SIC suggest a lag period (k=3); therefore, the lag period (k=3) is used in this study.

3.2. Correlation Analysis Result. Based on the VAR model introduced above, in this section, we compare the correlation analysis result to validate the correlation between HFT and market liquidity.

The experimental results are listed in Tables 3 and 4, where the correlation between the HFT agent index Algo_t and liquidity indicators including sprd_t, $r\text{Sprd}_t$, $e\text{Sprd}_t$, and AdvSel_t is investigated, as shown in Model 1 to Model 4, respectively.

First, since the HFT activeness period is not known, we use HFT data during a long period spanning the HFT restriction policy (2014.07.01–2016.05.31) for correlation analysis, and the result is shown in Table 3.

In Table 3, the coefficient factor in Models 1–4 shows the correlation result between the HFT agent index $algo_t$ and different liquidity indicators including sprd_t, $r\text{Sprd}_t$, $e\text{Sprd}_t$, and AdvSel_t, respectively. Panel C (Models 1–4) shows the weak correlation between HFT and liquidity indicators, for which the coefficient of the lag term at time t-1 is −0.0103, −0.004, 0.0333, and 0.0069 at a confidence level 0.05, respectively. It indicates that to some extent, HFT may correlate with the liquidity level from a large period which spans the trade restriction policy.

Considering a series of strict control measures on stock index futures trading since September 2015, especially the standard for setting the rule that abnormal trading is regarded as 10 hands per day, the activity of high-frequency trading has been greatly inhibited.

Table 1: Trading rules of CSI 300 index futures (until the end of 2018).

Time	Nonscheduled policy opening hands limit	Nonhedging (%), hedging position trading margin (%)	Transaction fee (‰)
2012.6.29	—	12, 12	0.035
2014.9.1	—	10, 10	0.025
2015.8.28	600	20, 10	0.115
2015.8.31	100	30, 10	0.115
2015.9.7	10	40, 20	23
2017.2.17	20	20, 20	9.2
2017.9.18	20	15, 15	6.9
2018.12.3	50	10, 10	4.6

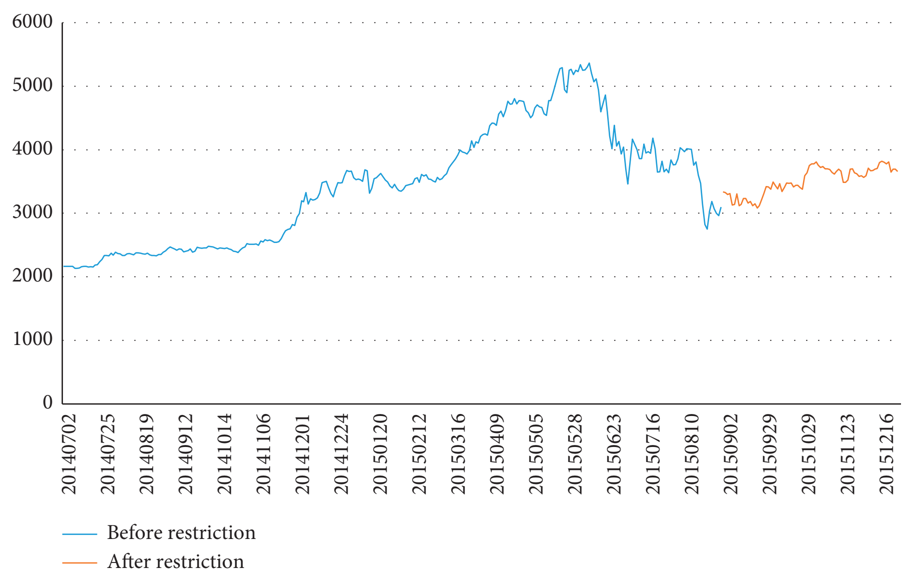

Figure 2: Closing price of CSI 300 index futures before and after trade restriction (2014.7.1–2015.12.31).

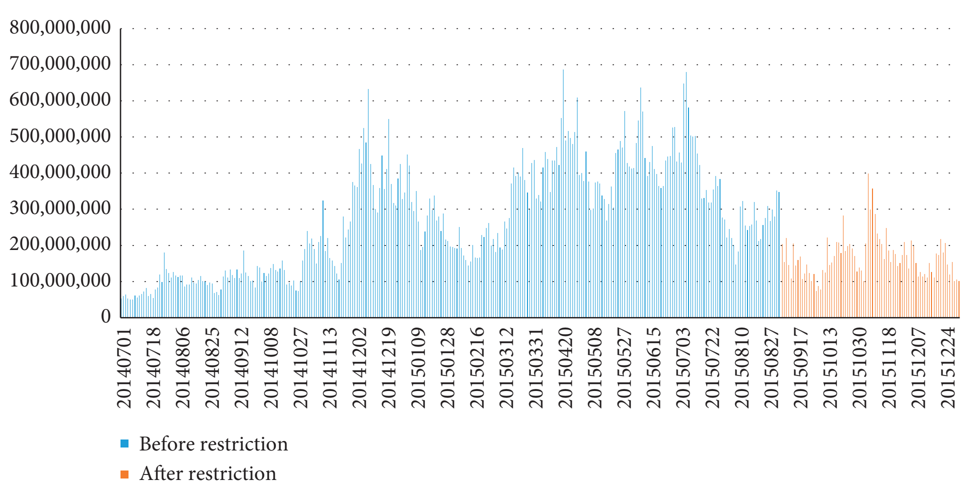

Figure 3: Volume of CSI 300 index futures before and after trade restriction (2014.7.1–2015.12.31).

Table 2: Experimental data.

Before restriction	After restriction
2014.07.1 ~ 2015.09.02	2015.09.07 ~ 2015.12.31

In this part, a more specific period range from July 1, 2014, to September 2, 2015, is selected to further analyze the correlation between HFT and market liquidity.

Table 3: Relationship between algorithmic trading and liquidity indicators (July 1, 2014–May 31, 2016).

Model 1				Model 2			
Algo_t		Sprd_t		Algo_t		$r\text{Sprd}_t$	
c_1	0.2154***	c_2	1.0475***	c_1	0.1487***	c_2	2.8018***
Panel A: contemporaneous variables							
Sprd_t	0.0236***	Algo_t	0.0825***	$r\text{Sprd}_t$	0.005***	Algo_t	1.3549***
Panel B: autoregressive lagged variables							
Algo_{t-1}	0.5215***	Sprd_{t-1}	0.6896***	Algo_{t-1}	0.5214	$r\text{Sprd}_{t-1}$	0.2288***
Algo_{t-2}	0.1724***	Sprd_{t-2}	0.1126***	Algo_{t-2}	0.1878*	$r\text{Sprd}_{t-2}$	0.0439***
Algo_{t-3}	0.1648***	Sprd_{t-3}	0.1029***	Algo_{t-3}	0.1598	$r\text{Sprd}_{t-3}$	0.1057***
Panel C: cross effect of lagged variables							
Sprd_{t-1}	−0.0103	Algo_{t-1}	−0.0747***	$r\text{Sprd}_{t-1}$	−0.0004	Algo_{t-1}	−0.2771
Sprd_{t-2}	−0.0043	Algo_{t-2}	0.0319	$r\text{Sprd}_{t-2}$	0.0041***	Algo_{t-2}	−0.4124*
Sprd_{t-3}	−0.0015	Algo_{t-3}	0.0311	$r\text{Sprd}_{t-3}$	0.0022***	Algo_{t-3}	−0.3044
Panel D: control variables							
Vol_t	−0.0251***	Vol_t	0.0232***	Vol_t	−0.0379***	Vol_t	1.1059***
Size_t	−0.4785***	Size_t	−0.4618***	Size_t	−0.4203***	Size_t	0.0059***
Model 3				Model 4			
Algo_t		$e\text{Sprd}_t$		Algo_t		AdvSel_t	
c_1	0.1171**	c_2	0.0692***	c_1	0.1383***	c_2	1.8431***
Panel A: contemporaneous variables							
$e\text{Sprd}_t$	0.1636*	Algo_t	0.0032*	AdvSel_t	−0.0055***	Algo_t	−0.6859***
Panel B: autoregressive lagged variables							
Algo_{t-1}	0.5201***	$e\text{Sprd}_{t-1}$	0.6776***	Algo_{t-1}	0.5372***	AdvSel_{t-1}	0.2436***
Algo_{t-2}	0.1723***	$e\text{Sprd}_{t-2}$	0.1199***	Algo_{t-2}	0.1869***	AdvSel_{t-2}	0.1019***
Algo_{t-3}	0.1544***	$e\text{Sprd}_{t-3}$	0.1029***	Algo_{t-3}	0.1600***	AdvSel_{t-3}	0.0906***
Panel C: cross effect of lagged variables							
$e\text{Sprd}_{t-1}$	0.0333	Algo_{t-1}	−0.0038*	AdvSel_{t-1}	0.0069***	Algo_{t-1}	0.9865***
$e\text{Sprd}_{t-2}$	0.0737	Algo_{t-2}	0.0036*	AdvSel_{t-2}	0.0049***	Algo_{t-2}	−0.1064
$e\text{Sprd}_{t-3}$	−0.1213	Algo_{t-3}	0.0038**	AdvSel_{t-3}	0.0024***	Algo_{t-3}	0.3277**
Panel D: control variables							
Vol_t	−0.0257***	Vol_t	0.0017***	Vol_t	−0.0307***	Vol_t	1.1320***
Size_t	−0.4324***	Size_t	−0.0237***	Size_t	−0.3814***	Size_t	0.7659***

*, **, and ***Significant levels of 0.05, 0.01, and 0.001, respectively.

Compared with Table 3, in Table 4, the coefficients in Panel C from lag term 1 to 3 all shows that the correlation between HFT and liquidity indicators increases to 0.1643, 0.19926, 0.0094, and 0.0094 at a confidence level 0.05, which is far greater than the corresponding coefficients in Table 3. It means before the restriction policy, HFT is obviously more active, and the correlation between market liquidity level is stronger. In Panel D, all the liquidity indicators show a positive correlation with volatility, indicating that when the volatility is higher, the liquidity is higher. *AT* activity is negatively correlated with volatility and trading size, indicating that algorithmic traders tend to trade when volatility and trading size are smaller. This means that algorithmic traders like HF traders tend to enter the market strategically with lower transaction costs and less information asymmetry, which indicates that HFT improves the market liquidity level.

Based on the above experiments, it can be concluded that before trade restriction when HFT behaviour is active, more algorithm-based trades are correlated with market liquidity indicated by a larger absolute spread (Sprd_t), larger effective spread ($e\text{Sprd}_t$), larger realized spread ($r\text{Sprd}_t$), and less adverse selection (advSel_t). It also indicates that the trade restriction policy greatly changes the activeness of HFT behaviour.

4. Impact of HFT on Liquidity Risk

The correlation between HFT and liquidity is demonstrated by the VAR model in Section 3. To further analyze how HFT influences exogenous liquidity risk before and after trade restriction, the LVaR is introduced in this section.

4.1. Liquidity Risk Value Measurement Model. The classis VaR model and the improved LVaR model-added market factors are introduced in this section, which is the basis for analyzing the impact of HFT on liquidity risk with the LVaR model in the next section.

4.1.1. VaR Model. In China's order-driven futures market, investors' trading orders are directly paired through the trading

Table 4: Relationship between algorithmic trading and liquidity indicators (September 7, 2015–December 31, 2015, excluding opening and closing time windows).

Model 1				Model 2			
Algo_t		Sprd_t		Algo_t		$r\text{Sprd}_t$	
c_1	0.0651	c_2	0.6159***	c_1	0.3095***	c_2	−0.7202
Panel A: contemporaneous variables							
Sprd_t	−0.1405***	Algo_t	−0.0928***	$r\text{Sprd}_t$	−0.0157***	Algo_t	−2.2388***
Panel B: autoregressive lagged variables							
Algo_{t-1}	0.5563***	Sprd_{t-1}	0.6350***	Algo_{t-1}	0.5653***	$r\text{Sprd}_{t-1}$	0.2318***
Algo_{t-2}	0.1956***	Sprd_{t-2}	−0.0413*	Algo_{t-2}	0.2185***	$r\text{Sprd}_{t-2}$	0.1695***
Algo_{t-3}	0.1648***	Sprd_{t-3}	0.1945***	Algo_{t-3}	0.1528***	$r\text{Sprd}_{t-3}$	0.0814***
Panel C: cross effect of lagged variables							
Sprd_{t-1}	0.1643***	Algo_{t-1}	0.0332**	$r\text{Sprd}_{t-1}$	0.0094***	Algo_{t-1}	1.5264***
Sprd_{t-2}	0.0582**	Algo_{t-2}	0.0154	$r\text{Sprd}_{t-2}$	0.0098***	Algo_{t-2}	0.6386**
Sprd_{t-3}	0.0257	Algo_{t-3}	0.0404***	$r\text{Sprd}_{t-3}$	0.0028**	Algo_{t-3}	0.3712*
Panel D: control variables							
Vol_t	−0.0312***	Vol_t	0.0291***	Vol_t	−0.0220***	Vol_t	1.0666***
Size_t	−0.2917***	Size_t	−0.2738***	Size_t	−0.3589***	Size_t	1.8179***
Model 3				Model 4			
Algo_t		$e\text{Sprd}_t$		Algo_t		AdvSel_t	
c_1	0.1261	c_2	0.0242***	c_1	0.3069***	c_2	−0.7350
Panel A: contemporaneous variables							
$e\text{Sprd}_t$	−1.5548***	Algo_t	−0.0069***	AdvSel_t	−0.0157***	Algo_t	−2.2388***
Panel B: autoregressive lagged variables							
Algo_{t-1}	0.5478***	$e\text{Sprd}_{t-1}$	0.6694***	Algo_{t-1}	0.5653***	AdvSel_{t-1}	0.2319***
Algo_{t-2}	0.1894***	$e\text{Sprd}_{t-2}$	−0.0705***	Algo_{t-2}	0.2183***	AdvSel_{t-2}	0.1694***
Algo_{t-3}	0.1598***	$e\text{Sprd}_{t-3}$	0.2118***	Algo_{t-3}	0.1529***	AdvSel_{t-3}	0.0816***
Panel C: cross effect of lagged variables							
$e\text{Sprd}_{t-1}$	1.9926***	Algo_{t-1}	0.0047***	AdvSel_{t-1}	0.0094***	Algo_{t-1}	1.5239***
$e\text{Sprd}_{t-2}$	0.7224**	Algo_{t-2}	0.0015	AdvSel_{t-2}	0.0098***	Algo_{t-2}	0.6369**
$e\text{Sprd}_{t-3}$	0.4966*	Algo_{t-3}	0.0033**	AdvSel_{t-3}	0.0028**	Algo_{t-3}	0.3732*
Panel D: control variables							
Vol_t	−0.0307***	Vol_t	0.0018***	Vol_t	−0.0220***	Vol_t	1.0658***
Size_t	−0.4101***	Size_t	−0.0069***	Size_t	−0.3589***	Size_t	1.8174***

*, **, and ***Significant levels of 0.05, 0.01, and 0.001, respectively.

system, and the flow of trading commissions is the fundamental driving force of liquidity.

Supposing that the investor's logarithmic return at time t in the long position dominant contract of the stock index futures conforms to the random walk process, then

$$P_t = P_{t-1} e^{\mu + \sigma \varepsilon_t}, \tag{4}$$

in which P_t is the midpoint price of the quote at time t, μ is the drift rate, σ is the standard deviation of the return rate, ε_t is the random disturbance term, and there is $\varepsilon_t \sim N(0,1)$. Assuming an offset rate of 0, the 1-day short position VaR at 99% confidence level under a standard normal distribution can be simplified as

$$VaR = P_t \left(1 - e^{-2.33\theta\sigma_t}\right). \tag{5}$$

There will be a large price change when the dominant contract rolls, so VaR in the form of yield is more reasonable as the following:

$$VaR = 1 - e^{-2.33\theta\sigma_t}, \tag{6}$$

where θ is the correction factor, and the calculation formula is

$$\theta = 1 + \phi \ln\left(\frac{k}{3}\right), \tag{7}$$

where k is the kurtosis value of the return rate and $\varnothing$ is a constant which can be obtained by regression of equation (5). When the return is a normal distribution, $k = 3$, so $\theta = 1$. The correction factor has a value greater than 1 when the return is a peak thick tail shape, which is used to correct the undervalued value risk.

4.1.2. LVaR Model. The traditional VaR model has an implicit assumption that regardless of the trading position of investors, the transaction can be completed at a fixed market price within a fixed period of time [19]. Obviously, the VaR model ignores the fluctuations in market prices and spreads that large deals can bring. In order to solve problems mentioned above, a liquidity risk estimation model is proposed.

Hisata and Yamai [12] believe that the uncertainty of bid-ask spread can be used as a performance of liquidity risk. Therefore, they introduced the volatility indicators of bid-ask spread to exogenous cost of liquidity (ECL) and proposed the liquidity-adjusted value at risk (LVaR) model.

The exogenous liquidity cost defined by the model is

$$\mathrm{ECL} = P_t \frac{\left(\overline{S} + a\widetilde{\sigma_t}\right)}{2}, \tag{8}$$

where P_t is the midpoint price of the quoted price at time t, $\overline{S}$ is the mean of the relative bid spread, $\widetilde{\sigma}_t$ is the volatility of the relative bid spread, and α is the scale factor. Therefore, the ECL is the maximum loss that can be caused by the exogenous fluidity risk when there is a spread at α confidence level. Correspondingly, the maximum loss that may be caused by the exogenous liquidity risk of multiple short commodities expressed by the yield is

$$\mathrm{ECL} = \frac{\left(\overline{s} + a\widetilde{\sigma_t}\right)}{2}. \tag{9}$$

The LVaR model is a liquidity-adjusted VaR model that adds the exogenous liquidity cost to VaR. Adding exogenous liquidity risk to the traditional VaR model is to correct the traditional liquidity risk prediction model:

$$\mathrm{LVaR} = P_t\left(1 - e^{-2.33\theta\sigma_t}\right) + P_t \frac{\left(\overline{S} + a\widetilde{\sigma_t}\right)}{2}. \tag{10}$$

The liquidity risk ratio can be obtained by removing the absolute price P_t:

$$\mathrm{LVaR} = \left(1 - e^{-2.33\theta\sigma_t}\right) + \frac{\left(\overline{S} + a\widetilde{\sigma_t}\right)}{2}. \tag{11}$$

As can be seen from equation (11), the following parameters are necessary to calculate the LVaR model:

(1) $\overline{S}$ is the mean of the relative bid spread

(2) $\widetilde{\sigma}_t$ is the volatility of the relative bid spread

(3) α is the scale factor

(4) $\widetilde{\sigma}$ is the volatility of the return rate

4.2. Impact Measurement with LVaR Model

4.2.1. Estimation of Volatility in Yield. The stock price index is usually a nonstationary time series, while the yield series shows stationarity. Therefore, this article takes the logarithmic yield of the CSI 300 index futures as the research object with following formula to calculate the yield:

$$\mathrm{R_t} = \ln\left(P_t\right) - \ln\left(P_{t-1}\right), \tag{12}$$

where R_t represents the logarithmic yield for period t and P_t and P_{t-1} represent the closing price of the t_{th} and $(t-1)_{\mathrm{th}}$ periods of the CSI 300 index futures.

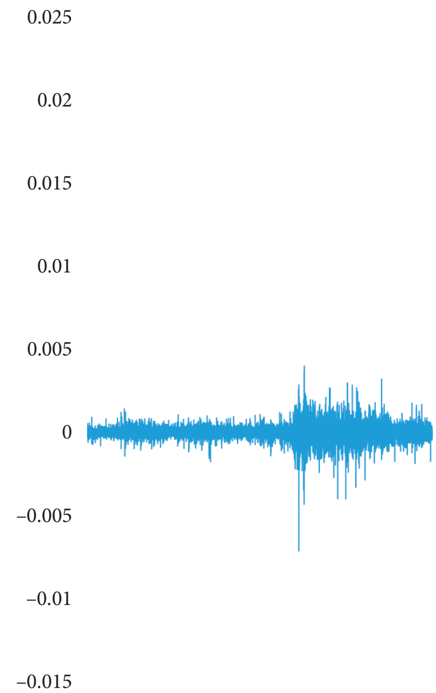

Figure 4: Return yield curve at minute level of CSI 300 index futures.

It is necessary to perform a stationary examination on the yield series before constructing the yield and volatility prediction model. Figure 4 shows the yield curve of the CSI 300 index futures at minute-level from July 1, 2014, to December 31, 2015. It can be observed that the yield curve fluctuates roughly within a range, indicating that the yield series may be stationary.

In order to further analyze the stationarity of the yield, the ADF unit root test is used. To be specific, if the ADF statistic value is less than the critical value at the given significance level, the null hypothesis that at least one unit root exists is rejected, indicating the time series is stationary, and conversely the time series is nonstationary. According to the unit root test result shown as −7.52, it can be concluded that the yield series of the CSI 300 index futures is stationary at the 5% significance level and can be fitted by regression.

It is necessary to first perform the ARCH effect test on the residual of the mean value equation of the yield series before modeling the volatility of the CSI 300 index futures return yield. Only the yield series satisfying the ARCH effect can use the GARCH model to analyze the volatility rate. In this paper, the Ljung–Box examination [20] is used to examine the autocorrelation of the square series of the yield. The statistic p value of the test is 0, so the null hypothesis that the square series of yield is white noise (no autocorrelation) can be rejected, indicating that the original series (the yield) does have an ARCH effect.

After proving that the yield series satisfies the stationary and ARCH effect, volatility is analyzed with the GARCH model in this section. Considering that the order of the GARCH model is hard to determine, the low-order GARCH(1,1) model is selected.

First, the AR(3) model is used to fit the yield series of the CSI 300 index futures active period. Then, the volatility rate

Table 5: The fitting results of the GARCH(1,1) model in the active stage of HFT.

Mean equation AR(3)				
Variable	Coefficient	Std. error	t-statistic	Prob
Const	−3.4198e−07	1.094e−05	−3.127e−02	0.975
AR(1)	0.0262	4.203e−03	6.228	1.794e−02
AR(2)	1.3168e−03	4.479e−03	0.294	−7.461e−03
AR(3)	−1.4527e−03	4.581e−03	−0.317	−1.043e−02
Volatility equation GARCH(1,1)				
Omega	4.4823e−08	3.940e−12	3.956	4.482e−08
Alpha(1)	0.0500	9.623e−03	5.196	3.114e−02
Beta(1)	0.7800	4.204e−02	18.554	0.698

Table 6: The fitting results of the GARCH (1,1) model during the HFT restricted period.

Mean equation AR(3)				
Variable	Coefficient	Std. error	t-statistic	Prob
Const	2.5018e−05	7.060e−06	3.5440	3.943e−04
AR(1)	−0.0338	6.850e−03	−4.940	−4.726e−02
AR(2)	0.0328	6.966e−03	4.712	1.917e−02
AR(3)	7.2765e−03	7.090e−03	1.026	−6.620e−03
Volatility equation GARCH(1,1)				
Omega	2.5232e−08	3.641e−12	6930.443	2.522e−08
Alpha(1)	0.0125	5.688e−03	2.197	1.351e−03
Beta(1)	0.9300	3.293e−03	282.391	0.924

of residual is modeled with the GARCH model. The results are shown in Table 5.

According to the fitting results in Table 5, the mean equation can be derived as

$$R_t = -3.7198e^{-7} + 0.0262R_{t-1} + 0.0013168R_{t-2} - 0.0014527R_{t-3}. \quad (13)$$

Volatility (conditional variance) equation:

$$\sigma^2 = 4.4823e^{-8} + 0.05\varepsilon_{t-1}^2 + 0.78\sigma_{t-1}^2. \quad (14)$$

It can be observed in Table 5 that the GARCH(1,1) model is remarkable at the 5% significance level, indicating that the fitting effect is satisfactory.

As shown in Table 6, the mean and volatility equations during the period that HFT is restricted can be calculated with the same method.

According to the fitting results in Table 6, the mean equation of the yield during the period that HFT is restricted can be obtained as

$$R_t = 2.5018e^{-5} + -0.0338R_{t-1} + 0.0328R_{t-2} + 0.0072765R_{t-3}. \quad (15)$$

Volatility rate (conditional variance) equation:

$$\sigma^2 = 2.5232e^{-8} + 0.125\varepsilon_{t-1}^2 + 0.93\sigma_{t-1}^2. \quad (16)$$

Similarly, the volatility rate equation of relative spread before and after trade restriction can be calculated separately as follows:

$$\sigma^2 = 4.2112e^{-11} + 0.2\varepsilon_{t-1}^2 + 0.78\sigma_{t-1}^2, \quad (17)$$

$$\sigma^2 = 4.3319e^{-10} + 0.1\varepsilon_{t-1}^2 + 0.88\sigma_{t-1}^2. \quad (18)$$

4.2.2. Estimation of the Correction Factor θ. To estimate the value of θ, we first calculate the yield VaR of the CSI 300 index futures from the one year before trade restriction to one year after trade restriction at the 99% confidence with the historical simulation method and estimate σ_t with the GARCH model. With the above two parameters, regression to equation (6) obtains that θ of the CSI 300 index futures is 1.046. At the same time, the kurtosis analysis of the yield inferred that the kurtosis value is 3.50. After that, the above two values are brought into equation (7), which inferred that ϕ at the 99% confidence level is 0.3.

4.2.3. Exogenous Liquidity Cost. The scale factor α in the exogenous liquidity cost model is an essential element of the calculation. In this section, the CSI 300 index futures α is obtained at 5.134 after regression to 20 with ECL, $\overline{S}$, and $\tilde{\sigma}_t$ calculated by HFT data from July 1, 2014, to December 31, 2015.

Therefore, the calculation formula for the exogenous liquidity cost before trade restriction is

$$\text{ECL} = \frac{1}{2}\left(1.12e^{-4} + 5.134\tilde{\sigma}_t\right). \quad (19)$$

The calculation formula for the exogenous liquidity cost after trade restriction is

$$\text{ECL} = \frac{1}{2}\left(3.86e^{-4} + 5.134\tilde{\sigma}_t\right). \quad (20)$$

The LVaR model is a liquidity-adjusted VaR model that adds the exogenous liquidity cost to VaR. Adding exogenous liquidity risk to the traditional VaR model is to correct the traditional low liquidity risk prediction model:

$$LVaR = P_t\left(1 - e^{-2.33\theta\sigma_t}\right) + P_t\frac{(\bar{s} + a\sigma_t)}{2}. \quad (21)$$

The liquidity risk ratio can be obtained by removing the absolute price P_t:

$$LVaR = \left(1 - e^{-2.33\theta\sigma_t}\right) + \frac{(\bar{s} + a\sigma_t)}{2}. \quad (22)$$

4.3. Comparison of Impact of HFT on Liquidity Risk before and after Stock Index Futures Trade Restriction. Firstly, $\tilde{\sigma}$ and $\tilde{\sigma}_t$ obtained by the yield equation and the relative price volatility rate equation constructed based on the GARCH model in the previous section and the correction factor θ can be used to calculate the corresponding VaR value. Then, the value of exogenous liquidity cost ECL is calculated with the scale factor α and the relative price volatility rate equation. Finally, the final LVaR value is obtained according to (22).

ECL/LVaR is defined as the exogenous liquidity risk ratio, an indicator that shows the proportion of liquidity risk in all risks of CSI 300 index futures. It can be seen from

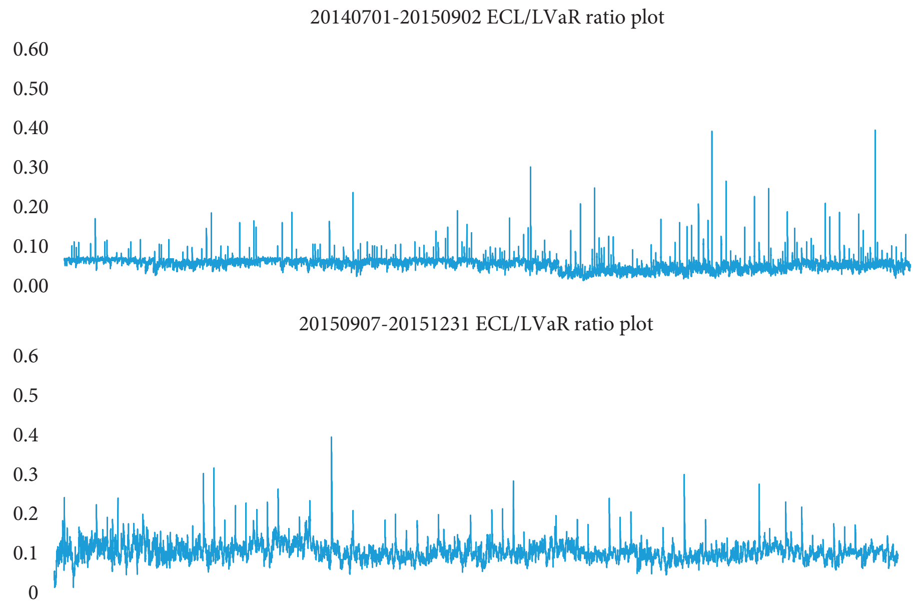

Figure 5: ECL/LVaR ratio chart before trade restriction of CSI 300 index futures (above) and after trade restriction (below) (minute level).

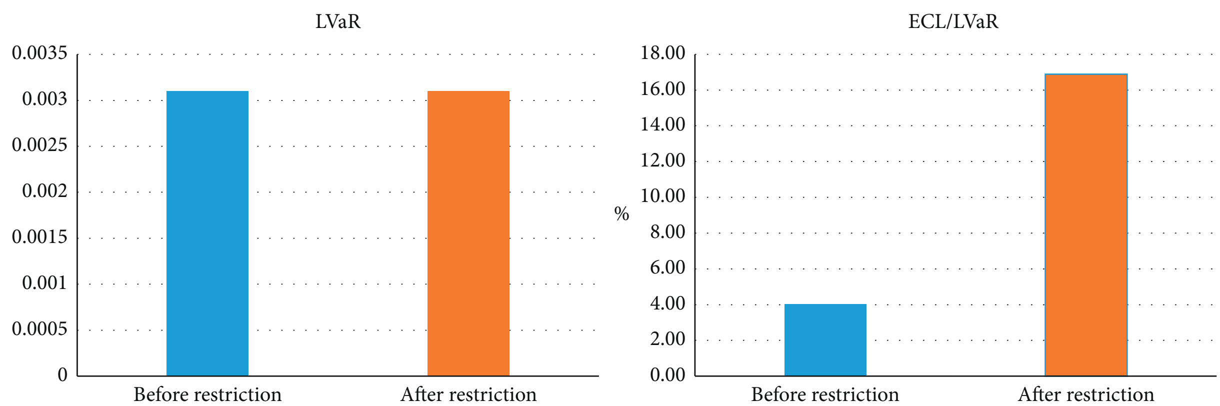

Figure 6: Comparison of ECL/LVaR and LVaR influenced by HFT behaviour.

Figure 5 that the mean value and volatility of ECL/LVaR rose obviously after the trade restriction policy.

To further analyze the impact on liquidity risk by HFT, Figure 6 shows the average value of ECL/LVaR and LVaR before and after trade restriction. It is interesting to find that the HFT restriction policy did not lift the liquidity risk level (LVaR), both remain at 0.0031. However, the proportion of exogenous liquidity risk in LVaR rose from 4.04% before trade restriction to 16.89% after trade restriction. It means that the trade restriction policy significantly increases the exogenous liquidity risk. If the period before trade restriction is regarded as the environment in which HFT behaviour may occur, the period after trade restriction is regarded as the environment in which no HFT behaviour occurs. The findings indicate that the behaviour of HFT can effectively reduce the proportion of exogenous liquidity risk in the overall risk in the Chinese stock index future market.

5. Conclusion

In this paper, our aim was to analyze how HFT influences exogenous liquidity risk of China's stock index future market. First, we make a problem statement about the concepts of exogenous liquidity risk, and then the experimental data are set according to the policy of trade restriction published in September 2015. To validate the relationship between HFT and liquidity risk, the VAR model is introduced to analyze the correlation between four agent indexes related to liquidity and HFT activeness. The experimental data have shown that HFT improves liquidity indicated by HFT causing fewer relative spread, effective spread, adverse selection, and larger realized spread.

Furthermore, the LVaR model is introduced to calculate how HFT influences the exogenous liquidity risk. The finding is that the exogenous liquidity risk drops from 16.89% after trade restriction to 4.04% before trade restriction, which in turn demonstrates HFT can reduce the exogenous liquidity risk level.

However, as the stock index future market and the spot market are highly related, the research about analyzing the impact of HFT on the spot market is a promising area. Therefore, for future research, it is necessary to study the cross-market HFT behaviour and the cross-market risk transmission mechanism to provide further theoretical and method guidance for the healthy and orderly development of China's stock index futures products and financial derivative markets.

Data Availability

Access to data used in this paper is restricted due to commercial confidentiality. Limited data can be provided upon request.

Conflicts of Interest

The authors claim no conflicts of interest.

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Research Article

Capital Gains Sensitivity of US BBB-Rated Debt to US Treasury Market: Markov-Switching Analyses

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We reexamine the relationship between credit spreads and interest rates from a capital gain perspective of bond portfolio. Capital gain sensitivity between US BBB-rated bonds and Treasury bonds is weak and positive in normal periods, but strong and negative during recessions. In the upward phase of business cycles, changes in interest rates are fully reflected in the bond yields, leaving spreads unchanged, while in the downward phase, rates and spreads move in opposite directions. This alternation between two distinct regimes reconciles a long-standing division in the literature. We then discuss the efficiency of shorting Treasury bonds as a hedging strategy and policy suggestions.

1. Introduction

The postcrisis monetary policy, which resulted into uncertainty regarding further moves in risk-free interest rates, poses questions on the resilience, profitability, and stability of the international financial system, especially in what concerns the financial health of banks and corporate firms. The recently observed low borrowing costs have allowed financial institutions to clear their budgets but have also limited profits and raised concerns on whether the restructuring of balance sheets and the increase of capital buffers will be enough when interest rates eventually increase. Such an increase is expected to apply pressure on the valuation of assets, particularly for companies with ongoing legacy burdens. Therefore, the historical relationship between risk-free rates and asset valuation becomes a key indicator, both for companies and investors. In addition, the choice of metrics used for assessing this sensitivity plays a vital role in what effects can be captured.

In this paper, we employ capital gains of bond portfolio containing risk-free government and risky BBB-rated nongovernment US securities to evaluate hedging strategies that consist of holding risky and selling risk-free assets. Our motivation for focusing the study on BBB-rated bond portfolios is based on their importance for institutional investors, such as pension funds and insurance companies, as the investment guidelines of a vast majority of them allow only very limited exposure to high yield debt securities, while the BBB-rated bonds provide more attractive returns than higher quality investment-grade instruments. We opt for studying bond portfolio instead of single securities, as for the institutional investors the large aggregates represent the main focus of their activity, contrary to cherry-picking of fixed-income exposures, which in a first place may interest individuals with a rather restricted funding capacities. This aspect also allows us to reduce the necessary computation capacity and still be able to produce valuable investment insights. By using the capital gains metric to study the sensitivity of relatively risky US BBB-rated bonds to risk-free US Treasuries (UST), we show that the relationship between credit spreads and yields of risk-free assets is not constant, as suggested by earlier research (e.g., [1–3]), but instead changes between two distinct regimes.

In the first regime, which takes place during normal periods of economic growth, any changes in the yield of risk-free assets are fully mirrored by changes in the yield of investment-grade BBB-rated bonds, keeping credit spreads stable. In that context, spread-to-rate sensitivity is null. From a capital gains perspective, the sensitivity of capital gains of US BBB-rated bonds to the capital gains of UST bonds is positive and equal to one.

In the second regime, which manifests during a recession and a subsequent sharp recovery, capital gains sensitivity turns to be negative. The spreads of US BBB-rated bonds and the yields of UST move in opposite directions due to flight-to-quality behavior and a fall in interest rates. Thus, spread-to-rate sensitivity becomes negative.

The large differences among previous results, based on spread-to-rate sensitivity analysis and on different choices of models and data, produce inconclusive answers to questions on the actual dynamics between credit spreads, yields, and interest rates. The literature is broadly separated to papers that identify a negative spread-to-rate relationship [2–5] and research that finds a weak positive or null spread-to-rate sensitivity [1, 6–8].

For instance, the Merton [4] structural model is based on contingent claims and implies that the probability of default of a debt issuer is affected by changes in the interest rate. It implies a permanently negative relationship between credit spreads and interest rates. On the other hand, Kamin and von Kleist [6] suggest that changes in the interest rate are passed fully or slightly augmented onto the yield of risky bonds in the context of emerging markets. There is a null or a slightly positive relationship between changes in bond spreads and changes in the risk-free rate. The same pattern is also documented by Eichengreen and Mody [7] for country spread of emerging economies with respect to the US interest rate.

Finding a common denominator between the two aforementioned streams of research on interest rate sensitivity is challenging. Thus, to reconcile a pile of contradictory results, we opt for a different capital gain approach and demonstrate its capacity to provide clearer results over the long-range observation intervals. It is also worth mentioning that the financial crisis caused a radical change in the real-world fundamentals and regulatory frameworks, so to revisit old problems, new techniques allowing for deeper insights are needed. Towards that direction, capital gains sensitivity is able to capture long-term effects better than spread-to-rate sensitivity, as the former directly focuses on the end-of-period bottom-line portfolio results, while the latter is usually obtained by averaging of the daily sensitivity figures, which are subject to greater computational uncertainty due to smaller amplitudes of examined changes.

A simple metric of the sensitivity of capital gains rather than the sensitivity of credit spread to risk-free interest rates has been proposed to study the interest rate sensitivity of US corporate debt [9], emerging market sovereign bonds [10], and emerging market corporate fixed-income securities [11]. This paper represents an extension of this line of research to the US BBB-rated debt, enhanced by Markov-switching analysis for rigorous detection of sensitivity regime changes.

The capital gains metric is defined as the change in capital gains of a portfolio containing only US BBB-rated bonds over the corresponding change in capital gains of a portfolio containing only UST. While the connection between risk-free interest rates and risky bond yields unavoidably underlines our work, the main focus, however, lies on the profits or losses of bond portfolio. This approach is not widespread in the main stream of financial analysis and usually is employed when the effects of taxation and tax regulation on the performance of financial assets are discussed because tax legislation usually differentiates between capital gains and interim payments.

It is also worth noting that hedging mid- to long-term exposures, usually classified as hold-to-collect and hold-to-collect-and-sell, may differ from intraday short-term hedge methodologies. Additionally, the differences across the normal and distressed market regimes in the behavior of risk-free and risky bond portfolios suggest that hedging interest rate risk by shorting UST, or equivalently holding an interest rate swap that receives a floating rate for a fixed rate, is rather not a completely efficient strategy.

This paper is further motivated by a series of recent reports from regulatory authorities that show a renewed public interest on the relationship between interest rate risk, asset valuation, and regulatory framework [12–14]; Committee on the Global Financial System (CGFS), 2018). The common denominator of these reports is to enhance a framework of interest rate risk management, as after a prolonged period of historically low interest rates, a general overvaluation of assets may pause dangers for financial stability. In that discussion, the sensitivity of financial assets to changes in yields, spreads, and capital gains plays a central role.

The rest of the paper is structured as follows. Section 2 describes the data and methodology. Section 3 provides the empirical results. Section 4 presents the application of Markov-switching model to confirm the robustness of the empirical results. Section 5 discusses the implications of the capital gains sensitivity approach from the theoretical and practical perspectives. Section 6 concludes the paper.

2. Data and Methodology

We use the monthly time series of blended yields and average coupons to model the price dynamics of the US BBB-rated and UST bond portfolios on a period from March 2001 to August 2016. Our data come from yield and coupon indices, which are used to model prices and investigate the dynamics of annual capital gains of both US BBB-rated bonds and UST securities. The reason for limiting the analysis to the US nongovernmental BBB bond portfolio and the UST portfolio is rooted in the importance of BBB-rated fixed-income exposures for institutional investors, in general, and insurance companies and pension funds, in particular, due to their attractive risk-return attributes. On the other hand, UST bonds represent investment targets of choice for many investors as they are largely considered to be safe-haven investments, which are also commonly employed as proxies for risk-free instruments used for designing diverse hedge strategies. In addition, by limiting the number of indices used in our research, we are able to keep under control the necessary computation capacity and produce valuable investment insights.

For US BBB bonds, we use the Citi Broad Investment-Grade US Credit BBB Yield to Maturity Local (Bloomberg ticker: S200YL) and the Citi Broad Investment-Grade US Credit BBB Average Coupon Local (Bloomberg ticker: S200CP). The constituent members of the pair of the S200YL and S200CP indices are the same and represent nongovernmental BBB-rated debt issued in the US, which comprises corporate, financial, and municipal issuers. For UST securities, we employ the Citigroup indices: Treasuries Yield to Maturity Local (Bloomberg ticker: SA14YL) and Treasuries Average Coupon Local (Bloomberg ticker: SA14CP). The constituent members of the SA14YL and SA14CP are identic and represent U.S. Treasury bonds, excluding Treasury Bills. We resort to yield and coupon indices to analyze capital gains because there is no price index available with similar length and characteristics and because the focus is on portfolios rather than individual assets. Since interest is not reinvested, a total return index is not necessary. Although herein only the US BBB bonds and UST portfolio are employed, we consider that our findings will hold also for many other portfolios, such as Corporates, Financials, Muni, Emerging Market (EM) Corporates, EM Financial, and EM Sovereigns, among many others.

Our methodology is based on [11], but the focus is on the US market rather than emerging economies. The average price of each portfolio can be calculated by discounting future cash flows of coupons and principals. For simplicity, we assume annual coupon payments, principal redemption at maturity, and a flat yield curve. Bonds that reach maturity or are downgraded are removed from the indices, while newly issued ones are added. In essence, we assume a portfolio that perfectly mimics the composition of the respective index and is continuously rebalanced according to any changes within that index. This assumption is frequently used to study risk minimization strategies for portfolio immunization (e.g., [15]). In our case, the continuous rebalancing happens on a monthly basis.

The price P_{UST} of a UST portfolio with an investment horizon (residual maturity) T, average annual coupon C_{UST}, face value F_{UST}, and yield y_{UST} is

$$P_{\mathrm{UST}} = \sum_{i=1}^{T} \frac{C_{\mathrm{UST}}}{\left(1 + y_{\mathrm{UST}}\right)^{k}} + \frac{F_{\mathrm{UST}}}{\left(1 + y_{\mathrm{UST}}\right)^{T}}, \tag{1}$$

where y_{UST} is the blended yield given by the SA14YL index and C_{UST} is the average coupon given by the SA14CP index. The nominal face value F_{UST} is set to US$ 1,000 million.

Capital gain is defined as the difference between the initial price and the final price of the entire portfolio, excluding interim coupon payments over a given period. In essence, the initial price is the price the investor would have to pay to purchase one fraction of the bond index, while the final price is the price at the end of the given period. As the indices are continuously rebalanced, our asset is continuously changing. Since we do not aim to assess the efficiency of rebalancing, the associated transaction costs and costs of carry are ignored. After the historical price series is constructed, the capital gain can be written as

$$CG_{\mathrm{UST}}(t, H) = P_{\mathrm{UST}}(t + H) - P_{\mathrm{UST}}(t), \tag{2}$$

where CG_{UST} stands for the capital gains of the UST portfolio, t is the initial date of the analyzed time interval, and H stands for a time horizon over which the capital gains are assessed. The time horizon is one year, since capital gains of investment funds are transferred at the end of each calendar year [16]. The same approach is also applied for analyzing the capital gains of the US BBB-rated bond portfolio. Similarly, the price of the modeled US BBB-rated portfolio with the same residual maturity as the UST portfolio is

$$P_{\mathrm{BBB}} = \sum_{i=1}^{T} \frac{C_{\mathrm{BBB}}}{\left(1 + y_{\mathrm{BBB}}\right)^{k}} + \frac{F_{\mathrm{BBB}}}{\left(1 + y_{\mathrm{BBB}}\right)^{T}}, \tag{3}$$

where C_{BBB} stands for average annual coupon, F_{BBB} stands for face value of a principal payment, and y_{BBB} is the blended yield. The yields and coupons are given by the respective indices S200YL and S200CP. The face value is again US$ 1,000 million. Capital gains of US BBB-rated bond portfolio can be written as

$$CG_{\mathrm{BBB}}(t, H) = P_{\mathrm{BBB}}(t + H) - P_{\mathrm{BBB}}(t), \tag{4}$$

with symmetric notation. Equations (2) and (4) can be used to construct a time series of capital gains CG_{UST} and CG_{BBB}, which can be used to calculate the sensitivity of the relatively risky US BBB-rated bond portfolio capital gains to the capital gains of the risk-free UST bond portfolio. Following the earlier definition, the sensitivity $S_{\mathrm{BBB/UST}}(t_2, t_1, \mathrm{H})$ is the ratio of the capital gain of the corporate bond portfolio to the capital gain of the UST portfolio over a period (t_1, t_2).

$$\begin{aligned} S_{\mathrm{BBB/UST}}(t_2, t_1, H) &= \frac{CG(t_2, H)_{\mathrm{BBB}} - CG(t_1, H)_{\mathrm{BBB}}}{CG(t_2, H)_{\mathrm{UST}} - CG(t_1, H)_{\mathrm{UST}}} \\ &= \frac{\Delta CG(t_2, t_1, H)_{\mathrm{BBB}}}{\Delta CG(t_2, t_1, H)_{\mathrm{UST}}}. \end{aligned} \tag{5}$$

The horizon H is moved forward by the number of days equal to $t_2 - t_1$. To make the capital gain-wise sensitivity more representative, we calibrate the rolling window of length H so that it captures the more pronounced moves in the capital gains time series of the modeled UST portfolio. An infinitesimal or even zero change in the capital gain of the UST portfolio amplifies the computational uncertainty for the ratio and a zero denominator may render it useless.

It is important to remark that although the measure practically uses bond face values and yields, it can also provide intuition for the dynamics of interest rates. Interest rates and the yields of UST move towards the same direction, so an increase in the Fed rate pushes the yield curve for UST bonds upwards. Changes in nominal rates (e.g., due to inflation, fiscal, or monetary policy) are matched by changes in the yield curve, with a direct effect on the credit spread between government and corporate bonds. Our method fits well with a strategy that hedges interest rate risk by shorting the UST portfolio and essentially assesses the profitability of a long position in US BBB-rated bonds coupled with a short position in government bonds. This intuition is useful for connecting our findings with the wider literature that explicitly uses interest rates and spreads.

3. Empirical Results

3.1. Present Values and Capital Gains of Bond Portfolios. Figure 1 presents the historical time series of the yields and coupons of the UST bonds and US BBB-rated bonds.

For UST bonds, the average coupon almost always exceeds the corresponding yield rate, with the exception of the two-year-long period preceding the global financial crisis, namely, from the second half of 2005 until the end of the first half of 2007. To a lesser extent, the same holds for corporate bonds apart from the financial crisis period: mid-2008 to mid-2010. Notably, the surge in the yields of corporate bonds during the financial crisis is well above the coupon curve, signifying a period where these assets were traded at a great discount. This change in trend will become apparent later on.

We then proceed to discount the future cash flows for the two portfolios based on the yield and coupon data. The resulting bond prices (see Figure 2) demonstrate a similar pattern between mid-2003 and the outbreak of the financial crisis in mid-2007. Since the second half of 2007 until the peak of the crisis, a large flight-to-quality event is observed, where the prices of safe assets increase and the prices of risky assets decrease [17]. In 2009, this flight-to-quality stops and the gap between the two curves vanishes. Notably, the ranges of the present values of the two portfolios differ considerably. The range relative to the UST portfolio (US$ 150 million) is narrower than the respective range of the present values of the US BBB-rated bond portfolio (US$ 250 million).

Capital gains for each portfolio can be directly calculated from our earlier definition. While the interpretation for the separate UST and US BBB-rated bond portfolios is straightforward, we also discuss the capital gains of a US BBB-rated portfolio hedged by taking a short position in UST bonds. In this case,

$$CG_{\text{hedged}} = \text{CG}_{\text{BBB}} - \text{CG}_{\text{UST}}. \quad (6)$$

Figure 3 represents the time behavior of yearly changes in present value for the US BBB-rated bond portfolio, the risk-free UST portfolio, and a portfolio of US BBB-rated bonds hedged by shorting the respective UST portfolio. Each point represents the changes in present value having taken place in the preceding year. Between July 2007 and December 2010, the period of the global financial crisis and its immediate aftermath, the annual capital gains of the BBB-rated bond portfolio and UST bond portfolio move in opposite directions. Hence, the interest rate hedging of US BBB-rated debt with the short UST positions does not compensate the negative impacts, when such compensation is most needed.

3.2. Capital Gain-Wise Interest Rate Sensitivity of US BBB-Rated Debt. The main intuition lies in the interpretation of capital gains sensitivity across the portfolios we consider, namely, the US BBB-rated and UST portfolios and the hedged portfolio. Instead of using average sensitivity over the entire sample, we examine the behavior of sensitivity within much shorter time intervals determined by local extrema. Local minima and maxima are treated as turning points which separate upward and downward tendencies in capital gains dynamics.

The tracking of large movements in UST capital gains reduces the uncertainty in the denominator of equation (5) and hence increases the precision of sensitivity measurements. The extrema are identified in the time series of the UST portfolio, as in [18]. This leads to 51 sufficiently large and distinct movements, both upwards and downwards, which define the intervals we use and are split into three groups according to the time of occurrence. 18 movements took place during the precrisis period (March 2002–May 2007), 8 movements belong to the crisis period (May 2007–October 2010), and 25 movements happened during the postcrisis period (October 2010–August 2016). Sensitivity is calculated separately for each of the intervals. The resulting pattern can be seen in Figure 4, along with average sensitivity for each of the three phases.

The bold line depicts the two different regimes. During normal economic conditions, the average sensitivity is positive, while during the crisis, it is negative and amplified. We clearly observe the time-varying behavior of capital gains sensitivity over each phase, similar to [9, 11]. The plot shows that sensitivity is mostly positive before 2007 and after 2011, while it turns negative between that time interval. This implies a regime change during and slightly after the period of the financial crisis. From 2001 till 2007, the sensitivity remains positive, from 2007 till 2011, it turns negative, and from 2011 till 2016, it reverts back to positive ground. To properly calculate the sign and value of sensitivity in a way that is not affected by time variation, we take the product of capital gains and duration (time interval) over which the sensitivity point estimates are given. This yields a weighted sum of capital gains for each portfolio, where the weight is the fraction of time over which sensitivity (capital gains) was calculated. The average period sensitivity is, thus, the ratio of the weighted sum of capital gains for the US BBB-rated portfolio divided by the UST equivalent. In comparison, spread-to-rate sensitivity typically takes daily values which are averaged over a longer period, whereas our metric focuses on start and end points.

As discussed earlier, the definition of our measure can be interpreted as a gauge of hedging success when a long position in the BBB-rated portfolio is balanced by a short position in the UST portfolio. In terms of cash flows, this can be seen as either a permanent position or an interest rate swap that pays a fixed rate to receive a floating rate equal to that of the corporate bond portfolio. It becomes apparent that all the gains from the short position in UST during the precrisis period are wiped away during the crisis downturn and recovery. As such, an all-weather hedge or its equivalent in the form of a swap is inefficient.

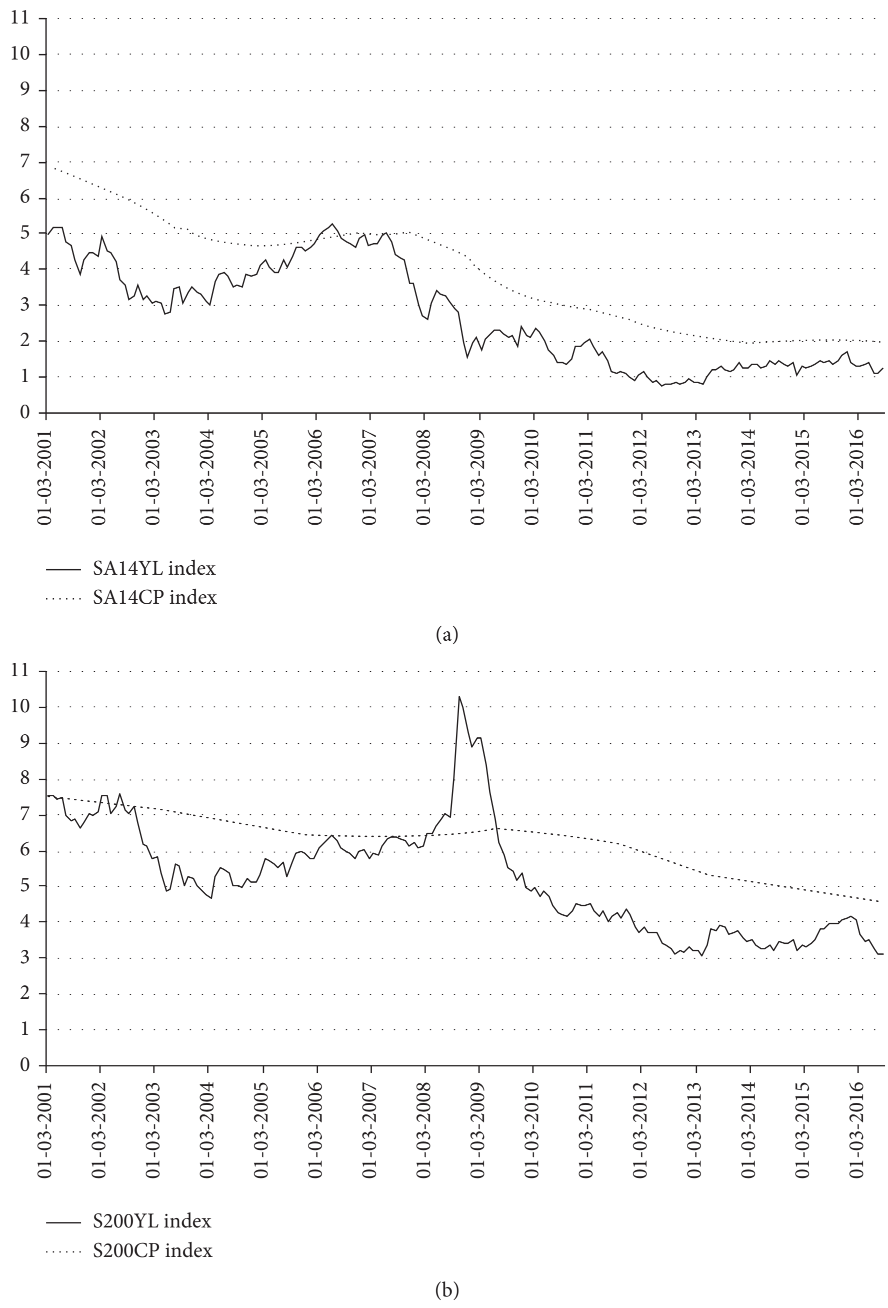


Figure 1: Yields and average coupons for the US BBB-rated (a) and UST bonds (b), %.

Section 4 confirms our empirical observation of capital gain-wise interest rate sensitivity regime changes by application of Markov-switching model.

4. Markov-Switching Modeling and Regime Changes

Up to this point, our empirical findings point towards a structural break in the time series we use. This underlines a functional discrepancy best represented by the contradiction between the Merton [4] model, implying a permanently negative relationship between credit spreads and interest rates, and the Kamin and von Kleist [6] approach, which does not identify such a relationship for a certain period. Given the direct correspondence between interest rates and the yields of government bonds, it is straightforward to connect the intuition of the previous section to the two regimes. To test the hypothesis of two alternating states, one where the Merton model is valid and capital gains sensitivity (and conversely the relationship between credit spreads and interest rates) is negative and one where capital gains sensitivity is close to zero (and the relationship between interest rates and credit spreads is roughly one-to-one), as in [6, 7], we estimate a simple Markov-switching model with two regimes using the time series of sensitivity and capital gains of the hedged bond portfolio. The figures in the

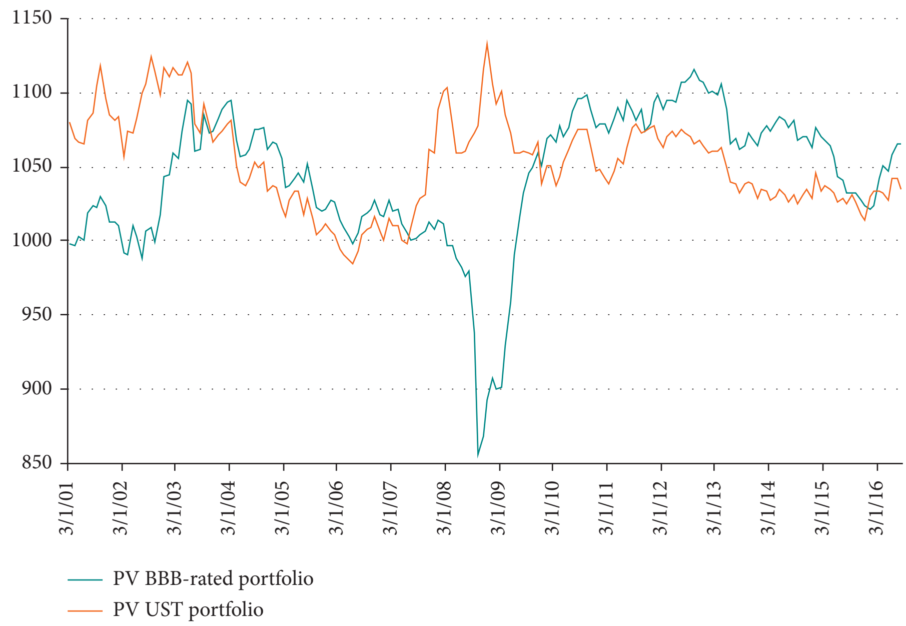


FIGURE 2: Present values of portfolios: US BBB-rated bonds vs. UST.

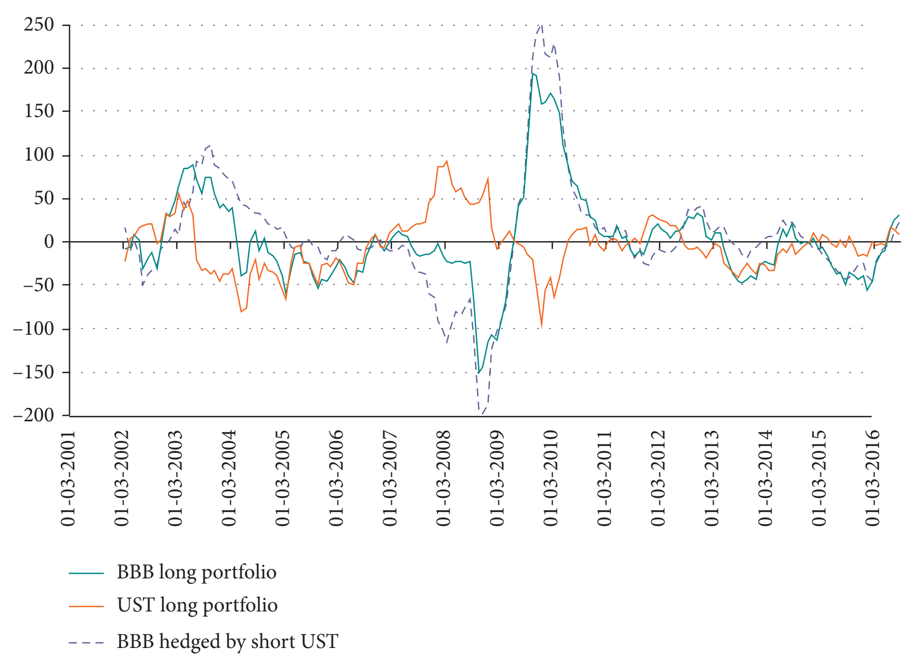


FIGURE 3: Yearly capital gains for the US BBB-rated, UST, and hedged portfolios.

previous section show a possible regime switch in the period averages, but we also examine whether the two different regimes may also have distinct volatilities.

From the vast literature on Markov-switching and regime-switching models, we select a set of simple applications in line with the arguments detailed in [19, 20]. For wider applications on asset pricing, portfolio optimization, and stochastic volatility, [21] contains a comprehensive literature review. We employ a simple two-state dynamic regression Markov-switching model (DRMS), which is more suitable to the monthly frequency of our data. A DRMS specification allows the probabilities to change instantaneously across states, since the realization of each state s_t does not depend on s_{t-1} but is drawn from a discrete probability distribution. On the other hand, an autoregressive (AR) specification where s_t follows a Markov process, thus allowing the transition probabilities to follow an AR process, would introduce autocorrelation in states since s_t would depend on s_{t-1}. This is an unwelcome feature for our model for many reasons. Markov-switching AR (MSAR) models are better suited for quarterly or annual data, and the introduction of lagged states multiplies the states. In our case, due to

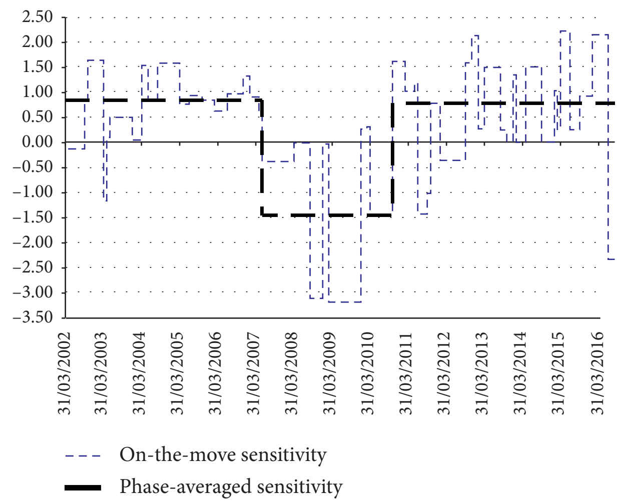


Figure 4: Phase-averaged sensitivity of US BBB-rated bonds, 2002–2016.

autoregression, there would be four possible regimes instead of two, without providing any additional intuition. Also, an MSAR specification would not allow the probabilities to adjust quickly enough to changes in states. Regardless, preliminary estimations of an AR specification yielded very similar results, so we base our discussion on the DRMS models only.

A general specification of the DRMS model that captures all the subcases we consider is

$$Y_t = \mu L_{st} + \varepsilon_{st}, \quad \varepsilon_{st} \sim N\left(0, \sigma_{st}^2\right), \tag{7}$$

where t denotes time, Y is the time series (sensitivity or portfolio capital gains), s denotes the state and is set to 1 or 2, μ and σ denote the state dependent model parameters of the mean (intercept) and the standard deviation, and innovations ε are independent and identically distributed, following a normal distribution with state-dependent variance. We consider two variations: one where the means are state dependent and one where not only the means but also the variances are state-dependent too. The notation can be simplified in the case where only the means are allowed to switch across states to ${\sigma^2}_s = \sigma^2$ (constant across both time and states) and remains as above in the case where both means and variances are state dependent (μ_s and ${\sigma^2}_s$ omitting t for brevity). This leads to four different estimations, two for sensitivity, and two for capital gains. The Akaike, Hannan–Quinn, and Schwarz information criteria show that the simplest model with no lagged terms is the most suitable one for all cases, for both sensitivity and capital gains; hence, we do not introduce lags.

4.1. Regime Switching in Sensitivity. Table 1 reports the results for capital gains sensitivity when only the means are state dependent, under a model specified as $Y_t = \mu_{st} + \varepsilon_t$, $\varepsilon_t \sim N(0, \sigma^2)$ for states $s = 1, 2$. State 1 corresponds to the Merton model, where s is negative, and state 2 corresponds to the Kamin and von Kleist approach, where s is near zero and positive. The estimation verifies our earlier observations, since $\mu_{1,2}$ are both statistically significant, with a negative value of −2.41 and a positive value of 0.70, respectively. The probabilities for each state are 0.838 and 0.968, respectively, which show very high persistence for both regimes.

The transition probabilities from state 1 (2) to state 2 (1) are 0.162 (0.032), which show a very low rate of change (see Table 2). This indicates very clear breaks in the time series and high certainty over which state occurs, which is a direct outcome of the DRMS specification.

Figure 5 shows the transition probabilities compared to the evolution of sensitivity during our period.

Figure 5 evidences a dominance of the second state up until 2009, with a brief exception around 2003 and a dominance of the first state between 2009 and 2011. State 1 briefly reappears at the end of 2012. During the 2009–2012 period, any changes from state 1 to state 2 are instantaneous, meaning that the sensitivity reverts immediately back to its initial regime. After 2012, the second state is always present.

These findings show that sensitivity and credit spreads vary over time, with two distinct regimes appearing, which correspond to two different theoretical approaches on the relationship between credit spreads and interest rates. During crises, credit spreads and interest rates move in opposite directions following the Merton pattern of negative sensitivity. During normal periods, any changes in interest rates (risk-free yields) pass on nearly completely to the yields of corporate bonds, which implies stable credit spreads and the Kamin and von Kleist pattern.

When regime changes are allowed in both the mean and the variance, the parameters and transition probabilities are generally similar (Table 3). The model specification follows equation (7). However, the plot of the transition probabilities over the time series reveals that only state 2 manifests throughout our entire period, i.e., there is not a switch from one pattern to the other and only the Kamin and von Kleist rationale is validated. The variance of state 1 (0.90) is considerably higher than the variance of state 2 (0.51) and slightly higher than the variance of the means-only regime-switching model (0.79). Moreover, the means of the two states are closer compared to the previous case. One possible explanation is that the higher variance combined with the higher mean of state 1 makes the first state redundant despite its high persistency. The mean estimate of −1.34 has a standard deviation of 0.2, which coupled with the standard deviation of the state brings it well within the range of state 2. We therefore conjecture that this similarity causes the model not to discriminate between states.

4.2. Regime Switching in the US BBB Portfolio Hedged by Shorting UST. We can now proceed to the capital gains of the hedged synthetic portfolio where UST bonds are shorted. The capital gains of the hedged portfolio are calculated as follows. First, the present values of the UST and BBB portfolios are calculated using equations (1) and (3), setting $T = 5$ and FV = 1.000. Since the S200YL, S200CP, SA14YL, and SA14CP indices are monthly, we calculate monthly

Table 1: Markov-switching regression in means only for sensitivity.

Parameter	Estimate	St. error	z	$P>\|z\|$	95% confidence interval
μ_1	−2.408	0.163	−14.74	0.000	(−2.729, −2.088)
μ_2	0.701	0.662	10.60	0.000	(0.571, 0.831)
σ	0.791	0.044			(0.709, 0.882)
p11	0.838	0.073			(0.644, 0.937)
p21	0.033	0.015			(0.014, 0.077)

The Merton case corresponds to state 1; the Kamin and von Kleist case corresponds to state 2.

Table 2: Transition probabilities between state 1 and state 2 for all models.

Regime switch in means only					
Sensitivity			BBB hedged by short UST		
State from/to	State 1	State 2	State from/to	State 1	State 2
State 1	0.838	0.162	State 1	0.987	0.013
State 2	0.033	0.967	State 2	0.104	0.897
Regime switch in means and standard deviations					
Sensitivity			BBB hedged by short UST		
State from/to	State 1	State 2	State from/to	State 1	State 2
State 1	0.837	0.163	State 1	0.987	0.013
State 2	0.111	0.889	State 2	0.087	0.913

The Merton case corresponds to state 1; the Kamin and von Kleist case corresponds to state 2.

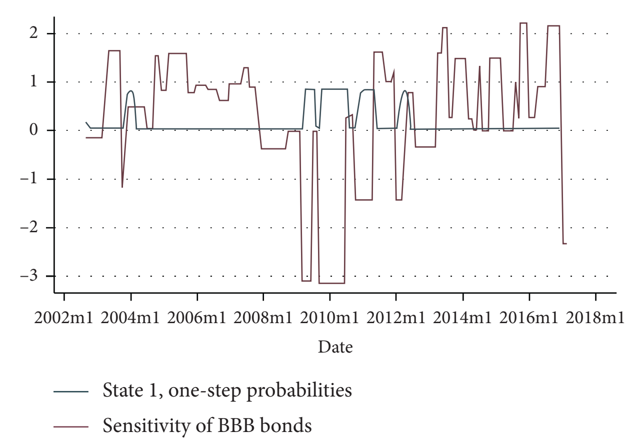


Figure 5: Regime change in means only: state plot for the sensitivity time series. Probability with respect to state 1.

Table 3: Markov-switching regression in means and standard deviations for sensitivity.

Parameter	Estimate	St. error	Z	$P>\|z\|$	95% confidence interval
μ_1	−1.345	0.201	−6.68	0.000	(−1.739,−0.951)
μ_2	0.842	0.142	5.94	0.000	(0.564, 1.119)
σ_1	0.909	0.097			(0.739, 1.119)
σ_2	0.516	0.042			(0.439, 0.606)
p11	0.837	0.048			(0.720, 0.911)
p21	0.111	0.032			(0.629, 0.190)

The Merton case corresponds to state 1; the Kamin and von Kleist case corresponds to state 2.

present values for the two portfolios. We then calculate the difference between the present value of month t and the present value of month $t-12$, or the difference over an annual interval. The capital gain of the hedged portfolio is, therefore, the capital gain of the long position on BBB corporate bonds minus the capital gain of the short position on US Treasury bonds. The generated capital gains span from March 2002 till September 2016. More succinctly, formula (6) can be written as follows for $H=12$ months and P the present value (price) of a portfolio:

$$CG_{\text{hedged}}(t,H) = CG_{\text{BBB}} - CG_{\text{BBB}} = P_{\text{BBB}}(t+H) - P_{\text{BBB}}(t) - P_{\text{BBB}}(t+H) - P_{\text{BBB}}(t). \quad (8)$$

The CG_{hedged} series is used to estimate different Markov-switching models, whose results are reported in Tables 4 and 5. We follow the same approach with sensitivity and employ a DRMS model with no lags. The pattern is similar to that of sensitivity. When the variance is common for the two states and only the means change, there are two major regime switches (Figure 6).

One of the changes, which lasts longer, takes place between 2010 and 2011, which corresponds to the financial crisis. The other change takes place in 2004, is slightly less pronounced, and coincides with a minimum in the time series of UST capital gains. It is worth noting that this minimum of UST capital gains occurs within the one-year-long time interval (June 2003–June 2004), when the federal fund target rate remains at its local minimum value of 1%. The transition probabilities are again very persistent, as shown in Table 4. State 1 has a probability of 0.99, state 2 has a probability of 0.896, and the probability to move from state 1 (2) to state 2 (1) is 0.01 (0.104). Similarly, the mean of the first state (−11.39) is negative and corresponds to the Merton case, while the mean of the second state (134.79) is positive and corresponds to the Kamin and von Kleist case (see Table 4).

In its turn, Table 5 demonstrates that when switches in both the means and the variances are allowed, the result is similar to the previous section. The means change marginally, but the much higher variance of one state (69.01) causes it to dominate over the second state, which has a variance similar to that of the means-only switch (42.97).

Figure 7 shows how the probability of a state to be realized remains at 2% or equivalently how the other state persists and there are no switches during the period. On the other hand, Figure 6 clearly shows two different states when the means are state dependent but the variance is not. This makes state-dependent variances inappropriate for our purposes. Allowing for a change in variances leads to much higher estimates, which cause one state to cover a much wider range of potential values. This makes the model uninformative and unable to pick the differences that interest the paper. As a result, we base our results in the cases where the variance across states is common and the regime switch is in the mean.

Table 4: Markov-switching regression in means only for the US BBB portfolio hedged by shorting UST bonds.

Parameter	Estimate	St. error	z	$P > \|z\|$	95% confidence interval
μ_1	−11.397	4.038	−2.82	0.005	(−19.312,−3.483)
μ_2	134.794	14.953	9.01	0.000	(105.486, 164.102)
σ	47.034	2.556			(42.281, 52.321)
p11	0.988	0.009			(0.951, 0.997)
p21	0.104	0.068			(0.027, 0.326)

State 1 is the Merton case; state 2 is the Kamin and von Kleist case.

Table 5: Markov switching regression in means and standard deviations for the US BBB portfolio hedged by shorting UST.

Parameter	Estimate	St. error	z	$P > \|z\|$	95% confidence interval
μ_1	−13.258	3.812	−3.47	0.001	(−20.745,−5.771)
μ_2	119.439	18.024	6.63	0.000	(84.112, 154.766)
σ_1	42.970	2.556			(38.241, 48.283)
σ_2	69.012	9.987			(51.969, 91.644)
p11	0.987	0.009			(0.949, 0.997)
p21	0.087	0.057			(0.023, 0.280)

Merton case: state 1; Kamin and von Kleist case: state 2.

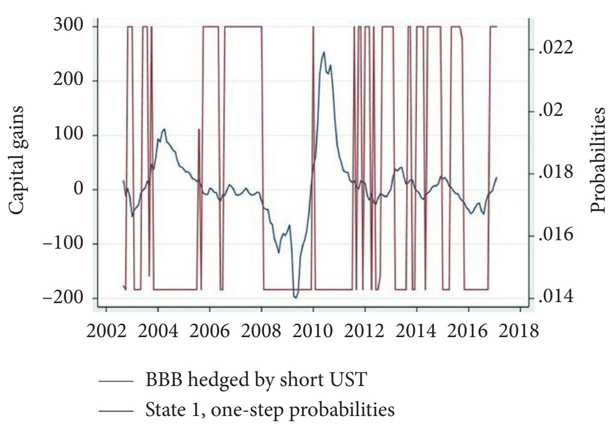


Figure 6: Regime change in means only: state plot for the capital gains hedged US BBB portfolio, 3/2002–9/2016.

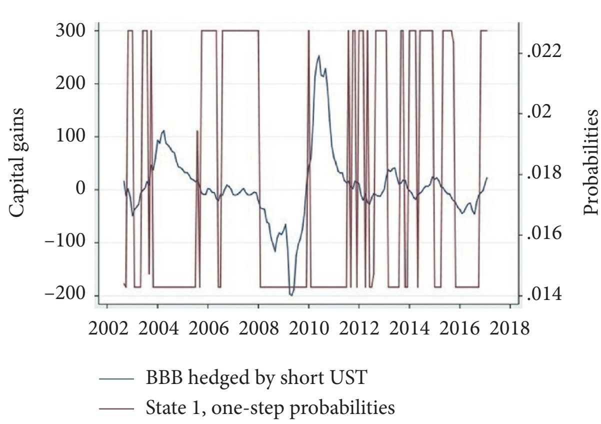


Figure 7: Regime change in means and standard deviations: state plot for the capital gains of the UST-hedged US BBB portfolio, 3/2002–9/2016.

It must be stressed that such effects can be identified only if averaging over a very long sample is avoided. The average sensitivity for the entire period is slightly below zero, meaning the strong negative sensitivity in the second period cancels out the low positive sensitivity in the first and third periods. This may lead to flawed or counterintuitive results, particularly if the effect of one regime is very strong or if strong effects in all regimes negate each other. It is even possible to conclude that there is no sensitivity relative to either yields or capital gains. This finding also provides an illustration on why long spread-to-rate sensitivity averages failed to capture the dynamics depicted by our measure.

5. Discussion and Implications

5.1. The Relationship between Credit Spreads, Interest Rates, and Yields. The estimation results provide sufficient evidence on the time variation in the relationship between credit spreads and yields or interest rates. They suggest a compromise between the pattern identified by Merton [4] of a negative relationship and the findings of Kamin and von Kleist [6] of no strong relationship between spreads and interest rates. We show that, on the contrary, the relationship is not constant and alternates between two phases, each of which corresponds to one of the two approaches. The Kamin and von Kleist intuition (state 2) appears in normal periods, while the Merton intuition (state 1) appears during distress times. During normal periods, changes in interest rates are fully passed on to the yields of BBB-rated bonds, leaving credit spreads unaffected. During crises, on the other hand, the increased uncertainty leads to a flight-to-quality from the riskier corporate bonds to the safe risk-free UST bonds, which pushes the respective yields to opposite directions. After the end of a crisis, the flight to quality stops and there is a reversion to the regime of the normal period. Our findings contradict literature that supports a constant relationship (e.g., [3]) both on the basis of constant sensitivity over time and on the effect of business cycles on credit spreads.

Capital gains of the hedged US BBB portfolio exhibit two regime changes which coincide with the two highest capital gains of the UST Long portfolio (see Figure 4 for a joint presentation). A potential answer to what triggers regime changes may lie in expectations on the risk-free rate as viewed through the Fed target rates. Between June 2003 and June 2004, the federal fund rate reached a minimum value of 1% (see Figure 8). At the same time, a maximum in UST capital gains was realized. A similar situation occurred in 2009, which coincides with another regime change.

The same discussion can be held in terms of default probabilities. In state 1, changes in risk-free interest rates (yields) have a significant opposite effect on US BBB bond yields, while in state 2, a change in risk-free interest rates is reflected by changes in US BBB bond yields of the same size and magnitude. During the precrisis period (state 2), the average capital gains sensitivity of US BBB-rated bonds is close to 1, averaging at 0.84, particularly between 2004 and 2007. Therefore, the response of US BBB bonds to changes in the yields of risk-free assets on a capital gains basis is slightly

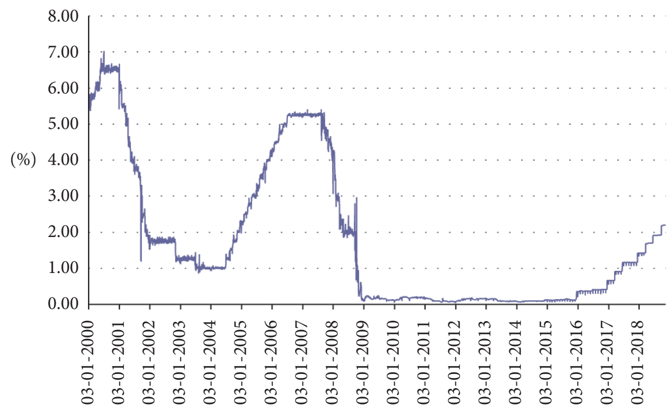


Figure 8: US federal fund effective rate.

lower than 1-to-1, and changes in the yield of risk-free assets passing on to the yield of corporate bonds are slightly reduced. According to [6], the probability of default is not affected by changes in the interest rate and hence a change in the latter does not result in a significant response. On the contrary, between 2007 and 2010 (state 1), sensitivity becomes much more volatile and dips in negative territory. The average sensitivity is clearly negative at a level of −1.47, which signifies a negative and amplified response of credit spreads to changes in interest rates. According to [4], which is based on contingent claims, such a negative response implies that the probability of default of a debt issuer is affected by changes in the interest rate. The increase in credit spreads signifies a higher credit risk and probability of default.

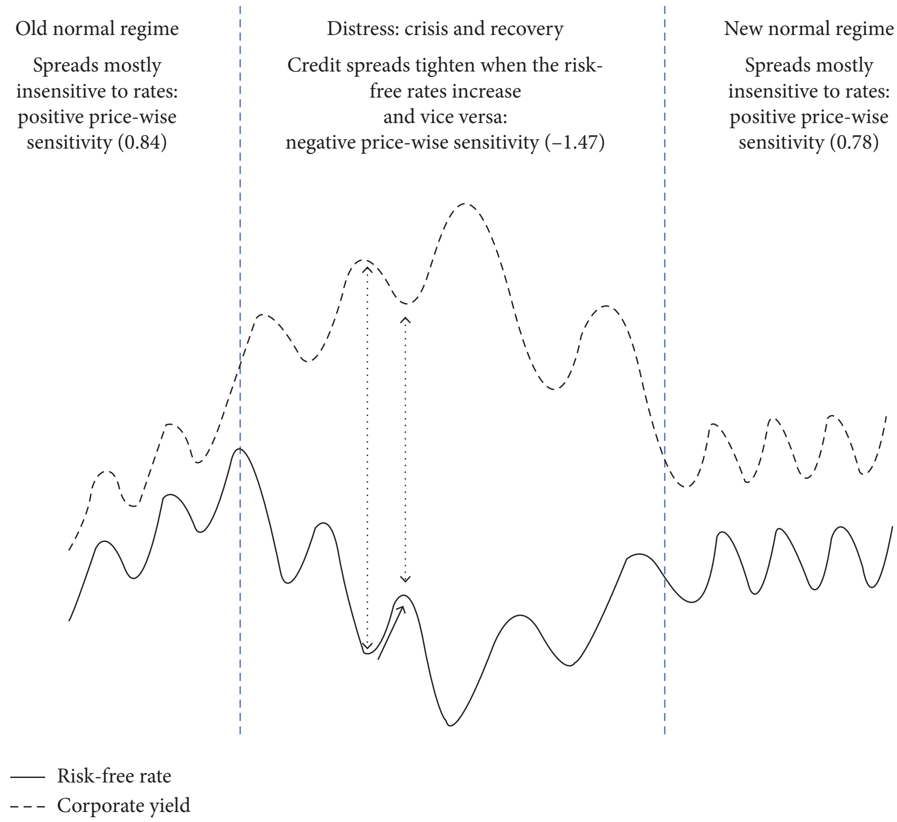
This, in turn, is a signal for the creditworthiness of debt issuers. After 2010, the intuition of Kamin and von Kleist emerges again, with a positive average sensitivity of 0.78.

Although the time span of our analysis ends in August 2016, there is an interesting period ahead with environments with prolonged low interest rates that had fostered risk-taking up to the coronavirus crisis. Such risk-taking scenario has been faced by advanced economies for some time and then, later, on the eve of the pandemic-fueled crisis, by some developing countries. As the impacts of the coronavirus crisis, from the point of view of the interest-rate-based finance, are commensurate with those of the 2007–2008 global financial crisis, we consider the interest rate sensitivity of the BBB-rated nongovernmental US bonds during the coronavirus recession to be negative and amplified. It is so because the US Treasury yields are diminishing towards the all-time low, while the precoronavirus bubble in the BBB-rated debt outstanding makes the yields of the nongovernmental relatively risky BBB-rated bonds climb. Thus, in accordance with our back-on-the-envelope estimates, our conclusions hold in this environment. However, thorough rigorous investigation of the low interest rates' influence and the impacts of coronavirus on the interest rate sensitivity is desirable and will be addressed in our further research. We also posit that during the initial recovery from the coronavirus crisis lows, the interest rate sensitivity will remain negative, this time because of the increase in UST treasury yields—due to the economic recovery—accompanied by the decrease in BBB-rated yields—due to improving business conjuncture and, hence, diminishing probabilities of default. The sensitivity plot around the coronavirus crisis will be qualitatively similar to that in Figure 4, but shifted, along the time scale to the right by roughly thirteen years, separating the two major crisis events.

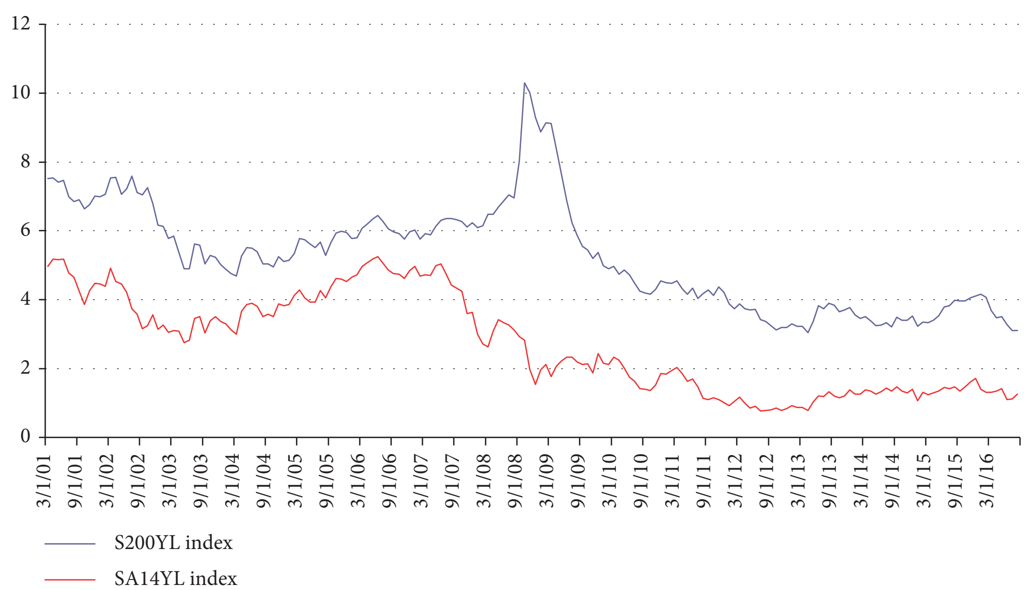
5.2. Sensitivity and Hedging during the Business Cycle. The performance across diverse asset categories changes according to the phases of the business cycle [22, 23]. These phases are typically split into early-, mid-, and late-cycle phases and recession. During the mid- and late-cycle phases of economic expansion, interest rates tend to be higher to prevent the economy from overheating. During the recession and early-cycle phases, interest rates are kept lower to stimulate growth. Notably, these phases match those observed in the results for sensitivity and capital gains.

The first and third period of our sample, where spreads are generally constant, can be related to the mid and late phases of the business cycle, both empirically and theoretically. During those periods of normal to moderate economic growth, default probabilities are low and creditworthiness is only moderately by changes in the risk-free rate. During the second period, however, the inverse relationship can be related to the downside of the business cycle, where a recession (crisis) and the first stage of recovery have taken place. The observed flight-to-quality puts pressure on the prices of UST bonds, which are coupled by a central bank trying to stimulate the economy by reducing interest rates. Either of these factors, or their joint occurrence, pushes the yields of the risk-free assets upwards. Figure 9 demonstrates these points along with the observed yields of US BBB-rated securities vs. UST yields. The divergence between the two yield time series matches the behavior of credit spread with relation to the risk-free interest rate and the phase of the business cycle.

At the same time, the deteriorating economic conditions, low business performance, and increased uncertainty make corporate debt riskier, which pushes US BBB-rated yields upwards. Thus, companies face more difficulties in servicing existing debt and issuing new one at an acceptable rate.



(a)



(b)

Figure 9: Spread-to-risk-free rate dynamics compared to observed yields. (a) Negative spread-to-rate sensitivity in distress compared to null sensitivity in "normal" times. (b) US BBB-rated (blue) and UST (red) bond yields.

Prices of corporate bonds move downwards and prices of government bonds move upwards. The movement from the second to the third period of our sample can be seen as the return to a "normal" state after an increase in interest rates from the central bank. Tighter monetary policy, coupled with an improvement of economic conditions, reduces the premia of corporate bonds since the yields of risk-free assets increase and default risk decreases. Capital losses are observed in UST portfolios while positive capital gains occur in corporate bond portfolios. The capital gains sensitivity of the US BBB-rated bonds during the recovery phase changes from negative to slightly positive.

Our findings for the downward phase of the business cycle agree and expand on [3] but contradict their conclusions on the upward phase. They find both a constant relationship and no connection of their results to the business cycle. While we agree with a negative relationship between spreads and interest rates during the recession and early-cycle phases, we interpret the periods of economic expansion described in [3] as periods of sharp recovery from recession. We present evidence that under the normal regime of the mid-cycle and the late-cycle expansion, the negative relation between interest rates and credit spreads turns to insensitivity.

Under these circumstances, the dilemma of an investor in US BBB-rated bonds is a choice between a short position in UST bonds or, equivalently, an interest rate swap that receives a floating rate for a fixed rate. Our findings suggest that such a hedge is meaningful and profitable in the upward section of the business cycle, where spreads are relatively stable. If this position, however, is maintained during a recession or an early recovery stage, any profits will likely be eliminated swiftly, as suggested by our results [14]. In the downward part of the business cycle, an interest rate swap that receives a fixed rate for a floating rate would be more beneficial. Hedging, therefore, must be dynamic and include at least some degree of rebalancing as the business cycle progresses. As a result, we are able to show that a business cycle approach to interest rate hedging can add value as part of intermediate-term hedge strategies.

6. Conclusion

To study the comparative dynamics of US BBB-rated debt and UST bonds, we propose a comprehensive measure of sensitivity based on capital gains of the representative portfolios. The approach puts direct emphasis on profits or losses incurred by a portfolio due to changes in the underlying yields. While compared to assessing spread-to-rate sensitivity metrics, the capital gains measure reveals itself as a more suitable for the long-run investment perspective as this measure, by construction, is primarily focused on the profits or losses of bond portfolio on a year-on-year basis.

We reconcile two opposing strings of literature that assume a constant relationship between credit spreads of US BBB-rated bonds and the yields of risk-free UST, by showing that the relationship is not permanent but changes over time between two different regimes. The first regime corresponds to periods of high and moderate growth in the business cycle, during which credit spreads have little to no reaction to changes in interest rates and risk-free yields [6]. The second regime corresponds to periods of recession and sharp recovery from it, when credit spreads and interest rates move in opposite directions with amplified effect [4]. Our proposed capital gain-based metric is able to shed light on the dynamics of spreads and yields and explain a long-standing theoretical contradiction.

Apart from the theoretical contribution, our findings also have practical value for portfolio management and policy regulation. A sensible hedging strategy for bond portfolio would be to hold a long position in government bonds and a short position in risk-free bonds. Note that holding a short position in UST in such a synthetic portfolio is largely equivalent to a fixed-for-floating interest rate swap. However, under time-varying sensitivity, such a position is economically inefficient since losses in an economic downturn may be so severe that they may cancel out the gains obtained in normal times. Therefore, for long-term investments, dynamic positions and a proper reassessment of fundamentals are crucial. A portfolio investor that considers the phase of the economic cycle would not always rely on shorting UST as a hedge strategy, but would alter, or even reverse crossing a crisis, his exposure to risk-free UST instruments along the business cycle.

The implications for policy makers and portfolio investors alike lie in the proper timing of trends. A policy maker, on the other hand, should expect that, other positive effects notwithstanding, a reduction in interest rates during a recession may put additional pressure on corporate yields during a time of low economic performance and perceived high default risk. Our remarks contribute to the ongoing discussion of exposure to credit risk and risk assessment under the Basel III capital accord, namely, Pillar II methodologies.

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

Structure and Dynamic of Global Population Migration Network

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People are the most important factors of economy and the primary carriers of social culture. Cross-border migration brings economic and cultural impacts to the origin and destination and is also a key to reflect the international relations of related countries. In fact, the migration relationships of countries are complex and multilateral, but most traditional migration models are bilateral. Network theories could provide a better description of global migration to show the structure and statistical characteristics more clearly. Based on the estimated migration data and disparity filter algorithm, the networks describing the global multilateral migration relationships have been extracted among 200 countries over fifty years. The results show that the global migration networks during 1960–2015 exhibit a clustering and disassortative feature, implying globalized and multipolarized changes of migration during these years. The networks were embed into a Poincaré disk, yielding a typical and hierarchical "core-periphery" structure, which is associated with angular density distribution, and has been used to describe the "multicentering" trend since 1990s. Analysis on correlation and evolution of communities indicates the stability of most communities, yet some structural changes still exist since 1990s, which reflect that the important historical events are contributable to regional and even global migration patterns.

1. Introduction

In the tide of globalization, the scale and diversity of international migration are substantially increasing [1, 2]. In 2015, approximately 244 million people, or 3.3% of the world's population, lived in a country other than their birthplace [3, 4], and this value is forecasted to double by 2050 [5]. Population migration could bring important effects on both importing and exporting countries [6–8], and some scholars have used quantitative models to analyze the influencing factors, evolution patterns, and trends of global population migration [2, 9].

Some early studies researched the mechanism of population migration, such as the conventional gravity model [10–12], the random utility maximization (RUM) model [13, 14], and the self-selection method [15–17]. But they most focus on the bilateral migration flow and relations between two countries. In reality, potential migrants usually face multiple optional destinations at the same time, and they have to make a decision after comparing the advantages of all possible choices. In some cases, these decisions even could be random or probabilistic [2]. So the existing methods based on bilateral relationship will bring the problem of information loss and distortion, which has promoted the development of multilateral models and theories. Subsequent scholars put forward the definition of the multilateral migration barrier and introduced the structural gravity model [18–20] and multilateral probability model [2, 21, 22]. Such improvements from bilateral to multilateral analysis are meaningful yet still insufficient, because the indefinite definitions of multilateral barriers and coupling parameters hinder the following quantitative work and bring some controversy in estimation [23]. So, some improvement in the method is still needed.

The asymmetric and multilateral flow data shows the complexity of global migration system, and it needs a systematic model to describe the individual choice based on multilateral relationship, where the influences of other countries should not be ignored when discussing the migration flow between any two countries [2, 21]. Complex network is a powerful framework to understand the multilateral relationships in the real world, where nodes are world countries (or other elements) and links represent interaction channels between countries. And it can show the overall structure and statistical characteristics of the system more clearly, such as in biological systems [24], cortical circuits [25], and geographic maps [26]. In recent years, some researchers have used the complex network method to study international migration and have achieved some preliminary results [5].

The statistical characteristics of the network, such as degree correlation, clustering coefficient, and connectivity [27], could describe the preference of migrants when selecting the destination and also indicate the global/local connectivity and topology structure of the migration network [28–30]. Fagiolo and Mastrorillo were the first scholars to study migration from a complex network perspective, and based on analyzing the statistical characteristics, they indicated that the global migration network was organized with a small-world binary pattern displaying the characteristics of disassortativity and high clustering [31]. This finding was later certificated by other scholars [29, 30]. Furthermore, the identification of communities could analyze the hierarchical structure, the relationships, and similarities of different countries [32]. Porat and Benguigui analyzed the degree distribution and connectivity of global migration networks and classified 145 destination countries into three classes [33]. Some scholars decomposed the world migration network into communities and analyzed its structure evolution [5], along with the glocalization, polarization, and globalization of the network [34]. In addition, it can also help conventional models to describe multilateral relations more scientifically, as Tranos analyzed the topology of a migration network and proposed the pull and push factors behind international migration flows between OECD countries with the network method and gravity model [35]. This paper comprehensively analyzes the statistical characteristics, topological structure, and evolution trend of the global migration networks, composed of 200 countries/regions, with an evolution time greater than 50 years.

Besides, in recent years, scholars have found hyperbolic features in some real-world networks [36, 37]. And here we try to study the geometric features of population migration networks. In addition to proposing the hyperbolic characteristics of the population migration network, the geometric configuration is also helpful for intuitively analyzing the regional and global structures of the whole system.

This paper is organized as follows: Section 2 introduces the data source and method to extract the backbone network of global bilateral migration, which is called GMN (global migration network) in the following sections. Section 3 analyzes the skeletal construction and community dynamics of GMNs, including the changes in network statistical characteristics from 1960 to 2015, and the structure evolution. The results confirm that the GMN is a disassortative network with high clustering coefficient, exhibiting globalized and multipolarized changes during 1960–2015. Additionally, the network represents the hyperbolic and hierarchical characteristics of international migration by embedding the countries on a Poincaré disk. The positions on the disk show the status of each country/region in the global migration network, and the hyperbolic distance can indicate the migration relations between countries. Section 4 provides the conclusions and discussion.

2. Materials and Methods

2.1. Data Source. The analysis requires the data of bilateral migration flow between countries. However, from the perspective of statistics, authoritative institutions generally only provide data on the composition of immigrants (immigration stock data), such as the "UN Global Migration database" [38] and "World Bank Global Bilateral Migration database" [39], which cover most of the countries in the world. Some existing global migration networks are directly based on the immigrant stock data, which could represent past flow quantities [5, 29, 31].

In addition, there are three common methods to estimate the bilateral migration flows based on the immigrant stock data published by the World Bank or United Nations [3]: (1) use the differences in successive bilateral stocks to estimate the corresponding migration flows [2, 30, 33]; (2) approximate the migration flow rates, which are then multiplied by additional data to obtain the estimated global migration flows [40]; and (3) frame the changes in migrant stocks as the residuals in a global demographic account [1, 41]. Among the literature, the third method, called "demographic accounting," could estimate migration flows to match increases or decreases in the reported bilateral stocks with births and deaths during the period. Some scholars consider "demographic accounting" with a pseudo-Bayesian method as the most effective estimating method [3, 42]. And this paper uses the third method provided by Abel based on 200 countries/regions during 1960–2015 [43].

To reduce the impact of contingency, we separate the data into 6 periods: 1960–1969, 1970–1979, 1980–1989, 1990–1999, 2000–2009, and 2010–2015. Since there are only five complete years of data after 2010, we have doubled the estimated flow data of 2010–2015 to match other periods.

2.2. Global Migration Network (GMN). From the data in the previous section, we construct an undirected complex network based on estimated bilateral migration flows for each period. Here, the nodes are the countries/regions, and the connection between nodes depends on whether there are migrant flows between them. The weight of the edge indicates the volume of migrants, which is the sum of emigrant and immigrant flows.

Global migration is a complex system with complicated microstructure and evolutionary characteristics [30, 31, 33]. The backbone of the network offers a perspective where the structural characteristics of the network are more prominent. There are many ways to extract the backbone network; we apply a method called disparity filter algorithm [44] (with details in Appendix A).

We first assess the effect of inhomogeneity at the local level; for each country i with k migration routes, we calculate the Herfindahl–Hirschman index $Y_i(k) = \sum_j (w_{i,j}/\sum_j w_{i,j})^2$ [37, 44] (in Appendix A). $w_{i,j}$ is the weight of the edge connecting i and j. The local heterogeneity in the distribution of migration reveals that not all migration channels are equally significant (in Figure 1(a), most blue triangles are below and near the red line of $y = x$, i.e., $kY < k$), and thus, the disparity filter can be applied to select only migration channels that are significant to at least one of the countries at the end of the channel.

N_{BB}, L_{BB}, and W_{BB} are the number of nodes, number of links, and total weights in the backbone network, respectively, while N, L, and W are those in the original flow network. As significance level α changes from 0 to 0.1, the fraction of remaining nodes N_{BB}/N and the fraction of remaining weights W_{BB}/W gradually decrease, and the absolute value of the decreasing slope becomes increasingly large. To keep more countries, more weights, and fewer links in the backbone network, we choose a position α_s (in Figure 1(b)) which can minimize the remaining links on the premise of remaining all nodes to extract the backbone network. The extracted backbone network, which is called the global migration network (GMN) in the following sections, is shown in Figure 2. The color of the node indicates the community of the country/region, which is consistent with Sections 3.3 and 3.4. The results show that the GMN became denser in the 2010s.

2.3. Hyperbolic Geometry and Embedding Methods. In a hyperbolic disk, the radius increases exponentially, and the distance between two points depends not only on the length of the line connecting the two points but also on the angle difference. The hyperbolic space can capture the centrality and hierarchy of the network easily, and some scholars have proposed that many real-world networks exhibit natural hyperbolic geometry [37, 45], ranging from biology to economics, finance, and trade [36, 37, 45–49]. Some machine learning methods, for instance, embeddings of graphs such as latent space embeddings, Node2vec, and Deepwalk, have found important applications for community detection and link prediction in social networks. Maximilian Nickel and Douwe Kiela present an efficient algorithm to learn the embeddings based on Riemannian optimization [50]. This method is carried out on the Poincaré ball model, as it is well suited for gradient-based optimization (details in Appendix B). Here, we embedded the GMNs using a 2-dimensional Poincaré disk, with a learning rate of 0.1 and a negative sample size of 30. This setup produced hyperbolic embeddings in which each node i—a country in the migration embedding—has radius r_i and angle θ_i. Nodes with small radius hold central positions in the circularly arrayed hierarchy. The hyperbolic distance (depending on angle and radius) between two nodes quantifies their migration relation. Please find the comparative evaluation of hyperbolic embedding and Euclidean embedding in Section 3.2.

3. Results and Discussion

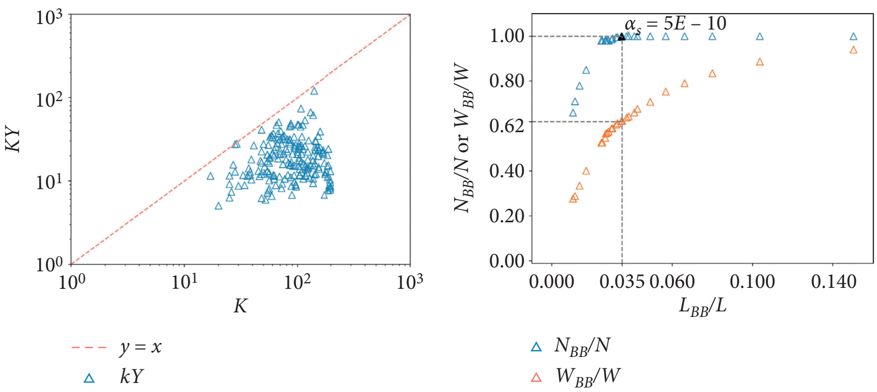
3.1. Basic Statistical Characteristics of GMNs. Figure 3(a) shows the evolution of the strength and numbers of edges for GMNs from 1960 to 2015. Obviously, the number of edges and the sum of weights exhibit a growth trend over time, which can also be observed in Figure 2. We believe that this growth implies a more frequent trend of global population migration. You can see Appendix C for the specific statistics of each network. Figure 3(b) shows the degree distribution of the backbone networks for all periods in gray and blue. We use the backbone network of 2010–2015 as an example to perform power rate fitting for the degree distribution by the nonequidistant bin method, shown in Figure 3(b) with red dots and line. It was found that the network essentially conformed to the power-law distribution. In other words, most countries have a single direction of population migration, while a small number of countries have population exchanges with many countries; this means that population migration exhibits local concentration.

The clustering coefficient measures the degree of connectivity of a network; the average shortest path reflects the difficulty of one node connecting to another node in the network. The clustering coefficients and the average shortest path (in the maximum connected subnet) of GMNs are shown in Figure 3(c). The clustering coefficient exhibits an upward trend, while the shortest path follows a downward trend, exhibiting the enhancement of small-world attributes. In our opinion, the global migration relations have become closer in recent years, which also indicates the increase in network clustering during 1960–2015.

The degree correlation in complex networks reflects the connection preference of nodes in the network, as defined as follows:

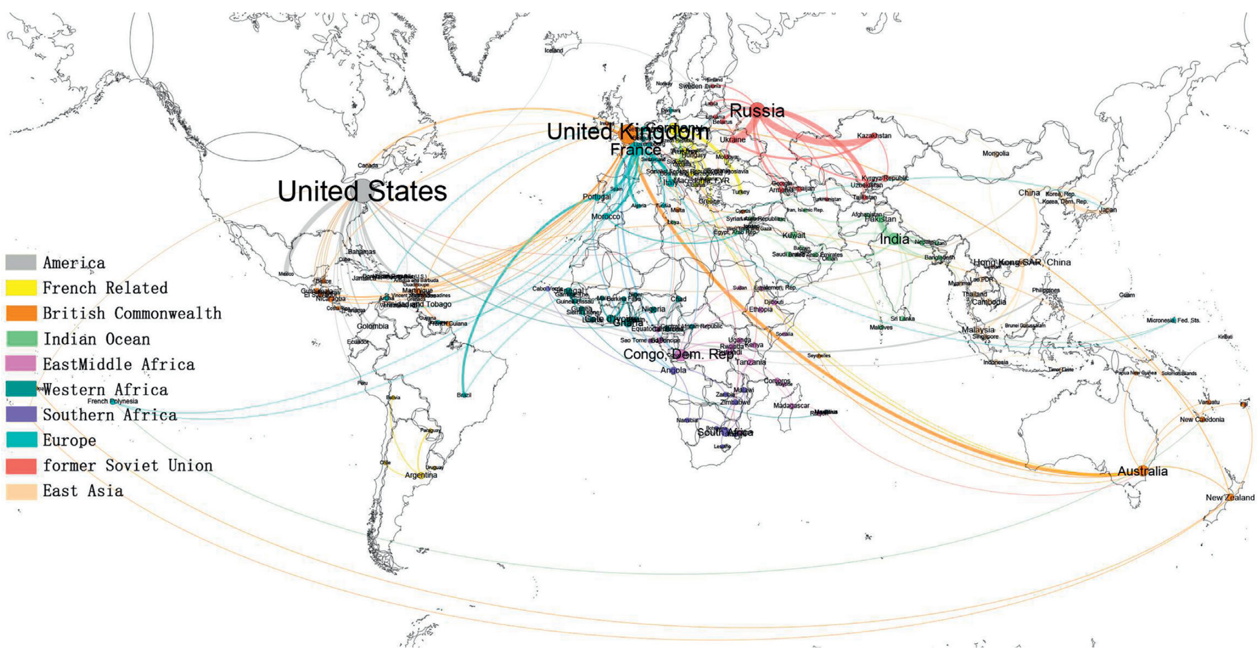
$$k_{nn}(k) \equiv \sum_{k'} k' P\left(k' \mid k\right), \tag{1}$$

with scaling hypothesis $k_{nn}(k) \propto k^{\mu}$. k_{nn} indicates the average degree of the first neighbors of nodes with degree k. If $\mu > 0$, then this is an assortative network; similarly, $\mu = 0$ indicates a neutral network, while $\mu < 0$ indicates a disassortative network. We calculate the degree correlation of each network by degree correlation function, and their μ values are all negative during 1960–2015. The degree correlation of the 2010–2015 GMN is shown in Figure 3(d). The GMNs in other years exhibit similar imagines. This method shows that all of the networks have the characteristics of negative matching, indicating that nodes with lower degrees are more likely to be connected with nodes with higher degrees. The reason may be that the migration of most small countries shows preferential movement to several large countries that have survival advantages or economic advantages. In fact, the disassortative characteristic of the international migration network has been verified in some existing studies [30, 31]. In addition to the migration networks, the international oil trading network shows a disassortative feature in which countries with fewer trading partners tend to develop oil trading relations with countries with more trading partners [51].



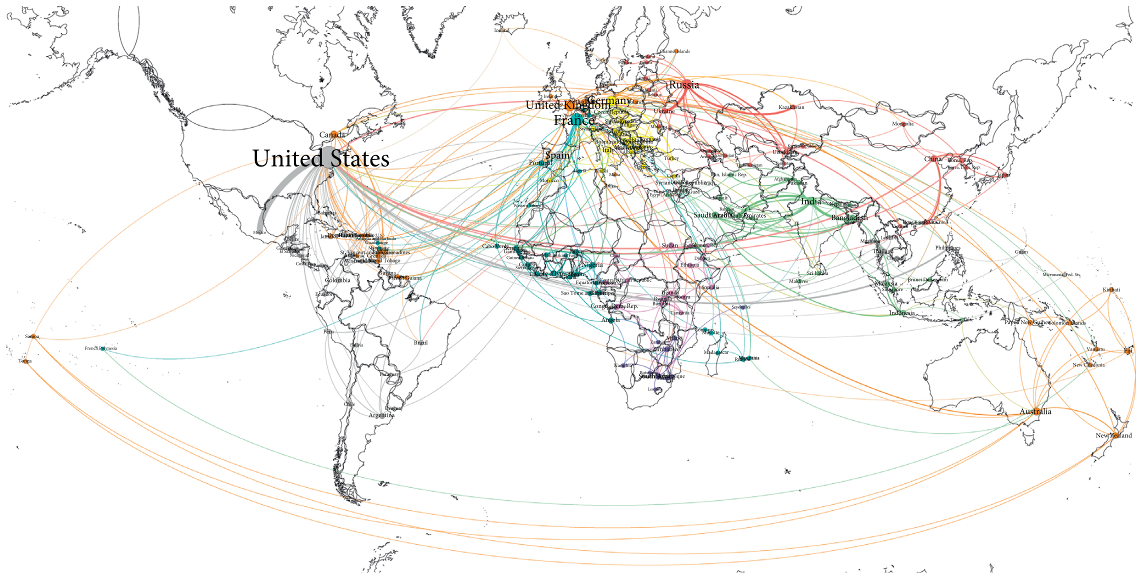
(a) (b)

FIGURE 1: (a) Local inhomogeneity levels during the period of 2010–2015. (b) N_{BB}/N and W_{BB}/W versus L_{BB}/L in the period of 2010–2015. The position with a black triangle is the optimized extracting parameter α_s that we selected, retaining 3.47% (385) of the edges and 62.22% ($5.95E+7$) of the weight.



(a)

FIGURE 2: Continued.



(b)

Figure 2: Backbone of the global migration network. (a) 1960–1969. (b) 2010–2015.

3.2. Hyperbolic Characteristics of GMNs. Some network structures could actually be better described by hyperbolic space [36, 37]. To further compare the advantages of hyperbolic embedding, we try to separately embed GMNs into Euclidean and hyperbolic planes. We consider the least-squares error function used in [52]. After unified measurement, the errors of two spaces are revealed in Figure 4 with dotted lines. In addition, we also compute the embedding score (details in Appendix B) in both two spaces (considering the error function performance, we only embed the network in Euclidean space by nonclassical MDS). The result is shown in Figure 4 with solid lines. This figure shows that all errors in hyperbolic embedding are lower than those in Euclidean embedding; according to the score, hyperbolic embedding also offers more professional performance in the expression of data size relations. This result indicates that the GMNs exhibit a significant hyperbolic characteristic during 1960–2015. The Poincaré disk embedding results of GMNs in the 1960s and the 2010s are visualized as shown in Figure 5.

Each node represents a country/region. The size of the node expresses its degree in GMN, the hyperbolic distances represent their relations in the global migration network, and the weights of edges are the same as those in the backbone network (after normalization). For clarity, only the names of nonperipheral countries whose distance less than 0.97 from the origin of the coordinates are shown. The color of the node indicates the geographical location of the country/region. The figure indicates that GMNs presents an obvious "core-periphery" structure. In the 1960s, the network is sparse, while in the 2010s, 200 countries have closer and more complex migration relations, which also conforms to the common law of global integration. The population migration in the 1960s primarily occurred within the regions or communities, and there are fundamentally fewer typical countries in the center of the Poincaré disk (Figure 5(a)). The Democratic Republic of the Congo (COD) is the second largest country in Africa. Once a Belgian colony, it became independent in 1960 and became a link in the global migration network between France (FRA) in Europe and African countries such as Sudan (SUD) and Madagascar (MDG).

Furthermore, for the period of 2010–2015, the network structure is more complex, and the hierarchy is more obvious. Here, the United States and Canada (with large degrees of $k = 53$ and $k = 30$, respectively), which have closer population migration relations with other countries in various regions of the world, are more centrally located in the disk. France and the United Kingdom, which mainly connect local communities such as European and some African countries, have been slightly more marginal since the 2010s. Although the degrees of Portugal and Yemen are not large ($k = 8$ and $k = 2$, respectively), their locations indicate their contributions on connecting the migration of several continents.

Additionally, Figure 5 also shows that the hyperbolic distance between countries/regions is not entirely determined by the geographical location. It represents the correlation of embedding distances and geographic distances, which is significant during 1960–2015 (with sig.≈0). This means that hyperbolic distance d_h is positively correlated with geographical distance d_g but encodes more than purely geographical information.

In order to describe the distribution characteristics of the countries on the hyperbolic plane more clearly, we define the angular density $f(\theta)$. First of all, we get some points on the hyperbolic plane (the points with polar coordinates of $[\pi, 0]$, $[\pi, 0.1]$, $[\pi, 0.5]$, $[\pi, 0.7]$, $[\pi, 0.9]$ in Figure 6(a)); then we draw neighborhood of the points with the same radius n_s.

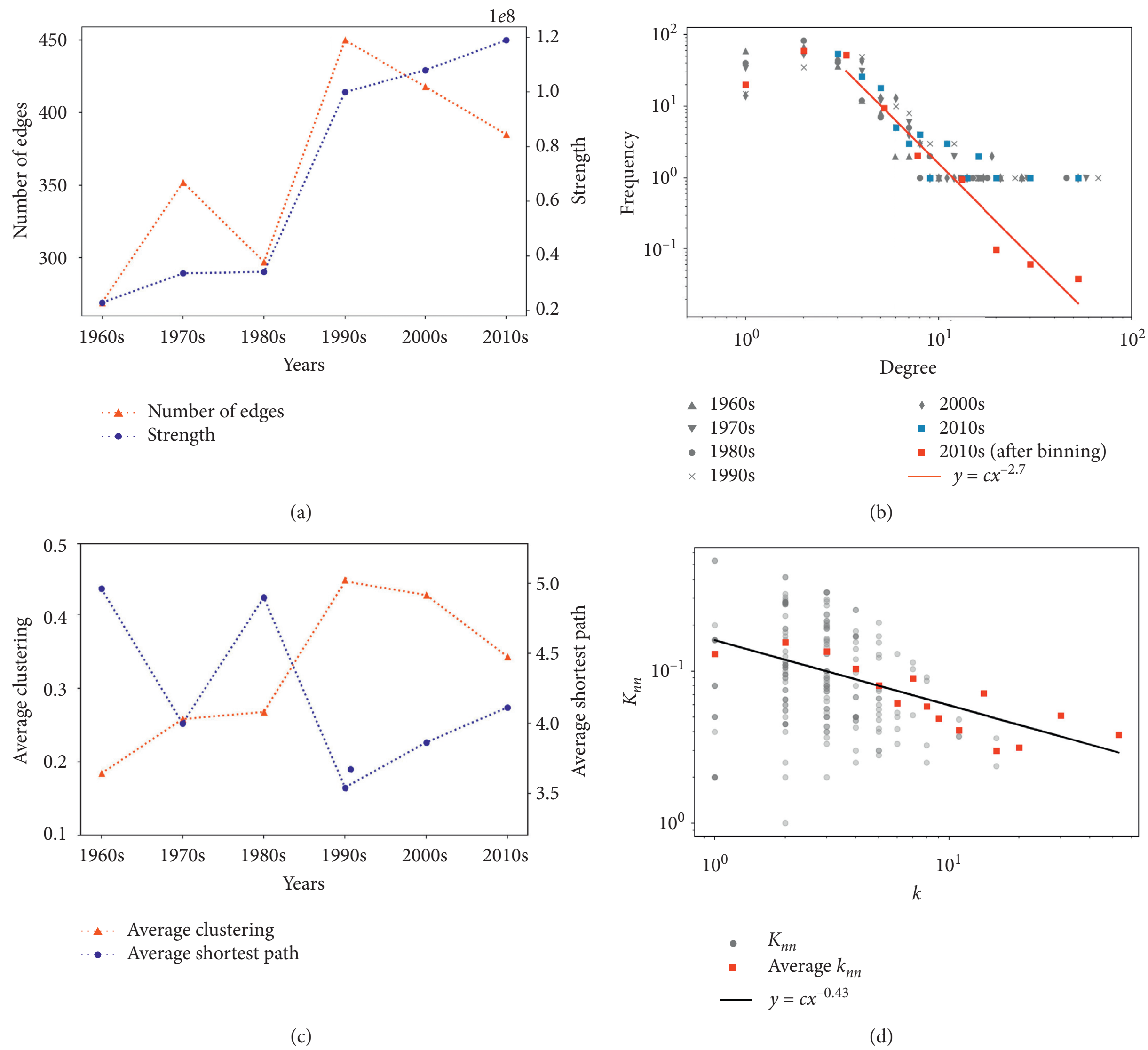


Figure 3: (a) Changes in the strength and numbers of edges of the backbone networks from 1960 to 2015. (b) The degree distribution of the backbone networks and power rate fitting of the population migration network for 2010–2015. The blue points are the original degree distribution, and the red points are the data after binning. (c) Changes in the clustering coefficients and the average shortest path of the backbone networks from 1960 to 2015. (d) Degree correlation of the migration network in 2010–2015.

As these points move away from the core ($r = 0$), their neighborhood looks smaller, and the center of the circle tends to shift toward the core, but on the hyperbolic plane, these circles have the same area. So the green circle with the center $[\pi, 0]$, blue with $[\pi, 0.1]$, orange with $[\pi, 0.5]$, yellow with $[\pi, 0.7]$, and purple with $[\pi, 0.9]$ have the same area. And we define the density of points as the number of countries loaded in their neighborhood.

Then, we sum the density for each $\theta \in [0, 2\pi)$ and get the angular density distribution $f(\theta)$. Angular density can more intuitively show the distribution characteristics of countries in hyperbolic space. Figure 6(b) shows the angular density for the 1990s-2000s. Blue dotted line indicates the angular density for each θ, and the countries are the representatives with the relatively centering positions and they belong to the corresponding peaks. The color of the country indicates its region.

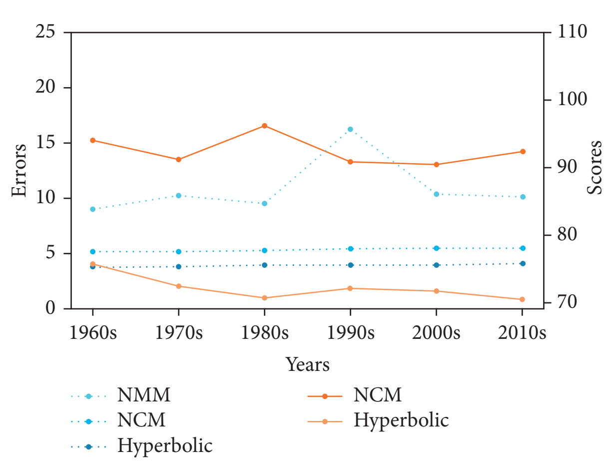
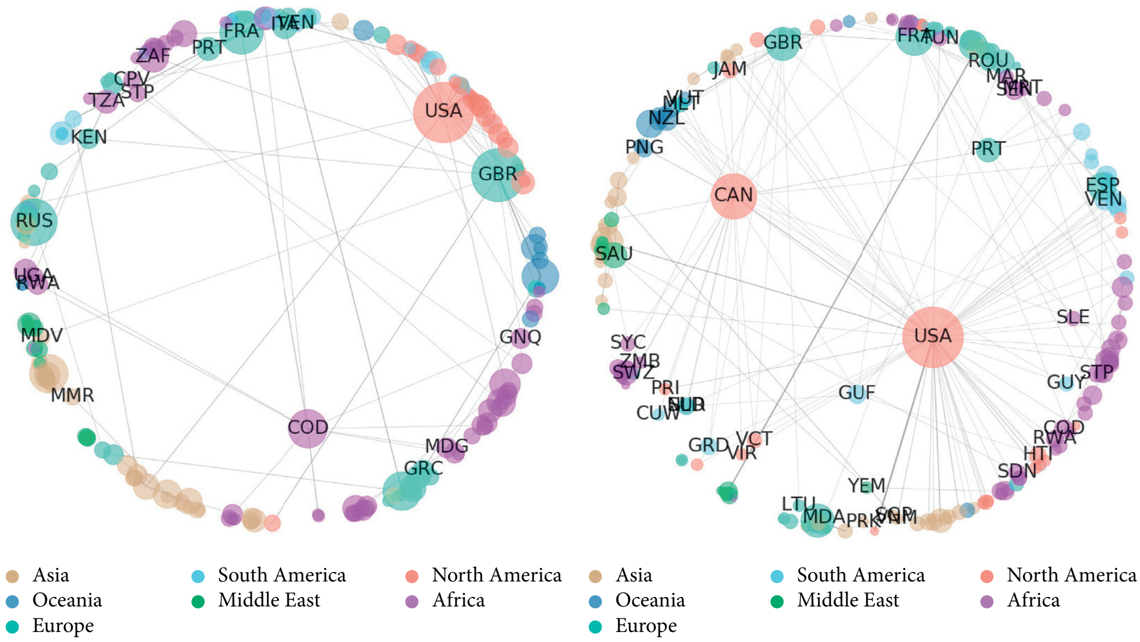


Figure 4: The error functions and embedding scores of GMNs in Euclidean and hyperbolic planes for 1960–2015.



(a) (b)

Figure 5: Hyperbolic embedding map of global migration network. (a) 1960–1969. (b) 2010–2015.

Angular density can help us see the aggregation of the global migration networks more intuitively: (1) In the 2010s, the aggregation has increased obviously, which is reflected by the increasing angular density, and more countries have gathered together. (2) Most of the countries in the center are located in North America or Europe. It is mainly because the countries in North America and Europe have the shorter migration distance from other countries, so they are naturally easier to be located in the center of hyperbolic plane. (3) Besides, in the 1990s, African countries were more aggregated, while in the 2010s, Latin American countries were more aggregated. (4) It shows a trend of "multicentering" of the global migration networks since the 1990s.

3.3. Communities Characteristics of GMNs. There are many ways to explore the communities of a complex network, such as the GN algorithm [53] based on network topology and Potts model [54] based on network dynamics. In this paper, the Louvain algorithm [55] based on modularity, which is rapid and exhibits an obvious clustering effect, is adopted. The algorithm divides each round of calculation into two steps: in the first step, the algorithm scans all nodes, traverses all neighbors of the node, and measures the modularity benefit of adding the node to the community of its neighbor; it then selects the corresponding neighbor node with the highest modularity gain and joins its community. This process is repeated until the results are stable. During 1960–2015, the modularity value Q is within 0.66–0.76, which proves the validity of clustering (green line in Figure 7(d)).

Figure 8 shows the communities of global migration networks during 1960–2015. Obviously, the result of clustering is relatively stable over the most recent fifty years. According to the composition of members, we define ten typical communities: (1) America: including the countries in North America, Central America, South America, and the Caribbean; (2) French related: including France and other neighboring European countries, as well as French territories and former colonies around the world; (3) British Commonwealth: including some original and current Commonwealth countries, including Australia, New Zealand, and Canada; (4) Indian Ocean: centered on India, including South Asia, North Africa, Southeast Asia, and other countries close to the Indian Ocean; (5–7) most sub-Saharan African countries divided into three communities: East-Middle, Western, and Southern Africa; (8) Europe: some countries in Western, Central, and Eastern Europe; (9) the former Soviet Union: including Russia and some former Soviet countries; and (10) East Asia: mainly East Asian countries, including some Southeast Asian countries in early times and Russia and some former Soviet countries in recent years.

After grouping, we could analyze the "globalization" or "polarization" trends based on comparing the global and local connectivity in migration communities. The cumulative distribution of degrees and weights (Figures 7(a) and 7(b)) shows that, on the whole, they both tend to be relatively flat. This means that many top countries are reducing their proportions of edges and flows, while other countries with low flows are experiencing relatively rapid development. The Gini coefficients of degree and weight both exhibit an overall downward trend, and the entire network becomes more balanced over time (Figure 7(c)).

In recent years, some scholars have proposed the "globalization of migration" hypothesis and emphasized both the progressively increasing number of countries involved in global migration and the diversification of origins

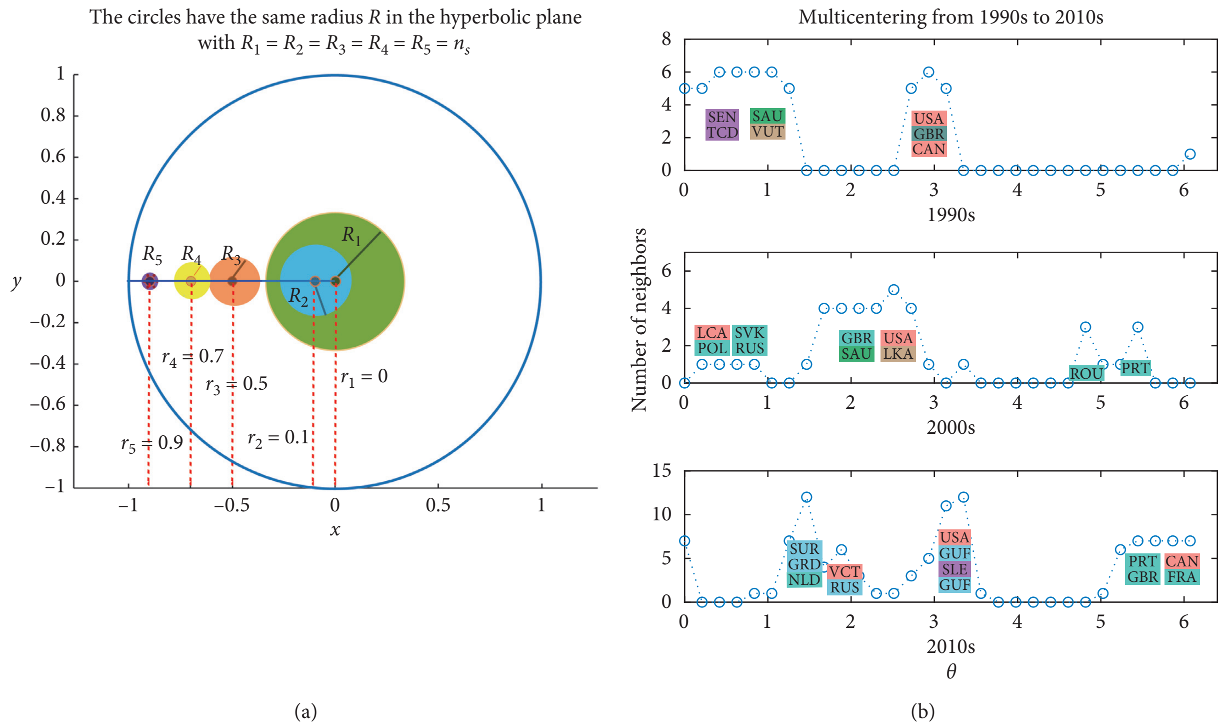


Figure 6: Angular density in hyperbolic plane which could describe the aggregation of countries and the multicentering characteristics of global migration networks. (a) Definition of neighborhood. (b) Angular density.

and destinations [34, 56]. Some other scholars offered an alternative understanding, suggesting that, in recent years, globalization did not contribute to an overall increase in mobility possibilities but instead widened the gap between rich and poor countries [57–59], leading to polarization of the global migration networks.

Here, we use the external-internal index (E-I index) to measure the comparison of local and global cohesion, which is widely used in group embeddedness [34, 60, 61]. We define the E-I index of GMNs as

$$\text{E-I index}_{(\text{degree})} = -\frac{\text{EK} - \text{IK}}{\text{EK} + \text{IK}},$$
$$\text{E-I index}_{(\text{weight})} = -\frac{\text{EW} - \text{IW}}{\text{EW} + \text{IW}}. \quad (2)$$

The "internal" edge connects the two nodes in the same community, and the "external" edge connects the nodes from the different communities. EK and EW are the sums of external degrees and weights for all nodes, respectively; IK and IW are the sums of internal degrees and weights for all nodes, respectively. The E-I index ranges from 0 to 1. Smaller E-I index values indicate stronger connectivity between communities; larger E-I index values indicate stronger connectivity within the community and show that the community is more independent.

Figure 7(d) shows a downward trend of the E-I index with respect to both degrees and weights. This figure indicates the continuous growth trend of cross-community connection and to some extent proves the significant trend of globalization in GMNs over the past fifty years.

Furthermore, Figure 9 shows E-I index values for ten typical communities; the countries/regions possessing the largest degree in the communities are listed, which could be regarded as the center of communities. For most communities, the central country/region is relatively stable and unchanged for these 50 years or is only adjusted between neighboring countries. It is worth noting that there are mergers and splits of communities 8–10, Europe, the former Soviet Union, and East Asia, which will be described with details in Section 3.4. Here, dark green indicates the smaller E-I index values for the community in the corresponding time period.

The results present that, over the past 50 years, the migration relation between different communities has become closer, which is reflected in the overall decline in E-I index values presented in Figure 9. In particular, the two communities of the former Soviet Union and the Indian Ocean are typically introverted, with most of the migration flow coming from the "internal edges" connecting the community members; the communities of America, French related, and Europe (since the 2000s) are extroverted, where the cross-community migration relation is greater than that within the communities. On the whole, the number of extroverted communities is increasing over time, and this also shows that, for the potential immigrants, the possible moving routes among communities become more abundant. In contemporary times, the number of communities with E-I index values below 50% (dark green grids) has increased from one to

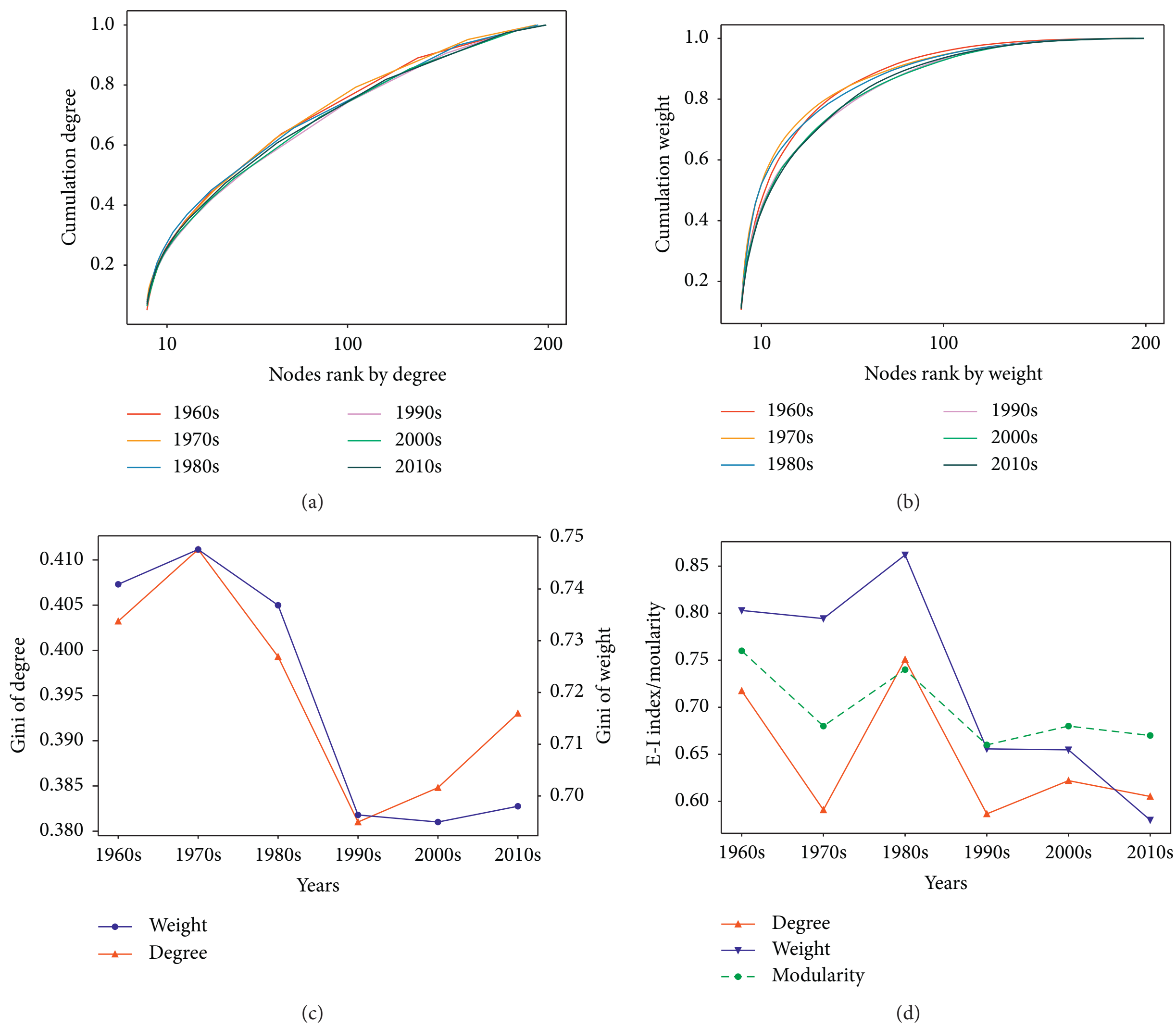


Figure 7: (a) The cumulative distribution of degrees for nodes from 1960 to 2015. (b) The cumulative distribution of weights for nodes from 1960 to 2015. (c) Changes in the Gini index for the degrees and weights from 1960 to 2015. (d) Changes in the E-I index from 1960 to 2015.

four, which indicates that the GMNs became more globalized and multipolarized from the 1960s to the 2010s.

3.4. Structural Evolution of GMNs. To assess the network structure more clearly, we analyze the correlation of the network communities with time. Figure 10 shows the matrix of Jaccard similarity coefficients of ten typical communities covering 90–97% of the countries/regions. In general, the composition of the members of each community is stable, and the characteristics related to geographical location are shown (Figure 11). Over more than 50 years, the central countries/regions of most communities have not changed. The green color indicates greater correlation, along with the higher coincidence of the members for the cluster between two eras. In contrast, the yellow color indicates that the structure of the communities changed greatly during this time.

Focusing on the yellow grids in Figure 10, combined with the specific composition of each community in Figures 7 and 11, we found some structural evolution of global migration networks during the past 50 years.

3.4.1. Community of the Former Soviet Union. The ninth community, centered on Russia, was an independent cluster in the 1960s-1970s; in the 1980s-1990s, it merged into the community of Europe centered on Germany. Such structural changes may be related to the collapse of the former Soviet Union in 1991, when it pursued the policy of deporting the nonnative population, together with the boom of immigrants from the East into Western Europe [62, 63]. After 2000, the former Soviet Union cluster left the Germany group and merged into the community of East Asia. In fact, since then, Russia gradually replaced Hong Kong SAR as the new center of the community. The map also shows that Russia and these former Soviet Union countries have had a closer relationship with East Asia in GMNs since 2000 (Figure 11).

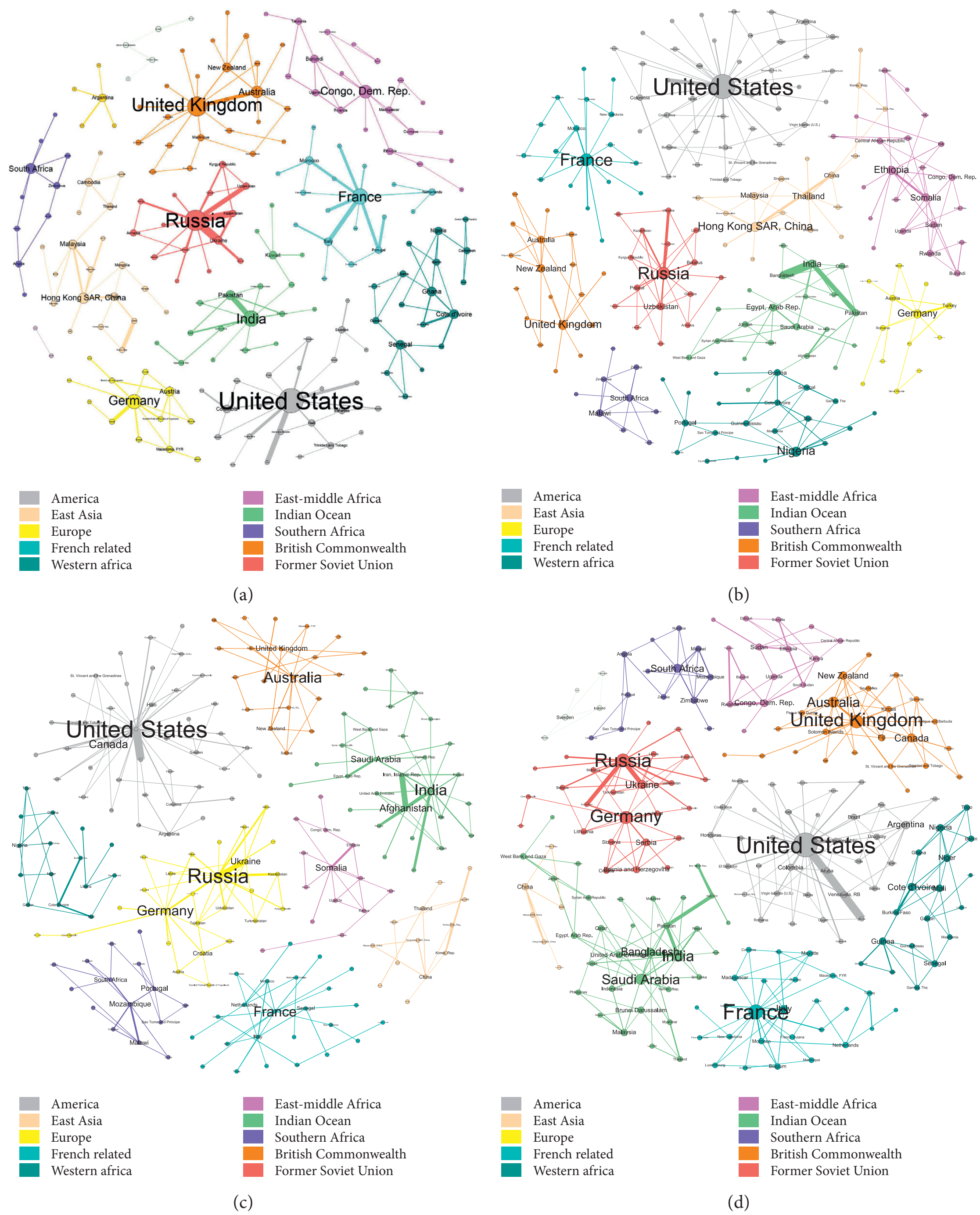


Figure 8: Continued.

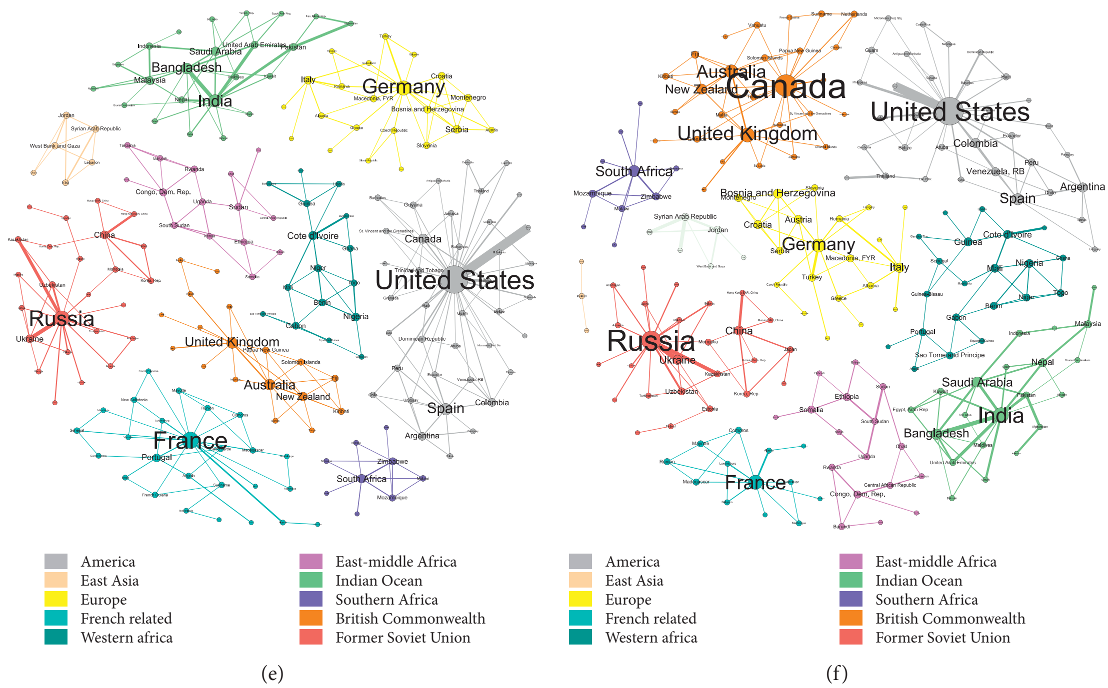


FIGURE 8: Communities and structural evolution of GMNs from 1960 to 2015. (a) 1960–1969. (b) 1970–1979. (c) 1980–1989. (d) 1990–1999. (e) 2000–2009. (f) 2010–2015.

Community	Name	1960s	1970s	1980s	1990s	2000s	2010s
1	America	United States					
2	French related	France					
3	British Commonwealth	United Kingdom					Canada
4	Indian Ocean	India					
5	East-Middle Africa	Congo, DR	Ethiopia	Somalia	Congo, DR		
6	Western Africa	Cote d'Ivoire	Nigeria		Cote d'Ivoire		
7	Southern Africa	South Africa					
8	Europe	Germany		Germany		Germany	
9	Former Soviet Union	Russia				Russia	
10	East Asia	Hong Kong SAR					

E-I index:	0–50%	51%–60%	61%–70%	71–80%	81–90%	91–100%

FIGURE 9: E-I index (degree) for each community from the 1960s to the 2010s. The countries/regions having the largest degrees in the communities are listed in the table.

3.4.2. Country of Canada. Once belonging to the British Commonwealth, Canada had a close relationship with Hong Kong SAR, and they were in the same community in the 1960s-1970s. Canada changed during 2000–2010 to join the community of America, which contained most of the American countries (Figure 11). In fact, some scholars have certified the relationships of the countries in Latin America and North America, including the United States [64, 65]. However, beginning in 2010, Canada left the United States community and became the new center of the British Commonwealth community; it is also the third closest country to the center on the hyperbolic plane, after the United States and French Guiana (Figure 5).

3.4.3. Community Centered on France. The structure of the second community centered on France also substantially changed. In the 1990s, 68% of its members belonged to European countries or their territories, but in the 2010s, the European members only accounted for 58%. In contrast, in the 1960s, African countries accounted for only 15% of this community, but after 2010, the proportion of African

	60s	70s	80s	90s	00s	10s	Num
60s	1.0000	0.4222	0.5238	0.3044	0.4546	0.3409	25
70s	0.4222	1.0000	0.6596	0.6444	0.6596	0.5870	39
80s	0.5238	0.6596	1.0000	0.5417	0.6596	0.5208	40
90s	0.3044	0.6444	0.5417	1.0000	0.6087	0.6829	35
00s	0.4546	0.6596	0.6596	0.6087	1.0000	0.7805	40
10s	0.3409	0.5870	0.5208	0.6829	0.7805	1.0000	34

(a)

	60s	70s	80s	90s	00s	10s	Num
60s	1.0000	0.4222	0.3438	0.3235	0.2500	0.1852	19
70s	0.4222	1.0000	0.4483	0.5714	0.5712	0.4762	18
80s	0.3438	0.4483	1.0000	0.3889	0.3514	0.1936	24
90s	0.3235	0.5714	0.3889	1.0000	0.5294	0.0278	26
00s	0.2500	0.5712	0.3514	0.5294	1.0000	0.4444	26
10s	0.1852	0.4762	0.1936	0.0278	0.4444	1.0000	13

(b)

	60s	70s	80s	90s	00s	10s	Num
60s	1.0000	0.3226	0.2647	0.3056	0.2813	0.3421	23
70s	0.3226	1.0000	0.6522	0.6153	0.5000	0.3529	18
80s	0.2647	0.6522	1.0000	0.4194	0.4074	0.2632	20
90s	0.3056	0.6153	0.4194	1.0000	0.4483	0.5294	24
00s	0.2813	0.5000	0.4074	0.4483	1.0000	0.4375	18
10s	0.3421	0.3529	0.2632	0.5294	0.4375	1.0000	28

(c)

	60s	70s	80s	90s	00s	10s	Num
60s	1.0000	0.6957	0.5667	0.5625	0.5729	0.6250	18
70s	0.6957	1.0000	0.7241	0.6563	0.5714	0.5556	21
80s	0.5667	0.7241	1.0000	0.8485	0.7333	0.7241	29
90s	0.5625	0.6563	0.8485	1.0000	0.7188	0.6563	32
00s	0.5729	0.5714	0.7333	0.7188	1.0000	0.9130	23
10s	0.6250	0.5556	0.7241	0.6563	0.9130	1.0000	21

(d)

	60s	70s	80s	90s	00s	10s	Num
60s	1.0000	0.4333	0.6667	0.5000	0.5000	0.4615	21
70s	0.4333	1.0000	0.5000	0.6087	0.6087	0.6250	22
80s	0.6667	0.5000	1.0000	0.6111	0.6111	0.5500	14
90s	0.5000	0.6087	0.6111	1.0000	1.0000	0.8824	15
00s	0.5000	0.6087	0.6111	1.0000	1.0000	0.8824	15
10s	0.4615	0.6250	0.5500	0.8824	0.8824	1.0000	17

(e)

	60s	70s	80s	90s	00s	10s	Num
60s	1.0000	0.5600	0.5713	0.8000	0.6190	0.6250	18
70s	0.5600	1.0000	0.5652	0.6957	0.6087	0.9091	21
80s	0.5713	0.5652	1.0000	0.7368	0.7222	0.6364	15
90s	0.8000	0.6957	0.7368	1.0000	0.7895	0.7727	18
00s	0.6190	0.6087	0.7222	0.7895	1.0000	0.6818	16
10s	0.6250	0.9091	0.6364	0.7727	0.6818	1.0000	21

(f)

	60s	70s	80s	90s	00s	10s	Num
60s	1.0000	0.7273	0.6667	0.7692	0.5833	0.6667	10
70s	0.7273	1.0000	0.6000	0.6923	0.8000	0.9000	9
80s	0.6667	0.6000	1.0000	0.8667	0.5000	0.5625	15
90s	0.7692	0.6923	0.8667	1.0000	0.5714	0.6429	13
00s	0.5833	0.8000	0.5000	0.5714	1.0000	0.9000	9
10s	0.6667	0.9000	0.5625	0.6429	0.9000	1.0000	10

(g)

	60s	70s	80s	90s	00s	10s	Num
60s	1.0000	0.7333	0.2581	0.2188	0.5217	0.5455	13
70s	0.7333	1.0000	0.3448	0.2188	0.5217	0.5455	13
80s	0.2581	0.3448	1.0000	0.7931	0.2308	0.2368	26
90s	0.2188	0.2188	0.7931	1.0000	0.2308	0.2368	26
00s	0.5217	0.5217	0.2308	0.2308	1.0000	0.9546	22
10s	0.5455	0.5455	0.2368	0.2368	0.9546	1.0000	21

(h)

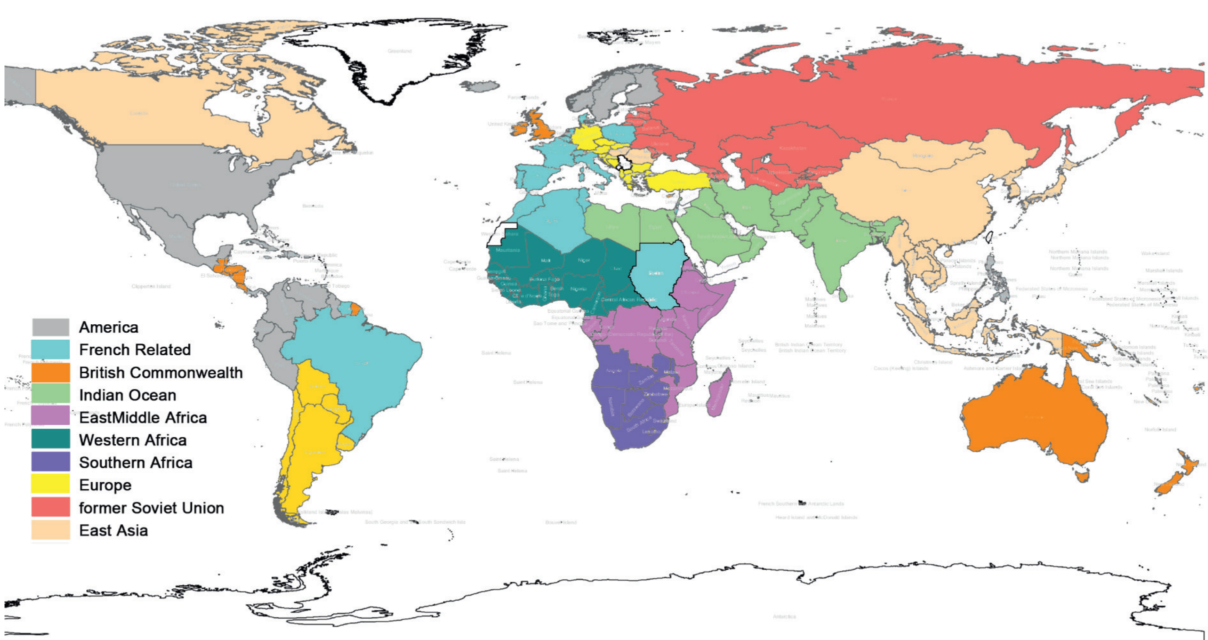
	60s	70s	80s	90s	00s	10s	Num
60s	1.0000	0.9375	0.5769	0.5769	0.5385	0.5769	15
70s	0.9375	1.0000	0.6154	0.6154	0.5185	0.5556	16
80s	0.5769	0.6154	1.0000	0.7931	0.3784	0.4054	26
90s	0.5769	0.6154	0.7931	1.0000	0.4167	0.4444	26
00s	0.5385	0.5185	0.3784	0.4167	1.0000	0.8889	25
10s	0.5769	0.5556	0.4054	0.4444	0.8889	1.0000	26

(i)

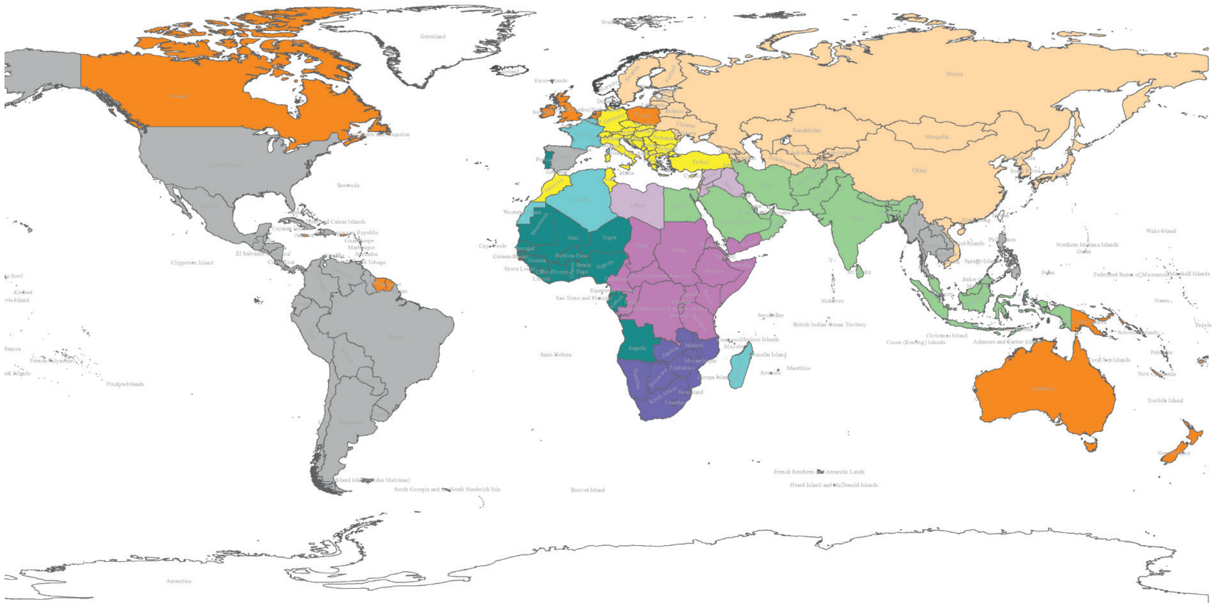
	60s	70s	80s	90s	00s	10s	Num
60s	1.0000	0.7273	0.5714	0.2400	0.1842	0.2105	20
70s	0.7273	1.0000	0.5500	0.2609	0.1944	0.1892	18
80s	0.5714	0.5500	1.0000	0.3333	0.2258	0.2581	13
90s	0.2400	0.2609	0.3333	1.0000	0.3333	0.2759	11
00s	0.1842	0.1944	0.2258	0.3333	1.0000	0.8889	25
10s	0.2105	0.1892	0.2581	0.2759	0.8889	1.0000	26

(j)

FIGURE 10: Jaccard similarity coefficients of ten typical communities for different time periods. "Num" means the number of members in the corresponding community. (a) Group 1, America. (b) Group 2, French related. (c) Group 3, British Commonwealth. (d) Group 4, Indian Ocean. (e) Group 5, East-Middle Africa. (f) Group 6, Western Africa. (g) Group 7, Southern Africa. (h) Group 8, Europe. (i) Group 9, the former Soviet Union. (j) Group 10, East Asia.



(a)



(b)

Figure 11: Community map of GMNs in the 1960s and the 2010s showing the characteristics related to geographical distribution. (a) 1960–1969. (b) 2010–2015.

countries increased to 42%, which also shows that France, as the representative and center of the community, became increasingly close to African countries in the global migration network. This trend should be closely related to the influence of language and historical colonies [2, 66].

3.4.4. Countries including Malaysia, Singapore, and Indonesia. In the 1960s-1970s, Malaysia, Singapore, and Indonesia were in the East Asia community, with Hong Kong SAR as the center. But since the 1980s, these three countries have been transferred to the community centered on India, which has greatly impacted the East Asia community and greatly reduced the number of its members. After 2000, the former Soviet Union community was merged and the center of the cluster was adjusted to Russia, which greatly changed the structure of the East Asia community again.

4. Conclusion

Global population migration is a typical complex system. At the microlevel, each potential migrant makes a rational decision on "whether" and "where" to migrate according to the diversity utility function. Although the individuals are heterogeneous, specific migration patterns and evolution rules are continually emerging on the macrolevel.

The migration relationship between countries is complex and multilateral, and network theories could provide better description and more clearly exhibit on its structure and statistical characteristics. This paper constructs undirected global migration networks (GMNs) based on estimated bilateral migration flows during 1960–2015. The GMNs display the characteristics of disassortativity and high clustering with a typical power-law in-degree distribution. In the most recent fifty years, the network density and clustering have been increasing; the Gini coefficient of the degree and weight both exhibit an overall downward trend; and the entire network becomes more balanced and exhibits greater connectivity with time.

From the network perspective, we analyze the evolution trend of international migration by comparing the global and local migration connectivity in communities. On the whole, the number of extroverted communities is increasing over time. This observation indicates the continuous growth trend of cross-community connection and, to some extent, proves the significant trends of "globalization" and "multipolarization" in the global migration network since the 1960s.

The existing literature does not discuss the geometric characteristics of the population migration network. This paper indicates that the GMNs exhibited a significant hyperbolic characteristic and hierarchical structure during 1960–2015, which is becoming more obvious in these years. We embed the GMNs into hyperbolic space and finally obtain the locations of 200 countries/regions on a 2-dimensional Poincaré disk. Based on the definition of angular density distribution, it showed a trend of multicentering of the global migration networks since the 1990s.

Finally, we analyze the correlation between network communities and the structural evolution of GMNs with time. In general, from 1960 to 2015, the composition of the members of each community remained stable, and the central countries/regions of most communities did not change. In addition, we still find some changes: the former Soviet Union community merged into Germany during the 1980s-1990s, which could be related to the collapse of the former Soviet Union, and it left the German group and replaced Hong Kong SAR as the center of the East Asian community after 2000; the community centered in France reduced the proportion of members from Europe, and more African countries, especially those with colonial relations and labor contracts with France, gradually joined the group beginning in the 1960s; some southeastern Asian countries such as Singapore, Malaysia, and Indonesia were in the East Asian community but transferred to the Indian Ocean community centered in India since the 1980s.

This paper provides a creative way to analyze the structural, statistical, and geometric characteristics and hierarchical structure of the population migration network. With respect to complex human migration behavior, it is far from sufficient to analyze only the migration flow data. In future research, we will consider the economic, social, and policy factors that affect the decision-making of potential migrants and research the features and evolution of population migration patterns more comprehensively and scientifically.

Appendix

A. Inhomogeneities and Disparity Filter Algorithm

To calculate inhomogeneities at the local level, for each country i with k migration routes, the authors calculate the Herfindahl-Hirschman index (HHI) $Y_i(k)$, which is extensively used as an economic standard indicator of market concentration, and it is also denoted as the disparity measure in the complex networks literature:

$$Y_i(k) = \sum_j \left(\frac{\omega_{i,j}}{s_i}\right)^2, \tag{A.1}$$

where ω_{ij} is the total flow between countries i and j and $s_i = \sum_j \omega_{i,j}$ is the strength (aggregated migration) of country i. If country i distributes its migration homogeneously between its migration partners, then $kY_i(k) = 1$; in the opposite case, if all its migration is concentrated on a single link, then $kY_i(k) = k$. For the inhomogeneities network, we can use the disparity filter to extract the backbone.

The disparity filter proceeds as follows. The authors first normalize the weights of edges linking node i with its neighbor j as $p_{i,j} = \omega_{i,j}/s_i$, with $s_i = \sum_j \omega_{i,j}$ being the strength of node i and $\omega_{i,j}$ being the weight of the edge connecting i and j. For each migration channel of a given country i, the authors compute the probability $\alpha_{i,j}$ that the link takes the observed value $p_{i,j}$ according to the purely random null model. By imposing a significance level α, the authors can determine the statistical significance of a given migration channel by comparing $\alpha_{i,j}$ to α. Therefore, if $\alpha_{i,j} > \alpha$, the flow through that migration channel can be considered compatible with a random distribution (with the chosen significance level α) and is thus discarded. The statistically relevant channels are those that satisfy

$$\alpha_{i,j} = 1 - (k-1)\int_0^{p_{i,j}} (1-x)^{k-2}\mathrm{d}x < \alpha, \tag{A.2}$$

for at least one of the two countries i and j. k represents the degree of node i.

By applying this selection rule to all of the links in the network, the authors find the backbone, a new graph containing, in general, fewer links and nodes, as the GMN in this paper. However, the number of links and nodes removed depends on the value of the significance level α. To find the appropriate value of α, it is convenient to plot the fraction of remaining nodes N_{BB}/N and the fraction of remaining weights W_{BB}/W in the backbone versus the fraction of remaining links L_{BB}/L for different values of α. As the filter becomes more restrictive, the number of links decreases while keeping almost all nodes until a certain critical point, after which the number of nodes begins a steep decay. To retain more countries, more weights, and fewer links, the authors choose a point where the number of nodes begins to be lower than the initial value as our specific indicator α_s for extracting the backbone networks [44].

B. Hyperbolic Embedding Method and Evaluation Index

The method proposed by Maximilian Nickel and Douwe Kiela is based on the Poincaré ball model, as it is well suited for gradient-based optimization [50]. In particular, let $\mathcal{B}^d = x \in \mathbb{R}^d \| \|x\| < 1$ be the *open* d-dimensional unit ball, where $\|\cdot\|$ denotes the Euclidean norm. The Poincaré ball model of hyperbolic space then corresponds to the Riemannian manifold $(\mathcal{B}^d, g_{\mathbf{x}})$, that is, the open unit ball equipped with the Riemannian metric tensor

$$g_{\mathbf{x}} = \left(\frac{2}{1-\|x\|^2}\right)^2 g^E, \tag{B.1}$$

where $x \in \mathcal{B}^d$ and g^E denotes the Euclidean metric tensor. Furthermore, the distance between points $\mathbf{u}, \mathbf{v} \in \mathcal{B}^d$ is given as

$$\mathrm{d}(\mathbf{u},\mathbf{v}) = \operatorname{arcosh}\left(1 + 2\frac{\|\mathbf{u}-\mathbf{v}\|^2}{\left(1-\|\mathbf{u}\|^2\right)\left(1-\|\mathbf{v}\|^2\right)}\right). \tag{B.2}$$

Note that equation (B.2) is symmetric and that the hierarchical organization of the space is solely determined by the distance of nodes to the origin. Due to this self-organizing property, equation (B.2) is applicable in an unsupervised setting where the hierarchical order of objects such as text and networks is not specified in advance. Remarkably, equation (B.2) therefore allows us to learn embeddings that simultaneously capture the hierarchy of objects (through their norms) as well as their similarity.

The authors embedded our GMN in all time periods (1960–2015), using a 2-dimensional Poincaré disk, with a learning rate of 0.1 and a negative sample size of 30. To further explain the embedding effect, the general form of the function is as follows:

Table 1: Descriptive statistics regarding the GMN.

	1960–1969	1970–1979	1980–1989	1990–1999	2000–2009	2010–2015
Number of nodes	195	195	196	200	200	200
Number of edges	269	352	297	450	418	385
Number of communities	13	10	9	10	10	11
APL	4.96	4.00	4.90	3.54	3.86	4.11
CC	0.18	0.26	0.27	0.45	0.43	0.34
Mean ND	2.76	3.61	3.03	4.41	4.07	3.79
Max. ND	27	58	45	66	52	52
Std. ND	3.05	4.87	3.93	5.58	4.81	4.73
Mean NS	$2.34E+5$	$3.44E+6$	$3.49E+5$	$9.47E+5$	$1.01E+6$	$1.14E+6$
Max. NS	$4.85E+6$	$7.48E+6$	$7.90E+6$	$2.36E+7$	$2.57E+7$	$2.63E+7$
Std. NS	$5.23E+5$	$8.69E+5$	$8.55E+5$	$2.22E+6$	$2.34E+6$	$2.52E+6$

Table 2: Community of GMN in 2010–2015.

Group	Name	Members
1	America	Aruba, Argentina, Antigua and Barbuda, Bahamas, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, Spain, Micronesia, Fed. Sts., Guatemala, Guam, Guyana, Honduras, Haiti, Cambodia, Lao PDR, Mexico, Myanmar, Nicaragua, Panama, Peru, Philippines, Paraguay, El Salvador, Thailand, Uruguay, United States, and Venezuela, RB
2	French related	Belgium, Comoros, Algeria, Western Sahara, France, Guadeloupe, Luxembourg, Madagascar, Martinique, Mauritius, Mayotte, French Polynesia, and Réunion
3	British Commonwealth	Australia, Barbados, Canada, Channel Islands, Curaçao, Fiji, United Kingdom, Grenada, French Guiana, Ireland, Jamaica, Kiribati, St. Lucia, Malta, New Caledonia, Netherlands, New Zealand, Papua New Guinea, Poland, Puerto Rico, Solomon Islands, Suriname, Tonga, Trinidad and Tobago, St. Vincent and the Grenadine, Virgin Islands (US), Vanuatu, and Samoa
4	Indian Ocean	Afghanistan, United Arab Emirates, Bangladesh, Bahrain, Brunei Darussalam, Bhutan, Egypt, Arab Rep., Indonesia, India, Iran, Islamic Rep., Kuwait, Sri Lanka, Maldives, Malaysia, Nepal, Oman, Pakistan, Qatar, Saudi Arabia, Singapore, and Timor-Leste
5	East-Middle Africa	Burundi, Central African Republic, Cameroon, Congo, Dem. Rep., Congo, Rep., Djibouti, Eritrea, Ethiopia, Kenya, Rwanda, Sudan, Somalia, South Sudan, Chad, Tanzania, Uganda, and Yemen, Rep
6	Western Africa	Angola, Benin, Burkina Faso, Cote d'Ivoire, Cabo Verde, Gabon, Ghana, Guinea, Gambia, The, Guinea-Bissau, Equatorial Guinea, Liberia, Mali, Mauritania, Niger, Nigeria, Portugal, Senegal, Sierra Leone, Sao Tome and Principe, and Togo
7	Southern Africa	Botswana, Lesotho, Mozambique, Malawi, Namibia, Swaziland, Seychelles, South Africa, Zambia, and Zimbabwe
8	Europe	Albania, Austria, Bulgaria, Bosnia and Herzegovina, Switzerland, Cyprus, Czech Republic, Germany, Greece, Croatia, Hungary, Italy, Morocco, Macedonia, FYR, Montenegro, Romania, Serbia, Slovak Republic, Slovenia, Tunisia, and Turkey
9	The former Soviet Union	Armenia, Azerbaijan, Belarus, China, Estonia, Finland, Georgia, Hong Kong SAR, China, Israel, Japan, Kazakhstan, Kyrgyz Republic, Korea, Rep., Lithuania, Latvia, Macao SAR, China, Moldova, Mongolia, Korea, Dem. Rep., Russian Federation, Sweden, Tajikistan, Turkmenistan, Ukraine, Uzbekistan, and Vietnam

$$E = c\sum_{j=1}^{n}\sum_{k=j+1}^{n} c_{j,k}\left(d_{j,k} - a\delta_{j,k}\right)^2, \tag{B.3}$$

where $\delta_{j,k}$ is the dissimilarity between nodes j and k and $d_{j,k}$ represents the embedded distances. Equation (B.3) is a general form from which several special embedding error functions can be obtained by substituting appropriate values of the constants c, c_{jk}, and a [52]. In our calculation, we made all of the constants equal to 1 for simplicity. To transfer the migration matrix to the dissimilarity matrix, for every weight $\omega_{i,j}$, we use $\sqrt{1-(\omega_{i,j}/\omega_{\max})}$ ($\omega_{\max}$ denotes the maximum weight in the matrix) to replace the original data. In Euclidean space, we use two kinds of regular MDS (multidimensional scaling) methods, namely, the nonmetric MDS (hereinafter referred to as NMM) and nonclassical MDS (hereinafter referred to as NCM), to embed the data for comparison.

The error function described in the previous section calculates the cumulative difference between the embedded distance and the actual data. However, it also concerns another issue: whether the two countries with closer relations are actually closer to each other than other countries after embedding. Here, the authors propose a scoring scheme to assess this possibility. For any two edges $l_{i,j}$ and $l_{m,n}$ that exist in the network, where $i \neq m$ and $j \neq n$, and with corresponding embedding distances $d_{i,j}$ and $d_{m,n}$, the authors calculate that

$$S = \begin{cases} 1 & (l_{i,j} - l_{m,n})(d_{i,j} - d_{m,n}) < 0, \\ 0 & \text{otherwise.} \end{cases} \quad \text{(B.4)}$$

The authors repeat this random selection n times and obtain the following scores: Score = $100 \cdot (\sum S/N)$. Since there are almost no consistent original migration data or embedding distances between different countries, $(l_{i,j} - l_{m,n})(d_{i,j} - d_{m,n}) = 0$ is almost nonexistent. Thus, Score indicates the probability of meeting the required rules for any two links. The closer the Score is to 100, the better the embedding distance can interpret the size relationship in the original data.

C. Statistical Characteristics of GMN

Table 1 shows the statistical characteristics and evolution trends of global migration networks (note that APL indicates average path length; CC indicates clustering coefficient; ND indicates node degree; NS indicates node strength). The authors can observe an increase in the edges and weights, along with increased network density and connectivity, which means that many countries have become closer to each other in the GMNs.

D. Results of Community Division

The authors use the Louvain algorithm to divide the community of all networks. For example, the complete community results from 2010 to 2015 are presented in Table 2.

Data Availability

The bilateral migration data used in this paper could be downloaded from https://figshare.com/collections/Bilateral_international_migration_flow_estimates_for_200_countries/4470464 or by contacting Dr. Xiaomeng Li (lixiaomeng@bnu.edu.cn).

Conflicts of Interest

The authors declare no conflicts of interest.

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Research Article

Prediction of Systemic Risk Contagion Based on a Dynamic Complex Network Model Using Machine Learning Algorithm

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It is well known that the interbank market is able to effectively provide financial liquidity for the entire banking system and maintain the stability of the financial market. In this paper, we develop an innovative complex network approach to simulate an interbank network with systemic risk contagion that takes into account the balance sheet of each bank, from which we can identify if the financial institutions have sufficient capital reserves to prevent risk contagion. Cascading defaults are also generated in the simulation according to different crisis-triggering (targeted defaults) methods. We also use machine learning techniques to identify the synthetic features of the network. Our analysis shows that the topological factors and market factors in the interbank network have significant impacts on the risk spreading. Overall, this paper provides a scientific method for policy-makers to select the optimal management policy for handling systemic risk.

1. Introduction

Systemic risk is defined by the Bank for International Settlements as the failure of a participant to meet its contractual obligations, which may in turn cause other participants to default with a chain reaction leading to broader financial difficulties [1]. Financial institutions are strongly linked to each other, and, therefore, a single large attack would quickly spread out to all the players in the market. In the past decade, there have been several unexpected extreme financial shocks that impacted the banking system. For example, in September 2008, due to the subprime mortgage crisis, a giant US-based investment bank (Lehman Brothers) collapsed, creating large impacts on almost all the financial institutions in the US, and the spread of systemic risk did not stop until a number of sovereign governments started intervening in the market. Another example is Greece's sovereign debt crisis, which gave rise to the significant instability of the major European banks from 2009 to 2015.

The interbank market and systemic risk contagion have drawn great attention from academia. Based on complex network theory, previous research papers have focused on the network evolution and the contagion of risk in accordance with different topological structures of the interbank market. Random networks [2], small-world networks [3], and scale-free networks [4] have been acknowledged as successful networks to model the interbank market. Recent studies have also indicated that the interbank networks could be classified by three different structures: the community structure [5], the tiered structure [6], and the core-periphery structure [7]. However, the real interbank networks cannot be described simply by these structures. Studies have shown that the interbank network can be characterized by the degree distribution of the nodes. Some studies suggest that the degree distribution of the interbank network follows a power law distribution in many regions (see, e.g., Brazil [8], Japan [9], and Russia [10]), while some other papers show that the degree distribution of the interbank networks follows a two-power-law distribution [11, 12] in which there are potentially two pronounced power-law regions [13].

In modern financial systems, financial relationships within the interbank market are linked through an intricate network of claims and obligations from the balance sheets.

Therefore, merely studying the network structure of the interbank market may not bring sufficient insight in the essence of systemic risk contagion. A ground-breaking study by Nier et al. [14] proposes an approach to associate the balance sheet of each bank with the banks' financial linkages. Through this process, they investigate how the structure of the interbank network relates to the systemic risk by varying the parameters, such as the degree to which banks are connected, the size of interbank exposures, and the degree of concentration of the system. They show that the effect of the connectivity of the interbank network is nonmonotonic, and an increase of the connectivity aggrandizes the spread effect. Meanwhile, the connectivity increases the banking system's ability to absorb shocks at the same value of the threshold. Since then, a number of papers have modeled the risk of the banking system with balance sheet regulations and complex network technology [15–17]. Silva et al. [18] innovated a new system to evaluate systemic risk, and the result proved the significance of considering new risk factors besides the traditional interbank market model of systemic risk. In particular, this paper only considers internal risks of interbank market; other risk factors are not the focus of consideration. Therefore, this limitation will lead to underestimation of systemic risks.

The research on risk contagion in the interbank market often relies on random networks and scale-free networks to simulate the interbank networks [19]. In addition, the methods of initial failures in the interbank network should be explicitly taken into account. Different methods have been proposed. Krause and Giansante [20] try to trigger a potential banking crisis by exogenously failing a bank with different bank sizes and under different power-law distributions of degrees, and then they investigate the spread of this failure through the banking system. Unlike prior studies focusing on the attacking methods to investigate the robustness of the interbank network, Georg [21] shows that banks become more vulnerable to endogenous fluctuations and occasional idiosyncratic insolvencies when a common shock strikes the entire banking system.

Systemic risk contagion can be well managed if there are sufficient capital reserves. However, risk management tools are used when there are limited capital reserves such that the interbank network structures have ineligible effects on controlling the risk. For instance, based on the concept of network communicability, Maria Guerra et al. [22] introduce the impact sensitivity index and show how the index can be used as a financial stability monitoring tool. To investigate the influence of network structures in this paper, we think the most effective method should be machine learning technologies. Since 2010, machine learning has been an important method to research bankruptcy predictions and the features of crisis evaluations. Convectional approaches such as the logistic regression, support vector machine, and neural network focus on the development of the automatic risk indicator and the feature selection instrument. However, Jörg Döpke et al. [23] show that the classification accuracies of these methods are usually insufficient in this field. To improve the prediction of the model, they use ensemble of boosted trees, where each base learner is constructed using additional synthetic features. This technique is able to recognize the impacts of features, which is what we are seeking. Therefore, we decide to investigate the influence of network structures for the financial crisis using Gradient Boosting Decision Tree (GBDT henceforth).

In this paper, we propose a new method to build interbank networks based on the complex network theory and use an empirical topological structure [24] of the interbank market to simulate the internal structure (the balance sheet). According to the statistical features of the complex network, we select a crisis-triggering approach to trigger a cascading default within the interbank network, which includes the clustering coefficient, eigenvector centrality, closeness centrality, betweenness centrality, and asset size of banks. Furthermore, we analyze the influences of contagion in an interbank network under an attack on the banking system. Finally, we study the importance of factors in systemic risk diffusion with machine learning technologies. The whole research process can be used to help policy-makers to better identify and monitor systemic risk as well as to mitigate the crisis.

2. Methods

2.1. Dynamic Growth Model of Interbank Network. The interbank market is able to provide an important liquidity supplement for each individual bank. With regard to the banking system, rather than being insolvent, banks are allowed to engage in liquidity demand-driven interbank trading, thus forming the bilateral interbank network. In addition, the banking system is considered as a complex network in the literature [25]. For the characteristics of the interbank network, some important conclusions have been summarized by Krause and Giansante [20]. Nonetheless, previous studies on interbank network structures did not effectively represent the evolution process of a banking system, and thus it is necessary to make an attempt to extend the research. Although we focus on interbank loans in this paper, this research could be easily extended to other financial linkages, such as payment systems or OTC derivative positions, without changing the critical features of the analysis. Regardless of the form of the trading relationship, the formation of linkages in the financial market is a dynamic growth progress. Next, we will create a dynamic growth model of the interbank network to simulate a real interbank transaction process in this paper, taking the critical factors such as the degree distribution of network, scale factor, and social factors into account.

2.1.1. Generating an Interbank Network. An interbank network consists of a sequence of banks and a sequence of loan relationships, which can be described as a directed graph $G(V, E)$. Banks (vertices) are denoted as V and the loan relationships (edges) are denoted as E. If i and j are vertices of $G(V, E)$ and there exists an edge from i and j, it denotes the loan relationship between i and j, where i and j serve as the lender and borrower, respectively. Supposing that the number of banks is $\aleph = \{1, 2, \ldots, n\}$ and the network of banks is a directed and weighted network in the interbank market, the total structure of the directed and weighted network consists of interbank loans L_i, $i \in \aleph$ and interbank borrowing B_i, $i \in \aleph$. In fact, there are capital flows rather than credit relationships between node i and j in the dynamic growth interbank network.

2.1.2. Starting a Trading in the Interbank Market. At first, the interbank network begins with n initial unconnected nodes of banks. There are some banks seeking other banks to build lending relationships with at any time. Therefore, a set of outgoing (loans) links Θ_i^{out} of node i and a set of ingoing (borrowing) links Θ_j^{in} of node j will be generated. Then, the probability P_{ij}^t from Formula (1) can determine whether there exists a trading linkage i to j. That is, bank node as a lender makes a loan of capital w_{ij} to another bank j as a borrower, where w_{ij} follows a normal distribution. At that time, we have $w_{ij} > 0$, interbank loans $L_i > 0$, and interbank borrowing $B_i > 0$, respectively:

$$P_{ij}^t(\mathfrak{R} \mid \alpha, \beta)\Big| = \left(1 + \alpha \frac{k_i^{\text{out}}}{\sum_{i=1}^n k_i^{\text{out}}} \frac{k_j^{\text{in}}}{\sum_{j=1}^n k_j^{\text{in}}} \exp \frac{\beta d^t(i, j)}{D}\right)^{-1}. \tag{1}$$

$$\text{Section } I\text{: } \alpha \frac{k_i^{out}}{\sum_{i=1}^n k_i^{\text{out}}} \frac{k_j^{in}}{\sum_{j=1}^n k_j^{\text{in}}}. \tag{2}$$

$$\text{Section II}: \exp \frac{\beta d^t(i, j)}{D}. \tag{3}$$

Here, the adjacency matrix $\mathfrak{R}_{n\times n}$ represents the interbank bilateral exposure matrix, $d^t(i, j)$ refers to the social distance from node i to j at time t, and D is the maximum distance of all nodes in the interbank network. k_i^{out} and k_j^{in} present the out-degree and in-degree of node i or node j, respectively. The trading process is able to be close to the real conditions by adjusting the parameters α and β, respectively. Furthermore, section I of P_{ij}^t denotes the impact of the degrees of nodes, which shows that banks with bigger degrees would be more likely to complete the transaction, and $\alpha\,(\alpha \leq 0)$ is the parameter of the network connection efficiency. Section II of P_{ij}^t denotes the impact of the social distance between two nodes. It shows how likely the social factors are to decide the connections between banks with their new neighbors. Parameter β plays a key role in generating different network structures, and the network will be more centralized by increasing β. This algorithm is also used by S. Lenzu [18]. Briefly, section I and section II of P_{ij}^t reflect the scale factor and social factor, respectively. Therefore, which trading linkage will be built is decided by the probability P_{ij}^t at time t, according to Formula (1). Just by setting the number of banks (nodes) n and the size of the time step (pace) t, we can simulate the whole process of an interbank transaction. Thus, an algorithm for generating the dynamic growth of the interbank network is characterized by the expression $N(n, t, \alpha, \beta)$. Then, we can get the total nominal claims c_{ij} of any bank i towards $j(i \in \aleph i \neq j)$, where $c_{ij} = \sum_t w_{ij}^t$. Similarly, the nominal obligations o_{ij} of any bank i from j are $(i \in \aleph i \neq j)$, where $o_{ij} = \sum_t w_{ij}^t$.

In summary, we have created a dynamic growth model of the interbank network to simulate a real interbank transaction process, and an interbank network has been simulated according to the model denoted by $N(n, t, \alpha, \beta)$. Table 1 displays all parameters of the model.

2.2. Bilateral Loans Matrix of Claims and Obligations. The interbank bilateral exposure can be represented by an adjacency matrix $\mathfrak{R}_{n\times n}$, where each element of $\mathfrak{R}_{n\times n}$ is the total nominal claims c_{ij} from node i to j. When we calculate the adjacency matrix $\mathfrak{R}_{n\times n}$, we must consider the fact that a bank cannot have exposure to itself. Therefore, the matrix $\mathfrak{R}_{n\times n}$ is a nonnegative real matrix, where no element is negative. In other words, each element is either zero or a strictly positive real number. Thus, the gross interbank loan of bank i is given by the matrix's row sum as $l_i = \sum_{i,j\in\aleph} c_{ij}$. In the same way, the gross interbank borrowing of bank i is given by the matrix's column sum as $b_i = \sum_{j,i\in\aleph} c_{ji}$:

$$\mathfrak{R} = \begin{matrix} 0 & c_{12} & \cdots & c_{1i} & \cdots & c_{1n} & l_1 \\ c_{21} & 0 & c_{23} & \cdots & \cdots & \cdots & l_2 \\ \vdots & c_{32} & \ddots & c_{i-1\,i} & \vdots & \vdots & \vdots \\ c_{i1} & \vdots & c_{i\,i-1} & \ddots & \ddots & \vdots & l_i \\ \vdots & \vdots & \cdots & \ddots & 0 & c_{n-1\,n} & \vdots \\ c_{n1} & \vdots & \cdots & \cdots & c_{n\,n-1} & 0 & l_n \\ b_1 & b_2 & \cdots & b_i & \cdots & b_n & \end{matrix} \tag{4}$$

2.3. Building the Balance Sheet of Each Bank. To build a network structure of the whole banking system, it is necessary to incorporate the balance sheet of individual banks into the network structure. Each bank $i \in \aleph$ is assumed to have a balance sheet with assets A_i and liabilities L_i. Figure 1 lists a stylized balance sheet of a bank that participates in the interbank market. The liabilities L_i side of bank $i \in \aleph$ consists of interbank borrowing b_i, equity e_i, and deposits d_i. On the other hand, the assets A_i side of bank $i \in \aleph$ consists of interbank loans l_i, external assets a_i, and capital reserves r_i. We define the capital reserves ratio as $\rho_i = (r_i/l_i)$. Equation (5) implies that total assets must be equal to total liabilities for each bank $i \in \aleph$ in the balance sheet:

$$b_i + a_i + l_i = e_i + d_i + b_i. \tag{5}$$

2.4. Interbank Network Cascading Default Mechanism. To simulate the cascading default of the banking system, it is necessary to combine the bilateral loans matrix and the balance sheet of an individual bank. This is because when we trigger a cascading default in interbank network, no matter whether the crisis is a part of banks' bankruptcy or the whole banking system is suffering from a common shock, the systemic risks will spread via the interbank network, which is observed directly by the bilateral loans matrix. When

Table 1: Description of parameters.

Parameters	Description
n	Number of nodes (banks)
t	Size of time steps (paces)
α	Connecting efficiency parameter of the network
β	Distance influence parameter of the network

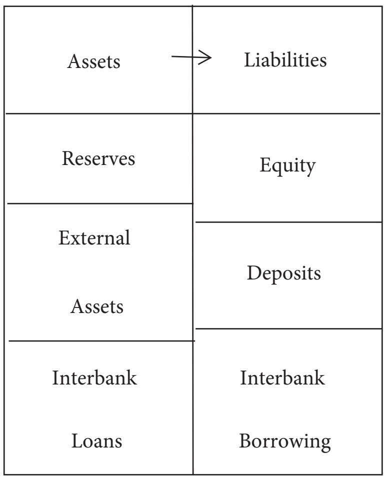

Figure 1: The stylized balance sheet of bank $i \in \aleph$.

systemic risks spread to each bank, the risk tolerance of each bank decides on whether the banking system is healthy or not. By analyzing banks' balance sheets, we can assess whether whole banks can absorb further shocks and maintain the system's financial health. If there are one or more banks that have failed, systemic risks will transit to the interbank networks again. Thus, the whole banking system has to share the consequences of the failures.

In this paper, the banking crisis begins by assuming that one or more banks failed due to a series of mistakes. For simplicity, we assume that a single bank fails initially, starting the risk contagion mechanism described above. When a bank $x \in \aleph$ has failed, it implies that its interbank borrowing from other banks does not need to be paid back as follows: $b_x = \sum_{j\in\aleph} c_{jx}$ and $c_{ix} = 0, i \in \aleph$. Moreover, there are still interbank loans of bank $x \in \aleph$ to other banks. If the condition is $(C_{xi} - C_{ix}) > 0$, which is represented as $C'_{xi} = (C_{xi} - C_{ix})^+$, it shows that the number of interbank loans of bank from bank is more than the number of interbank borrowing of bank from bank $x \in \aleph$. If the condition is $(C_{xi} - C_{ix}) < 0$, which is represented as $C'_{xi} = (C_{xi} - C_{ix})^-$, it shows that the impact of the failure of bank $x \in \aleph$ is not able to be absorbed by the interbank market. Then, the adjacency matrix $\mathfrak{R}_{n\times n}$ is as follows:

$$\mathfrak{R}_{\text{bankxdefault}} = \begin{pmatrix} 0 & c_{12} & \cdots & C_{1x} = 0 & \cdots & c_{1n} \\ c_{21} & 0 & c_{23} & \cdots & \cdots & \cdots \\ \vdots & c_{32} & \ddots & C_{(x-1)x} = 0 & \vdots & \vdots \\ (C_{xi} - C_{ix})^+ & \vdots & \left(C_{x(x-1)} - C_{(x-1)x}\right)^+ & \ddots & \ddots & (C_{xn} - C_{nx})^+ \\ \vdots & \vdots & \cdots & C_{(n-1)x} & 0 & c_{n-1n} \\ c_{n1} & \vdots & \cdots & \cdots & C_{n(n-1)} & 0 \end{pmatrix}. \tag{6}$$

Then, we check the balance sheet of bank $i \in \aleph$ to judge whether the capital reserves r_i supply a sufficient buffer to cover the loss $C'_{xi} = (C_{xi} - C_{ix})^-$. Moreover, according to the balance sheet, it is easy to understand that the capital reserves are $r_i = \rho_i l_i$. Meanwhile, external assets a_i keep enough liquidity for an individual bank when the bank $i \in \aleph$ has been affected by the crisis. If bankruptcy is inevitable, the external assets will be forced into a fire sale for extra cash. For simplicity, this paper studies the model without this condition and this step is omitted. Therefore, for the interbank loans vector C'_{xi} $i \in \aleph$, the following condition holds:

$$C'_{xi} = \begin{cases} (C_{xi} - C_{ix}), & \text{case 1: if } (C_{xi} - C_{ix})^+ > 0, \\ 0, & \text{case 2: if } (C_{xi} - C_{ix})^- < 0 \text{ and } \dfrac{-(C_{xi} - C_{ix})^-}{l_i} > \rho, \\ 0, & \text{case 3: if } (C_{xi} - C_{ix})^- < 0 \text{ and } \dfrac{-(C_{xi} - C_{ix})^-}{l_i} < \rho. \end{cases} \tag{7}$$

Consequently, bank $i \in \aleph$ is solvent in cases 1 and 2, and it defaulted in case 3. Then, the current wave of cascading default is finished in the interbank network. If there is one or more new banks that failed due to the shock of the previous wave, the above progress is going to be repeated until all banks are able to be solvent, and systemic liquidity shortages no longer spread in banking system.

2.5. Attack Strategies for Cascading Default. Based on the interbank network cascading default mechanism above, it is important to assess how to select the initial default banks as attack strategies since the features of the initial failed banks greatly decide the final result of the size of the bankrupt banks in the banking system. In this paper, we choose five statistical features of complex networks as selection methods and accordingly make the top 1% of nodes bankrupt in every method. Using 1000 Monte Carlo simulations for building the interbank network and cascading default to detect the performance of risk tolerance, we evaluate the effects of the selection methods. The typical statistical features are the eigenvector centrality [26], closeness centrality [27], betweenness centrality [28], clustering coefficient [29], and total assets of banks. In consideration of the impact of large banks, we have also added the total assets of banks to the selection methods.

2.6. Calculating the Variable Importance (VI) Based on Gradient Boosting Decision Tree. The following content introduces the Gradient Boosting Decision Tree [30] and its derivation algorithm for the evaluation of feature importance. The theory of GBDT derives from boosting, which is a stagewise additive method that iteratively adds a function to the combined estimator and adjusts the weights of training data in order to build a strong classifier by linearly combining a set of weak classifiers. Similar to the boosting, GBDT constructs many regression trees iteratively as base-learners, which use a tree-like graph or model and are built through an iterative process that splits each node into child nodes by certain rules, unless it is a terminal node that the samples fall into. The principle idea behind GBDT is to construct the new base-learners to be maximally correlated with the negative gradient of the loss function in order to get higher accuracy of the model. The Gradient Boosting Decision Tree in the settlement of classification problems is a competitive, highly robust algorithm and is appropriate for mining less than clean data [31]. One essential advantage of GBDT is that its interpretation performs well because we can clearly understand the variable importance of GBDT that represents the influences of the features. VI is computed as the (normalized) total reduction of the split criterion brought by the current variable. The higher it is, the more important the variable is. In this paper, we describe the algorithm of VI in the GBDT framework.

For a GBDT with M trees, the VI of variable j is $I_j = (1/M)\sum_T I_j(T)$, where T is a single tree in the GBDT and $I_j(T)$ represents the VI of variable j in the T. Then, $I_j(T)$ can be calculated as follows:

$$I_j(T) = \sum_{v_t=j} i_t, \quad t \in \mathbb{Z}, \tag{8}$$

and $\mathbb{Z}$ represents all nonterminal nodes in T and v_t represents the variable chosen at node t. Function i_t (function of t) is used to calculate $I_j(T)$ generated from the "impurity," which we choose to split the node.

We let D_t represent the data set at tree node t, and D_t^l or D_t^r represents those of its left or right child, respectively. There are two types of the impurity, namely, entropy and Gini impurity. We use Gini impurity to present the enumeration theory of i_t:

$$i_t = \mathrm{Gini}(D_t) - \left(\frac{|D_t^l|}{|D_t|}\mathrm{Gini}(D_t^l) + \frac{|D_t^r|}{|D_t|}\mathrm{Gini}(D_t^r)\right). \tag{9}$$

To sum them up, we get

$$I_j = \frac{1}{M}\sum_{v_t=j}\left(\mathrm{Gini}(D_t) - \frac{|D_t^l|}{|D_t|}\mathrm{Gini}(D_t^l) - \frac{|D_t^r|}{|D_t|}\mathrm{Gini}(D_t^r)\right), \quad t \in \mathbb{Z}. \tag{10}$$

3. Results and Simulations

We select 768 banks with over U.S. $100 billion in total assets as of the end of 2018 from the EU15. The EU15 consists of the following 15 countries: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, and the United Kingdom. We first obtain the banks' financial data, such as the number of banks and the assets of each bank, from BANKSCOPE. Figure 2 shows the distribution of banks' total asset value in 2018. According to the empirical analysis of the interbank network structure, the network of EU15 has an obvious two-power-law degree distribution. This network, which is able to describe a special scale-free network, is also characterized as a two-power-law functional relation. Technically, a two-power-law degree distribution network is characterized by a complementary cumulative distribution function (CCDF) of assets (weights). Figure 3 describes the log-log plot for the histogram, where the CCDF of the assets of banks is. This figure shows that the number of degrees and the total assets do follow a two-power-law distribution.

3.1. Simulating an Interbank Network. In this paper, we develop dynamic complex network model to simulate EU15 interbank network in 2018 according to the model denoted by $N(768, 100, 2, 5)$. Then, we have a dynamic growth interbank network, which is from a complicated dynamic evolvement process. Figure 4 shows the CCDF of the degrees and weights that also fall into two-power-law distributions. Notably, the CCDF of the degrees divides into two sections with different slopes. The first section with the dotted green line corresponds to the power-law distribution $p(k) \propto k^{-\gamma}\gamma = -0.4224$, and the second one corresponds to

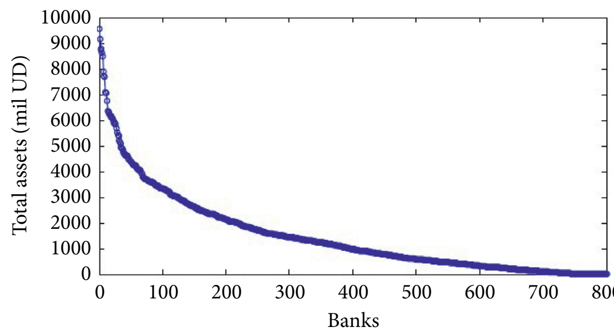

Figure 2: Total assets (mil UD) distribution of banks sorted by global bank ranking.

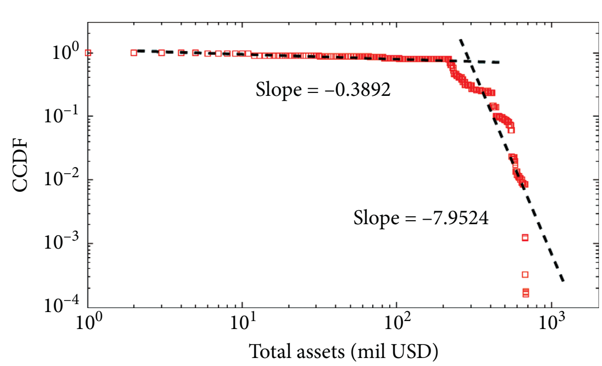

Figure 3: A log-log complementary cumulative distribution function (CCDF) of assets (weights), according to dataset of interbank markets of EU15 in 2018.

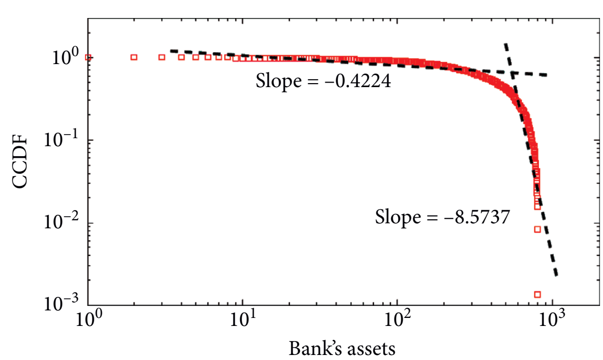

Figure 4: A log-log complementary cumulative distribution function (CCDF) of the assets (weight), according to simulation of our modeling using the network configuration of $N(768, 100, 2, 5)$.

$\gamma = -8.5737$, where k is the degree of nodes. This method is based on the assumption that similar distributions possess similar structures, and thus we can simulate the interbank network of the EU15 with the same network structure. By contrasting Figures 3 and 4, we have come to the conclusion that the simulation and the real interbank network's CCDF have similar structures and slopes. Therefore, we can use the model to build the interbank network without the relative data of balance sheets, which is superior when simulating the loan relationship between two banks, and to generate a bilateral trading matrix. Figure 5 presents the directed graph of the global interbank networks. To better illustrate this network, we select only the top 100 degree banks; the sizes of the nodes and edges hinge on the degree and weight of the respective bank in the left panel of Figure 5.

As mentioned above, substituting data is needed when the data of interbank trading are difficult to obtain. By simulating the same structured network, the bilateral trading matrix of claims and obligations can be estimated by a dynamic growth interbank network. Kanno [32] was the first to combine the above method and the balance sheets of banks, which are used to solve this type of question. So far, a dynamic growth model of an interbank network, including the directed graph of the interbank network, the bilateral trading matrix of claims, and the obligations and every bank's balance sheet, has been constructed.

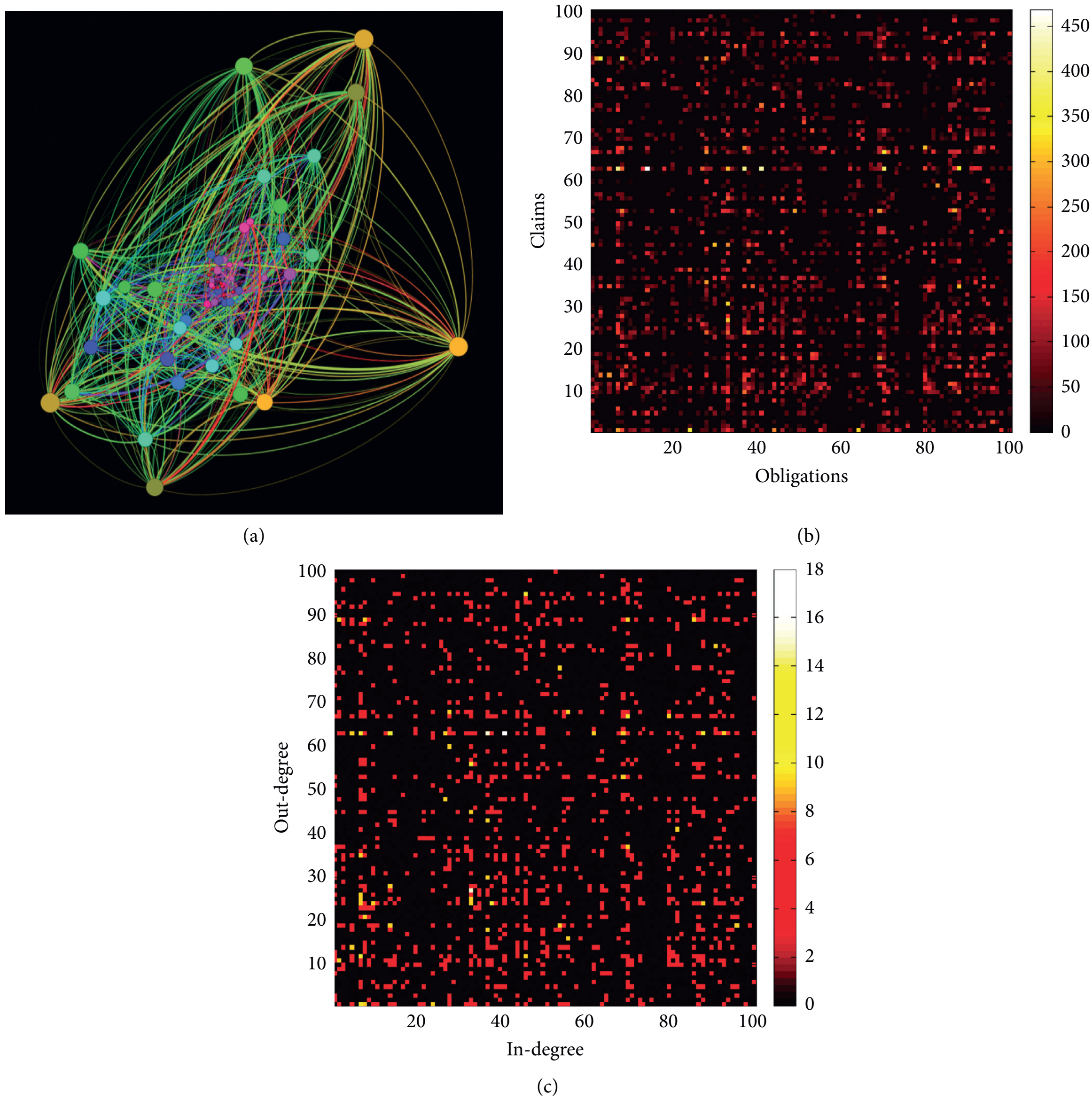

FIGURE 5: Organization of the interbank network in the simulation, with $N(768, 100, 2, 5)$. The left panel is the graph of the interbank network (where the 100 biggest degrees are selected). The bilateral exposures matrix of the claims and obligations (top right side) and the bilateral exposures matrix of the out-degree and the in-degree (bottom right side).

3.2. Cascading Default in Interbank Network. To investigate the likelihood of cascading default, we must trigger a crisis in the interbank network. Here, a financial crisis is one or more bank failures giving rise to a lot of bad assets in the banking system. We attack some nodes as initial failures, respectively, based on the top 1% rank of the clustering coefficient, eigenvector centrality, closeness centrality, betweenness centrality, and assets of banks. To investigate the impacts of different attacking methods on financial stability, Figure 6 shows how systemic risk spreads in the interbank network based on different attacking strategies in the different reserves ratios r.

3.3. Feature Influence of Interbank Network. Based on the above framework, we evaluate the influence of the capital reserve ratio on the stability of banking system under the different attack strategies. However, the feature influence of interbank network has not been taken into account comprehensively, and we largely ignore the importance of interbank network structures. In this case, we design experiments to research the influence of the interbank network structures for five different capital reserve ratios r. Following Gai et al. [33], the definition of a financial crisis is an environment in which at least 5% of banks go bankrupt. Therefore, when the percentage of bankrupt banks exceeds 5%, we identified that the financial crisis occurred in the interbank network. Based on the above discussion, the 1000 groups of networks $N(768, 100, 2, 5)$ are generated via a Monte Carlo simulation, and we randomly select an attack strategy that triggers a cascading default until the end of the

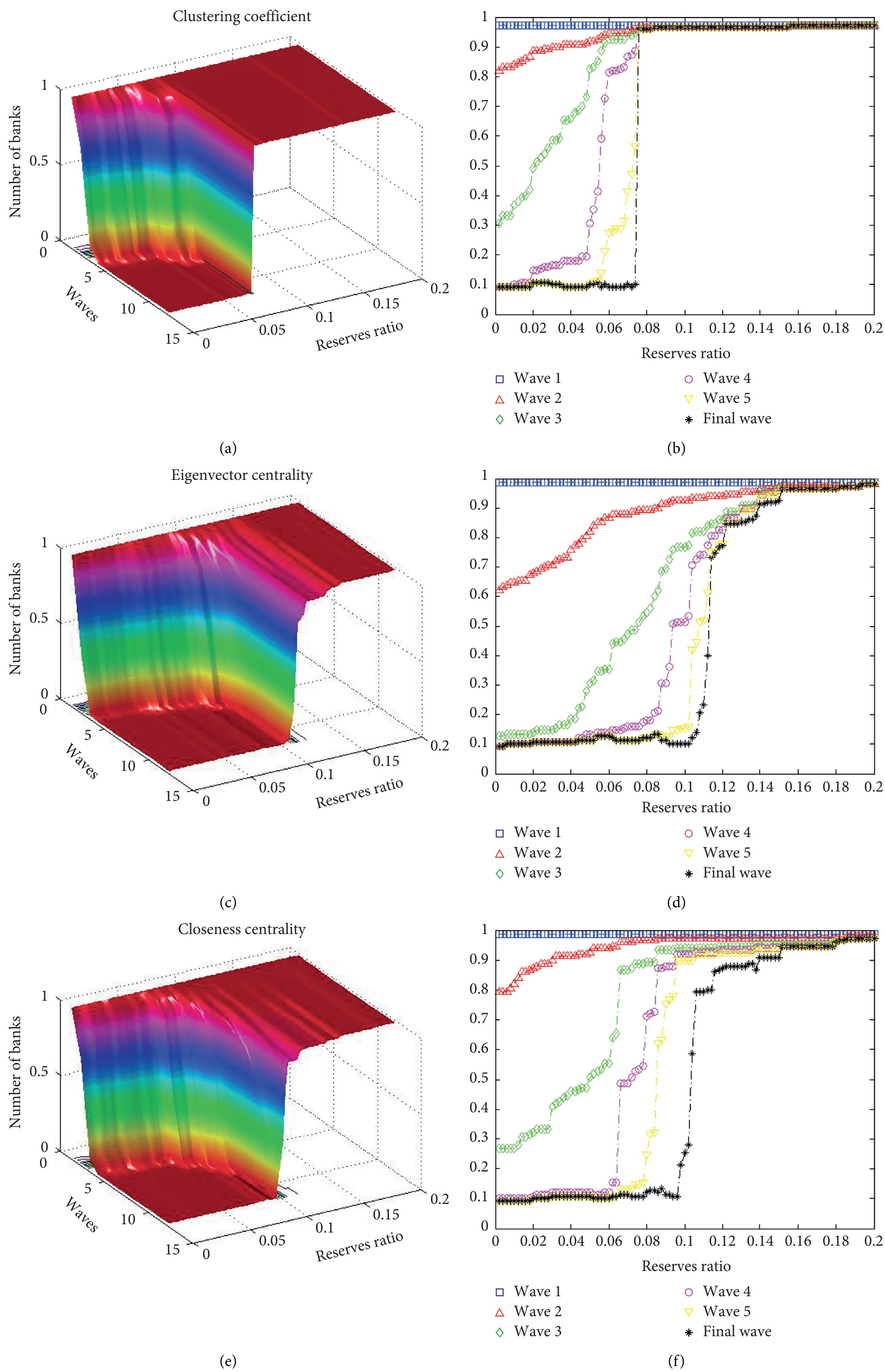

Figure 6: Continued.

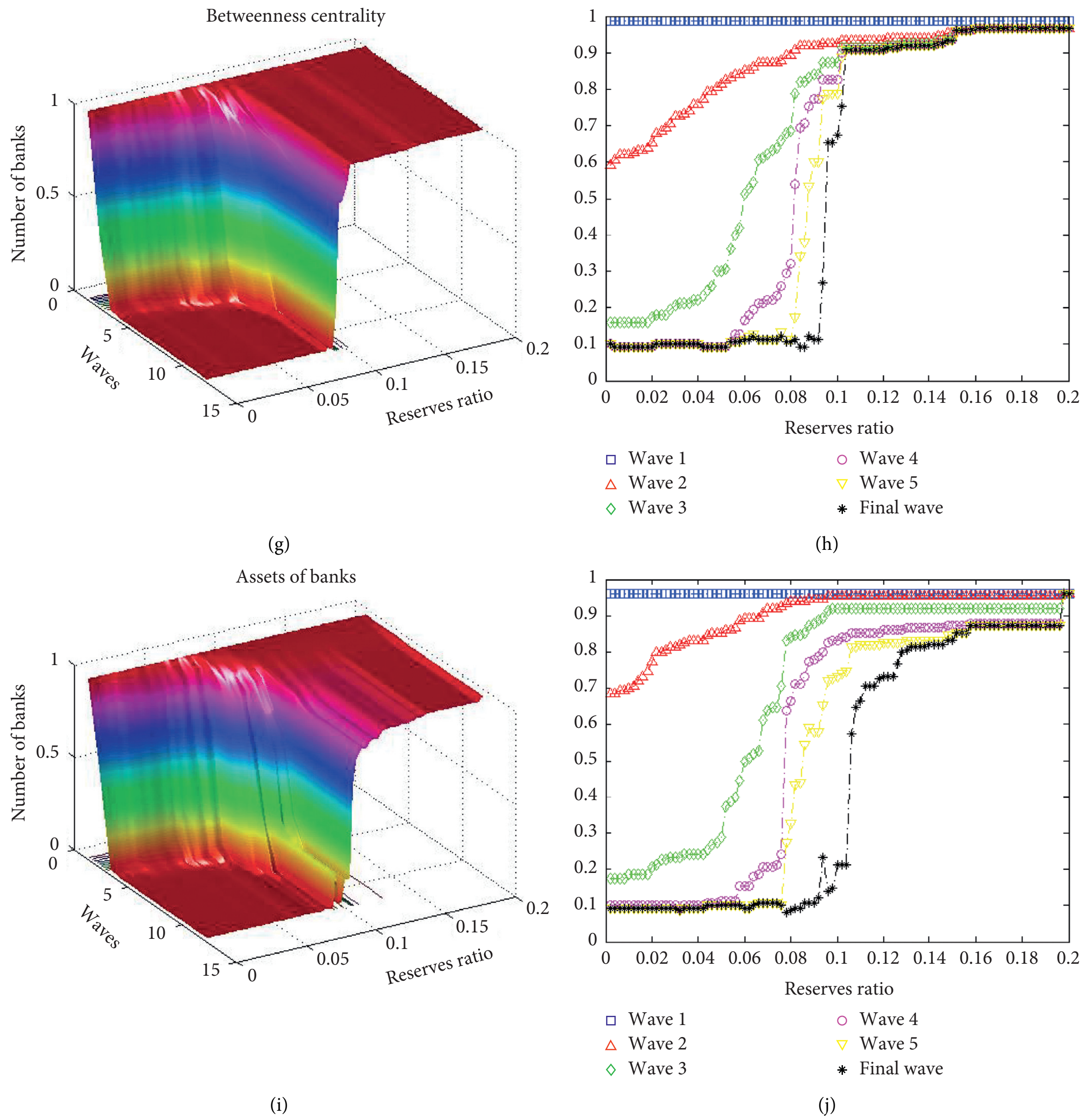

FIGURE 6: Impacts of the capital reserves ratio on the proportion of unaffected banks by financial contagion. The left panel shows the proportion of unaffected banks by financial contagion as a wave of cascading defaults and a function of the percentage of the reserves ratio (left panel). The right panel shows a cross-sectional view of the left panel in which the different colored dotted lines represent different waves of cascading defaults. We use 1000 Monte Carlo simulations to develop the networks with different types of targeted default strategies.

risk's contagion. Eventually, we would see that the financial crisis occurred or that nothing occurred in each group of networks. Based on complex network theory, we calculate the statistical network features of each network, which can be evaluated by machine learning technology. As Table 2 indicates, there are 32 generated features for assessment: the features of the network, the attack strategies, the financial information, and so on. Most of the features could be interpreted in a straightforward way by complex network theory. In this paper, we train 1000 sets of features' data to forecast a financial crisis using GBDT. In the meantime, the feature influence is assessed by the derivation algorithm of GBDT.

4. Discussion

In Figure 6, it is noticeable how the reserves ratio impacts the stability of the interbank network. When the financial risk propagates in the interbank market over time, the systemic liquidity shortages no longer spread in the banking system. This finding indicates that there are no more bank failures in a certain wave, and we consider this wave as the final wave (Figure 6, right side). Investigating the final wave is a meaningful work, and Figure 7 summarizes the forms of the final waves for different initial attack strategies. It is easy to see that, under the clustering coefficient attack strategy, the number of defaulting banks shrinks rapidly at the reserves

Table 2: The set of features considered in the interbank network.

No.	Abbreviation	Description
1	1% ABC	Average betweenness centrality of the top 1% ranked banks
2	1% ACCO	Average clustering coefficient of the top 1% ranked banks
3	1% ACCEN	Average closeness centrality of the top 1% ranked banks
4	1% AEC	Average eigenvector centrality of the top 1% ranked banks
5	1% AD	Average degree of the top 1% ranked banks
6	5% ABC	Average betweenness centrality of the top 5% ranked banks
7	5% ACCO	Average clustering coefficient of the top 5% ranked banks
8	5% ACCEN	Average closeness centrality of the top 5% ranked banks
9	5% AEC	Average eigenvector centrality of the top 5% ranked banks
10	5% AD	Average degree of the top 5% ranked banks
11	10% ABC	Average betweenness centrality of the top 10% ranked banks
12	10% ACCO	Average clustering coefficient of the top 10% ranked banks
13	10% ACCEN	Average closeness centrality of the top 10% ranked banks
14	10% AEC	Average eigenvector centrality of the top 10% ranked banks
15	10% AD	Average degree of the top 10% ranked banks
16	20% ABC	Average betweenness centrality of the top 20% ranked banks
17	20% ACCO	Average clustering coefficient of the top 20% ranked banks
18	20% ACCEN	Average closeness centrality of the top 20% ranked banks
19	20% AEC	Average eigenvector centrality of the top 20% ranked banks
20	20% AD	Average degree of the top 20% ranked banks
21	50% ABC	Average betweenness centrality of the top 50% ranked banks
22	50% ACCO	Average clustering coefficient of the top 50% ranked banks
23	50% ACCEN	Average closeness centrality of the top 50% ranked banks
24	50% AEC	Average eigenvector centrality of the top 50% ranked banks
25	50% AD	Average degree of the top 50% ranked banks
26	1% of TA	Proportion of total assets in the top 1% ranked banks of total assets
27	5% of TA	Proportion of total assets in the top 5% ranked banks of total assets
28	10% of TA	Proportion of total assets in the top 10% ranked banks of total assets
29	20% of TA	Proportion of total assets in the top 20% ranked banks of total assets
30	50% of TA	Proportion of total assets in the top 50% ranked banks of total assets
31	NB	Number of banks
32	AS	Attacking strategies

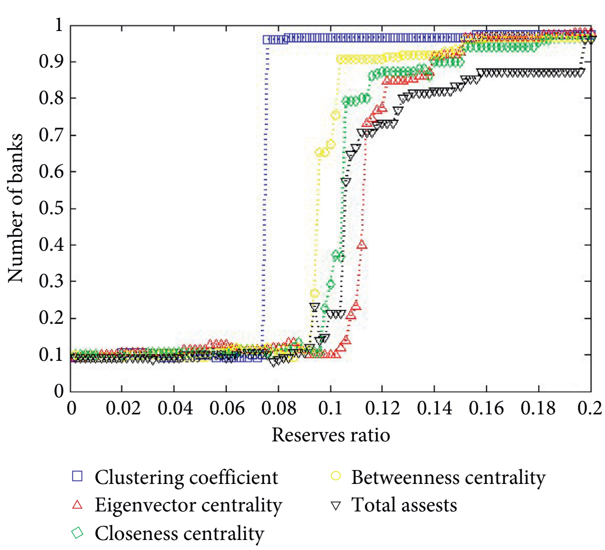

Figure 7: The frontier of cascading defaults with the reserves ratios based on different initial attack strategies.

ratio $r = 7.44\%$, while under other attack strategies, the reserves ratio r begins to shrink under a range of values from 9% to 11%. To survive during the attack on the banks of top 1% asset, the highest reserves ratio is needed to prevent financial contagion in the interbank network when compared to the other attack strategies. The specific effects of the initial attack strategy are shown in Figure 8.

Of course, we cannot ignore the fact that the topological structure of the network has a significant impact on potential financial crisis. β is the critical parameter of the network's generation. With the increase of β, the network connection will gradually become more centralized. However, too high or too low β is harmful for the stability of the banking system. An undesired value of β can increase the capital reserves required by the banks to control the spread of the cascading default, as shown in Figure 9. In addition, we want to understand the impacts of other features.

In this paper, we evaluate the influence of features by calculating the VI of GBDT. The greater the feature's impact on the stability of the banking system, the bigger the VI of the feature. In Table 3, we present the top 10 features for each of the considered capital reserve ratios r. From this, we study the popularity of the features for different capital reserve ratios. As shown in Figure 6, regardless of adopting any attack strategy to trigger the initial failures, the crisis should be controlled by setting the capital reserve ratio $r > 20\%$. On the other hand, the crisis would be nearly inevitable when capital reserve ratio is less than 5%. Therefore, the influences of features are meaningless for the crisis at reserve ratios of

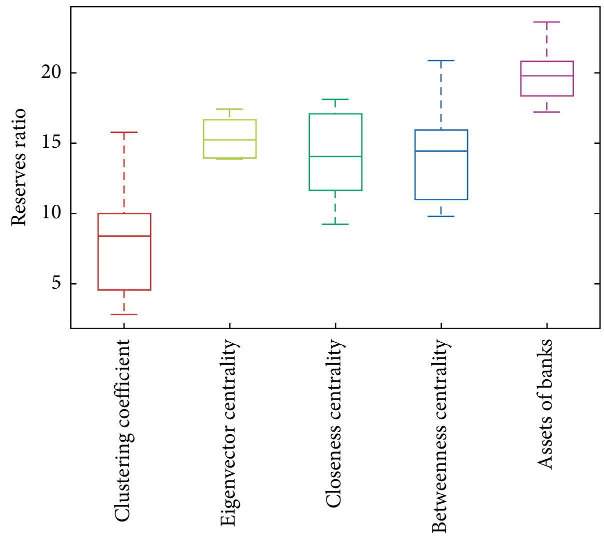

Figure 8: The relationship between the average percentage of the reserves ratio and the different initial attack strategies based on 1000 Monte Carlo simulations to organize networks $N(768, 100, 2, 5)$ when the cascading default spreads no further.

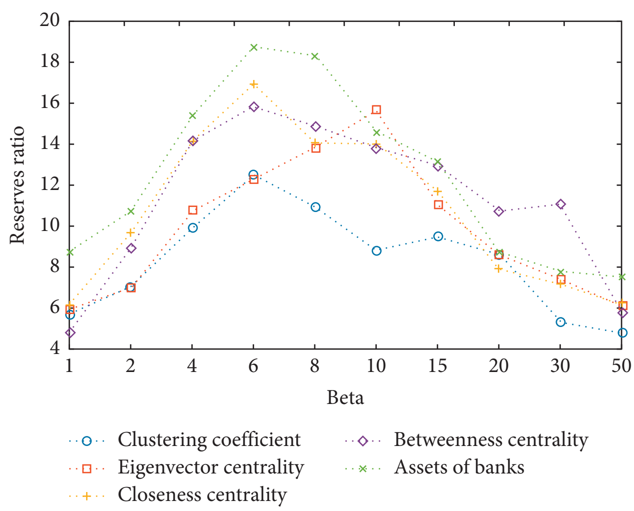

Figure 9: Impact of the topology of networks on the capital reserves ratio. Different attack scenarios and the key parameters of the network topology when β = 1, 2, 4, 6, 8, 10, 15, 20, 30, and 50.

Table 3: Ranking of features for each of the capital reserves ratios r.

Rank	$r = 5\%$		$r = 10\%$		$r = 15\%$		$r = 20\%$	
	ID	VI	ID	VI	ID	VI	ID	VI
1	5% AD	0.0907	AS	0.084	AS	0.065	10% ABC	0.0436
2	5% ACCO	0.0575	1% AD	0.0445	1% AEC	0.0521	20% TA	0.0417
3	1% ACCO	0.0539	1% ACCEN	0.0419	5% ACCO	0.0498	10% ACCEN	0.0392
4	5% AD	0.0507	1% ACCO	0.0378	1% ABC	0.0489	20% ACCEN	0.0358
5	10% AEC	0.0386	5% ACCO	0.0374	5% AEC	0.0487	NB	0.0336
6	5% AEC	0.0363	5% ABC	0.033	1% TA	0.0441	5% TA	0.0313
7	1% ACCEN	0.036	5% TA	0.0323	1% ACCEN	0.043	50% ABC	0.0296
8	1% ABC	0.0353	1% TA	0.0309	1% AD	0.0396	AS	0.0275
9	1% of TA	0.0271	1% AEC	0.0278	1% ACCO	0.0344	50% AEC	0.0269
10	5% ACCEN	0.0245	10% ABC	0.0251	5% ACCEN	0.0291	5% AD	0.0259

$r = 5\%, 20\%$. Furthermore, AS (attack strategies) are the most important feature that is observed at $r = 10\%, 15\%$, and the statistical characteristics of high-ranking banks also tend to have bigger impacts on crises. Some of the features, such as 1% ACCEN and 5% ACCO, are very popular for each reserve ratio. It is necessary to pay particular attention to high-VI features for policy-makers in order to cope with the effect of high-VI features changes.

In this paper, we build a dynamic growth interbank network based on the complex network theory and empirical analysis with the balance sheet of banks. Based on the above algorithmic framework, we investigate the impacts of the crisis-triggering approaches and network features on the stability of the interbank network. By controlling the capital reserves ratio of each bank, we can satisfy the requirements of financial security at the minimum costs. The findings of this paper can serve as guiding policies from the macroscopic angle and quantify the systemic risks based on the network structures for policy-makers. On the other hand, we find that when banks with higher total assets have defaulted, the whole financial system appears to be vulnerable. However, when banks with higher clustering coefficients go bankrupt, it would be better, and the concentration of the interbank network being too high or too low would benefit the dispersion of risk. Thus, this paper develops a method for policy-makers to take action to prevent liquidity shortages in the interbank market and discusses the key influencing features for a crisis.

Data Availability

The data source of this paper is produced by Bureau Van Dijk from BANKSCOPE (https://bankscope.bvdep.com/).

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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Research Article

Research on Innovation Performance in Heterogeneous Region: Evidence from Yangtze Economic Belt in China

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Innovation has become the main impetus for regional development. Effective utilization of innovation resources is crucial in promoting sustainable innovation. From the theoretical aspect, there still exists uncertainty of how to effectively evaluate innovation performance. From the empirical aspect, we still doubt whether regions of higher economic level or high innovation quantity really show positive regional innovation performance, especially in heterogeneous regions. This paper uses DEA-Malmquist index to measure regional innovation performance of the Yangtze River Economic Belt in China. Regions of similar performance levels are grouped by ward clustering, analysis regional innovation performance characteristics, and problem-solving paths of regions in different development stages. The empirical research proves that overall performance of Yangtze River Economic Belt is not high. The economic core area has realized increase of innovation volume through large amount of material input and resource consumption, instead of realizing full utilization of innovative resources; how to improve the utilization rate of existing technical resources has been neglected. Different regions with similar innovation performance show different characteristics and innovation problems, including resource mismatch, input redundancy, or insufficient output. There are also some differences in the way the region's specific innovation performance is improved.

1. Introduction

With the development of economy, knowledge has replaced capital and became the resource with great strategic value. Innovation has become the main impetus of economic development [1, 2]. Knowledge production, allocation, and uses had become basic factor for economic growth [3, 4]. Romer had pointed out that R&D research aimed at pursing economic profits can realize knowledge accumulation and promote long-term economic growth [5]. That means, in the era of knowledge and learning economy, R&D ability of region is the key factor for regional economic development. Promoting development of Yangtze River Economic Belt is national strategy that affects the development of China. The Yangtze River Economic Belt has achieved remarkable development in recent years, and internal heterogeneity is obvious. The interregional economic and innovation levels are quite different. How to realize interregional coordinated development and sustainable development of innovation resources is a strategic problem that needs to be solved urgently in China.

Innovation performance includes ability of firms to put new products into market [6] or refer to technological innovation ability [7]. Relation between innovation performance and economic development has become a consensus; this paper, based on knowledge production function, selected metropolis of Yangtze Economic Belt and analyzed overall level, spatial distribution, and various tendencies of the innovation performance. The following problems are expected to be solved. (1) What is the overall level and trend of regional R&D performance in Yangtze River Economic Belt? Which cities are nodes with high R&D performance? (2) What are the main problems of R&D performance in Yangtze River Economic Belt? (3) The Yangtze River Economic Belt is divided into groups of similar levels according to R&D performance. What are their problems and the main directions for solving these problems?

This paper is organized as follows: the next section is critical review of regional innovation and innovation performance; the third section is description of data and methodology of our research; the fourth section describes economic and innovation feature of Yangtze River Economic Belt; regional performance analysis and problem of each region are presented in the fifth section. In the last part, we offer some concluding remarks.

2. Literature Review

Regional innovation performance has been investigated in the literature [8–10]. Existing researches have systematically discussed the issue of what regional innovation performance means and how it should be measured [11–14]. Nelson had pointed out that innovations do not "fall from heaven" [15]; they need creative actors and wide range of resources; the absolute count of innovations generated by regional organizations within certain time period can be used as an indicator of regions' innovative success [16]. From the economic standpoint, it is more interesting to evaluate innovation success in light of the invested resources [13, 17]. From this perspective, regions achieving competitive advantage by increasing investment of R&D resources has become a consensus.

Inventions and innovation are not evenly distributed in space but tend to be clustered in certain locations [18, 19]. That is because of regional differences in availability and quality of local inputs, as well as geographically bounded knowledge spillovers [20]. So when talking about regional innovation performance, we should not merely focus on one side of R&D input or output quantity, as there will be great R&D resource difference among regions and also for the same region of different development stages. What matters is that we should set innovative output and input factors into relation on regional level, as it implies that both are known and can be meaningfully measured in the context of regions [21]. That means we should use R&D performance logic in evaluating innovation performance.

The R&D performance means ability of a country or region that can transform various input resources (capital or personnel) to multioutput in R&D activities, which can be regarded as relation between R&D input and output [22]. As it has been indicated by Broekel [16] and Fritsch and Slavtchev [23], innovation performance may be impacted by a wide range of regional factors such as urbanization economies, knowledge spillover, the presence of universities, and regional cooperation intensity [24]. That is to say, the location difference relates to "quality" or "performance" of the region, leading to different levels of innovative output even if the inputs are identical in quantitative as well as in qualitative terms.

In recent research, some of the empirical approaches are focusing on relation between innovation input and output resources [25–27]. The economic unit appears to be inefficient if it cannot generate maximum feasible output from given inputs. As we have mentioned before, regional economy and resources difference may lead to imbalance of innovation (it does not mean it has higher innovation performance); what is more important is that it should also have the abilities to maximize transformation of input resources to output.

So from the regional innovation performance aspect, what we are thinking about is not only whether regions of higher economic or higher resources input quantity will have higher abilities in knowledge transfer, but also when the overall innovation performance improves and whether the technology level and technology performance improve at the same time, which will then move us one step further to making clear what (technology improvement or tech-resource fully utilization) really matters for regional innovation improvement under different circumstance. We attempt to make a preliminary regulation summary of innovation performance in different economic stages, trying to find out its main route in improving regional innovation performance.

3. Methodology

3.1. Research Method

3.1.1. Data Envelopment Analysis. This method was established by Charnes and Cooper in 1978; it is widely used in evaluating R&D performance for countries or regions. This paper is based on existing research method of performance evaluation Constant Returns to Scale (CRS) (CRS is based on situation of Constant Returns to Scale, $\theta_m = 1$ indicates R&D resources are all applied on production, and the output has reached optimal level combined with resources input; when $\theta_m < 1$, the R&D resources ineffectiveness; if $\theta_m$is closer to 1, indicates that R&D resources of the city are more efficient. DEA (M is the city number of our research; K means this system is divided into K kinds of indicator; L is the output index, we assume $x_{mk}\,(x_{mk} > 0)$ represents the kth kind of input resource of the mth city. $y_{ml}\,(y_{ml} > 0)$ represents the lth kind of output of the mth city. For these M cities $m\,(m = 1, 2, \ldots, M)$, $\theta\,(0 < \theta \leq 1)$ represents the overall efficiency index) and added $\sum_{m=1}^{M} \lambda_m = 1$ into formula, making the Variable Returns to Scale (VRS) model. Through the VRS model, we can divide the overall performance as product of θ_{TE} (technical performance), $0 < \theta_{\mathrm{TE}} \leq 1$, $\theta_{\mathrm{TE}} \geq \theta_m$ and θ_{SE} (scale performance), $0 < \theta_{\mathrm{SE}} \leq 1$, $\theta_{\mathrm{SE}} \geq \theta_m$. The same thing is when θ_{TE} and θ_{SE} approach 1, both technical performance and scale performance of R&D input and output going higher. When $\theta_{\mathrm{TE}} = 1$ or $\theta_{\mathrm{SE}} = 1$, this means either technical performance or scale performance has reached optimal level.

$$\begin{cases} \min\left(\theta - \varepsilon\left(\sum_{k=1}^{K} s^{-} + \sum_{l=1}^{L} s^{+}\right)\right), \\ \text{s.t.} \sum_{m=1}^{M} x_{mk}\lambda_m + s^{-} = \theta x_k^m, \quad k = 1, 2, \ldots, K, \\ \sum_{m=1}^{M} x_{ml}\lambda_m + s^{+} = y_l^m, \quad l = 1, 2, \ldots, L, \\ \lambda_m \geq 0, \quad m = 1, 2, \ldots, M. \end{cases} \tag{1}$$

3.1.2. Malmquist-DEA Index. Malmquist index was initially proposed by Malmquist in 1953 as a consumption index. Researches as Caves in 1982 applied it to productivity various analysis. It is used in measuring improvement of total factor productivity, various performances, and technology improvement ((x_{t+1}, y_{t+1}) and (x_t, y_t) distinctively represent the input and output of the years $t+1$ and t. d_0^t and d_0^{t+1} indicate the distance functions of the years t and $t+1$).

$$M_0 = \left[\frac{d_0^t(x_{t+1}, y_{t+1})}{d_0^t(x_t, y_t)} \cdot \frac{d_0^{t+1}(x_{t+1}, y_{t+1})}{d_0^t(x_t, y_t)}\right]^{(1/2)}. \tag{2}$$

Under circumstance of constant scale returns, the index can be divided into overall performance change index (EC) and technical change index (TC); the divided process is as follows. Under the circumstance of Variable Scale Returns, EC can be one step further divided into pure technology performance (PTF) and scale performance (SE).

$$M_0(y_{t+1}, x_{t+1}, y_t x_t) = \frac{d_0^{t+1}(x_{t+1}, y_{t+1})}{d_0^t(x_t, y_t)}\left[\frac{d_0^t(x_{t+1}, y_{t+1})}{d_0^{t+1}(x_{t+1}, y_{t+1})} \cdot \frac{d_0^t(x_t, y_t)}{d_0^{t+1}(x_t, y_t)}\right]^{(1/2)} = \text{EC} \cdot \text{TC}. \tag{3}$$

When the index exceeds 1, productivity tends to increase; otherwise, it means productivity is decreasing; if technical change index exceeds 1, this indicates improvement of existing technology; whereas in technology retrogression if technical performance exceeds 1, this indicates technology performance improved; otherwise, technology performance worsened. Also if scale performance exceeds 1, this indicates the time "$t+1$" is more close to constant scale returns, or gradually approaches fitted scale compared to time "t"; otherwise it is getting farther to fitted scale. Malmquist-DEA index not only comprehensively evaluates performance of knowledge innovation but also analyzes performance evolution among various regions. Based on this aspect, this paper combined two methods together in measuring metropolis performance circumstance of Yangtze Economic Belt.

3.2. Data and Index Construction. From the data aspect, the measure for innovation output is generally based on number of patents, which included some limitations [23]. As patents are granted for invention, invention is not necessarily transformed into an innovation, a new product, or production technology, and there are other ways besides patenting to appropriate the returns of successful R&D activities [28]. Crepon used a number of patents and sales of new products in manifested innovation [29]; researchers think that R&D only represented parts of innovation output, while number of papers published in the science journal and number of new products developed are all variables of R&D output. Hagedoorn used number of patents, patent citation, and number of new products in reflecting the performance of enterprises [30], while Belderbos et al. used labor productivity rate and innovation products in measuring innovation performance [31]. So based on the traditional index selection, this paper uses patent, publications, and high-tech industry output rate as output index.

Focus on relationship between R&D input and output is called knowledge production function, and a consensus has been reached on the input indicators which mainly contain R&D personnel and R&D expenditure. As a proxy for input to the innovation process in the private sector, R&D employees were classified as working in R&D if they have tertiary degree in engineering or in the natural science [32]. Based on these facts, this paper chose full-time equivalent of R&D employees and R&D expenditure as input index (Table 1).

Considering the availability and comprehensiveness of existing data, the cross-sectional data analysis from 2000 to 2018 takes into account the time lag between input and output in R&D activities, and the maximum time lag for R&D resource input to output is 1 year. Therefore, the output indicators are selected from the data of t years, and the input indicators are selected from the data of t – 1 years.

4. Economic and Innovation Feature of the Case Region

4.1. Economic Heterogeneity. Yangtze River Economic Belt includes 11 provinces and cities: Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Chongqing, Sichuan, Yunnan, and Guizhou. Yangtze River Economic Belt accounts for 21% and 43% of China's land area and population; it is representative region of innovation in China. By comparing R&D proportion of Yangtze River Economic Belt and China, proportion of R&D expenditure in Yangtze River Economic Belt accounts for 46% of China, and R&D personnel accounts for 45%.

Moreover, there is huge economic heterogeneity among these regions; GDP per capita of Shanghai has reached 12.7 million yuan in 2018, while GDP per capita is only 3.9 million yuan in Sichuan province (middle region) and 3.4 million yuan in Yunnan province (western region). Based on regional economic heterogeneity, this research divided

Table 1: The evaluation index of input and output performance of R&D resources.

Type	First grade indicator	Second grade indicator
Input indicator	R&D input	R&D expenditure per unit of GDP R&D personnel of full-time equivalent (ten thousand/year)
Output indicator	Patent output Innovation output	Number of patents per thousand Number of scientific papers per thousand High-tech product output rate

Yangtze River Economic Belt into three regions: Region 1 (according to "Yangtze River Delta Regional Planning (2010)," there are one direct-controlled municipality and two provinces, Shanghai, Jiangsu, and Zhejiang, and 16 core cities within this region) is Yangtze River Delta; this region accounts for only 2% and 12% of the country's area and population (Table 2). But it accounts for 1/5 of the country's GDP and nearly half (42%) of the country's international trade volume. This region is one of the earliest open-up regions in China; it has policy advantages from the government. So Region1 is relatively small region, has start advantages and higher economic development level, and owns more enterprise headquarters and FDI. This region sets Shanghai as economic leader, which makes it grow faster than others.

Region 2 (Region 2 contains four provinces: Anhui, Jiangxi, Hubei, and Hunan) is located in midland China, which accounts for 7% and 17% of the country's area and population. Region 2 acts as a bridge between east and west China; manufacturing accounts for more than half (51%) of the region's GDP. Region 3 (Region 3, western metropolis area, contains three provinces and one direct-controlled municipality: Chongqing, Sichuan, Yunnan, and Guizhou) is economic periphery region in the west of China. It accounts for 12% of the country's area but only 14% of the whole population. It has large land area (12%) but low population density; population outflow is serious and GDP only accounts for 9% of China. According to Chenery, industrialization can be divided into six stages; cities in Region 1 have already stepped into post-industrialization stages, but cities in Region 2 or Region 3 are still in initial industrialization stage.

From interregional economic relation aspect, density of economic linkages among regions in Yangtze River Economic Belt is still at a low level. The density of Region 1 is the highest, with Shanghai, Suzhou, and Nanjing as economic center of Region 1 and playing the role of economic radiation to Region 2 and Region 3; Wuhan, Nanchang, and Changsha are the economic center of Region 2, which have close economic linkages with Region 1, playing the role of connecting east and west regions; most cities in Region 3 have weaker links with other regions, but Chongqing has strong economic ties with Region 2 through Yichang.

4.2. Spatial Distinction of Innovation. Innovation output is considered to be an important indicator reflecting the level of regional innovation; level of R&D investment in Yangtze River Economic Belt accounts for important proportion in China. Innovation output shows spatial distinction. Specifically, trend-surface analysis of innovation output from northeast to southwest direction of Yangtze River Economic Belt changes from high to low and shows "core-periphery" feature. Spatial correlation analysis of innovation output shows that Moran's I index of the Yangtze River Economic Belt is all positive, and spatial dependence characteristics of innovation output are becoming obvious. According to LISA local autocorrelation analysis, high-value output agglomeration of Yangtze River Economic Belt is not significant; no city is located in High-High area; Shanghai, Suzhou, Ningbo, Hangzhou, Wuhan, Changsha, and Chongqing cities show higher value characteristics than surrounding cities. The Low-Low cluster is prominently located in Lijiang, Linyi, Baoshan, and Lishui in Region 3. High-value cluster of innovative output continues to expand northward in Region1, while level of innovation output between Region 1 and Region 2 tends to be similar, but the level of agglomeration is relatively low (Figure 1). Otherwise, from interregional innovation connection aspect, centrality of innovative network was enhanced, network density decreased due to expansion of network scale, and the core of network structure is significant; network core-peripheral structure is increasingly significant.

Due to huge regional economic heterogeneity, differences in innovation volume among regions are inevitable. Therefore, when analyzing areas with large spans and significant internal differences, we should not only focus on the absolute amount of innovation volume but also ignore problem of whether knowledge or R&D resources are reasonably configured. Therefore, this paper proposes problems of innovation in heterogeneous regions of China through innovation performance analysis. On the whole, the economic development level, innovation level, and resource elements of different regions of the Yangtze River Economic Belt must be quite different. Therefore, the cooperation network between regions not only enhances the connectivity of innovation resources, but also realizes the rational allocation of innovation resources.

5. Spatial Analysis of Innovation Performance in Yangtze River Economic Belt

5.1. Regional Overall Innovation Performance. Through the performance calculation of R&D investment and output factors, the overall innovation performance level of the Yangtze River Economic Belt is low. The comprehensive innovation performance of the Yangtze River Economic Belt rose from 0.237 to 0.408 during 2000 to 2018. The average level of innovation performance in Yangtze River Economic Belt is still less than 50% of optimal performance in the last 18 years. From 2000 to 2018, the overall innovation

Table 2: Context of the research regions.

Region/Nation (%)	Region 1	Region 2	Region 3
Area	2%	7%	12%
Population	12%	17%	14%
GDP	20%	13%	9%
Export-import volume	42%	3%	2%
R&D expenditure/GDP	2.4%	1.2%	0.9%
Sector/overall GDP (%)	Region 1	Region 2	Region 3
Sector one (agriculture)	5%	13%	13%
Sector two (manufacturing)	49%	51%	49%
Sector three (service)	46%	36%	38%
Total no. of regions	Region 1	Region 2	Region 3
Area (square km)	211,300	710,000	1,132,000
Population (thousand)	157,090	228,100	190,690
GDP (billion USD)	1561	1028	708
Export-import volume (million USD)	362706.98	22640.09	18326.67
Total no. of nations	Overall	Cooperate	Cooperate/overall
Patenting	2,799,829	22,699	1%
Publication	26,248	3,749	14%

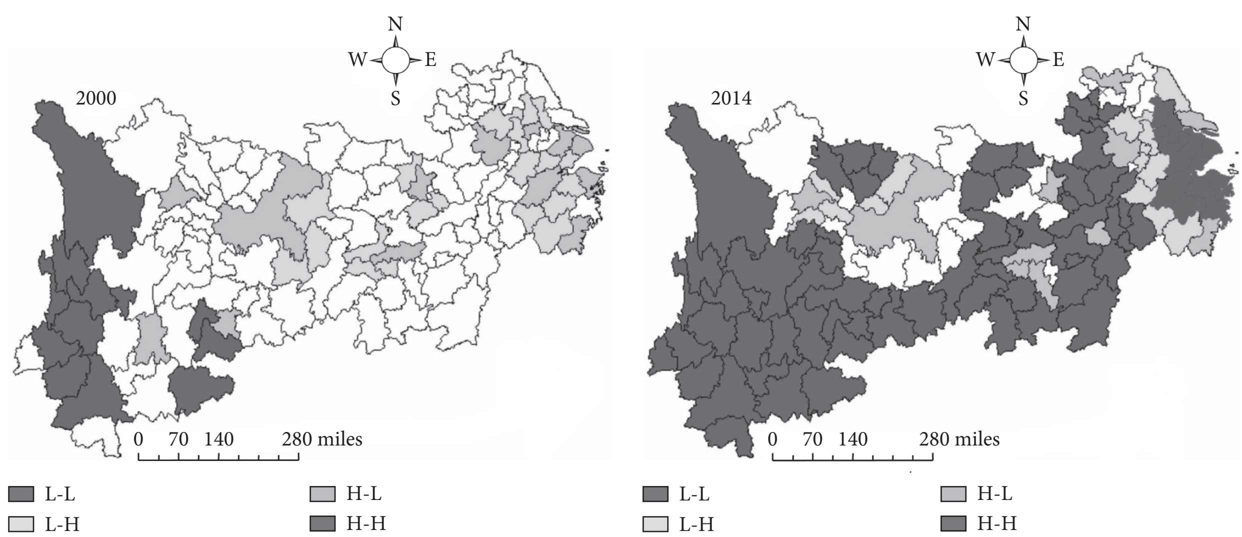

Figure 1: Spatial co-relation of innovation in Yangtze Economic Belt.

performance showed an upward trend, specifically, only 15 of the cities with a performance level of more than 50% in Yangtze River Economic Belt in 2000. Among them, Shanghai, Nanjing, Wenzhou, and Quzhou in Yangtze River Delta, Nanchang, Wuhan, Jiujiang, and Zhangjiajie in the middle regions, and Kunming and Tongren in west regions reached the optimal level. By 2018, the number of cities with an optimal performance level of over 50% increased to 33. Overall performance level is improving but slow; one of the important issues to be solved in Yangtze River Economic Belt to enhance regional innovation is how to effectively use innovative resources and improve innovation performance.

From the perspective of pure technical performance, 68% of the city's pure technical performance is gradually rising, and pure technical performance is higher than overall performance. From 2000 to 2018, pure technical performance rose from 0.411 to 0.553. In 2000, there were 15 cities with the highest technical performance in the Yangtze River Economic Belt; the number of cities with the best technical performance has increased to 20 cities by 2018. This phenomenon is not only found in central economic cities, but also distributed in peripheral cities in Region 2 and west Region 3. In 2000, 33 cities with pure technical performance of more than 50% accounted for 31.4% of the total number. Among them, 24 cities have a pure technical performance of over 70%. By 2018, there were 55 cities with a pure technical performance of more than 50%, accounting for 52.4% of the total number. Among them, the number of cities with pure technical performance of 70% or more increased to 37. For areas with large numbers of cities and huge development differences, from 2000 to 2018, the change in pure technical performance indicates that the overall technical level of the Yangtze River Economic Belt has improved.

From the perspective of scale performance, scale performance of the Yangtze River Economic Belt is normally higher than technology and overall performance of the same period. From 2000 to 2018, the scale performance decreased from 0.635 to 0.739. In 2000, the scale performance reached more than 50%, which accounts for 62% of the total. Among them, 53 have an optimal performance of more than 70%. By 2018, proportion of the optimal performance of more than 50% increased to 84.8%, of which 62 cities reached over 70% of the optimal performance. Therefore, the trend of the scale performance of Yangtze River Economic Belt is stable. How to realize resource integration and utilization is key to solving the problem of overall innovation performance and sustainable development.

5.2. Regional Total Factor Productivity Change. In this chapter, we use Malmquist-DEA model to calculate the Malmquist index of R&D resources of Yangtze River Economic Belt from 2000 to 2018 (Figure 2). From data analysis, R&D Resources Comprehensive Performance Change Index (0.911) and Pure Technical Performance Change Index (0.889) are less than 1, while Technology Progress Change Index (4.683), the Scale Performance Change Index (1.025), and the Total Factor Productivity Change Index (4.267) are all greater than 1. The total factor productivity index of the Yangtze River Economic Belt from 2000 to 2018 was 5.263, which indicates that productivity has increased during this period. The technical change index is 4.683, indicating that the overall regional technology level is gradually improving. Since the technical performance is less than 1 (0.889), although the technical level is improving overall, the technical performance of the region is gradually decreasing. It shows that the performance change of Yangtze River Economic Belt is mainly due to the innovation and progress of technology, but the existing technology is not necessarily fully utilized. The scale performance is 1.025, indicating that regional innovation is gradually changing to the optimal scale and gradually approaching fixed-scale compensation these years.

Moreover, from trend of productivity and technology changes in Yangtze River Economic Belt from 2000 to 2018, regional production performance has increased and the overall technical level has been greatly improved, but technical performance has decreased. The gap between the improvement of technology level and the decline of technical performance has gradually widened, indicating that the existing technologies in the economic region have not been fully utilized. Changes of innovation performance mainly depend on the improvement of the overall technical level in the process of technological development. From the perspective of innovation scale, the Yangtze River Economic Belt has been adjusted and its scale has gradually become rationalized. At the same time, various regions within Yangtze River Economic Belt are at different stages of development. So the innovation performance is also affected by factors such as regional innovation investment, economic level, technical level, institutional conditions, and social and cultural conditions. Therefore, it is necessary to carry out cluster analysis on areas with similar performance levels and to specifically analyze the specific characteristics and constraints in different groups.

5.3. Regional Grouping and Problems of Yangtze River Economic Belt. In this chapter, through cluster analysis of regions with similar levels of innovation performance, we try to find out the problems faced by regions with different performance levels in Yangtze River Economic Belt and propose effective ways and directions for solving problems.

With ward cluster analysis of innovation performance of Yangtze River Economic Belt in 2018, cities can be divided into 4 major groups; the innovation performance of the four groups was, respectively, 0.809, 0.499, 0.308, and 0.122 (Table 3). The number of cities in Group 1 is the lowest among the four groups (22%), but the overall level of innovation performance is the highest. Comprehensive performance, pure technical performance, and scale performance all achieve more than 60% of optimal performance. Cities of Group 2 have a combined performance of 0.499, a pure technical performance of 0.656, and a scale performance of 0.766. The other two groups have a large number of cities but the performance level is relatively low; the overall performance of Group 3 is 0.308, the pure technical performance is 0.479, and the scale performance is 0.730. Group 3 is higher than Group 4 (comprehensive performance is 0.122, pure technical performance is 0.245, and scale performance is 0.629). Overall, the two groups have less input redundancy. Compared with Group 1 and Group 2, problems of these two groups are insufficient innovation output; 77.6% of cities in Group 3 and Group 4 have insufficient output. Group 4 is particularly significant (93.3%), and the problem of insufficient output is mainly reflected in applied knowledge and insufficient high-tech output.

From our specific analysis, in Group 1, cities like Shanghai, Hangzhou, and Nanjing and other cities in the eastern part of the economic belt have achieved the best performance. The absolute values of economic development level and innovation input and output of other cities in Group 1 are much higher than cities in other groups. From the performance analysis, most of the R&D resource inputs and outputs in these cities are not problematic; the main reason for the low performance is the incompatibility of R&D resources and inputs and outputs. The DEA calculation results show that R&D resources of the Yangtze River Delta in Group 1 are diminishing returns to scale. Therefore, comprehensive performance can be improved by reducing the R&D resources invested.

87.5% of cities in Group 2 have input redundancy; particularly, cities such as Wenzhou, Yangzhou, Zhenjiang, Lianyungang, and Huzhou in Region1; Xiangtan, Huaihua, and Yingtan in Region 2; and Meishan and other cities in Region 3 have problems of redundant R&D personnel and funding. Therefore, the main way to achieve best performance of Group 2 is to encourage development of basic scientific research and at the same time appropriately adjust the input of R&D funds. As cities in Group 2 are often declining in scale, they cannot always expand the scale of resources when strengthening basic innovation research. Cities in Group 2 can achieve regional optimal development by enhancing the rational allocation of resources across regions or interregional cooperation among universities.

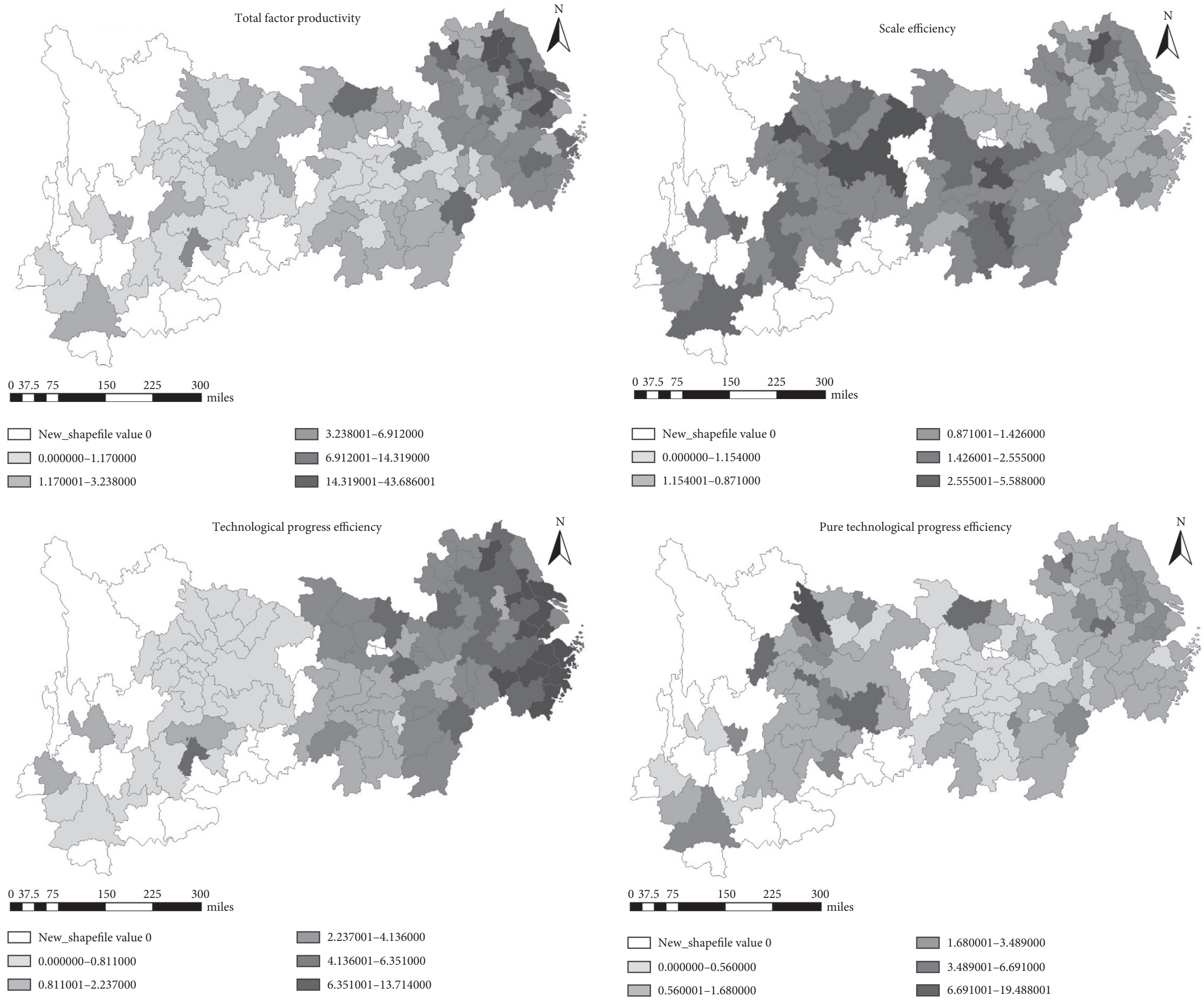

Figure 2: The Malmquist index analysis of Yangtze Economic Belt until 2018.

Table 3: Innovation performance of groups in Yangtze Economic Belt.

Group	City no.	%	Total performance	Technology performance	Scale performance
Group 1	23	22	0.809	0.940	0.864
Group 2	24	23	0.499	0.656	0.766
Group 3	28	27	0.308	0.479	0.730
Group 4	30	29	0.122	0.245	0.629

In Group 3, 60.7% of cities have insufficient high-tech and application knowledge output. The high-tech output value and application knowledge output in Group 4, respectively, accounted for 60% and 36.6%. By comparison, cities in Group 3 are mostly diminishing returns to scale; only few cities can continue to increase output by increasing the size of resources, while 37% of the cities in Group 4 show increase in returns to scale; therefore, although the cities in Group 4 have the lowest innovation performance, they can achieve performance optimization by continuing to expand the scale of resource input.

Combining the spatial differentiation of the four groups, 85% of the cities in Groups 1 and 2 are located in Yangtze River Delta and middle Yangtze River regions, which are in post-industrial or late industrialization development stage; 87.9% of the cities in Groups 3 and 4 are in the western regions of Yangtze River Economic Belt, which are in industrialization or early industrialization development stage; 57.1% of the cities in Group 3 are located in the middle region of Yangtze River Economic Belt, and 63.3% of the cities in Group 4 are located in the western region of Yangtze River Economic Belt. Existing researches have confirmed that there is correlation between economic development and regional innovation. Our research further confirms these points through our empirical analysis. Further, in the same economic development stage, regions with similar performance levels have different ways to achieve the best performance.

6. Conclusion and Discussion

This paper constructs an evaluation index system to measure regional innovation performance; the index system includes R&D expenditure per unit of GDP, R&D personnel of full-time equivalent, number of patents per thousand, number of scientific papers per thousand, and high-tech product output rate. Malmquist-DEA index is used to measure innovation performance of heterogeneous regions in the Yangtze River Economic Belt.

Cities of Yangtze River Economic Belt have strong heterogeneity; from the perspective of economic development, the eastern Region 1 is core economic development region which developed in post-industrialization stage. Most cities in Region 2 and Region 3 are economic periphery cities; these cities are still in middle industrialization and early industrialization stage. The main conclusions and recommendations from the analysis of our research include the following:

(1) The intraregional differences of cities in Yangtze River Economic Belt are significant; the overall level of regional innovation performance is low. The economic core region increased volume of innovation through large amount of material input and resource consumption. How to improve the optimal allocation and coordination of interregional resources to improve performance of innovation resources has become the primary problem to be solved in such regions.

(2) In the case of low economic development level region, regional technical level has improved; on the contrary, the regional production performance has not increased but is gradually decreasing. The trend of technical level and technical performance is reversed, and improvement of comprehensive performance level is achieved through a large amount of resources invested in technological innovation. Therefore, how to improve the utilization of existing technology resources is worth further consideration.

(3) Regions with similar performance levels in Yangtze River Economic Belt can be divided into 4 groups. Specifically, the overall level of regional innovation performance in the post-industrial development stage is higher; the reason for the low performance is problem of mismatch among R&D resource scale, input, and output. Such cities need to adjust their scales to achieve performance optimization. Regions with relatively low economic development levels need reasonable regional resource optimization and allocation.

The view that there is a positive correlation between the level of regional economic development and regional innovation output has been proposed by some innovation-related research. However, this paper emphasizes that it does not mean that regions with higher economic development level or higher innovation input or output will have better innovation performance, especially for heterogeneous regions in different economic stages. Specifically, this paper attempts to summarize the general regulation of innovation performance in heterogeneous regions of China, especially in regions or cities in different economic development stages. Through the analysis, this paper tries to find out the main problems existing in regional innovation performance of China and put forward relative solutions for heterogeneous region, which may have certain significance in promoting the research of regional differential innovation.

This paper proposes that cities in the post-industrial economic development stage in China have better innovation ability, and these cities rarely have problem of insufficient innovation input and output. The main problem that affects innovation performance is the mismatch between innovation scale and innovation input-output. Therefore, it is a better choice for such cities to achieve the optimal performance not to blindly pursue the scale effect, but to appropriately reduce the innovation scale. Cities in middle stage of industrialization have the main problems of redundant resource input or reduced return on scale. Therefore, it is not the best way to only focus on increasing the scale of innovation output by increasing input. Better suggestion is to improve the utilization of exising resources or establish interregional organization alliance to improve the regional innovation performance. The innovation performance of cities in primary stage of industrialization is relatively low. The main characteristic of these cities is that the innovation output is obviously insufficient, especially in the field of basic scientific research and high-tech research.

From the perspective of how to effectively solve the problem of heterogeneous regional innovation performance, this paper suggests that cities with higher economic development level achieve the goal of improving innovation performance by improving the utilization of existing resources or building efficient cross-regional alliances. The marginal cities with relatively underdeveloped economy show the characteristics of increasing returns to scale. Therefore, it is necessary to expand the scale of R&D resources to improve innovation performance, or to improve the regional commercialization ability through R&D of new products.

In this paper, panel data is selected to analyze the innovation performance of China's heterogeneous regions. DEA method is an important scientific method to solve the problem of heterogeneous regional innovation performance, but its limitation is that it cannot effectively analyze the causes of performance differences or regional low performance. In the follow-up research, the main factors affecting the innovation performance of heterogeneous regions and their influencing mechanism will be further discussed.

Data Availability

The R&D expenditure, R&D personnel of full-time equivalent data and patent, and scientific papers data supporting this innovation performance analysis of this study have not been made available. Because these data belong to third-party rights, the authors can only use these data for academic research but have no right to publish the data source.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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Research Article

Reducing Trade Inequality: A Network-Based Assessment

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International trade, the network that underpins globalization, shows an extreme inequality. Despite efforts of multilateral organizations to foster a more fair world through trade agreements, it is hard to assess the effect of these changes on such a complex system. We have measured, using numerical simulation on a recently published network model, the impact of simple policies to boost trade chances among the weakest economies. Results suggest that global inequality may be reduced improving trade among low-income economies.

1. Introduction

Trade liberalization creates larger gains than losses for most of the world [1]. However, in most low- and middle-income economies, the prevailing tariff structure induces sizable welfare losses. What could happen if that structure changed? What would happen if low- and middle-income economies increased trade between them? In this paper, we test whether an increase in the participation on the global trade network for low- and middle-income economies would generate a more balanced network and, consequently, a more fair distribution of the gains and losses derived from it. Regional and economic country groupings follow World Bank's classifications. From the economic point of view, we use the term "low- and middle-income economies", rather than "developing countries" or "developing world," to define the policy target; we contemplate income differences without assuming additional barriers on their economic progress [2].

The missing globalization puzzle [3] stresses that that the volume of trade has become increasingly sensitive to distance in the last 40 years. This paradoxical result, given the reduction in communications and transport costs, is particularly strong for low- and middle-income economies; poorest countries have increased their trade share with geographically closer partners as the relative trade costs with them fell more than with further-away partners [4]. Despite this fact, the fraction of trade within this group is tiny compared to the global figure.

Trade inequality is easy to measure because statistical series are well curated. Empirical data and the available research on international trade have shown that some countries are underrepresented in the global trade network; their participation on it is below their share of Gross Domestic Product (GDP). Conversely, other economies are overrepresented [5, 6].

Economic theory and empirical evidence suggest that the creation of a more equal international trade network may be achieved through different complementary channels: preferential trade agreements, global value chains integration [7], industrial policy reforms [8–10], and migration strategies [11]. However, the experimental validation and quantitative assessment of the global impact of a particular policy are a hard challenge.

Numerical simulation is a convenient way to address this kind of problems where the system is so complex. Network models are a nice choice for trade among nations and so it is usual to refer to this system as the World Trade Network (WTN) [12–16].

The stochastic model developed in [17] produced synthetic networks with a high degree of adjustment to international trade flows from 1962 to 2017. Its generative mechanism suggests that inequality is a structural property of the network. The volume traded by the most connected nodes tends to have a value higher than that corresponding to a random process, a well-known property of some weighted complex networks as the WTN [18]. This distribution emerges as the product of a simple multiplicative process where probabilities are proportional to the fraction of global trade of each country. However, what happens if some external policy improves the chances of the weak players?

Belloc and Di Maio summarized the most successful strategies and practices for export promotion by low- and middle-income economies [19]. Of all the policies proposed, the establishment of new trade deals is the most straightforward policy tool to increase trade participation. The other alternatives (increase productivity, institutional development, etc.) would depend more on the organic evolution of the different economies; they cannot be contemplated as a one-act external policy.

In this paper, we examine if a politically driven increase of trade among underrepresented countries, regionally and globally, would contribute to a more balanced and equal network. We build synthetic networks and disturb their organic growth by boosting the trade chances of a small fraction of nations.

We analyze the impact that an increase in trade derived from new trade dealing within this set would have on the equity of the network, measured through the Gini index. We simulate those agreements between pairs of countries ranked in the bottom 1%, 2%, and 5% of the global trade probability distribution, both regionally (underrepresented countries reach an agreement with underrepresented countries in their same region) and globally (without regional limitations).

2. Materials and Methods

We work with the historical data series curated by the Observatory of Economic Complexity [20]. This collection contains yearly records of traded merchandise in US dollars per product category between two countries, from 1962 to 2017. We study the trade volume, just adding the monetary value of all exchanged goods between each pair of exporter/importer to build the empirical weighted matrix. As computations are quite time-intensive, we have focused our attention on the last available years, from 2010 to 2017, adding 2005 to have a sample of the pre-Lehman Brothers crisis.

The empirical network is bipartite, with two guilds: exporters and importers with each country playing a dual role. For instance, the node for Germany as exporter country is different from the node of Germany as importer. The yearly aggregated trade flow between two countries is a weighted link directed from Exporter_A to Importer_B. The network is bidirectional as the value of traded goods and services from Exporter_B to Importer_A is different from that in the opposite direction. The model deals with each year as a different network and there is no memory from year to year. The number of links of each node is called *degree* and it is the number of countries it trades with. *Strength* is the sum of *weights* of any given node. Distributions of degree and strength are a valuable source of information of network properties [21].

We apply a soft mitigation strategy to deal with the heterogeneous data classification and sources over such a long span of time, and we filter the links that fall within the lower 0.1% of the trade distribution to avoid the strongly meshed condition [22]. We refer to the original paper for details [17].

To emulate the dynamics of the WTN, we use the *Synthrade* stochastic model. Network growth is driven by two different mechanisms. The first one, called *node aggregation regime*, acts during a short period of emulation time, under the hypothesis of neutrality. Nodes arrive at a pace that is a function of the cardinality of its own guild at a particular simulation instant and attach to opposite class nodes by preferential attachment [23]. When the synthetic network matrix reaches the dimensions of the empirical one, this process stops at t_F that we call *formation instant*. The second one drives the birth and weight accretion of trade links. At each simulation step, the volume traded by any pair of countries may raise according to an stochastic aggregation process. The probability for each cell is the product of marginal probabilities of its importer and exporter edges. These marginal probabilities equal the ratio of traded goods of each country divided by the total yearly world trade. With this simple mechanism, the *weight aggregation regime* shapes the synthetic network until its number of links reaches the number of links of the empirical one. The emulation time grows up as $O(n^2)$.

A goodness-of-fit analysis of the Kolmogorov distance between empirical and synthetic distributions revealed that synthetic matrices are a fair statistical approximation. Figure 1 shows how the synthetic matrix closely follows the empirical distribution although it is less noisy. The synthetic matrix does not convey regional information.

Synthrade is a phenomenological approximation, but its simplicity provides some useful hints. As each cell of the probability matrix is proportional to the trade it represents, major world traders keep on growing during all the simulation time. Proportionality is the origin of the extremely skewed volume distribution that closely fits as a log-normal that arises as a result of the multiplicative process [24, 25]. Inequality is a structural property of the network and is self-sustained, an example of the *Matthew Effect* in the international trade [26].

Not all mitigation strategies would work under these circumstances. If trade barriers are lowered without exception for weak economies, powerful nodes will attract new chances. The overall effect is maintaining the imbalance. Raising tariffs, on the other hand, just worsens the isolation of minor players.

Our aim has been to assess the impact of policies to improve trade just among underrepresented countries. We have modified the original model to take into account geographical information. Policies are implemented with a simple function.

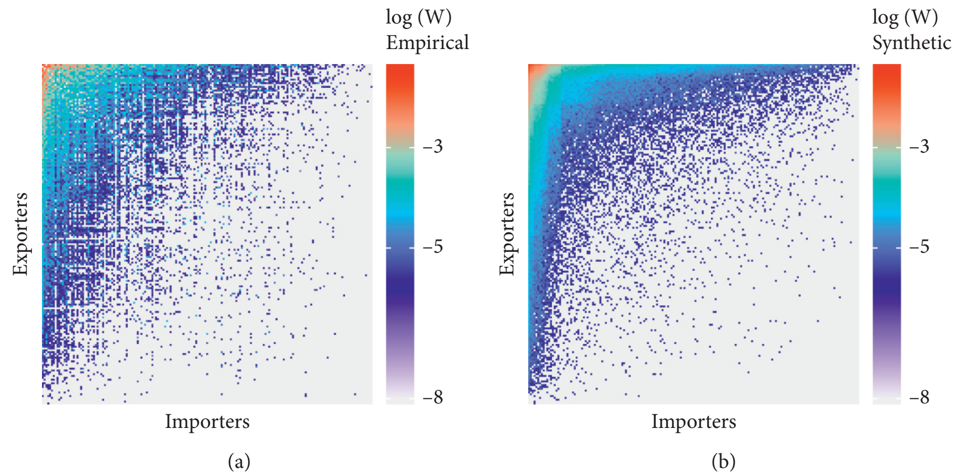

Figure 1: Empirical and synthetic trade matrices for year 2017. Normalized weight matrices $\mathbf{W}_{EI}/\sum_{ij}\mathbf{W}_{EI}$: (a) empirical and (b) synthetic. Color is assigned according to the normalized weight of that particular yearly trade volume. The synthetic matrix is the result of running a particular experiment. Both matrices have equal number of nodes and links.

For the first purpose, we use the Lending Group classification of the World Bank that defines seven regions [27]. We must perform a first step, to identify which country is each node. This decision is not trivial; we know the final picture that sheds the empirical matrix, but as *Synthrade* builds a growing model its size is not fixed and the relative position of each node can be modified along time. As our previous work showed, the distribution shape is quite the same from t_F up to the end of the experiment, so nodes are labeled at the formation instant with the country names of the empirical distribution.

Once the table that relates countries and regions is built, policies may be applied and they will affect the experiment during the weight aggregation regime. That means more than 90% of the experiment simulation time.

To make it simpler, we simulate the impact of trade agreements modifying three parameters: *improved trade percentage, boost percentage*, and *scope*. With the first one, we select those nodes that are eligible for the improvement policy. For instance, the value of 1% discards all probability matrix cells (exporter/importer pair products) in the upper 99% of the distribution. The policy only benefits trade among weak nodes, whose individuals' contributions to global trade are tiny. This selection is performed at each step of the simulation after t_F. The *boost percentage* ranges from 25% to 200% and is the increase in the probability of that particular matrix cell (obviously, the probability matrix must be normalized after applying this procedure). We do not make any assumption about the political or technical nature of the improvement policy; for that particular pair of weak nodes, the trade probability rises. Finally, the *scope* factor restricts the policy to countries that belong to the same region or extends it to whatever pair of countries if they met the improved trade percentage condition.

For each year, we have built 30 synthetic experiments without any kind of improvement and 30 for each combination of *scope* (global, regional), *improved trade fraction* (1%, 2%, and 5%), and *boost percentage* (from 25% to 200% by 25% steps). That makes 1470 experiments per year and a total of 13230 synthetic networks built.

To assess inequality, we use the Gini index of both the exporter and importer normalized strength distributions [28]. The estimation of the Gini index may be problematic with infinite variance distributions, as these we are dealing with, because of underestimation [29]. Our study focuses on the comparative evolution of inequality before and after the application of a mitigation policy on a synthetic model, so we think that Gini is a good enough proxy for this purpose.

3. Results

To set a baseline for comparisons, we compute the Gini indexes of the empirical networks and those of the set of 30 synthetic experiments without improvement policies (Figure 2). The average values of the Gini indexes for both exporter and importer series of the empirical matrices are, respectively, 0.82 and 0.81. The synthetic networks overestimate this parameter by a 6%, and the average Gini values are 0.86 for both distributions. As we mentioned, the synthetic networks are less noisy than the empirical ones, and small disorder is the origin of this offset.

As the statistical differences between exporter and importer distributions are minimal, we show just the results for the latter.

The improvement policy raises the chances of weak nodes to attract trade chances and acts only upon the intraweak trade. The goal is divesting a small volume of global exchanges towards the lower tail of the original distribution.

The upper row in Figure 3 shows, from left to right, the synthetic matrix without improvement policy, with a mild policy (50% boost), and with the strongest one (200%) for the lower 2% of global trade. The topology is roughly the

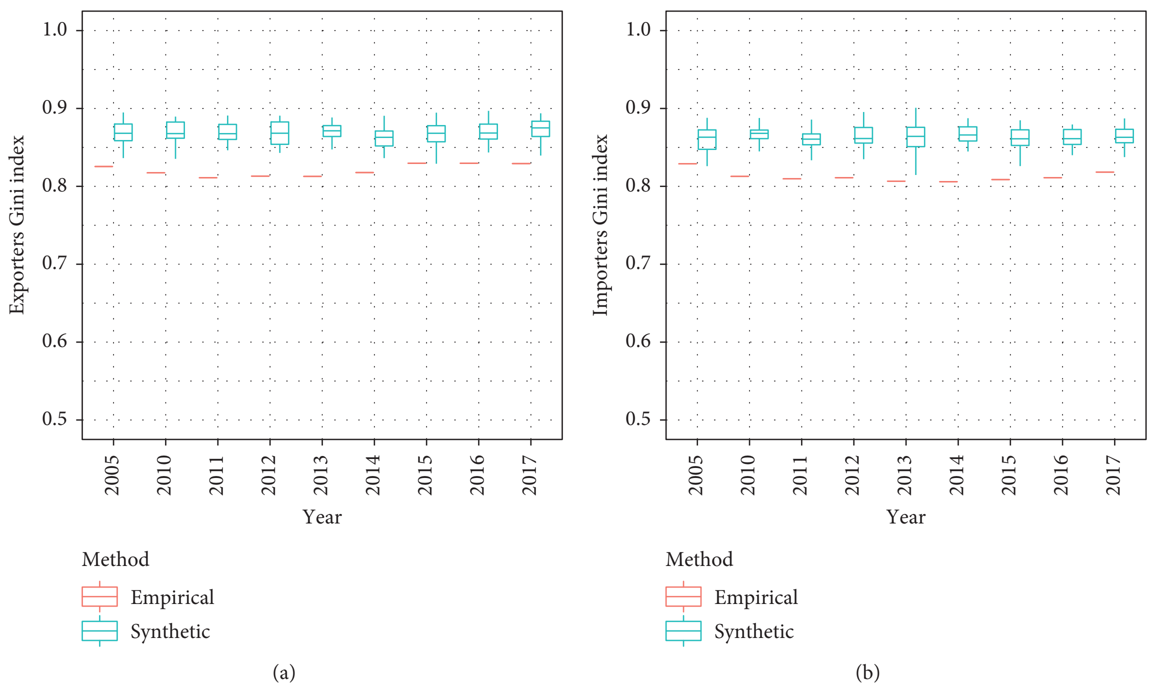

Figure 2: Gini indexes. Comparison of the Gini indexes for empirical networks and a set of 30 synthetic networks for each one: (a) exporter distributions and (b) importer distributions.

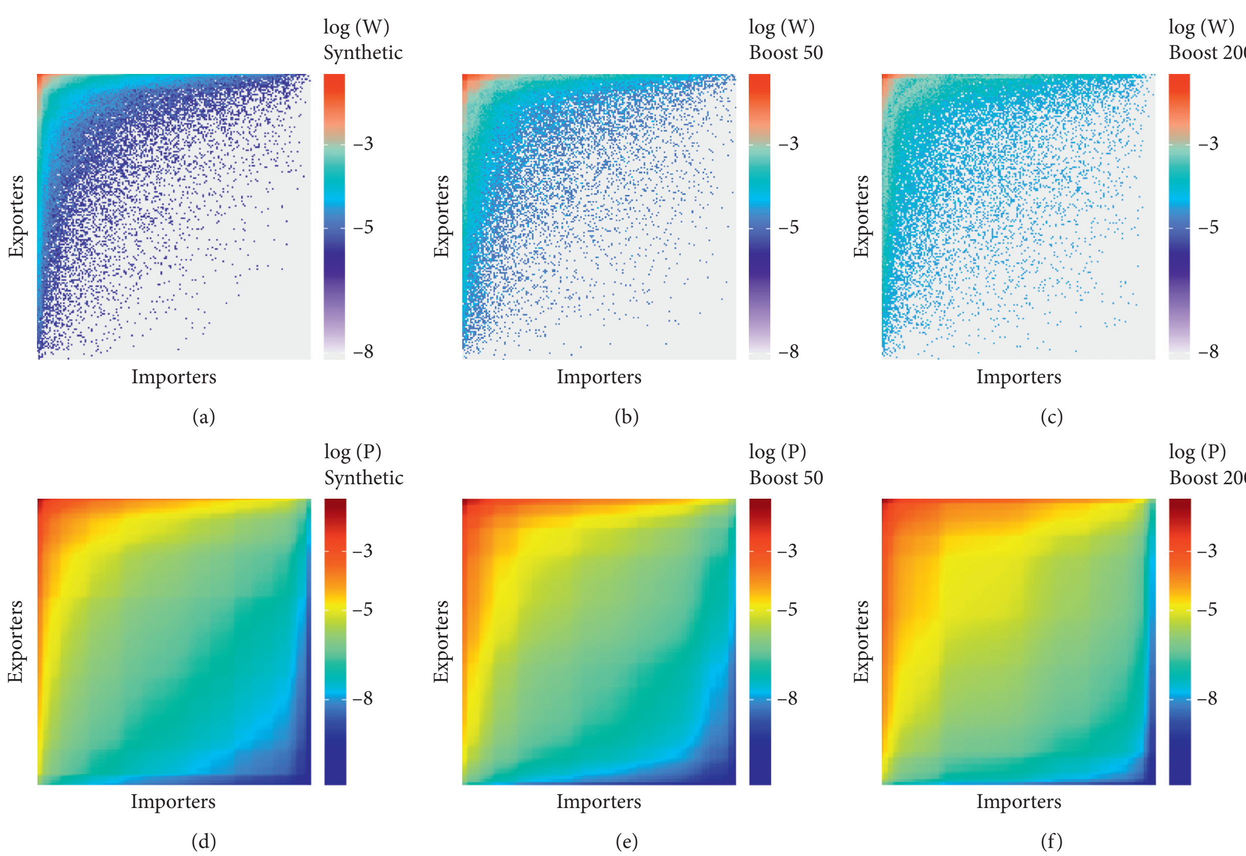

Figure 3: Synthetic matrices for year 2011. (a) Normalized weight network. (b) Result with 50% boosted probability for the lower 2% of global trade, with no regional restrictions. (c) The same with 200% boosted probability. Under these three plots (d), (e), and (f) are the heat maps of each corresponding final probability matrix.

same for the three matrices as they share number of nodes, number of links, and build-up mechanism. The color map allows to detect how the gradient gets smoother, with more nodes in the middle range of values (light blue).

This shift is more evident in the corresponding probability matrices. The area of cells with tiny trade values (dark blue) shrinks as the improvement policy fosters a more equitable distribution.

For any given year, both degree and normalized strength distributions are nearly log-normal. The policy should not modify degree distributions, as Figures 4(a) and 4(b) show, except for the lower tail, where there is a higher chance of connection of weaker nodes. The contrast with strength distributions, on the contrary, is quite sharp. As the impact of the policy gets more aggressive, the shape of the distribution gets narrower, trade volumes are now more equitable, and so the dispersion decreases. The upper tail seems unshakeable. The logarithmic nature of this distribution makes it possible to get a more even share of world trade without a radical change of its structure.

The Gini coefficient of the importer distribution falls from 0.863, when no mitigation policy is applied, to 0.744 for a trade boost of 100% and 0.691 if the trade boost is raised up to 200%, as far as there are no regional restrictions. If the policy excludes interregional exchanges, then the reduction is quite smaller, from 0.863 to 0.802.

The Gini reduction for the year 2005 (Figure 5) without regional restrictions may be fitted by a second-order polynomial:

$$y = 3.16 \cdot 10^{-6} x^2 - 0.00147x + 0.861, \quad (1)$$

where y is the average Gini index and x is the trade boost. The adjusted R^2 value is 99.6. For the regional series, a linear regression yields an accurate predictor:

$$y = -3.1 \cdot 10^{-4} x + 0.864. \quad (2)$$

The adjusted R^2 value is 99.4. Figure 6 shows both the computed average series and the results of the predictors.

Improvement figures and fair adjustment to both types of predictor models are quite similar for every year we have included in this study.

The linear law, with regional restrictions, has a constant negative slope and so the Gini coefficient reduction is proportional to the boosting percentage. The slope of the quadratic formula for the global improvement, however, suggests that boosting effect saturates.

So far, all the results were computed choosing the lower 2% fraction of global trade. This factor seems to have little impact in the Gini index reduction (Figure 7). A 2% yields, in general, the best performance, very close to the results with 1%, whereas reduction is less step applying the policy to the lower 5%.

The effect on the trade distribution of the seven regions (Lending Groups) is quite complex (Figure 8). EUCA and SASIA follow closely the global pattern. MENA and LAC show mild increases at higher boost percentages. This unexpected behavior is stronger for SSAF. Improving the chances of intraregional trade seems to increase inequality. The reason behind that is that trade volume for weaker countries is so small that minor changes in the long tail distribution have a strong overall effect. LAC, MENA, and SSAF have relatively moderate intraregional Gini index values and so are more sensitive. When trade agreements are not restricted to the intraregional trade the Gini index is always reduced. Finally, NAM only comprises USA, Canada, and tiny islands (Mexico belongs to LAC in this classification). Policies cannot have any effect as both nations are strong international trade players.

4. Discussion

The stochastic model of the World Trade Network works as a digital testbed to compare the effects assessment of inequality mitigation policies.

The results of the numerical experiments show that trade agreements between underrepresented countries with no regional limitations have a sensible larger impact on reducing inequality of the international trade network than deals limited to the same region. Results also confirm one of the network's most relevant properties: self-fulfilling structural inequality. *Matthew Effect* applies for the different trade boosts simulated for 1%, 2%, and 5% underrepresented countries; in order to reduce the Gini index of the international trade network, it is more effective to promote trade agreements among the bottom 1% of countries than among the bottom 5%.

This striking fact has a simple explanation, as trade volume distributions are log-normal. If the policy applies to the lower 5% of countries, the best-in-class of this group will have a high advantage over the weakest to attract the improved fraction of trade. For instance, the Gini indexes of SSAF and MENA worsen if improvement is restricted to the same regional group trade.

Pushing the policy to the limit, the structural network inequality would always benefit the strongest nodes. On the contrary, countries of the lower 1% are more even in their trade poverty, and a small general boosting has a notable effect on global inequality.

We have found two additional insights that may be helpful to design and deploy these kinds of policies. First, Gini index reduction has no sensible effect on the right tail of the distribution, and major traders are not threatened. Second, the improvement ratio, without regional restrictions, follows a quadratic pattern. Even small actions may reduce inequality if they are focused on the group of extremely poor nodes.

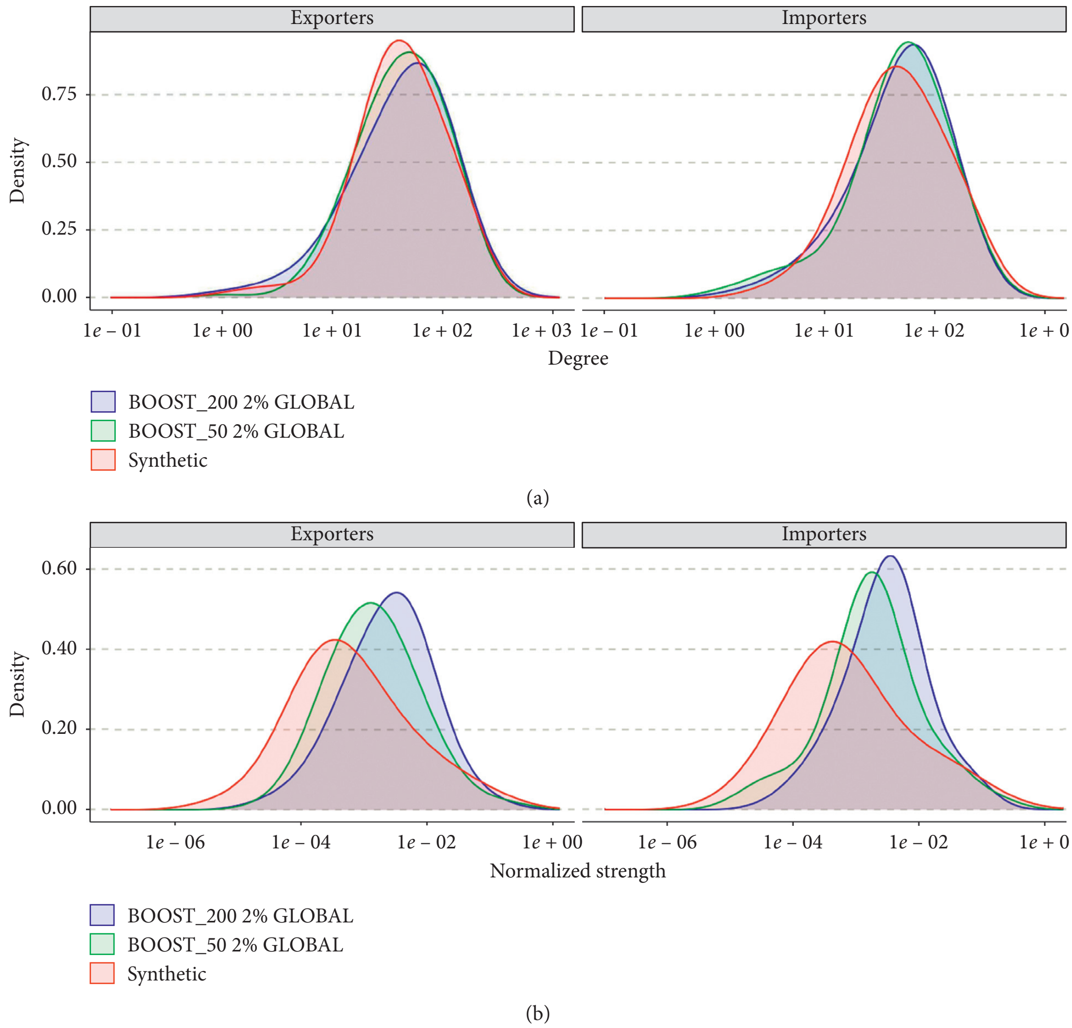

FIGURE 4: Density distributions for year 2005. (a) Degree. (b) Normalized strength. Plots show the values of the original synthetic experiment and two improved networks with probability boost of 50% and 200% for the lower 2% of global trade without regional restrictions.

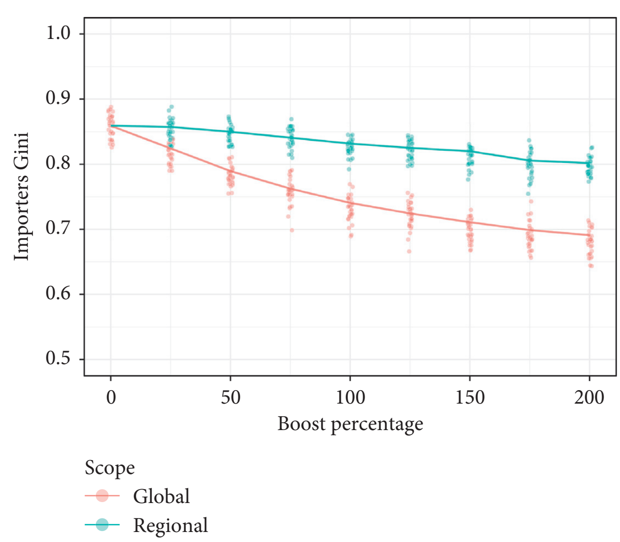

FIGURE 5: Effect of the improvement policy for year 2005. The policy is applied to the lower 2% of global trade. Dots are the results of individual experiments. Solid lines join the average values for each boost percentage.

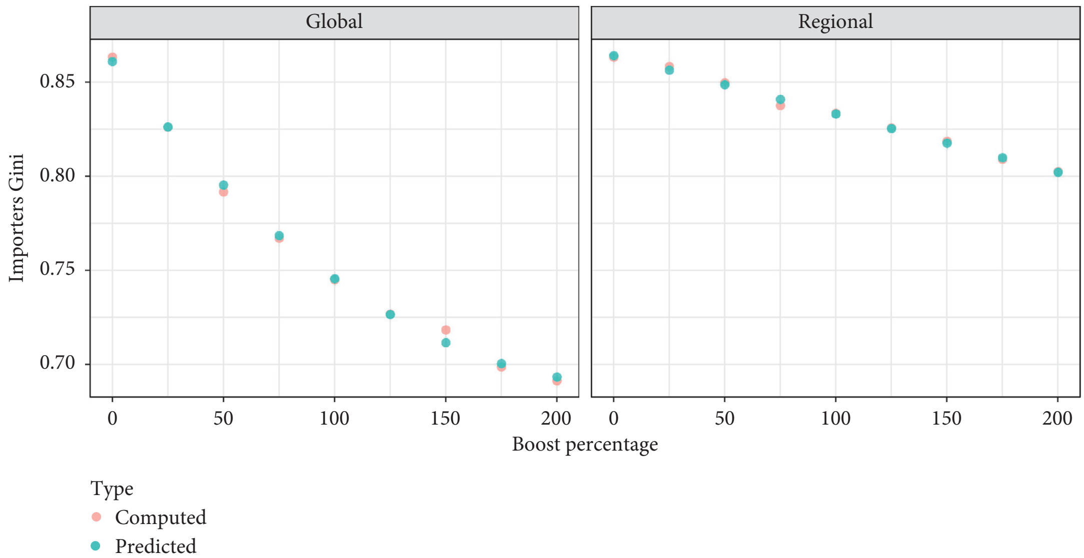

FIGURE 6: Computed and predicted average improved importer Gini indexes for year 2005. A second-order polynomial was fitted to the global data while regional data follows a linear model.

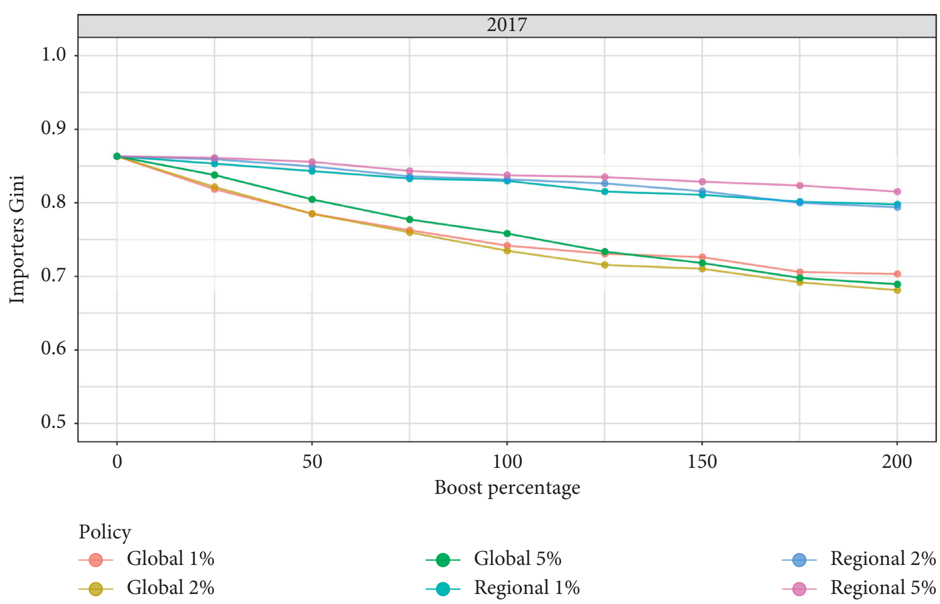

FIGURE 7: Effect of the improvement policies for year 2017. Reduction of Gini index for the importer distribution as a function of the policy.

Two important implications can be derived from these findings. First, to increase the representation of poorest countries in the international trade network, trade agreements between underrepresented countries should be promoted globally and not only through regional blocks; overcoming the missing globalization puzzle would be key for the establishment of a more balanced network. Second, the persistence of the *Matthew Effect* suggests that, beyond those trade agreements, inequality is a structural property of the network.

The current trend towards deglobalization and protectionism on developed countries should not become an obstacle to follow the policy course recommended in this article. Countries can improve their representation on the international trade network following their own agendas.

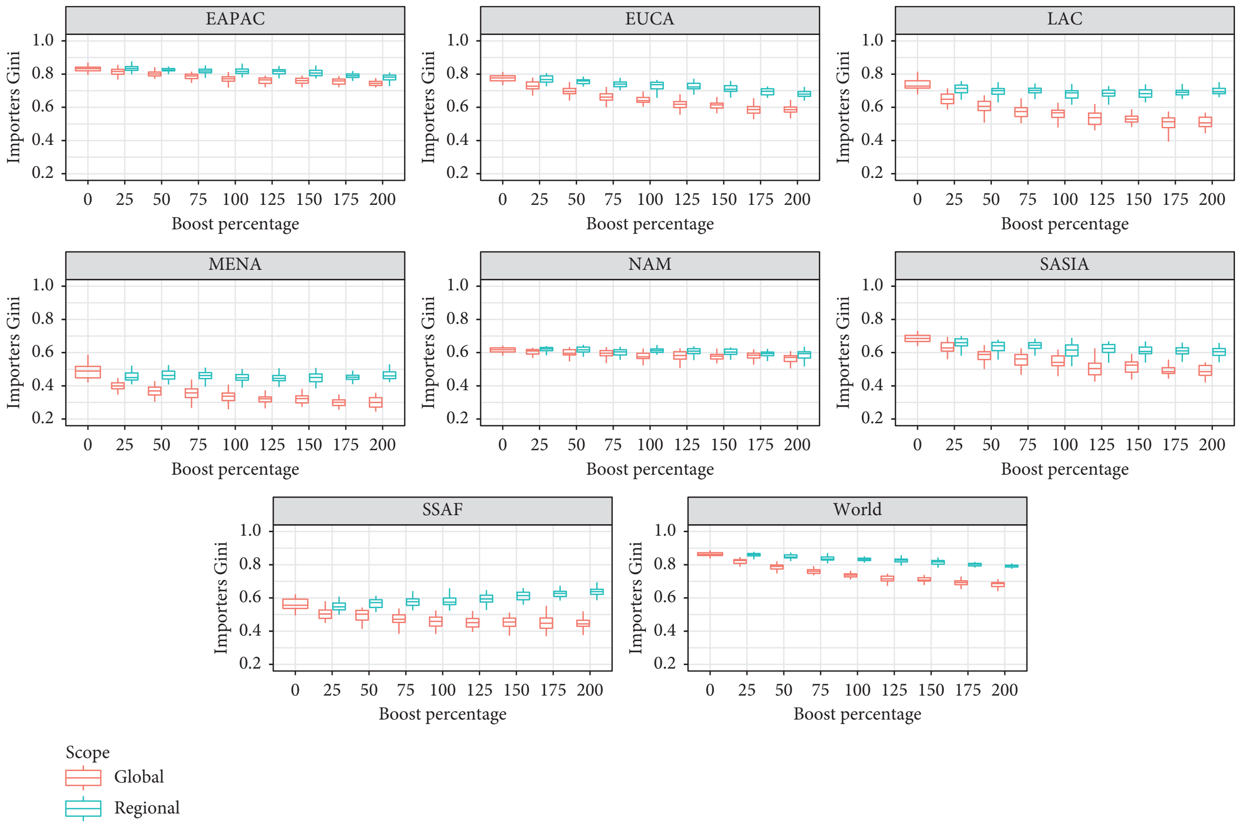

Figure 8: Effect of the improvement policies by region for year 2017. The policy is applied to the lower 2% of global trade. Each boxplot represents 30 experiments. Acronyms of the World Bank Lending Groups: EAPAC: East Asia and Pacific, EUCA: Europe and Central Asia, LAC: Latin America and the Caribbean, MENA: Middle East and North Africa, NAM: North America, SASIA: South Asia, SSAF: Sub-Saharan Africa.

Data Availability

Data are available from the following link: https://zenodo.org/badge/latestdoi/241584918.

Additional Points

Programming language is R. Gini indexes of exporter and importer normalized strength distributions were computed with the package ineq 0.2.13 [30] and densities estimations are plotted with the ggplot2 [31] (geom_density() with bandwidth adjustment = 2).

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

Effects of Regional Trade Agreement to Local and Global Trade Purity Relationships

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In contrast to the rapid integration of the world economy, many regional trade agreements (RTAs) have also emerged since the early 1990s. This contradiction has encouraged scholars and policymakers to explore the true effects of RTAs, including both regional and global trade relationships. This paper defines synthesized trade resistance and decomposes it into natural and artificial factors. Here, we separate the influence of geographical distance, economic volume, and overall increase in transportation and labor costs and use the expectation maximization algorithm to optimize the parameters and quantify the trade purity indicator, which describes the true global trade environment and relationships among countries. This indicates that although global and most regional trade relations gradually deteriorated during the period 2007–2017, RTAs generate trade relations among members, especially contributing to the relative prosperity of European Union (EU) and North American Free Trade Agreement (NAFTA) countries. In addition, we apply the network to reflect the purity of the trade relations among countries. The effects of RTAs can be analyzed by comparing typical trade unions and trade communities, which are presented using an empirical network structure. This analysis shows that the community structure is quite consistent with some trade unions, and the representative RTAs constitute the core structure of international trade network. However, the role of trade unions has weakened, and multilateral trade liberalization has accelerated in the past decade. This means that more countries have recently tended to expand their trading partners outside of these unions rather than limit their trading activities to RTAs.

1. Introduction

With the rapid development of international trade, as of 2020, the World Trade Organization (WTO) has 164 members representing 98 percent of world trade. However, in addition to this extensive multilateral trading system, the world has also witnessed unprecedented proliferation of regional trade agreements (RTAs) since the 1990s [1]. In 2013, 546 notifications of RTAs were received by the General Agreement on Tariffs and Trade (GATT)/WTO [2]. The role of RTAs raises questions among scholars and policymakers: what drives an increasing number of countries to join regional trade unions, and how will this affect regional trade patterns and globalization processes? Trade creation and trade diversion have been proposed to describe the effects of RTAs [3, 4]. Trade creation refers to new trade arising between member countries due to the deduction of tariffs, while trade diversion means that imports from a low-cost outsider country are replaced by imports from a higher cost member country because of RTAs [5]. Some scholars have advocated for RTAs by arguing that, unlike multilateral trade liberalization, they promote a "deeper" integration [6].

Despite the controversy in the literature, previous studies usually focus on the influence of RTAs on countries in given regions instead of quantitative analyses on a global scale. A common approach is to operationalize RTA membership as a categorical independent variable and analyze the influence of trade unions on bilateral trade using a gravity model

[7–10]. However, the roles of RTAs in regional and global trades differ, which can also be seen in the description of trade creation and trade diversion. It is not comprehensive to study them separately, and we need to break through the limitations of existing research. In fact, international trade is a complex system with global characteristics and regional structures, and we should analyze the effects of RTAs on both regional and global trade environments. It is necessary to use quantitative models and network methods to analyze global trade as a whole, and the influence of other countries should not be ignored when discussing the trade flow between any two countries.

RTAs are usually signed between neighboring countries, so their effects on regional trade are coupled with geographical distance and other factors. The innovation of this paper is to study and describe the trade purity relationship of countries, with some other typical factors, such as economic volume, geographical distance, and overall increase in transportation and labor costs, being separated. In contrast to the existing literature, which consistently increases observable variables to quantify trade costs [11–13], here, we define synthesized trade resistance [14], decompose it into natural and artificial factors, and propose a trade purity indicator (TPI) to describe the true trade environment and relationships between countries. The role of RTAs can be studied by comparing the TPI and its evolution within and outside a trade union. Here, we apply the expectation maximization (EM) algorithm to optimize the parameters and quantify the trade purity indicator.

Compared with the exogenous parameter estimation in the existing research on trade cost quantification [15–18], the method in this paper is more scientific and effective, and it could be extended to discuss the effects of RTAs on a number of countries around the world.

Furthermore, international trade is a system that involves numerous countries and trade relations, and complex network modeling has the advantage of analyzing a number of entities and complex relationships [19–21]. Additionally, network theory can also facilitate the examination of both local and global properties [22], which is consistent with the goal of our work. However, trade flows are the direct result of trade openness, and related studies usually apply trade flows to weight the network [9, 19]. Since trade flows could be influenced by a country's economic volume, geographical factors, and artificial barriers, we prefer trade resistance, which removes the impact of the economy, to reflect the purity of the trade relationship between countries. In addition, communities in the international trade network are represented by clusters of countries where trade relations between countries in the same community are closer than those in different communities [9]. Therefore, comparing the members of typical trade unions and trade communities in the global trade network could facilitate research on the effectiveness of RTAs.

The paper is organized as follows: Section 2 briefly describes the data source and the gravity model with synthesized trade resistance. Here, we establish a maximum likelihood function to simultaneously estimate the unobserved parameters and quantify the trade purity indicator. Section 3 presents the results. Here, we focus on six typical RTAs: Belt and Road (BRI), European Union (EU), North American Free Trade Agreement (NAFTA), Organization of African Union (OAU), Caribbean Free Trade Area (CARIFTA), and Association of Southeast Asian Nations (ASEAN). We discuss the evolution of TPI at both the regional and global trade levels and analyze the effects of RTAs during the period 2007–2017. In addition, we discuss the evolution of trade communities based on network methods. This shows that the representative RTAs constitute the core structure of international trade network, but the role of trade unions has weakened, and multilateral trade liberalization has accelerated in the past decade. Finally, Section 4 provides the conclusion and discussion.

2. Data and Methods

2.1. Data Source. In this paper, we use trade data from the UN Comtrade Database, which includes 198 countries/districts. Here, we choose the "Goods" type of product and use the annual total of all HS commodities (Harmonized Commodity Description and Coding Systems). In view of differences in time and statistical caliber, the flow data reported by the importer and exporter are not always the same. Here, we use the importer's report, with a supplement from the exporters when the data are missing.

For GDP (current US$), we use the World Bank national accounts data and OECD National Accounts data files. It is calculated without making deductions for depreciation of fabricated assets or for the depletion and degradation of natural resources. Data are in current US dollars. Dollar figures for GDP are converted from domestic currencies using single-year official exchange rates.

There are several methods for calculating geographical distance. As some countries have many import and export ports, we do not choose the coordinates of the capital but use the mean position of the longitude and latitude to calculate the distance. A full description of the data sources is provided in Table 1.

2.2. Quantifying Trade Resistance with the Gravity Model. The gravity model is one of the most successful empirical methods in the field of social science [14]. Specifically, Isard and Tinbergen were pioneers in applying the gravity model to describe the patterns of bilateral aggregate trade flows among countries [23, 24]. Their work spawned a vast empirical literature that appears to perform well at modeling trade flows and exploring the factors influencing them [14, 25, 26], as 80% – 90% of the variation in the flows could be captured by the fitted relationship [27].

Scholars have introduced possible explanatory variables and performed regressions with panel data to confirm whether trade growth or loss is more significant [3, 5, 28, 29]. However, it is impossible to include all the relevant factors, so the estimation of effects might be biased and inconsistent due to omitted variables, with the possibility of significant over-estimation or underestimation [9].

Table 1: Data description.

Indicator	Indicator description	Data source
Trade flows	Country-to-country trade flows, from UN Comtrade Database, for "goods," "HS" commodities, and annual data during the period 2007–2017	https://comtrade.un.org/
GDP	GDP (current US$) for countries, from the World Bank Database, with code NY.GDP.MKTP.CD., annual data during the period 2007–2017	https://data.worldbank.org/indicator/NY.GDP.MKTP.CD
Distance	Geographical distance between mean positions of countries; the coordinate data are from blue marble geographics	https://www.bluemarblegeo.com/index.php

In Tinbergen's gravity model, distance $d_{i,j}$ is not limited to geographical distance, and it could be broadly construed to include all factors that might create trade resistance [24, 26]. More recently, some papers have estimated synthesized trade costs or resistance from the observed pattern of production and trade across countries [30–32] and performed analyses based on quantified trade costs.

Based on defined trade resistance $r_{i,j}$, the improved model used in this paper is depicted by the following formula:

$$F_{i,j} = \frac{\left(m_i \cdot m_j\right)^{\alpha}}{r_{i,j}} - \varepsilon_{ij}, \tag{1}$$

where m_i and m_j are the gross domestic products of countries i and j; $r_{i,j}$ is a defined composite variable; α is the parameter to be estimated; and ε_{ij} is the error term. Here, if we consider $r_{i,j}$ to be symmetric, the mechanism described in equation (1) is similar to Anderson's structural gravity model [15, 33] but with a simpler expression. Here, $r_{i,j}$ is a representative of trade resistance, which we use as a composite of all the other factors that affect trade volumes other than countries' GDP. Equation (1) indicates that the trade amount $F_{i,j}$ is proportional to m_i and m_j but inversely proportional to the integrated effective distance between them, denoted as $r_{i,j}$.

In contrast to the traditional gravity model, here, a country's geographical distance $d_{i,j}$ is replaced with trade resistance $r_{i,j}$. The new model not only captures proximity or distance in terms of geographical distance but also fully demonstrates the true and comprehensive relationships between entities in the system, which is significant for understanding the global economy, politics, and culture [34].

In the literature, the trade cost measure can be derived from a broader range of models [33], which have different methods and results in the parameter estimation, such as the elasticity of substitution σ [15], the Frechet parameter ϑ [35], and the Pareto parameter γ [16–18]. With the estimated parameters and observed trade flow $F_{i,j}$, m_i, and m_j, the symmetrical trade resistance can be obtained from equation (1) using the least squares method.

The existing exogenous parameter estimation method will introduce unnecessary errors and doubts about validity. However, further analysis of trade resistance will inevitably involve the estimation of latent variables or parameters, and here, we use the EM algorithm from machine learning. In addition, there are many zero values in bilateral migration data, which is also a problem that has long puzzled researchers [36–39]. Here, we use the pseudo maximum likelihood (PML) method to preprocess the zero-value flow; for details, please see Appendix B.

2.3. Decomposing Trade Resistance through the Expectation Maximization Algorithm (EM).

For each pair of countries i and j, trade resistance $r_{i,j}$ is quantified by equation (1), and we assume that trade resistance can be separated into two components. The data $\mathbf{R} = \{\ln r_{1,2}, \ldots, \ln r_{i,j}, \ldots\}$ can be divided into two categories: I is mainly related to natural factors such as geographical distance $d_{i,j}$, and II is affected more by artificial barriers than natural factors:

$$\ln r_{i,j} = \begin{cases} a + b \ln d_{i,j} + \eta_{i,j}, & \left(r_{i,j}\right) \in \text{I}, \\ \xi_{i,j}, & \left(r_{i,j}\right) \in \text{II}. \end{cases} \tag{2}$$

Here, a and b are constants. $\eta_{i,j}$ and $\xi_{i,j}$ are normally distributed random variables with different means and standard deviations $\eta_{i,j} \sim N(0, \sigma_1)$ and $\xi_{i,j} \sim N(\mu, \sigma_2)$. How should one estimate parameters $\Theta = \{\mu, \sigma_1, \sigma_2, a, b\}$ based on observed data $\mathbf{R}$ and place each $\ln r_{i,j}$ into the appropriate category?

To solve the parameter problem of two mixed distributions, we apply a commonly used method, namely, the EM algorithm. In statistics, the EM algorithm is an iterative method to find the maximum likelihood or maximum a posteriori (MAP) estimates of the parameters in statistical models, where the algorithm depends on unobserved latent variables [40–43].

The EM algorithm seeks to obtain the MLE (maximum likelihood estimate) of the marginal likelihood by iteratively applying the expectation step (E step) and maximization likelihood step (M step), with $t = 1, 2, \ldots$ representing the number of iterations. The detailed process is as follows:

(1) Expectation step (E step): in step t, based on the last estimation of the parameters $\widehat{\Theta}^{(t-1)}$, calculate the expected value of the probability of belonging to a certain category.

Separately calculate the probabilities of observation $\ln r_{i,j}$ belonging to category I and category II:

$$p_1\left(r_{i,j} \mid \widehat{\Theta}^{(t-1)}\right) = \frac{1}{\sqrt{2\pi}\sigma_1} \exp \frac{-\left[\ln r_{i,j} - \left(a + b \ln d_{i,j}\right)\right]^2}{2\sigma_1^2},$$

$$p_2\left(r_{i,j} \mid \widehat{\Theta}^{(t-1)}\right) = \frac{1}{\sqrt{2\pi}\sigma_2} \exp \frac{-\left[\ln r_{i,j} - \mu\right]^2}{2\sigma_2^2}. \tag{3}$$

Then, normalize them as follows:

$$\hat{\tau}_{i,j}^{(t)} = \frac{p_1\left(r_{i,j} \mid \hat{\Theta}^{(t-1)}\right)}{p_1\left(r_{i,j} \mid \hat{\Theta}^{(t-1)}\right) + p_2\left(r_{i,j} \mid \hat{\Theta}^{(t-1)}\right)}. \quad (4)$$

The unobserved latent variables $\hat{\Theta}_{\tau}^{(t)} = \left\{\hat{\tau}_{1,2}^{(t)}, \hat{\tau}_{1,3}^{(t)}, \ldots, \hat{\tau}_{i,j}^{(t)}, \ldots\right\}$, where $\hat{\tau}_{i,j}^{(t)}$ $(0 \le \hat{\tau}_{i,j}^{(t)} \le 1)$ represents the probability of trade resistance ln $r_{i,j}$ belonging to category I.

(2) Maximization likelihood step (M step): based on the $\hat{\Theta}_{\tau}^{(t)}$ obtained from the E step, we find the parameter estimate $\Theta^{(t)}$ that maximizes this likelihood. The likelihood function L of $\mathbf{R}$ occurring is multiplied by the expected probability of all trade resistances as follows:

$$L(R; \Theta, \Theta_{\tau}) = \prod_{i \ne j} \left\{ \underbrace{\tau_{i,j} \cdot p_1\left(r_{i,j} \mid \Theta\right)}_{\text{Category1}} + \underbrace{\left(1 - \tau_{i,j}\right) \cdot p_2\left(r_{i,j} \mid \Theta\right)}_{\text{Category2}} \right\}. \quad (5)$$

The optimum value of $\Theta^{(t)}$ based on $\mathbf{R}$ and $\hat{\Theta}_{\tau}^{(t)}$ can be calculated from that function:

$$\begin{aligned} \hat{\Theta}^{(t)} &= \max_{\Theta} \log \quad L\left(\mathbf{R}; \Theta \mid \hat{\Theta}_{\tau}^{(t)}\right) \\ &= \max_{\Theta} \sum_{i \ne j} \log\left\{\hat{\tau}_{i,j}^{(t)} \cdot p_1\left(r_{i,j} \mid \Theta\right) + \left(1 - \hat{\tau}_{i,j}^{(t)}\right) \cdot p_2\left(r_{i,j} \mid \Theta\right)\right\}. \end{aligned} \quad (6)$$

2.4. Exploring Community Evolution Based on the Extracted Backbone Trade Network. Here, we regard countries as the nodes, and the relationship between two nodes can be described by an edge. The reciprocal of trade resistance is the weight of the edge. Since trade resistance is symmetric for country pair (i, j), the network is also symmetric. For node i, the node cluster coefficient C_i is calculated by the following equation [44]:

$$C_i = \frac{2e_i}{k_i\left(k_i - 1\right)}, \quad (7)$$

where e_i is the number of edges connected to adjacent nodes and k_i denotes the number of nodes that are adjacent to node i. The cluster coefficient of the network is the mean of the cluster coefficients of all nodes.

To make the community classification more efficient, we apply the disparity filter method to obtain a backbone network [45]:

$$\alpha_{ij} = 1 - (k-1) \int_0^{p_{ij}} (1-x)^{k-2} \mathrm{d}x < \alpha_s, \quad (8)$$

where α_{ij} is the probability of an edge between node i and j, k indicates the degree of a given node, p_{ij} is the normalized weight of the edge, and α_s is a significance level for the null hypothesis.

After extracting the backbone network, to classify the network into several communities, we apply the Louvain community detection algorithm [46] and evaluate the result using the Q index [47]:

$$Q = \frac{1}{2m} \sum_{i,j} \left[w_{i,j} - \frac{A_i A_j}{2m} \right] \delta\left(c_i, c_j\right), \quad (9)$$

where w_{ij} is the weight of the edge between nodes i and j, $A_i = \sum_j w_{i,j}$ is the sum of the weights of the edges attached to node i, c_i is the community to which node i belongs, and $\delta(c_i, c_j)$ is 1 if $c_i = c_j$ and 0 otherwise. $m = (1/2)\sum_{i,j} w_{i,j}$ is the sum of the edge weights. Based on the quantified trade resistances during the period 2007–2017, we can construct the backbone network of global trade for each year and attempt to explore the community classification of the network.

3. Results and Discussion

3.1. Alienation of Global Trade Relationships

3.1.1. Trade Purity Indicator for Countries. Based on the extended gravity model, we can quantify the international trade resistance $r_{i,j}$ for 198 entities (Figure 1). We suppose that most trade resistance can be divided into two categories. The first has low expected barriers, which are mainly related to natural factors such as geographical distance, and the other includes countries with relatively high artificial trade barriers, such as trade restrictions, border blockades, cultural differences, and political policies. It shows that most of the trade relations among the United States (red dots), China (green dots), and other countries belong to the first category; that is, most of the trade resistances are positively related to geographical distance, so they are concentrated near the blue dotted line (Figures 1(a), 1(c), and 1(e)). For the United States and China, only a small number of bilateral trade relations are affected by more artificial barriers.

Using the EM algorithm and the defined latent parameter $\Theta = [a, b, \mu, \sigma_1, \sigma_2]$, we can fit the distribution of trade resistance $r_{i,j}$ well and obtain the characteristics of the two categories [42]. The fits of the distribution for 2007, 2012, and 2017 all pass the Kolmogorov–Smirnov test, and the parameters efficiently convert to the optimal values (Figures 1(b), 1(d), and 1(f)), which confirms our hypothesis of two categories of trade relations.

Here, the trade resistance of each pair has a probability of belonging to the limited trade resistance group (natural barriers or category I). For each country i, we define the trade purity indicator TPI_i by summing the probability that its trade relation $r_{i,j}$ belongs to category I as $\text{TPI}_i = (1/N)\sum_j P(z_{ij} = 1 \mid \hat{\Theta})$, where N is the number of countries, z_{ij} equals 1 when the trade relations between i and j belong to category I, and 0 otherwise. The TPI indicator provides a quantitative measure of the openness of a country's trade environment.

3.1.2. Alienation of Trade Relationships between Countries. Figure 2(a) shows the evolution of trade resistance. Different colors represent the distribution of trade resistance for

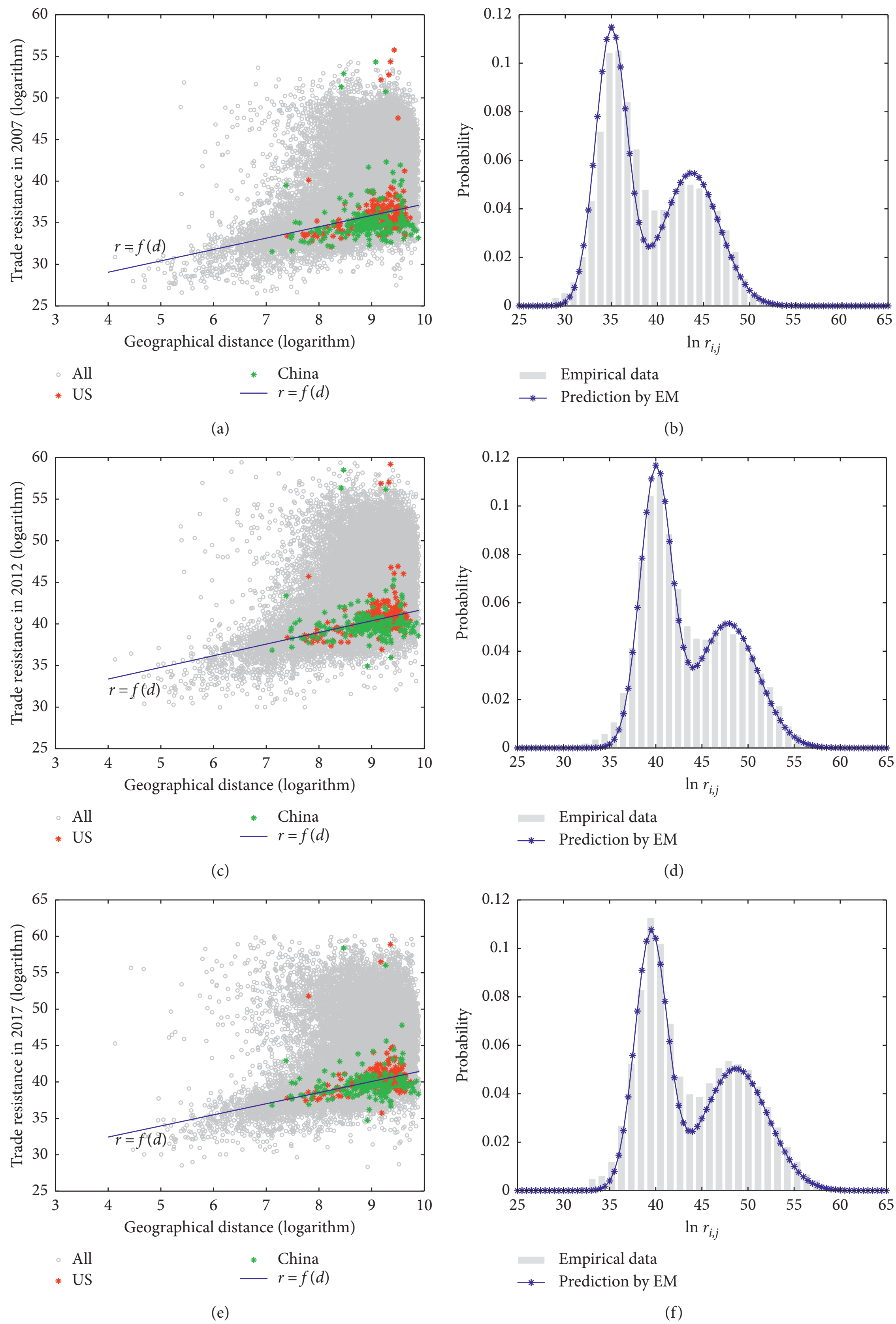


FIGURE 1: Fitting the distribution characteristics of trade resistance, based on the hypothesis of two categories. In (a), (c), and (e), gray dots show the trade resistance between countries around the world. In (b), (d), and (f), gray bars express the trade resistance quantified from the extended gravity model; the blue dotted line is the fitted results with the EM algorithm.

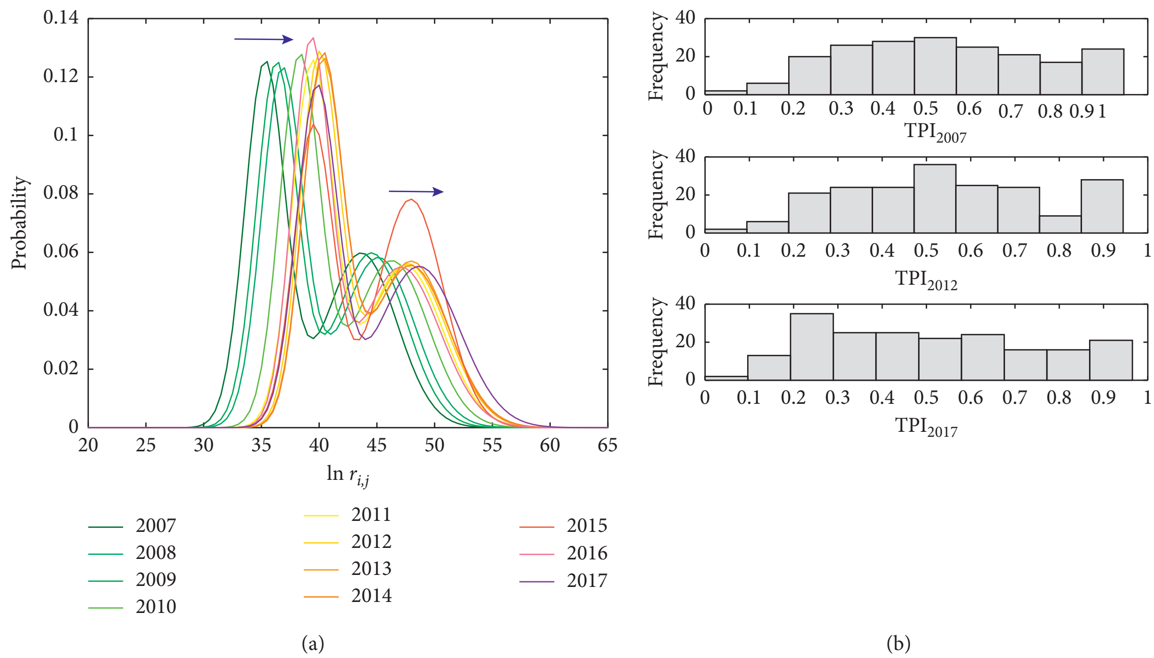


FIGURE 2: Evolution of trade resistance during the period 2007–2017: (a) distribution of trade resistance ln r_{ij}; (b) distribution of the trade purity indicator (TPI) in 2007, 2012, and 2017.

corresponding years. With optimized parameters, in the decade considered, the distribution of trade resistance (the expectations of categories I and II) shifts to the right overall, which indicates an average increase in global trade resistance during the period 2007–2017.

Considering that global trade resistance could be affected by the growth of transportation costs or other factors, we also analyze the trend of the trade purity indicator from a more rigorous perspective. The distribution of the trade purity indicator (Figure 2(b)) also indicates the alienation of the global trade network. Obviously, the mean TPI decreased from 2007 to 2017.

The alienation of global trade is thought-provoking. In recent years, some scholars have highlighted this trend in international trade [48, 49]. To protect trade interests, some countries seek to maintain the friendly regional trade relations by signing trade agreements and creating trade unions. Since the 1990s, RTAs have proliferated, including regional unions with members that are geographically near one another (e.g., EU and NAFTA) and countries or regional blocs with diverse and geographically distant partners (e.g., ASEAN and BRI) [50, 51]. The effect of RTAs has always interested politicians and scholars. Can RTAs adapt to such an international trade environment? Why might a government be willing to compromise its sovereignty and sign an agreement? The answer is interdependence. Based on the quantified TPI, we attempt to analyze the effects of regional trade unions in the following sections.

3.2. Effects of Regional Trade Agreements (RTAs). The policies imposed by any government could affect the wellbeing not only of its own citizens but also those in other countries. Trade creation and trade diversion are common effects of RTAs identified in the recent literature [52, 53], and in empirical work, their mixed effects are more complex; the results are difficult to quantify [54, 55]. This paper attempts to describe the effects of RTAs on both global and local trade relationships through a quantitative model and empirical analysis.

3.2.1. Relatively Closer Trade Relationships between Union Members. By 2013, 546 RTAs were proposed. Here, we selected 6 representative RTAs for feasibility, including 28 EU countries, 52 OAU countries, 13 CARIFTA countries, 10 ASEAN countries, 3 NAFTA countries, and 66 BRI countries. These 155 member countries (after deleting duplicate members) have covered nearly 66.5% of the countries and around 69.4% of the trade flows, involving 5 continents and occupying a large area of the world (Figure 3). In addition, EU, NAFTA, ASEAN, and BRI are always mentioned in related research [5, 19], so they are relatively representative RTAs.

First, we compare the trade resistance within and outside the six unions. In Table 2, the average trade resistance between member countries is lower than that outside the unions. This demonstrates that the member countries of a union generally have closer trade relations with one another.

In addition, in Figure 4, with the x-coordinate expressing the TPI within the union and the y-coordinate expressing the TPI beyond the union, different colors represent different trade unions, and the color of spots becomes deeper as time passed by. The arrow around the spots describes the overall trend during 2007–2017. Obviously, most spots are located below the diagonal, which means that the

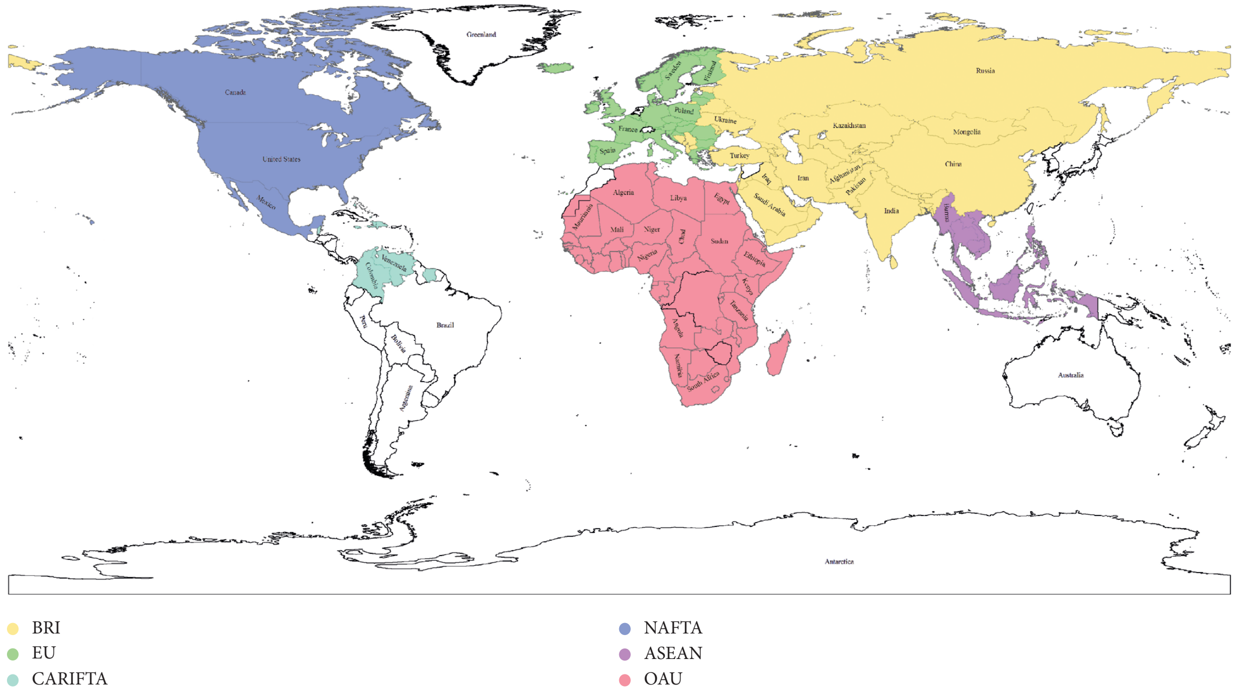


Figure 3: The map of six trade unions (RTAs). They have 155 members, covering nearly 66.5% of the countries and around 69.4% of the trade flows, involving 5 continents and occupying a large area of the world.

relationships between union members are closer than those with other countries outside the union.

Therefore, it indicates that all trade unions help to lower average trade resistances and create closer trade relations among the members compared with other countries.

3.2.2. Decreasing Trend in Trade Relationships for Union Members. These six unions can be divided into two types. Specifically, the EU and NAFTA form type one, and most countries in these unions are developed countries. For these two RTAs, the spots move vertically over time, so as the arrows (Figure 4). The TPI inside the unions barely changes, but the TPI outside the unions fluctuates and tends to increase. BRI, OAU, CARIFTA, and OAU belong to type two, and the spots of these unions move towards the bottom left, so as the arrows in Figure 4. In brief, by comparing the TPIs in 2007 and 2017, except for the EU and NAFTA, the TPIs within unions all declined. This means the trade environments of the EU and NAFTA are more friendly than those in the other four unions.

In Figure 7 (in Appendix A), we can more clearly see these two types of unions. The red labels indicate a trade deficit, while blue labels indicate a trade surplus, and the size of spots represents the net outflow (exports minus imports). The EU and NAFTA (Figures 7(a) and 7(e)) with fewer members have a higher economic development and TPIs. Therefore, the dots are highly concentrated. Other unions (BRI, OAU, CARIFTA, and ASEAN) (Figures 7(b)–7(d), and 7(f)) are more uneven, as the dots distributed from low TPI to high TPI, and some member countries have a trade surplus, while the others have a trade deficit. In addition, it indicates that the countries with large trade flows always have a higher TPI both inside and outside their unions.

3.3. Comparison of Trade Unions and Trade Communities. Trade unions are formed through agreements signed by countries. With the development of globalization, it is worth further exploring whether they can reflect real trade affinity. As mentioned in Section 2.4, we extract the backbone of the global trade network based on quantified trade resistance and classify it into several communities. Trade communities are obtained from the analysis of the network structure, which can objectively describe the trade relationships between countries.

3.3.1. Communities in the Global Trade Network. We did community classification for trade backbone network, and Table 3 shows the modularity of community classification during 2007–2017. All of them are bigger than 0.7, which means the network structure has clustering characteristics. Here, we take 2007 and 2017 as examples and show community partition in Figure 5. The nodes that share the same color are assigned to the same community. Obviously, there were some structural changes between 2007 and 2017.

First, in 2007, the communities showed significant regionality. The map (Figure 5(a)) shows that countries on the same continent are more likely to be clustered in the same community, confirming that geographical characteristics play an important role in forming trade patterns. For most members, the six trade unions are signed among regional countries, and based on their relatively close trade relations, it is not difficult to understand that most members

Table 2: Average trade resistance within and outside trade unions.

Year	BRI		EU		OAU		CARIFTA		ASEAN		NAFAT		World
	Member	Others	Member	Others	Member	Others	Member	Others	Member	Others	Member	Others	
2007	36.66	39.57	33.40	37.14	38.51	40.31	33.38	40.63	32.85	38.51	33.50	36.68	39.18
2008	38.16	41.10	34.92	38.59	40.01	41.80	34.59	41.97	34.57	39.87	35.09	38.17	40.66
2009	37.65	40.47	34.27	38.08	39.55	41.16	34.33	41.42	33.83	39.27	34.34	37.45	40.06
2010	39.45	42.33	36.30	40.04	41.24	42.98	36.42	43.43	35.95	41.10	36.71	39.71	41.97
2011	40.68	43.47	37.37	41.13	42.43	44.11	37.18	44.45	37.01	42.31	37.92	40.84	43.07
2012	41.22	43.93	37.86	41.61	42.83	44.62	37.63	44.90	37.61	42.63	38.54	41.31	43.54
2013	41.26	44.00	37.85	41.68	43.02	44.74	37.79	45.07	37.74	42.54	38.52	41.39	43.66
2014	41.27	43.94	37.81	41.44	43.38	44.73	37.95	45.11	37.41	42.71	38.48	41.39	43.65
2015	41.51	44.21	36.91	42.03	44.69	45.37	39.87	45.34	36.85	42.93	37.58	42.32	44.13
2016	40.18	42.96	36.79	40.45	42.99	43.95	38.16	44.46	36.49	41.65	37.41	40.33	42.79
2017	41.59	44.23	37.27	41.41	43.90	45.14	38.75	45.47	39.47	43.44	37.89	40.80	43.98

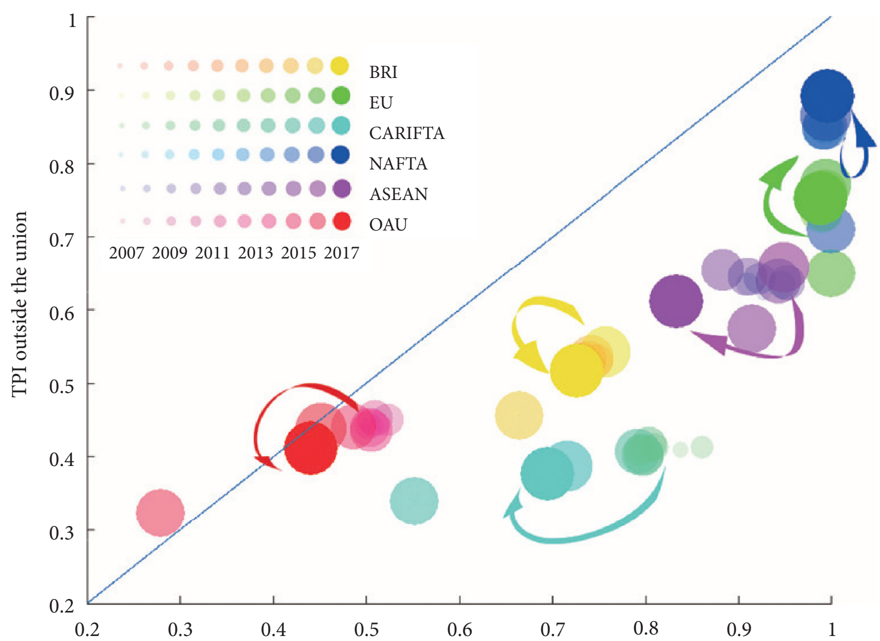


Figure 4: Trade purity indicator within and outside unions during the period 2007–2017. The *x*-coordinate expresses the TPI inside the union, and the *y*-coordinate expresses the TPI outside the union. The lightest color refers to year 2007, while the darkest color refers to year 2017.

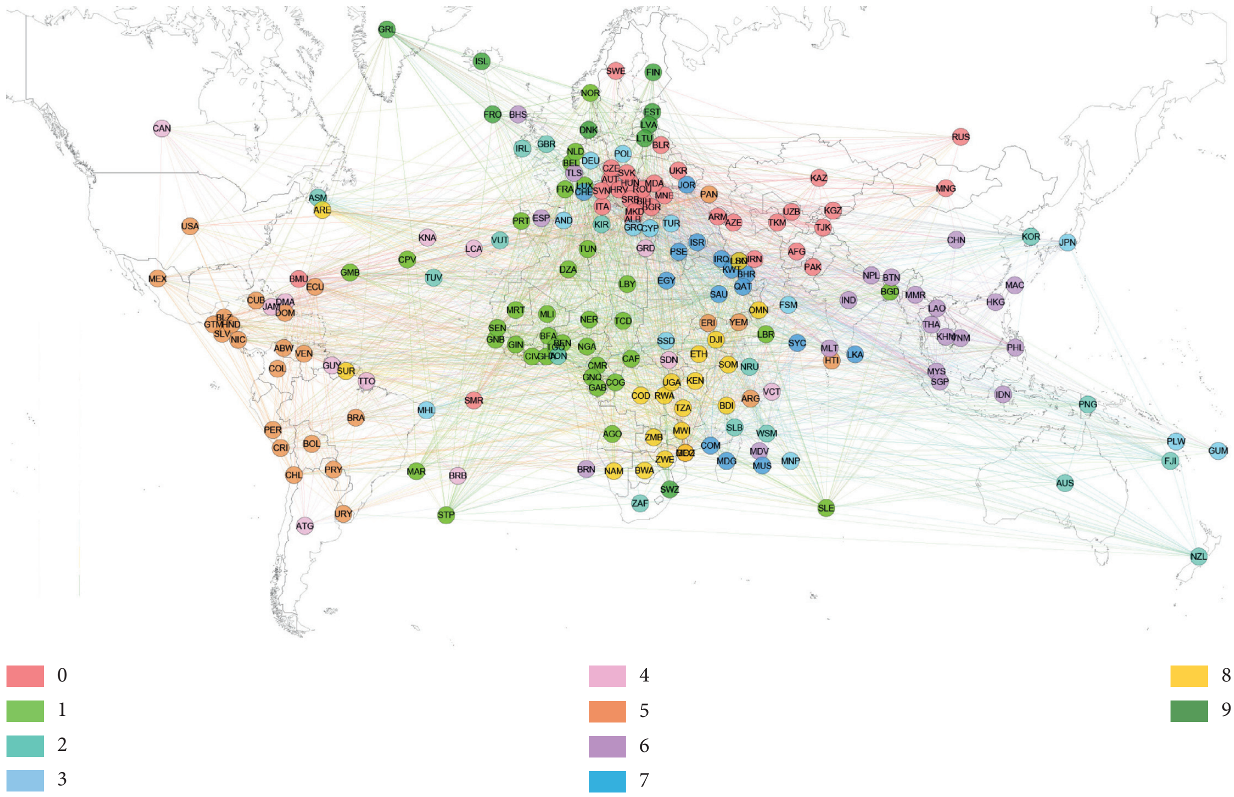
Table 3: The modularity of community classification based on Louvain algorithm.

	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
$Q(\alpha_s = 0.01)$	0.780	0.771	0.766	0.750	0.745	0.736	0.720	0.715	0.744	0.727	0.769

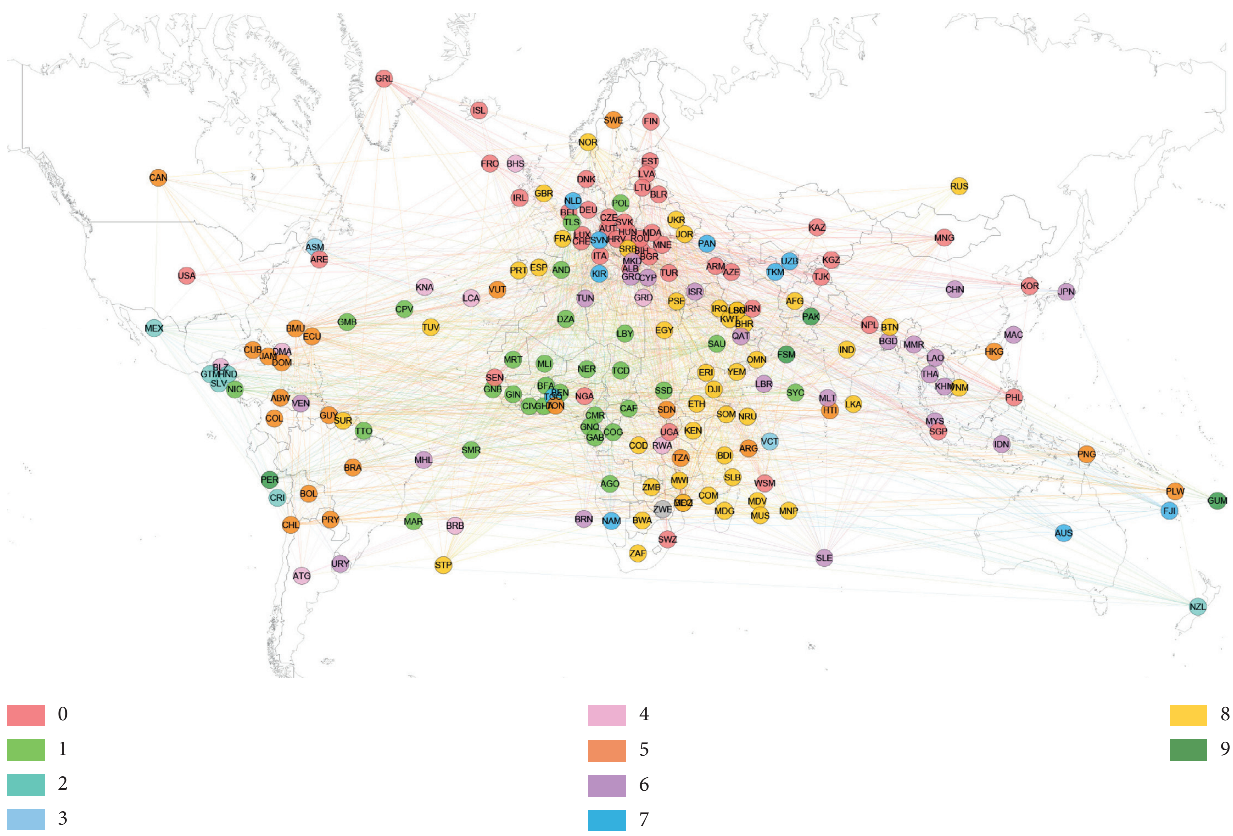
of RTAs are clustered in the same community. In 2017, the distribution of community members was more divergent. With the development of globalization, trade between countries is no longer restricted by geographical or transportation factors.

Second, from the empirical results, over these ten years, the network density decreased, which means that countries in the global trade network are connected more loosely (the cluster coefficient changed from 0.1370 to 0.1006).

There is another interesting phenomenon. Some countries are on the same continent and belong to the same RTA but are more closely related to countries in other unions than the members of their RTAs. Most African countries have multiple RTA memberships [56], and the continent's east and west coasts belong to different marine routes in the global marine transport network [57]. Therefore, it is easy to understand why Eastern Africa and Western Africa are clustered into different communities. France, Spain, Portugal, and Belgium are EU countries, but they are classified into the community where most members are African countries. This shows that they have closer trade relations with African countries than with other EU members, which



(a)



(b)

FIGURE 5: Communities in the global trade network in 2007 (a) and 2017 (b).

may be due to language, culture, colonial influence, and their trade structures.

Here, we apply the external-internal index (E-I index) and compare regional trade cohesion and global trade cohesion as follows:

$$\begin{aligned} \mathrm{E-Iindex}_{(\text{degree})} &= -\frac{\mathrm{EK}-\mathrm{IK}}{\mathrm{EK}+\mathrm{IK}}, \\ \mathrm{E-Iindex}_{(\text{weight})} &= -\frac{\mathrm{EW}-\mathrm{IW}}{\mathrm{EW}+\mathrm{IW}}. \end{aligned} \tag{10}$$

External edges connect nodes from different communities, while internal edges connect two nodes belonging to the same community. EK and IK are the sum of external and internal degrees for all nodes; EW and IW are the sum of external and internal weights for all nodes. Based on the results of the backbone network in 2007 and 2017, the E-I index (degree) dropped from 0.2711 to 0.1000, and the E-I index (weight) increased from −0.1019 to 0.0281. The relationships in the global trade network are more diversified, but trade intensity is concentrated in local communities.

3.3.2. Correlation and Evolution of Unions and Communities. We have identified the trade unions resulting from negotiations between countries, and the trade communities clustered from the empirical data. What is the correlation between them? Do the members of trade unions truly have closer trade relations? Which trade unions have no obvious effect on restraining and helping member countries? To answer these questions, we measure the correlation coefficient between the members of trade unions and trade communities. Figure 6 shows the matrix of the Jaccard similarity coefficient of six trade unions and ten typical communities. "Others" indicates countries that do not belong to the six unions. Green color means a greater correlation and a higher commonality of members between trade unions and communities. In contrast, yellow color means that the members of the union and community are basically different.

In general, the similarity matrices of 2007 and 2017 have similar structures. Each trade union has only one or two grids with a great deal of green, which indicates that some trade unions and communities have high consistency in membership. Several very green grids are shown in Figure 6(a), which presents the overlap of ASEAN and community 6, BRI and community 0, CARIFTA and community 4, OAU and community 1, etc. The EU and NAFTA are relatively "free" trade unions, and their members are not limited to one or two communities, which overlap with several separate communities. In addition, in 2007, the "Other" countries that do not belong to six trade unions are also relatively concentrated in three communities, with a certain aggregation, and it is quite different from the results from 2017.

The similarity was higher in 2007; that is, the trade unions were more similar to the actual trading clustering result. In 2017, the role of the trade unions weakened. For most trade unions, the maximum matching of members to communities is decreasing. Here, the EU and NAFTA remain exceptions, having relatively higher similarity with communities 1 and 8. This might be due to their mature trading background. In addition, the TPIs of the EU and NAFTA remained stable, while the TPIs of other trade unions decreased (Figure 4). TPI indicates a trade-friendly relationship with other countries, while communities also reflect the different trade relations between countries inside and outside the community. Therefore, it is reasonable and scientific to conclude that EU and NAFTA have particularities in both results. Compared with 2007, the community structure of "Other" countries has become more decentralized.

In short, RTAs appear to have an impact on strengthening the formation of true trade relations [9]. Based on the similarity matrix, each trade union is mainly concentrated in one or two communities. However, in 2017, this kind of consistency clearly weakened, and multilateral trade liberalization has accelerated over the past decade.

4. Conclusion and Discussion

The innovation of this paper is to study and describe the trade purity relationships between countries, considering some other typical factors, such as economic volume, geographical distance, overall increased transportation and labor costs, are separated. In addition, this paper does not use the exogenous parameter estimation method, and we define latent parameters and use the likelihood function and EM algorithm to quantify and analyze the trade purity indicator more scientifically and effectively. In brief, the extended model prompts the development of the gravity model in theoretical research on international trade.

In the empirical analysis, some unobserved characteristics of the trade relationships can simultaneously be defined and optimized, and the analysis uses a trade purity indicator to describe the trade environments and positions of countries in both regional and global trade relationships.

With the data from the UN Comtrade Database, we quantify the international trade resistance of 198 countries/districts. This analysis shows that the trade relationships of the 198 entities can be divided into two categories. The trade resistance of countries in category I has an approximate log-linear relation with geographical distance, and these countries have a relatively open and friendly trade environment, where the main trade barriers are natural factors. The countries in category II have higher artificial trade barriers, and countries with poor trading environments frequently fall into category II. Here, we obtain well fitted results using the EM algorithm from machine learning. All latent variables converge rapidly to optimal points, which validates the extended gravity model proposed in this paper.

In addition, this paper defines and identifies a trade purity indicator for different RTA countries during the period 2007–2017. It can describe the true trade environment and relationships. Countries with higher indicators have friendly trade environments and obtain large trade flows, such as the United States, China, Japan, Korea, South Africa, Singapore, Australia, and Malaysia. For these

	ASEAN	BRI	CARIFTA	EU	NAFTA	OAU	Others	Num
0	0.0000	0.3750	0.0200	0.1961	0.0000	0.0000	0.0132	33
1	0.0000	0.0128	0.0000	0.0862	0.0000	0.4576	0.0260	35
2	0.0000	0.0000	0.0000	0.0476	0.0000	0.0308	0.2500	16
3	0.0000	0.0179	0.0000	0.1081	0.0000	0.0000	0.1633	13
4	0.0000	0.0000	0.4286	0.0000	0.0714	0.0161	0.0182	12
5	0.0000	0.0147	0.1622	0.0000	0.0769	0.0133	0.2778	25
6	0.4762	0.1207	0.0263	0.0426	0.0000	0.0000	0.0156	21
7	0.0000	0.2000	0.0000	0.0000	0.0000	0.0806	0.0169	16
8	0.0000	0.0328	0.0278	0.0000	0.0000	0.2500	0.0161	19
9	0.0000	0.0192	0.0000	0.1563	0.0000	0.0169	0.0392	9
Num	10	44	18	28	3	52	44	199

(a)

	ASEAN	BRI	CARIFTA	EU	NAFTA	OAU	Others	Num
0	0.018519	0.2192	0.0161	0.0735	0.0000	0.2152	0.0595	45
1	0.0588	0.0435	0.0208	0.2982	0.0208	0.0430	0.0588	46
2	0.0000	0.0137	0.0213	0.0175	0.0000	0.3500	0.0882	30
3	0.0000	0.0000	0.0526	0.0000	0.0000	0.0000	0.0222	2
4	0.0000	0.0000	0.3500	0.0000	0.0000	0.0169	0.0192	9
5	0.0000	0.0152	0.2059	0.0200	0.0400	0.0423	0.1754	23
6	0.0000	0.0385	0.0000	0.0270	0.0000	0.0339	0.1020	10
7	0.2692	0.0984	0.0250	0.0625	0.0000	0.0423	0.0469	23
8	0.0000	0.0000	0.0000	0.0000	0.1250	0.0000	0.1111	6
9	0.0000	0.0213	0.0000	0.0000	0.0000	0.0000	0.0667	4
Num	10	44	18	28	3	51	44	198

(b)

Figure 6: The similarity matrix between trade unions and trade communities in 2007 (a) and 2017 (b). "Num" means the number of members in the corresponding trade union or community.

countries, most trade partnerships are mainly related to natural factors such as geographical distance, and they have no obvious trade barriers. The analysis of the indicator and its evolution could help to research the characteristics and trends of international trade. This indicates that although the global and most regional trade relations gradually deteriorated over the period 2007–2017, the RTAs bring closer trade relations between members, especially contributing to the relative prosperity of the EU and NAFTA.

Finally, based on the trade resistance matrix, we build a network mapping the relationship of 198 countries/districts. The Louvain community detection method identifies several communities in the global trade network. Here, we analyze the effects of RTAs by comparing the members of trade unions and communities. The results show that the representative RTAs constitute the core structure of international trade network, but the role of trade unions has weakened, and multilateral trade liberalization has accelerated in the past decade. This means that more countries have recently tended to expand their trading partners outside their unions rather than limit their trading activities to their RTAs.

In general, during the past decade, the structure and some characteristics of world trade are constantly changing, but its pattern has remained basically stable. On the whole, the openness trade environment of the whole world is declining, no matter among the members or among the countries from different unions, and it shows the degradation of multilateral free trade, which has aroused the discussion of the scholars and policymakers. It is significantly meaningful to study what strategies the countries should adopt, which is inseparable from the economic level, trade basis, affiliated RTAs, and the development of these countries, and the detailed conclusions need to be drawn through more rigorous analysis. In light of the above results, here we could give more general policy recommendations: the recent global trade alienation is a challenge for most countries. RTAs can promote regional trade, but in such an era with declining global trade environment, the countries should not pay too much attention to the profits brought by regional trade protection; conversely, facing the accelerating trend of multilateral trade liberalization in the past decade, the countries need to actively expand trade outside their unions rather than limit their trading activities to their RTAs. Especially, for the related members of BRI, ASEAN, CARIFTA, and OAU, they could continue to explore the trade cooperation with "new" trade partners, through implementing regulatory reforms and reducing trade restrictive measures. This study is a basic research, and more recommendations on policy aspects needs to be combined with the policy details for further discussion.

Appendix

Trade Resistance in Six Different Trade Unions

Figure 7 (Appendix) presents some detailed information. The x-coordinate expresses the TPI between a specific country and other countries in the same union, while the y-coordinate expresses the TPI between a specific country and other countries outside the union. The size of dots is proportional to the net outflow, measured as the absolute value of the difference between exports and imports; a red label

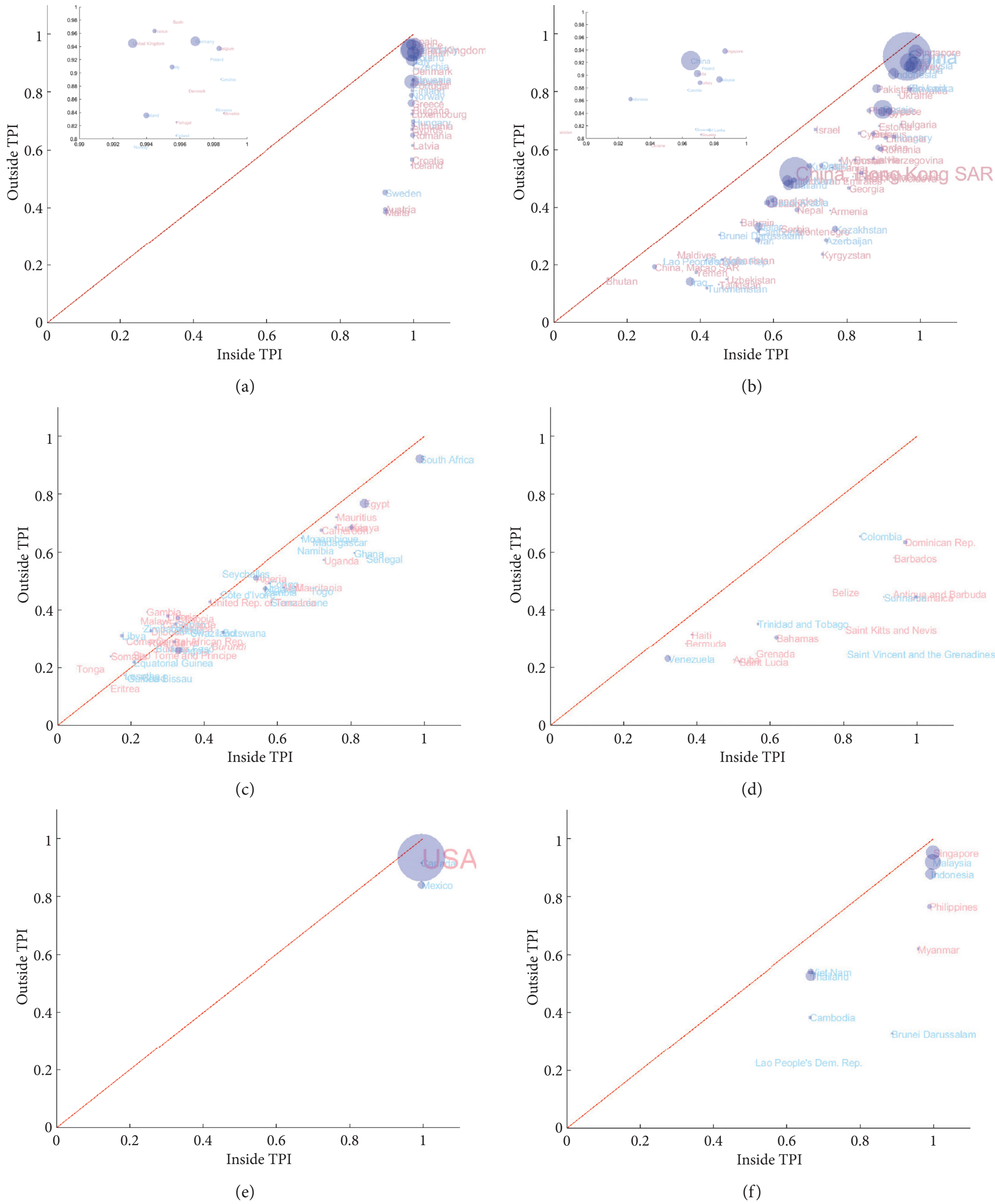


FIGURE 7: Trade resistance in six different trade unions for the year 2017: (a) European Union (EU) countries; (b) Belt and Road (BRI) countries; (c) Organization of African Union (OAU) countries; (d) Caribbean Free Trade Area (CARIFTA) countries; (e) North American Free Trade Agreement (NAFTA) countries; (f) Association of Southeast Asian Nations (ASEAN) countries.

means that the country had a trade deficit, while a blue label means a trade surplus flow. Most dots are below the red diagonal line "$y = x$," which means that the TPIs of most countries inside the union are higher than those outside the union. In addition, countries with large trade flow have a higher TPI both inside and outside the union.

B. Pretreatment of Flow Zero Value

For the gravity model (equation (1)), $F_{i,j}$ is the trade flow from country i to country j, m_i and m_j are the combined size of their economies, and $r_{i,j}$ is the trade resistance that needs to be quantified. It is generally believed that the model cannot describe zero flow because the gravity is universal [36], even if the size of two countries is very small and the geographical distance or trade resistance is very large, as long as the volume $m_i \cdot m_j$ is not equal to zero and the resistance $r_{i,j}$ is not infinite, and the trade flow between them may be very small, but not zero.

However, the situation of zero-value flow is very common in the empirical data, around 50% in the global trade network [18], and it creates an additional problem for the log-linear form of the gravity equation (including the traditional and structural gravity model in trade studies). In the early studies, some scholars often deal with the zeroes trade observation by the truncation method, such as deleting them completely or substituting by small positive constant [58, 59]. It is obviously not rigorous enough [36]. In reality, the zero-value trade flow is generally considered to be not observable due to measurement errors from rounding. So stochastic versions of equation are used in empirical studies [18, 38]. Here, we can add an error term ε_{ij}, and assume that the error function is positive and obeys lognormal distribution [38], as $\ln \varepsilon_{ij} \sim N(\mu, \sigma^2)$ in the following equation:

$$F_{i,j} = \frac{\left(m_i \cdot m_j\right)^{\alpha}}{r_{i,j}} - \varepsilon_{ij} = \exp\left(\alpha \ln\left(m_i \cdot m_j\right) - \ln r_{i,j}\right) - \varepsilon_{ij}, \tag{B.1}$$

where

$$E\left(\varepsilon_{ij}\right) = e^{\mu^2+\sigma^2/2}, \quad \operatorname{Var}\left(\varepsilon_{ij}\right) = \left(e^{\sigma^2} - 1\right)e^{2\mu^2+\sigma^2}. \tag{B.2}$$

For clarity, we assume $X = \varepsilon_{ij}$ and $Y = F_{i,j} = \left(\left(m_i m_j\right)^{\alpha}/r_{i,j}\right) - X$. The probability density function of the random variable X is

$$f_X(x) = \begin{cases} \dfrac{1}{\sqrt{2\pi}\,\sigma x} \exp\left[-\dfrac{1}{2\sigma^2}(\ln x - \mu)^2\right], & x > 0, \\ 0, & x \le 0. \end{cases} \tag{B.3}$$

The probability density function of Y is calculated as follows:

$$\begin{aligned} F_Y(y) &= P(Y \le y) = P\left(\frac{\left(m_i m_j\right)^{\alpha}}{r_{i,j}} - X \le y\right) \\ &= P\left(X \ge \frac{\left(m_i m_j\right)^{\alpha}}{r_{i,j}} - y\right) \\ &= 1 - P\left(X \le \frac{\left(m_i m_j\right)^{\alpha}}{r_{i,j}} - y\right) \\ &= 1 - F_X\left(\frac{\left(m_i m_j\right)^{\alpha}}{r_{i,j}} - y\right) \\ &\Longrightarrow f_Y(y) = F_Y'(y) = -f_X\left(\frac{\left(m_i m_j\right)^{\alpha}}{r_{i,j}} - y\right) \times (-1) = f_X\left(\frac{\left(m_i m_j\right)^{\alpha}}{r_{i,j}} - y\right). \end{aligned} \tag{B.4}$$

If we assume that trade resistance is bilateral, then we can simply deduce $r_{i,j}$ for each pair of countries by the least square method with

$$\min\left(\phi = \left(F_{i,j} + \varepsilon_{ij} - \frac{\left(m_i m_j\right)^{\alpha}}{r_{ij}}\right)^2 + \left(F_{j,i} + \varepsilon_{ji} - \frac{\left(m_i m_j\right)^{\alpha}}{r_{ij}}\right)^2\right), \tag{B.5}$$

$$\frac{\partial \phi}{\partial r_{ij}} = 0 \Longrightarrow r_{ij}^{*} = \frac{2\left(m_i m_j\right)^{\alpha}}{F_{i,j} + F_{j,i} + \varepsilon_{ij} + \varepsilon_{ji}}.$$

Different kinds of pseudomaximum likelihood (PML) methods are proved to be effective to deal with the zero-valued trade flow and the logarithm transformation [38, 60, 61]. The method in this paper is not exactly the same as the gravity model, and the main different is that we replace the geographical distance with $r_{i,j}$ which needs to be quantified. So we use the idea of PML but improve the likelihood function here. Then, we maximize the probability $Y = F_{i,j}$, with the defined likelihood function as

$$\begin{aligned} L &= \prod_{i,j} f_Y\left(F_{i,j} \,\middle|\, \mu, \sigma\right) = \prod_{i,j} f_X\left(\frac{\left(m_i m_j\right)^{\alpha}}{r_{ij}} - F_{i,j} \,\middle|\, \mu, \sigma\right) \\ &= \prod_{i,j} f_X\left(\frac{F_{i,j} + F_{j,i} + \varepsilon_{ij} + \varepsilon_{ji}}{2} - F_{i,j} \,\middle|\, \mu, \sigma\right) \\ &\simeq \prod_{i,j} f_X\left(\frac{F_{j,i} - F_{i,j}}{2} + E\left(\varepsilon_{ij}\right)\mu, \sigma\right). \end{aligned} \tag{B.6}$$

With the method of maximum likelihood estimation, we can optimize the parameters μ and σ to get the $\max_{\mu,\sigma}(L)$, which make $Y = F_{i,j}$ the most likely to occur in reality.

Table 4: Optimized parameters.

	μ	σ	$E(\varepsilon_{ij})$
2007	0.00694	0.00050	1.00697
2008	0.00228	0.00020	1.00229
2009	0.02364	0.00047	1.02392
2010	0.56409	0.00027	1.75785
2011	0.00339	0.00024	1.00340
2012	0.01529	0.00072	1.01540
2013	0.81314	0.00018	2.25498
2014	0.05607	0.00061	1.05767
2015	0.40263	0.00017	1.49575
2016	0.31945	0.00028	1.37637
2017	0.02362	0.00047	1.02390

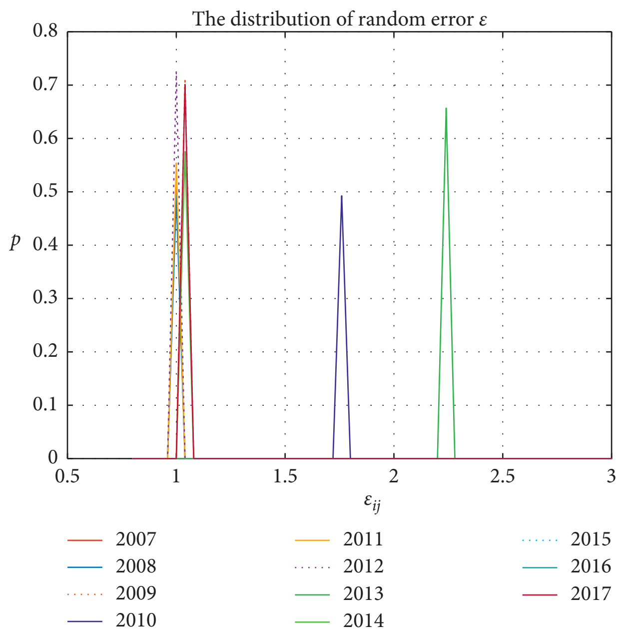


Figure 8: The random error obeys lognormal distribution during 2007–2017.

The optimized parameters are listed in Table 4, and Figure 8 shows the distribution of random error ε_{ij} during 2007–2017. It can be seen that the mean value of random variables is basically around 1-2, and the variance is relatively small, which conforms to the basic assumption of statistical error in trade flows.

With the optimized $\hat{\mu}$ and $\hat{\sigma}$, we will use the $E(X) + F_{i,j}$ as the revised trade flows with no zero values.

Data Availability

The empirical data used in this paper could be downloaded from the sources listed in Table 1 or would be available from Dr. Xiaomeng Li (lixiaomeng@bnu.edu.cn) upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest including any financial, personal, or other relationships with other people or organizations.

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Research Article

Channel Selection Strategy for a Retailer with Finance Constraint in a Supply Chain Based on Complex Network Theory

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This paper establishes a two-echelon supply chain consisting of one manufacturer and one retailer. We consider the retailer buys a product from the manufacturer and sells it to consumers through a store channel and an online channel. The retailer needs to bear a fixed investment cost to running its store/online channel. We discuss the impact of the fixed investment cost, the operating cost for the product, and substitutive factor between the two channels on the optimal strategy for the retailer using complex network theory. The result shows that the ratio of net surplus and the ratio of the operating cost between the two channels play a significant role in the retailer's optimal decisions. Moreover, finance constraint and the fixed investment cost are also two vital factors for the retailer to channel selection strategy. Numerical experiment shows the effectiveness of the conclusion, and some meaningful insights are generated.

1. Introduction

With the rapid development of information technology and globalization, the supply chain structure becomes more complex. The supply chain network is a type of complex network consisting of the related firms such as suppliers, manufacturers, and retailers. There exist lots of the interaction and interdependency between different firms, which are highly nonlinear and complex. When a new firm enters the system or an incumbent runs a new selling channel, the supply chain structure changes and creates new connections between firms. As a result, the interaction and interdependency also become more complex. This leads to the self-organization movement of the supply chain network [1]. Based on complex network theory, the node represents firm unit which can make decision independently, and the link between nodes represents exchange relationship and underlined order. Thus, the complex network theory can be applied to the supply chain management [2, 3]. This paper studies the retailer's decision when the supply chain network changes through using complex network theory.

With the rapid development of e-commerce, a growing number of people have begun shopping directly online. Forrester Research [4] reported that there is $290 billion on online shopping in 2014 in the U.S., and can reach about $400 billion in 2018. In the recent Tmall "double eleven" shopping festival in 2019, the turnover was as high as $38.4 billion in just one day. The rapid increase in online shopping has attracted manufactures and retailers to adopt a dual-channel retail system, i.e., sell their products through a retail channel and an online channel. For instance, besides using traditional retail channels, many manufacturers, such as IBM, Hewlett Packard, and Nike, open their own online direct channels to sell products to customers. In addition, may retailers, such as Walmart, Carrefour, and RT-Mart, also open their own online direct channels to sell products to customers.

In the past two decades, operating a dual-channel retail system including a store channel and an online channel has been widely discussed by experts and scholars and achieved fruitful results. The research is mainly divided into two categories. The first category is the manufacturers sell their products through both a retail channel and an online channel. It mainly focuses on the topics of price competition, inventory control, channel conflicts, and channel coordination. In price competition and inventory control, Sun et al. [5] showed that introducing a direct channel can force the retailer to lessen the pricing, thus weakening the double marginalization. Hua et al. [6] established the price competition model considering the factor of delivery lead time. Li et al. [7] discussed the impact of the retailer's risk indicator on the retail price and the ordering quantities and indicated an improved risk-sharing contract can coordinate the dual-channel supply chain and ensures that both supply chain members achieve a win-win outcome. Wei et al. [8] established five pricing models under decentralized decision cases with consideration of different market power structures among two manufacturers and one common retailer. Alptekinoglu and Tang [9] discussed the optimal inventory distribution policy to satisfy demand that should be handled by each fulfillment location without considering fixed operating costs. Netessine and Rudi [10] studied the conditions in which the drop-shipping mode was more effective than the traditional mode. Geng and Mallik [11] considered inventory competition between the retail channel and the direct channel and indicated that a mild capacity constraint could improve the situation of both agents and increase the profit of the whole supply chain. Yao et al. [12] study three different inventory strategies (centralized inventory strategy, Stackelberg inventory strategy, and online channel inventory outsourcing strategy) and obtained the optimal inventory levels in retail and online channels from the manufacturer's perspective. Based on a single-period news-vendor model [13], Roy et al. [14] discussed the optimal stock level, sales prices, promotional effort, and service level for the two channels. In channel conflict and channel coordination, Geyskens et al. [15] showed that less powerful firms with larger online market offerings would obtain less profit than powerful ones with a fewer online paths. Cai et al. [16] evaluated the impact of price discount contracts and pricing schemes on the dual-channel supply chain competition and found that the former scenarios can outperform the non-contract scenarios. Yan and Zaric [17] studied all possible coordinating contracts for a dual-channel supply chain and showed that different contract families have different levels of efficiency, flexibility, and required information for coordination.

In addition, much literature has shown that an online channel may lessen a retailer's effort to sell a product [5, 18–21] and can also sometimes target a different market segment, and these customers would buy elsewhere if there were no direct channel [22–24]. Bell et al. [25] and Li et al. [26] discuss the impact of showroom on the members' demand and profit in a dual-channel supply chain. They show that the showroom increases the sales through online channels. Similarly, based on a quantity competition model, Arya et al. [27] show that introducing an online channel not only increases the manufacturer's revenue but also motivates the manufacturer to offer a lower wholesale price to the retailer, which can reduce the retail price and mitigate double marginalization. Li et al. [28] and Huang et al. [29] expand the research of Arya et al. [27] by considering a retailer with private information about the market demand. They find that introducing an online channel can sometimes amplify the double marginalization and hurt both the manufacturer and retailer. However, the above studies focus only on the manufacturer's dual-channel decision in the two-echelon supply chain structure. Our work complements this stream of research by considering the retailer's dual-channel strategy.

The second category is that the retailer sells through a physical channel and an online channel. With the rapid development of e-commerce, about 80% of retailers in the US have adopted a dual-channel retail strategy [30]. Such a strategy can allow retailers to reach wider segments of customers and increase revenue [31] and can add flexibility to a retailer's dual channel. This flexibility allows customers to order a product online and pick it up from a physical store or purchase a product online and return it to a physical store [32]. Undoubtedly, adding another channel can not only improve retailer' profitability but can also lead to a better bargaining power with upstream manufacturers [8, 27, 33]. However, retailers must take the loss of the vested benefit from the existing channel. Generally, both the store channel and the online channel are intersubstitutive, so the demand transfers the existing channel to the new opening channel, which does not increase the retailer's profit. In additional, the retailer must pay a large fixed capital (the investment cost) to develop a new channel before selling its product through this channel. This is a vital factor for the retailer to whether open a new channel or not. Finance constraint has also significant influence on the firms' operations [34–36], and the retailer needs to determine how to maximize the utilizing efficiency of the finite finance.

To the best of our knowledge, there is no research on the operational decisions in capital-constrained retailer considering the fixed investment cost. This paper attempts to fill the gap by introducing the fixed cost into a capital-constrained retailer's channel selection model. This pare is different from the existing literature in the following two aspects. One is that the existing literature on channel selection has regarded the traditional store channel as an incumbent channel and discussed whether to introduce an online channel besides the store channel. In fact, with the development of e-commerce, many pure e-retailers have begun to develop an offline channel in addition to their existing online channel. In this paper, we assume that the retailer can adopt one of three retail modes: only a store channel, only an online channel, and both the two channels. The other difference is that the existing literature on capital-constrained supply chain focuses on financing strategy such as bank credit financing and trade credit financing [34, 37]. However, many small- and medium-sized firms in China have difficulty to solve fund shortage through bank credit financing and trade credit financing because of their low credit rate and high default risk. Thus, this paper discusses how a capital-constrained retailer chooses retail channel to sell its product when borrowing is forbidden. Besides, the fixed cost for developing a new channel has a significant effect on channel selection when capital is constrained, so this paper considers a nonzero fixed cost, while it is normalized to be zero in much literature. The paper considers a capital-constrained retailer buys a product from its upstream manufacturers and sells it through the two alternative channels: store channel and online channel. We assume that the upstream manufacturer who does not play any strategy with the retailer. We investigate the optimal quantity strategy and channel selection decision for the retailer. We discuss the impacts of the ratio of net surplus between the two channels, the cost for developing and operating the channel, and finance constraint on the retailer's optimal decision. The results shows that when borrowing is allowed, the retailer's optimal strategies depend on the ratios of the maximum achievable surplus and the ratios of substitution factors of the online channel and the store channel. When borrowing is prohibited, the retailer can improve the efficiency of capital by reducing the quantity demanded level of more expensive channel and replacing them with the cheaper one. Besides, the nonzero-investment cost makes the probability of the retailer simultaneously running the two channels small.

The rest of this paper is organized as follows. Section 2 provides a basic model and assumption. Section 3 and Section 4 analyze the retailer's optimal strategy considering capital constraint and the fixed cost when borrowing is permitted and is forbidden, respectively. Section 5 employs numerical studies to gain more managerial insights. Section 6 provides concluding remarks. All the proofs are presented in the Appendix.

2. Model Description

Consider one retailer (she) who buys a product from an independent manufacturer and sells it to consumers through the store (hereafter "s-channel") and online (hereafter "o-channel") channels. We assume that the independent manufacturer does not play any strategic role with the retailer, so the wholesale price charged by the independent manufacturer is normalized to zero for brevity. The retailer incurs the per-unit selling cost of c_s/c_o for the "s-channel"/"o-channel." Besides, the retailer needs to pay a fixed cost C_s/C_o for opening the "s-channel"/the "o-channel."

We assume that the market demand satisfies a linear and downward-sloping demand function which is in line with Cui et al. [38] and Wang et al. [36]. The inverse demand functions are

$$\begin{aligned} p_s &= a - q_s - \gamma q_o, \\ p_o &= a - q_s - q_o, \end{aligned} \tag{1}$$

where q_s/q_o represents the quantity demanded in the "s-channel"/"o-channel," $a > 0$ represents the market size (i.e., the maximum achievable retail price), and $\gamma \in (0, 1)$ denotes the degree of affect the quantity of the "o-channel" to the "s-channel." We consider the price of the "s-channel" is higher than the "o-channel" because consumers usually believe the product in the "o-channel" is inferior than in the "s-channel."

For the retailer, the total cost is $C_T = c_s q_s + c_o q_o + C_s + C_o$ when $q_s > 0$ and $q_o > 0$, $C_T = c_s q_s + C_s$ when $q_s > 0$ and $q_o = 0$, and $C_T = c_o q_o + C_o$ when $q_s = 0$ and $q_o > 0$. We assume that the retailer has a self-owned finance $F > C_s + C_o$, and there exists a perfect bank who provides an identical risk-free rate, $\rho - 1 > 0$, for saving and borrowing. Thus, the retailer can gain the interest when $F > C_T$ and takes a loan from the perfect bank when $F < C_T$. The profit function of the retailer is

$$\pi_R(q_s, q_o) = (a - q_s - \gamma q_o)q_s + (a - q_o - q_s)q_0 - F + \rho(F - C_T), \tag{2}$$

where the first two terms are the revenue of the retailer selling through both the channels and the last term includes the total costs and the financial expense for $F < C_T$ (or income for $F > C_T$).

From the inverse demand function in (1), when both the quantities the s-channel and the o-channel increase one unit, the price of o-channel decreases $1 + \gamma$, while the price of s-channel increases 2, thus we denote $1 + \gamma/2$ to represent the ratio of the substitution factor of o-channel to s-channel (conversely, $2/1 + \gamma$ represents the ratio of the substitution factor of s-channel to o-channel). Moreover, a is the maximum achievable price of selling the unit product and ρc_i is the return for the retailer when he puts capital c_i in the bank. Thus, $A_i = a - \rho c_i$ is the maximum achievable surplus of selling a per-unit product through the i-channel, $i \in \{s, o\}$. Let $\Delta \equiv A_o/A_s$ represent the ratio of the surplus of selling through the o-channel to the s-channel and reflect the relative competitiveness of the o-channel over the s-channel [39]. The larger the Δ is, the stronger the relative competitiveness of the o-channel over the s-channel will be. This means that selling the product through the o-channel is more profitable than through the s-channel.

3. Optimal Strategy When Borrowing Is Permitted

In this section, we discuss how the substitution factor γ, the operating cost c_i, the investment cost C_i, and the self-owned finance F affect the optimal decision for the retailer. In practice, opening a channel usually is a long-term plan for the retailer and, once implemented, cannot be altered as easily as an order/pricing decision. Before the order/pricing decision, the retailer needs to invest a huge capital, which is regarded as the investment cost, to construct a new channel. Thus, the fixed investment cost and the operating cost for selling the products are separate, and much literature on dual-channel supply chain has not considered the investment cost and normalized it to zero. In this paper, we consider the following two cases. The first case is that we do not consider the fixed investment cost, i.e., normalize it to zero, which is consistent with that of much literature. On the other hand, when the retailer's capital is restricted, the investment cost has a significant effect on opening a new channel, so we consider a nonzero-investment cost in the second case. Thus, we first discuss the effects of other factors on the optimal decisions for the retailer under the zero-investment cost ($C_s = 0$ and $C_o = 0$) in Section 3.1 and then investigate the effects under the nonzero-investment cost ($C_s > 0$ or $C_o > 0$) in Section 3.2.

3.1. Zero-Investment Costs. In this subsection, we discuss the optimal strategy for the retailer when both of the investment costs are zero, i.e., $C_s = 0$ and $C_0 = 0$. In such a case, the retailer has three alternative strategies: (i) only running the "s-channel" ($q_s > 0$, $q_o = 0$), (ii) only running the "o-channel" ($q_s = 0$, $q_o > 0$), and (iii) running both of the "s-channel" and the "o-channel" ($q_s > 0$, $q_o > 0$).

From (2), the retailer determines the selling quantities of q_s and q_o to maximize her profit as the solution to

$$\max_{q_s\geq 0, q_o\geq 0} \pi(q_s, q_o) = (a - q_s - \gamma q_o)q_s + (a - q_o - q_s)q_0 - F + \rho(F - C_T). \tag{3}$$

It is easy to prove that $\pi(q_s, q_o)$ is the concave function on (q_s, q_o). Solving the first-order conditions obtain the optimal solutions (indexed by superscript BA), which is shown in Proposition 1.

Proposition 1. *Suppose that borrowing is permitted and the investment costs are zero, the optimal decisions for the retailer are as follows.*

(1) $q_s^{BA} = A_s/2$, $q_o^{BA} = 0$ *when* $\Delta \leq 1 + \gamma/2$

(2) $q_s^{BA} = A_s(2 - (1+\gamma)\Delta)/4 - (1+\gamma)^2$, $q_o^{BA} = A_s(2\Delta - (1+\gamma))/4 - (1+\gamma)^2$ *when* $1 + \gamma/2 < \Delta \leq 2/1 + \gamma$

(3) $q_s^{BA} = 0$, $q_o^{BA} = A_o/2$ *when* $\Delta > 2/1 + \gamma$

From Proposition 1, we draw the following conclusions. (i) A big/small Δ means that selling through the o-channel/s-channel is more profitable for the retailer. Therefore, q_s is increases with Δ, while q_s decreases with Δ. (ii) The channel selection strategy for the retailer depends on the ratio (Δ) of surplus of product and the ratio ($1 + \gamma/2$ and $2/1 + \gamma$) of the substitution factor. Specifically, the retailer would only run the s-channel/o-channel when Δ is big/small enough. Moreover, the larger the substitution factor γ, the stronger the effect of the o-channel on the s-channel will be, so the probability that the retailer simultaneously running the two channel becomes small. (iii) The threshold of sufficient finance is $F_s = c_s q_s^{BA} = A_s c_s/2$ when the retailer only runs the s-channel ($q_s^{BA} > 0$, $q_o^{BA} = 0$), $F_{so} = c_s q_s^{BA} + c_o q_o^{BA} = A_s[(2 - (1+\gamma)\Delta)c_s + (2\Delta - (1+\gamma))c_o]/4 - (1+\gamma)^2$ when the retailer runs both of the s-channel and the o-channel ($q_s^{BA} > 0$, $q_o^{BA} > 0$), and $F_o = c_o q_o^{BA} = A_o c_o/2$ when the retailer only runs the o-channel ($q_s^{BA} = 0$, $q_o^{BA} > 0$).

According to the channel selection strategy for the retailer in Proposition 1, the retailer's profit $\pi^{BA}(q_s^{BA}, q_o^{BA})$ can be obtained as follows:

$$\pi^{BA}\left(q_s^{BA}, q_o^{BA}\right) = \begin{cases} \pi_s^{BA}\left(\dfrac{A_s}{2}, 0\right) = \dfrac{A_s^2}{4} + (g-1)F, & \Delta \leq \dfrac{1+\gamma}{2}, \\ \pi_{so}^{BA}\left(\dfrac{A_s(2-(1+\gamma)\Delta)}{4-(1+\gamma)^2}, \dfrac{A_s(2\Delta-(1+\gamma))}{4-(1+\gamma)^2}\right) & \\ = \dfrac{A_s^2(1-(1+\gamma)\Delta+\Delta^2)}{3-2\gamma-\gamma^2} + (g-1)F, \dfrac{1+\gamma}{2} < & \Delta \leq \dfrac{2}{1+\gamma}, \\ < \pi_o^{BA}\left(0, \dfrac{A_o}{2}\right) = \dfrac{A_o^2}{4} + (g-1)F, & \Delta > \dfrac{2}{1+\gamma}, \end{cases} \tag{4}$$

3.2. Nonzero-Investment Costs. In Section 3.1, we discuss the optimal strategy for the retailer when the channel investment costs are zero. In practice, the retailer needs to pay a finance to develop the s-channel/o-channel before selling the product through s-channel/o-channel; we regard the finance as the investment cost for developing the channel. In this section, we study the optimal strategy for the retailer when the channel investment costs are nonzero. Note that the investment costs are the fixed cost and does not affect the decisions for the selling quantity in the each channel. According to (4), we can obtain the retailer's profit (index by superscript "FA") in three channel selection strategies.

If the retailer only runs the s-channel, then her profit is

$$\pi_s^{FA}\left(q_s^{FA}, q_o^{FA}\right) = \pi_s^{FA}\left(\frac{A_s}{2}, 0\right) = \frac{A_s^2}{4} + (\rho - 1)F - \rho C_s. \tag{5}$$

If the retailer only runs the o-channel, then her profit is

$$\pi_o^{FA}\left(q_s^{FA}, q_o^{FA}\right) = \pi_o^{FA}\left(0, \frac{A_o}{2}\right) = \frac{A_o^2}{4} + (\rho - 1)F - gC_o. \tag{6}$$

If the retailer only runs the o-channel, then her profit is

$$\pi_{so}^{FA}\left(q_s^{FA},q_o^{FA}\right)=\pi_{so}^{FA}\left(\frac{A_s(2-(1+\gamma)\Delta)}{4-(1+\gamma)^2},\frac{A_s(2\Delta-(1+\gamma))}{4-(1+\gamma)^2}\right)$$
$$=\frac{A_s^2(1-(1+\gamma)\Delta+\Delta^2)}{3-2\gamma-\gamma^2}+(\rho-1)F-\rho(C_s+C_o), \quad (7)$$

where the subscripts "s," "o," and "so" represent the s-channel, o-channel, and the two channels, respectively.

Comparing π_s^{FA}, π_o^{FA}, and π_{so}^{FA} in (5)–(7), we can obtain the following conclusion, shown in Proposition 2.

Proposition 2. *Suppose that borrowing is permitted and the investment is nonzero, the retailer's optimal decision is as follows:*

(1) *If* $\{1+\gamma/2<\Delta<2/1+\gamma\}\wedge\{C_o<[2A_o-(1+\gamma)A_s]^2/4\rho(3-2\gamma-\gamma^2)\}\wedge\{C_s<{}^{[2A_s-(1+\gamma)}\ A_o]2/4\rho(3-2\gamma-\gamma^2)\}$, *then the retailer chooses simultaneously to run the s-channel and the o-channel, and the selling quantities are* $q_s^{BA}=A_s(2-(1+\gamma)\Delta)/4-(1+\gamma)^2$ *and* $q_o^{BA}=A_s(2\Delta-(1+\gamma))/4-(1+\gamma)^2$

(2) *If condition in (1) fails, then retailer chooses only to run the s-channel/o-channel when* $C_s-C_o<A_s^2-A_o^2/4\rho/C_s-C_o>A_s^2-A_o^2/4\rho$, *and the selling quantity is* $q_s=A_s/2/q_o=A_s/2$

Proposition 2 shows that only when the ratio (Δ) of surplus of the o-channel to the s-channel is medium and both the investment costs (C_s and C_o) for the two channels are low, the retailer chooses to run the two channel. This means that the probability of running simultaneously the two channels becomes smaller than that when the investment costs are zero. In additional, the investment cost C_o/C_s has a positive effect on running an o-channel/s-channel and a negative impact on running a s-channel/o-channel. This is consistent with our intuition.

4. Optimal Strategy When Borrowing Is Forbidden

In Section 3, we study the retailer's optimal decisions in the presence of sufficient finance, or the self-owned finance is insufficient while the retailer can obtain a loan from the bank. In practice, finance constraint is a popular phenomenon for firms, so it is very necessary to explore the retailer's optimal decisions when she has no sufficient finance and cannot obtain a loan from the bank. We first gives the finance threshold of the three alternative strategies and then discuss the optimal channel selection strategy.

4.1. Zero-Investment Costs. From Proposition 1, we have known the thresholds of sufficient finance are F_s, F_o, and F_{so} when the retailer runs the s-channel, o-channel, and the two channels, respectively. In this section, we will discuss the impact of finance constraint on the optimal strategy. In order to analyze the impact of finance constraint, we assume that the self-owned finance is not larger than the finance threshold, i.e., $F\le F_s$, $F\le F_o$, and $F\le F_{so}$; otherwise, the finance constraint is not an ineffective for the optimal strategy for the retailer.

If she does not takes a loan from the perfect bank when her finance is insufficient, the retailer determines the quantities of q_s and q_o to maximize her profit as the solution to

$$\max \pi_R(q_s,q_o)=(a-q_s-\gamma q_o)q_s+(a-q_o-q_s)q_0-F+\rho(F-C_T),$$
$$\text{s.t.}\quad\begin{cases}q_s\ge 0,\ q_o\ge 0,\\ F-c_sq_s-c_oq_o\ge 0.\end{cases}\quad (8)$$

According to the K-T conditions, we can obtain the retailer's optimal decisions as follows.

Proposition 3. *Suppose that the self-owned finance is not larger than the sufficient finance threshold, i.e.,* $F=c_sq_s+c_oq_o$ *and borrowing is forbidden, then the retailer's optimal decision (index by superscript "BF") is as follows:*

(1) $q_s^{BF}=F/c_s$, $q_o^{BF}=0$ *when* $\{F\le F_s\}\wedge\{(c_o/c_s-1+\gamma/2)F\le A_sc_s/2(c_o/c_s-\Delta)\}$

(2) $q_s^{BF}=0$, $q_o^{BF}=F/c_o$ *when* $\{F\le F_o\}\wedge\{(2/1+\gamma-c_o/c_s)F\le A_sc_o/1+\gamma\ (\Delta-c_o/c_s)\}$

(3) $q_s^{BF}=[2c_s-(1+\gamma)c_o]F-A_oc_sc_o+A_sc_o^2/2[c_s^2+c_o^2-(1+\gamma)c_sc_o]$, $q_o^{BF}=[2c_s-(1+\gamma)c_s]F-A_sc_sc_o+A_oc_s^2/2[c_s^2+c_o^2-(1+\gamma)c_sc_o]$ *when* $\{F\le F_{so}\}\wedge\{(c_o/c_s-1+\gamma/2)F>A_sc_s/2(c_o/c_s-\Delta)\}\wedge\{(2/1+\gamma-c_o/c_s)F>A_sc_o/1+\gamma(\Delta-c_o/c_s)\}$

From Proposition 3, we can obtain that the retailer's optimal decisions depend on not only the ratios of surplus (Δ) and substitution factors ($1+\gamma/2, 2/1+\gamma$) for the two channels but also the ratio of operating costs (c_o/c_s) for the two channels. The ratio of operating costs (c_o/c_s) is involved because the utilizing efficiency of self-owned finance becomes very important when borrowing is forbidden. In order to better understand the effects of these parameters on the retailer's optimal decision, we give the feasible range of F for the optimal strategy in different situations, shown in Table 1.

From Table 1, we draw the following conclusions. (1) When the ratio of surplus for the two channels is very small (i.e., $\Delta\le 1+\gamma/2$), it induces $c_o>c_s$, which means the operating cost for the o-channel is higher than for the s-channel. In such case, the retailer only runs the s-channel. Conversely, when the ratio of surplus for the two channels is very high (i.e., $\Delta>2/1+\gamma$), it induces $c_o<c_s$, which means the operating cost for the o-channel is lower than for the s-channel. In such case, the retailer only runs the o-channel. This is consistent with the sufficient finance, shown in Proposition 1. (2) When the ratio of surplus for the two channels is medium (i.e., $1+\gamma/2<\Delta\le 2/1+\gamma$), the retailer does not choose the o-channel/s-channel if $c_o>c_s/c_o<c_s$. In such case, the retailer chooses both the two channels when the self-owned finance is not small. If the self-owned finance is very small, the retailer only chooses the o-channel/s-channel if $c_o<c_s/c_o>c_s$.

From Table 1, the retailer's profit $\pi^{BF}(q_s^{BF},q_o^{BF})$ is given as follows:

Table 1: The optimal strategy in different cases.

Channel selection	Only o-channel	Both channels	Only s-channel
$\Delta \le 1+\gamma/2\,(\Rightarrow c_o > c_s)$	—	—	$F \le F_s$
$1+\gamma/2 < \Delta \le 1\,(\Rightarrow c_o \ge c_s)$	—	$F_1 < F \le F_{so}$	$F \le F_1$
$1 < \Delta \le 2/1+\gamma\,(\Rightarrow c_o < c_s)$	$F \le F_2$	$F_2 < F \le F_{so}$	—
$2/1+\gamma \le \Delta\,(\Rightarrow c_o < c_s)$	$F \le F_o$	—	—

$F_1 = A_s c_s c_o - A_o c_s^2/2c_o - (1+\gamma)c_s$, $F_2 = A_o c_s c_o - A_s c_o^2/2c_s - (1+\gamma)c_o$.

$$\pi^{BF}\left(q_s^{BF}, q_o^{BF}\right) = \begin{cases} \pi_s^{BF}\left(\dfrac{F}{c_s}, 0\right) = \left(A_s - \dfrac{F}{c_s}\right)\dfrac{F}{c_s} + (\rho - 1)F, \\ \pi_{so}^{BF}\left(\dfrac{[2c_s - (1+\gamma)c_o]F - A_o c_s c_o + A_s c_o^2}{2[c_s^2 + c_o^2 - (1+\gamma)c_s c_o]}, \dfrac{[2c_s - (1+\gamma)c_s]F - A_s c_s c_o + A_o c_s^2}{2[c_s^2 + c_o^2 - (1+\gamma)c_s c_o]}\right) \\ = \dfrac{(A_s c_o - A_o c_s)^2 + 2F[A_s(2c_s - (1+\gamma)c_o) + A_o(2c_o - (1+\gamma)c_s)] - (3 - 2\gamma - \gamma^2)F}{4(c_s^2 - (1+\gamma)c_s c_o + c_o^2)} + (\rho - 1)F, \\ \pi_o^{BF}\left(0, \dfrac{F}{c_o}\right) = \left(A_o - \dfrac{F}{c_o}\right)\dfrac{F}{c_o} + (\rho - 1)F. \end{cases} \tag{9}$$

4.2. Nonzero-Investment Costs. In this subsection, we discuss the effect of the nonzero-investment costs C_s and C_o on the optimal decision for the retailer when borrowing is forbidden, i.e., the retailer cannot take a loan from the bank. We first give the retailer's profit under three alternative channel strategies and then discuss the optimal channel selection strategy.

Because the investment costs are fixed and does not affect the decision on selling quantities, according to (9), we can obtain the retailer's profit in there alternative channel strategies.

If she only runs the s-channel, the retailer's profit is

$$\pi_s^{FF}\left(\frac{F - C_s}{c_s}, 0\right) = \left(A_s - \frac{F - C_s}{c_s}\right)\frac{F - C_s}{c_s} + (\rho - 1)F - \rho C_s. \tag{10}$$

If she only runs the o-channel, the retailer's profit is

$$\pi_o^{FF}\left(0, \frac{F - C_o}{c_o}\right) = \left(A_o - \frac{F - C_o}{c_o}\right)\frac{F - C_o}{c_o} + (\rho - 1)F - \rho C_o. \tag{11}$$

If she runs the two channels, the retailer's profit is

$$\begin{aligned} &\pi_{so}^{FF}\left(\frac{[2c_s - (1+\gamma)c_o](F - C_o - C_s) - A_o c_s c_o + A_s c_o^2}{2[c_s^2 + c_o^2 - (1+\gamma)c_s c_o]}, \frac{[2c_s - (1+\gamma)c_s](F - C_o - C_s) - A_s c_s c_o + A_o c_s^2}{2[c_s^2 + c_o^2 - (1+\gamma)c_s c_o])}\right) \\ &= \frac{(A_s c_o - A_o c_s)^2 + 2(F - C_o - C_s)[A_s(2c_s - (1+\gamma)c_o) + A_o(2c_o - (1+\gamma)c_s)] - (3 - 2\gamma - \gamma^2)(F - C_o - C_s)}{4(c_s^2 - (1+\gamma)c_s c_o + c_o^2)} \\ &\quad + (\rho - 1)F - \rho(C_o + C_s). \end{aligned} \tag{12}$$

Comparing the profits under three alternative channel strategies, we can obtain the channel selection strategies for the retailer.

Proposition 4. *Suppose that borrowing is forbidden and the self-owned finance is not large than the finance threshold, i.e., $F - C_s - C_o = c_s q_s + c_o q_o$, the retailer's channel selection strategy is as follows:*

(1) *If $\{1+\gamma/2 < \Delta < 2/1+\gamma\} \wedge \{\max(F_1, F_2) < F - C_s - C_o < F_{so}\} \wedge \{\pi_{so}^{FF} \ge \max(\pi_s^{FF}, \pi_o^{FF})\}$, then the retailer simultaneously runs the two channels, and the selling quantities are $q_s = [2c_s - (1+\gamma)c_o]\ (F - C_o - C_s) - A_o c_s c_o + A_s c_o^2/2[c_s^2 + c_o^2 - (1+\gamma)c_s c_o]$ and $q_o = [2c_s - (1+\gamma)c_s](F - C_o - C_s) - A_s c_s \quad c_o + A_o c_s^2/2[c_s^2 + c_o^2 - (1+\gamma)c_s c_o]$, respectively*

(2) *If the condition in (1) fails, then retailer chooses only to run the s-channel/o-channel when $\pi_s^{FF} > \pi_o^{FF}/\pi_s^{FF} < \pi_o^{FF}$, and the selling quantity is $q_s = F - C_s/c_s/q_o = F - C_o/c_o$.*

Proposition 4 shows that only when the ratio (Δ) of surplus of the o-channel to the s-channel is medium and both the investment costs (C_s and C_o) for the two channels are low, the retailer chooses to run the two channels. This means that the probability of running simultaneously the two channels becomes smaller than that when the

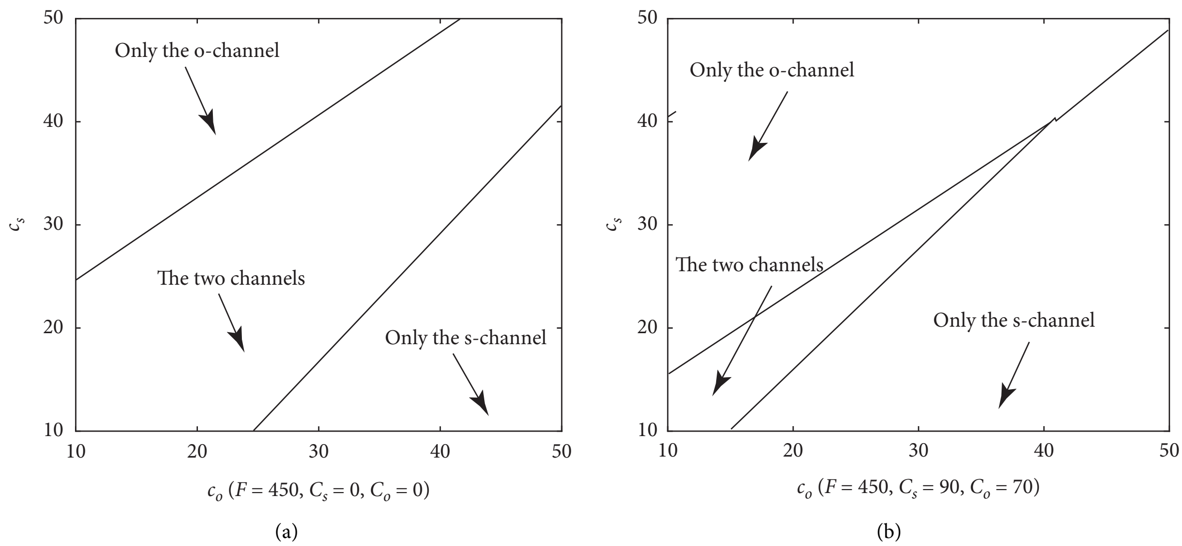

Figure 1: The channel selection strategy when borrowing is permitted.

investment costs are zero. The reason is that the retailer needs to pay a finance to develop a channel before selling the product through the channel, so the retailer will not open a channel until the investment cost for the channel is small. This is consistent with our intuition. Moreover, the investment cost C_o/C_s has a positive effect on running an o-channel/s-channel and a negative impact on running a s-channel/o-channel.

5. Numerical Example

Consider the following data: $a = 100$, $\gamma = 0.6$, $\rho = 1.2$, and $F = 450$. Figure 1 shows the impact of the operating costs (c_o and c_s) on the channel selection strategy for the retailer when borrowing is permitted. (a) The case with zero-investment costs and (b) the case with nonzero-investment costs. From Figure 1, we can obtain the following conclusions. Only when the difference between the operating costs is small, the retailer chooses to run the two channels. If the difference between the operating costs is large, the retailer will choose to the channel with the lower operating cost. In addition, the nonzero-investment cost has a negative effect on running the two channels. The larger the investment costs are, the probability that the retailer runs the two channels will become smaller. The reason is that the utilizing efficiency of the finance is very important for the retailer and the s-channel and the o-channel are substituted for each other. Thus, only when both the operating costs are not large, the retailer chooses to run the two channels.

Figure 2 shows the impact of the operating costs on the optimal strategies for the retailer when borrowing is forbidden. (a) The case with the zero-investment costs and (b) the case with the nonzero-investment costs. From Figure 2, we can obtain as follows. Only when the difference between the operating costs is very small, the retailer chooses to run both channels. Because the self-owned finance is limited and the loan from the bank cannot be obtained, the retailer must use the finite finance to produce/buy more product and the probability of running the two channels becomes very small. Moreover, the investment cost has a significant influence on the channel selection strategy for the retailer. The retailer always runs the channel that the investment cost for this channel is lower than another channel even if the operating cost for this channel is slightly higher than that for another channel.

5.1. Discussion and Implications. The prior literature mainly focused on inventory control, pricing, channel selection, and coordination in a dual-channel supply chains [5, 6, 9, 14, 28, 29], ignoring the impact of capital constraint. Lots of literature in a capital-constraint supply chain focuses on financing strategy such as bank credit financing and trade credit financing but does not consider small- and medium-sized firms which do not ability to finance because of their low credit rate and high default risk. This study has concentrated on how capital constraint affects a retailer's channel selection, thereby enriching literature in this area. The managerial insights of this paper are shown as follows.

When borrowing is permitted and the investment cost is zero, the retailer's optimal strategies depend on the ratio of the surplus of selling through the o-channel to the s-channel. When the ratio is close to one, the retailer chooses both the two channels to sell her product. This means that if the differentiation of the two channels is small, the retailer should adopt dual-channel strategy to increase his profit. If the differentiation of the two channels is large, the retailer prefers to sell through the single channel. In addition, when the investment cost is nonzero, because the retailer can obtain finance from bank loan, the optimal strategy is not unchanged. That is, the differentiation of the two channels is small, and the retailer prefers to sell through the two channels. Different from the zero-investment cost, if the investment costs for the two channels are large, the retailer prefers to sell through a single channel even if the ratio of the

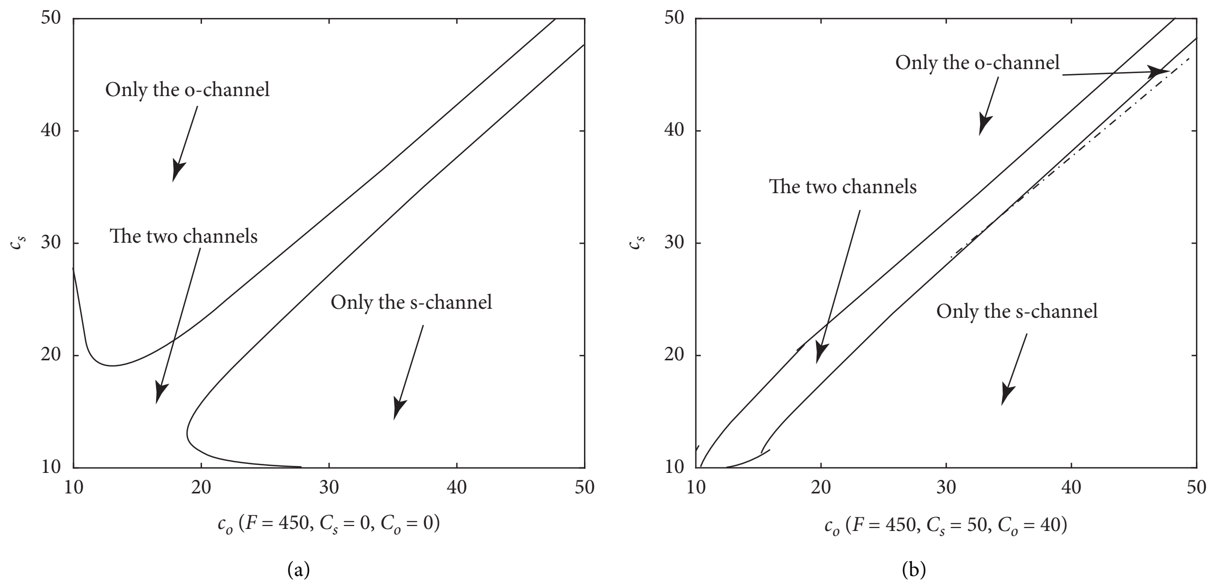

Figure 2: The channel selection strategy when borrowing is forbidden.

surplus of selling through the o-channel to the s-channel is close to one. This means that the retailer becomes cautious to adopt the two channels in order to reduce expenditure of the investment costs. When borrowing is forbidden, the limited capital is a significant resource for the retailer, so the feasible area of adopting the two channels becomes smaller. This means that only when the ratio of the surplus of selling through the o-channel to the s-channel is close to one, the retailer prefers to adopt the two channels.

6. Conclusion

This paper considers a dual-channel retailer's potential channel selection topic. The retailer can sell a product provided by an independent manufacturer who does not play any strategy through a traditional store channel or a fashionable online channel. We investigate how the investment cost (fixed cost), the operating cost, the substitution factor, and the finance constraint between the two channels affect the retailer's selling quantity strategy and the channel selection decision. The results show the following. (i) The operating cost has a significant influence on the retailer's channel selection strategy. The retailer always runs the channel with the lower operating costs. It is cautious for the retailer to simultaneously run the two channels. Only if the difference of the operating cost between the two channels is very small, the retailer opens the two channels. (ii) The two channels are substitution for each other and there exists the competition, so the retailer runs the channel with the competitive channel. The larger the substitution factor is, the stronger the competition between the two channel will be, so the smaller the probability that the retailer runs the two channel will be. (iii) The nonzero-investment cost makes the retailer running the two channels become small. The retailer always opens the channel with a lower investment cost whether borrowing is permitted or not.

This paper has a few limitations. In this paper, we assume that the manufacturer is an independent partner and does not play any strategy with the retailer. In practice, the wholesale price charger by the manufacturer is a significant factor for the retailer to determine the selling quantity, thus the further research may consider a two-echelon supply chain that consists of the manufacturer and the retailer. Moreover, there exists a certain risk in opening the new-fashioned online channel. It would be interesting to incorporate the risk element into the model in the future research.

Appendix

Proof of Proposition 1. From equation (3), the Hessian matrix of $\pi(q_s, q_o)$ is $\begin{bmatrix} -2 & -(1+\gamma) \\ -(1+\gamma) & -2 \end{bmatrix}$. Obviously, the Hessian matrix is a negative definite matrix, so the critical point of $\pi(q_s, q_o)$ is a local maximum. The only critical point from $[\partial\pi(q_s, q_o)/\partial q_s, \partial\pi(q_s, q_o)/\partial q_o] = [0, 0]$ is $[q_s^{BA}, q_o^{BA}] = [A_s(2-(1+\gamma)\Delta)/4- (1+\gamma)^2, A_s(2\Delta-(1+\gamma))/4-(1+\gamma)^2]$. If $1+\gamma/2 < \Delta \leq 2/1+\gamma$, we have $q_s^{BA} > 0$ and $q_o^{BA} > 0$. If $\Delta \leq 1+\gamma/2$, we have $q_s^{BA} = A_s/2$ and $q_o^{BA} = 0$. If $\Delta > 2/1+\gamma$, we have $q_s^{BA} = 0$ and $q_o^{BA} = A_o/2$. □

Proof of Proposition 2. The proof is straightforward, so it is omitted. □

Proof of Proposition 3. Suppose the self-owned finance F is not higher than the sufficient finance threshold and borrowing is forbidden, the retailer determines the optimal quantities for the two channels by solving the following optimization problem:

$$\max \pi_R(q_s, q_o) = (a - q_s - \gamma q_o)q_s + (a - q_o - q_s)q_0 - F + \rho(F - C_T), \tag{A.1}$$

$$\text{s.t.} \quad \begin{cases} q_s \geq 0,\ q_o \geq 0, \\ F - c_s q_s - c_o q_o \geq 0. \end{cases} \tag{A.2}$$

The corresponding Lagrangian function is

$$L(q_s, q_o, \lambda) = (a - q_s - \gamma q_o)q_s + (a - q_o - q_s)q_0 - F + \rho(F - c_s q_s - c_o q_o) + \lambda(F - c_s q_s - c_o q_o). \tag{A.3}$$

According to K-T conditions, we have

$$\begin{cases} \dfrac{\partial L}{\partial q_s} = a - 2q_s - (1+\gamma)q_o - \rho c_s - \lambda c_s \leq 0, & \dfrac{\partial L}{\partial q_s} q_s = 0, \\ \dfrac{\partial L}{\partial q_o} = a - 2q_o - (1+\gamma)q_s - \rho c_o - \lambda c_o \leq 0, & \dfrac{\partial L}{\partial q_o} q_o = 0, \\ \dfrac{\partial L}{\partial \lambda} = F - c_s q_s - c_o q_o \geq 0, & \dfrac{\partial L}{\partial \lambda}\lambda = 0. \end{cases} \tag{A.4}$$

(1) The condition $F \leq F_s$ and $q_s > 0$, $q_o = 0$ is equivalent to

$$\begin{cases} a - 2q_s - \rho c_s - \lambda c_s = 0, \\ a - (1+\gamma)q_s - \rho c_o - \lambda c_o \leq 0, \\ F - c_s q_s = 0. \end{cases} \tag{A.5}$$

Thus, we have $q_s^{BF} = F/c_s$ and $q_o^{BF} = 0$ when $\{F \leq F_s\} \wedge \{(c_o/c_s - 1 + \gamma/2)F \leq A_s c_s/2(c_o/c_s - \Delta)\}$.

(2) Similarly, the condition $F \leq F_o$ and $q_s = o$, $q_o > 0$ is equivalent to

$$\begin{cases} a - 2q_o - \rho c_o - \lambda c_o = 0, \\ a - (1+\gamma)q_o - \rho c_s - \lambda c_s \leq 0, \\ F - c_o q_o = 0. \end{cases} \tag{A.6}$$

Thus, we have $q_s^{BF} = 0$, $q_o^{BF} = F/c_o$ when $\{F \leq F_o\} \wedge \{(2/1 + \gamma - c_o/c_s)F \leq A_s c_o/1 + \gamma(\Delta - c_o/c_s)\}$.

(3) The condition $F \leq F_{so}$ and $q_s > 0$, $q_o > 0$ is equivalent to

$$\begin{cases} a - 2q_s - (1+\gamma)q_o - \rho c_s - \lambda c_s = 0, \\ a - 2q_o - (1+\gamma)q_s - \rho c_o - \lambda c_o = 0, \\ F - c_s q_s - c_o q_o = 0. \end{cases} \tag{A.7}$$

Thus, we have $q_s^{BF} = [2c_s - (1+\gamma)c_o]F - A_o c_s c_o + A_s c_o^2/2[c_s^2 + c_o^2 - (1+\gamma)c_s c_o]$, $q_o^{BF} = [2c_s - (1+\gamma)c_s]F - A_s c_s c_o + A_o c_s^2/2[c_s^2 + c_o^2 - (1+\gamma)c_s c_o]$ when $\{F \leq F_{so}\} \wedge \{(c_o/c_s - 1 + \gamma/2)F > A_s c_s/2 \quad (c_o/c_s - \Delta)\} \wedge \{(2/1 + \gamma - c_o/c_s)F > A_s c_o/1 + \gamma(\Delta - c_o/c_s)\}$. □

Proof of Proposition 4. The proof is straightforward, so it is omitted. □

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

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

Authors' Contributions

Both the authors contributed equally to this work.

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Research Article

A Social Network Analysis on Venture Capital Alliance's Exit from an Emerging Market

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This study investigated the impacts of network structure on a venture capital (VC) alliance's successful exit from an emerging market by empirically analyzing joint VC data in China. We find that, compared to a mature capital market, the mechanism not only has a certain commonality but also shows the emerging market's particularities. From the commonality perspective, the mechanism has a positive effect on successful exit by obtaining heterogeneity information. These particularities are manifested in the following three aspects. First, the mechanism is not conducive to deepening the enterprise value chain to establish credibility by obtaining short-term cash during an initial public offering with the enhancement of the VC alliance's intervention ability for enterprise development. In addition, a VC alliance's independent judgment is bound by the VC market. Furthermore, the problem of over-trust in investees reduces the likelihood of a VC alliance's successful exit. Therefore, we should pay more attention to the particularity of emerging markets such as China to improve the relevant management mechanism.

1. Introduction

The financial capital provided to startups and small business with perceived potential for long-term growth is widely known as venture capital (VC), which is an important source of funding for startups with low levels of access to financial support. Currently, the high-tech sector (e.g., integrated circuit, big data, artificial intelligence, and eHealth) received more support from VC. For instance, at the end of 2019, Qualcomm Ventures announced to invest up to $200 million in startups helping build the 5G ecosystem, to help accelerate 5G innovation beyond the smartphone and drive 5G adoption (the information was accessed on 2020/03/01 at https://www.qualcommventures.com/5g-ecosystem-fund). By supporting a wide range of high-tech startups, VC ultimately promotes both economic growth and industry innovation [1].

Because of the constraints of resources endowment and information cost, VC firms are generally restricted by the shortage of necessary information [2]. To this end, VC firms build strategic alliances through joint investments. Depending on the unique advantages of promoting complementary information resources and overcoming the constraints of information boundaries [3–5], VC firms' joint investment helps decrease the possibility of adverse selection when choosing investment project, provides specific support for investees, achieves effective control of the investment environment, and even improves exit performance [6–8]. Therefore, as one of the most important forms of VC, VC alliance has become the mainstream method of investment in the VC market. VC alliance not only helps improve the financial status and operating performance through synergy but also effectively alleviates the financial constraints for VC alliance partners [9].

The entire VC alliance's successful exit in the investees becomes the representative method of increasing a VC's competitive advantages and promoting the effective circulation of investment value chain because it not only reflects joint investment's performance but also helps guarantee the persistence of each VC firm's investment capacity. There are various ways for VC firms to exit the investment, including buy-back, merger and acquisition (M&A), stock-right transfer, an initial public offering (IPO), management buyout, and reverse merger. Exit through IPO is generally considered successful because it is the most profitable for VC firms [10–12]. The growth of VC in the US market guarantees the availability of exit through IPO. However, if regulations are stricter (unlike in the US) or the financial market is underdeveloped, VC firms find it difficult to implement an IPO as an exit strategy [13]. Taking a firm public through an IPO would be more expensive, complex, and time-consuming in an emerging market that is underdeveloped (e.g., China, Vietnam, Thailand or Malaysia) than in a developed market (e.g., US, UK, Germany) [13]. Thus, understanding the mechanism of a VC alliance's exit through IPO in emerging markets is critical, whereas most studies investigate VC-related issues in the US market [14–16].

Extant studies have widely investigated the determinants of the VC's successful exit from both VC (including VC firm, entrepreneurial firm, VC fund, and VC market) and macroeconomic environmental perspectives [2, 17–21]. This study is different from previous researches in two ways. First, we primarily explore the impacts of the VC alliance's social network on its likelihood of successful exit. Given that high-quality information resources are crucial for the formation of competitive advantages in each link of the value chain, a VC's information superiority contributes to its successful exit. Based on a joint investment network, a VC alliance can enhance its information search capacity through efficient network structure (i.e., interorganizational network). In addition, a VC alliance can rely on the information-sharing relationship between the VC alliance and its investees (i.e., intraorganizational network) to strengthen its capacity to understand information. Thus, both the interorganizational and intraorganizational network structure of a VC alliance are expected to significantly affect its likelihood of successful exit. Second, we study the potential factors that would affect the entire VC alliance's successful exit instead of the exit of a single VC firm. By empirically analyzing the effects of network structure on the likelihood of a VC alliance's exit through IPO using a sample of 496 VC alliances formed by all 630 VC firms in China from 2000–2013, we observe that a VC alliance's interorganizational and intraorganizational network structure (i.e., information heterogeneity, network cohesion, network compactness, alliance size, and so on) significantly affect its likelihood of successful exit.

2. Literature Review

2.1. Value Chain of Venture Capital Investment. VC typically generates above-average returns while entailing high risk for VC investors [8, 17]. To achieve success in VC investment, we can further analyze the competitive advantages of VC firms based on the value chain analysis [22, 23]. VC's value chain can be divided into four main links: identifying high-quality entrepreneurs (entry), proposing valuable suggestions for investees (incubation), monitoring investees' behaviors (control), and successfully exiting the investment (exit). Of these links, exit is critical for the survival and growth of the VC industry [24]. First, it is only when the VC successfully exits that the value of the investment can be achieved and the VC firm's reputation on the market can improve [12, 25]. Second, the likelihood of a successful and timely exit partially determines a VC firm's investment decisions because it allows the VC firm to effectively predict its returns [11]. Third, given that exit enables the recycling of VC backers' funds into new investments, a VC's successful exit enhances investors' willingness to provide capital for initial and follow-on funds [10]. Therefore, understanding how VC firms can successfully exit is critical for both academia and practitioners.

2.2. Successful Exit of Venture Capital. Prior studies find that exit through IPO is the most profitable way of exit for VC firms, followed by exit through M&A [10–12]. Exit through IPO thus is typically considered as a successful VC exit way. Extant studies on VCs' successful exits [18–20] have widely investigated the determinants of the time and method of VC exit. As shown in Table 1, prior studies have primarily examined the impacts of the following four aspects of potential factors on a VC firm's successful exit (i.e., the likelihood of exit through IPO), including VC firm, entrepreneurial firm, VC fund, and VC market perspectives. In addition, researchers have empirically tested the impacts of country-level factors such as trade protection, legality, economic freedom, government size, price stability, cultural distance, economy size, and burden of taxation when investigating the successful exit of international joint ventures [18, 20, 26].

The second research stream focuses on the impacts of a VC's successful exit on a firm's optimal strategies and performances. Among them, Schwienbacher [27] analyzes the influence of a VC firm's exit method on a startup's innovation strategy by developing an analytical model. He proves that the startup has incentives to distort the innovation strategy to induce the VC to take the firm public. Bascha and Walz [28] investigate the dynamics of exit methods and contract design in VC through an analytical approach. Their results indicate that, using convertible securities, the ex ante agreed optimal exit strategy can be achieved. Gerasymenko and Arthurs [29] empirically prove the positive effects of a VC firm's forecast of IPO exit on the breadth of its advice and the possibility of founder-CEO replacement.

Although these studies have adequately discussed the determinants and consequences of a VC's successful exit, little research has been done to investigate the potential factors that can significantly affect the successful exit of the entire VC alliance. By recognizing a joint VC's unique advantages in improving investment performance based on

Table 1: The determinants of VC's successful exit.

Perspective	Factors	References
VC firm perspective	Syndicate size (the scale of joint VC), age, round of investment, investment experience, partnership	[17–20]
Entrepreneurial firm perspective	Industry, stage of development, stage of technological development, geographical location, investment duration, total amount of investment	[17–20]
VC fund perspective	Fund age, old fund, fund size	[18]
VC market perspective	VC industry competition, IPO market conditions, market depth	[20]

the information superiority of strategic alliances [9], joint investments are widely adopted by VC firms in the current market. Given that network structures significantly affect the alliance formation and information superiority of joint VCs [16, 30], VC alliances with different network structures are expected to have different possibilities of successful exit. Therefore, it is necessary to empirically examine the successful exit of a VC alliance from a social network perspective.

2.3. Social Network and Venture Capital's Successful Exit. VC alliance generates different collaboration and communication networks. Social network analysis thus adopts a curial approach to analyzing the characteristics of these networks. A few studies have investigated VC firms' successful exit from a social network perspective. Dai et al. [17] indicate that firms with both foreign and local VC partnership are more likely to successfully exit the investment. Jääskeläinen and Maula [31] examine the impacts of financial intermediaries' direct and indirect network ties on a VC's successful exit. Their results show that, as a critical dimension of distance in addition to its cultural and geographical dimensions, network distance (network ties) directly affects the likelihood of a VC firm's successful exit. Meschi and Wassmer [32] empirically examine the influence of structural embeddedness (including centrality and network density) on the successful exit of international joint ventures. Hochberg et al. [2] and Nie et al. [21] investigate the influence of network position (i.e., degree centrality, closeness, betweenness, and density) on the success of VC investment (which is operationalized as the exit through IPO). However, these studies have focused only on the impacts of structural embeddedness on a VC firm's successful exit. In addition, by utilizing the studies in a mature market (i.e., the US VC market), they found that a better network position (i.e., a higher level of network centrality) would positively contribute to the success of VC investment. To fill these research gaps and examining whether the network position still significantly affect VC success in an emerging market, we empirically investigate how both interorganizational and intraorganizational network structure affect a VC alliance's successful exit in the Chinese market.

3. Research Hypotheses

By summarizing previous literature on social network analysis (e.g., [17, 33–36]), we investigate the impacts of both interorganizational and intraorganizational network structure on the successful exit of VC alliances. Interorganizational network structure of a VC alliance describes the structure of all members' network positions, which directly measures the structure of ties among VC firms. On the contrary, by measuring the relationship between investors (i.e., VC firms) and investees, intraorganizational network structure captures the status of the ties between VC firms and investees. Thus, all the possible relationships among key actors (i.e., investors and investees) in the VC ecosystem are included in our analysis.

3.1. Interorganizational Network Structure. We investigate the impacts of interorganizational network structure from three aspects: information heterogeneity, network cohesion, and network compactness.

3.1.1. Information Heterogeneity. The superiority of information heterogeneity of the VC alliance can promote the investee's development. Specifically, it helps alliance members eliminate redundant partners and devote more efforts to managing complementary connections. The VC alliance thus can increase its information-search efficiency and capture more useful information, thereby not only encouraging investees to develop more competitive products and service but also monitoring investees' operations better. In addition, the superiority of information heterogeneity of the VC alliance could increase investees' market influences. It makes benefits for VC firms to obtain unique information from heterogeneous fields [37]. Thus, the VC alliance with the superiority of information heterogeneity can comprehensively identify its opportunities and challenges and provide better suggestions for the investee. Thus, the VC alliance's advantages in the area of heterogeneous information search promote the investee's development, thus increasing the VC alliance's likelihood of successful exit. Therefore, we hypothesize the following.

Hypothesis 1. (H1). A venture capital alliance is more likely to successfully exit when its capacity for controlling heterogeneous information increases.

3.1.2. Network Cohesion. Network cohesion reflects the closeness of the connection between an alliance member and other members. A higher level of network cohesion indicates a larger amount of social capital that can form trust and collaborative relationships [38]. The social capital that is increased can promote the consistency of internal members' behaviors, produce consistent behavioral expectations, and increase the efficiency of decisions and behaviors [39]. Thus, relying on close connections with other VC firms, a VC firm can increase its capacity for information search to guarantee its investee's healthy development and deliver that investee's value to the VC alliance. However, its investment opinion would be limited in a small scope and is likely to produce herd behaviors because of high network cohesion. During the early stage of the VC market, VC firms' overall capacities to reduce information asymmetry are weak and most VC firms are active in a small group because they usually invest in a few industries to form their expert fields because of the shortage of information resources. If the VC firm has more connections in the small group, its decision is more affected by the constraints of the group, and it is more likely to emulate others' behaviors. Thus, although increased social capital can improve a VC firm's capacity to acquire information, the firm also becomes much more reliant on other members, likely causing herd behaviors. We therefore hypothesize the following:

Hypothesis 2. (H2). When a VC alliance's network cohesion is increased, the alliance is more affected by the constraints of VC market information, and its likelihood of successful exit decreases.

3.1.3. Network Compactness. According to social network theory, network compactness [40] is related to the efficiency of problem solving, perception of leadership, and the personal satisfaction of participants. The VC alliance with a higher level of network compactness can promote the investee's development, monitor the investee's operations, and provide necessary support for the investee to increase market reorganization. In the context of an emerging market, a VC alliance's network compactness is more likely to negatively affect its successful exit because the alliance has the speculative motivation to increase its reputation by raising IPO-based short-term cash. This type of speculative motivation is not beneficial for increasing the depth of the enterprise's incubation. On one hand, a VC alliance pays more attention to short-term benefits. Most VC firms in the Chinese market are quite young and need to increase their self-reputation and competitive abilities through their investees' IPOs. To accelerate the IPO process, a VC alliance might not consider an enterprise's long-term development or enhance the depth of its incubation. When an alliance exhibits a higher level of network compactness, its industrial influence will increase. Thus, the higher compactness alliance has greater capacity to promote enterprises that engage in short-term-based strategies, thus negatively affecting the success of the investment. On the other hand, a VC alliance's support for an investee is more likely to decrease. The higher compactness network would continuously focus its resources on the investee that can raise short-term cash through an IPO because the member can observe more investment opportunities depending on its network superiority. Thus, when an investee's product value and market share cannot support an investor's need for IPO-based short-term cash, the alliance with higher compactness is more likely to exit through M&A or stock right transfer. The investee's obtained support thus would decrease. Therefore, in the Chinese VC market, the higher compactness of the VC alliance is more likely to have a negative impact on its successful exit based on the investment incentive of establishing a short-term reputation. We thus hypothesize the following:

Hypothesis 3. (H3). The higher network compactness of the VC alliance is more likely to have a negative impact on its successful exit based on the investment incentive of establishing a short-term reputation.

3.2. Intraorganizational Network Structure. Intraorganizational network structure focuses on information sharing relationships among alliance members, which can reflect members' capacities for understanding information. We investigate the impacts of intraorganizational network structure from two aspects: ties to investee and alliance size.

3.2.1. Ties to Investee. Abundant ties to investees help VC firms share more personal and implicit knowledge, such as strategies and profit margins. Because implicit knowledge is tacit, viscous, and difficult to imitate [41], network members find it difficult to identify, copy, and merge, and it is difficult for a VC alliance to acquire such information based on network location. The increase in the number of ties to investees promotes the transformation of implicit knowledge, the formation of information-sharing customs, and even the collaborative solution of problems [42]. However, such an information-sharing relationship between a VC alliance and its investee that is too close can cause the over-relational embeddedness problem, decreasing the likelihood of the VC alliance's successful exit. According to the analysis of over-relational embeddedness [43, 44], trust is considered the foundation of the existence of relational embeddedness. A VC alliance's over-trust in its investee is considered to be the over-relational embeddedness problem. More specifically, if a VC alliance is too close to the investee, the alliance not only is more likely to over-believe in the investee's positive and optimal behaviors [43] but also finds it difficult to identify the firm's irrational investment behaviors and the "inside story" underlying a healthy transaction [44]. Therefore, the investee's development is negatively affected, and we hypothesize the following:

Hypothesis 4. (H4) A greater number of ties between a venture capital alliance and its investee negatively affects the alliance's successful exit.

3.2.2. Alliance Size. The size of the alliance significantly affects the scope and quality of the information that can be obtained by the VC alliance. The likelihood of successful exit thus is influenced by the size of the VC alliance [19]. According to the theory of "implicit contract," the VC alliance and the investee have greater capacities and incentives to promote the investee's IPO when the size of VC is increased [25]. Thus, we hypothesize the following:

Hypothesis 5. (H5) The alliance size positively affects the alliance's successful exit.

4. Methodology

4.1. Data. The data was collected from the Zero2IPO database, which provides academic data services for VC/PE investment institutions, government, and investment banks. The data for all of the VCs from 2000–2013 in the Zero2IPO Database were collected as the initial sample, which contains 2365 VC firms and 7559 investees in 22 industries. After deleting the items with missing data (including investee data, partner data, or financing amount data), we obtain our final sample. There are 496 VC alliances invested by 630 VC firms. VC firms with higher levels of centrality are expected to have more market influence. Based on the analysis of network centrality, we find that each year's Top 50 VC firms play dominant roles in the Chinese VC market. According to the statistics, the number of IPO enterprises supported by these Top 50 VC firms covers 61% of IPO enterprises.

4.2. Network Construction. A VC alliance's network is constructed based on its past cooperation relationships with other firms. We use a dummy 0-1 indicator to code the past cooperation relationship between two VC firms, which takes the value of 1 if these two VC firms have previously cooperated and the value of 0 if they have not. A matrix of 0-1 type that can reflect a VC firm's cooperation history is obtained after the coding; that matrix is considered the VC firm's social network. We establish each VC firm's network in a four-year window. For instance, the VC firm's interorganizational network structure in the year 2013 is calculated by its network connections from 2010–2013. Similarly, VC firms' intraorganizational network structure in 2012 is computed by its network relationships during 2009–2012.

4.3. Measurement. The unit of analysis in this study is VC alliance. We firstly ensure the concepts of the joint VC firm's network and VC alliance used in this study. Compared to the case in which the VC alliance begins the investment, the impacts of networked information superiority on a VC alliance's successful exit are more obvious and serious when the alliance exits the investment. Moreover, it is only when the VC alliance exits the investment that networked information superiority can comprehensively reflect the alliance's support intensity for the investee throughout the VC process. Therefore, the VC alliance refers to the set of all VC firms when the alliance exits the investment. For instance, a successfully exited VC alliance is the set of all VC firms that support the enterprise's IPO. In addition, the VC alliance's network is measured by the information-sharing relationship formed by all VC firms in the process of joint investment before the alliance's exit.

4.3.1. Dependent Variable. Given that an IPO is the most profitable way for a VC alliance to exit the investment [12], we denote the dependent variable, the VC alliance's successful exit (SE), as whether the alliance exits the investment through IPO, which takes the value of 1 if the alliance exits through an IPO and the value of 0 if the alliance does not exit through an IPO.

4.3.2. Independent Variables. We measure the interorganizational and intraorganizational network structure of VC alliances based on prior social network studies. With the superiority of information heterogeneity, there will be fewer redundant connections, and the marginal benefits of information will increase [37]. The structural hole measures the network members' capacities to acquire heterogeneous information and control other members' informative communications. Thus, the alliance member can use the advantages of the structural hole to increase its variety of perspectives and opinions, obtaining additional benefits through the cumulative and nonredundant network [45]. The Burt constraint index can effectively reflect an alliance member's lack of structural holes [45]. Researchers often use the differentiation between 1 and the Burt constraint index to measure the richness of structural holes [36], which can reflect the number of a VC firm's structural holes. The VC firm with a lower Burt constraint index exhibits more structural holes and a higher level of information heterogeneity superiority. Based on the former assumption, the VC firm j's Burt constraint index (C_j) is given as

$$C_j = \sum_{l=1}^{M} C_{jl} = \sum_{l=1}^{M} \left(P_{jl} - \sum_{q=1}^{M} P_{lq} \cdot P_{ql} \right)^2, \quad j \neq l \neq q, \tag{1}$$

where C_{jl} is a measure of the VC firm j's dependence on the VC firm l and P_{jl} represents the proportion of the VC firm j's network time and energy spent on the VC firm l. In particular, $P_{jl} = Z_{jl}/\sum_q Z_{jq}$ and variable Z_{jl} measures the strength of connection between the VC firm j and l. The calculations of P_{lq} and P_{ql} are the same as the computation of P_{jl}. We measure the VC alliance i's information heterogeneity as the maximum structural hole of the alliance members. Mathematically,

$$\text{heterogeneity}_i = \max_{j=1,2,\ldots,M} \left\{ 1 - C_j \right\}. \tag{2}$$

VC alliance's network cohesion can reflect its connection with other network members, indicating the degree to which it can obtain support or constraint from the networked information resources. A member's network cohesion is measured by network density, which is computed as the ratio of its real connections with other members and all potential connections in the alliance. The maximum network density of the VC firm in the alliance is employed to represent the VC alliance's network cohesion. Suppose that the VC firm j has T_j connections with other members and there are M VC firms in the VC alliance i. Thus, the alliance's network cohesion is calculated as

$$\text{cohesion}_i = \max_{j=1,2,\ldots,M}\left\{\frac{T_j}{[M(M-1)]/2}\right\}. \quad (3)$$

According to Freeman [34], network compactness is measured by the network centrality. In the network of VC alliance, a VC firm's centrality is represented by the number of other VC firms that are directly connected with it [9]. In this study, we define the VC alliance's network centrality as the maximum degree of centrality of the VC firms in the alliance. Suppose that the VC alliance i is formed by M VC firms and that there are N_j ($N_j \leq M$) VC firms connected with the VC firm j. Then, the VC firm j's network centrality is N_j and the alliance i's network compactness is

$$\text{compactness}_i = \max_{j=1,2,\ldots,M}\{N_j\}. \quad (4)$$

Furthermore, prior studies (e.g., [46, 47]) have widely used the term "past cooperation relationship" among network members to measure the impact of relational embeddedness, thus providing theoretical foundations for this research. If the VC firm participates in additional rounds of financing, its implicit knowledge is deeply shared and its cooperation relationship with others will be enhanced. Thus, the total number of investment rounds in which the VC firm participates can better reflect its degree of information sharing with others. The VC alliance's ties to investee is measured by the maximum number of financing rounds in which the VC firm (in the alliance) participates. Suppose that the VC firm j (in alliance i) has participated in R_j rounds of joint investments. In that case, the VC alliance i's ties to investee is given as

$$\text{relationship}_i = \max_{j=1,2,\ldots,M}\{R_j\}. \quad (5)$$

The alliance size (Size_i) is computed by the number of VC firms in the alliance.

4.3.3. Control Variables. Regardless of these network characteristics, there are other important factors that significantly affect how a VC alliance exits. Prior related studies [48, 49] have claimed that when an alliance member's investment experience (Experience_i) increases, the VC alliance's personal information superiority also increases, thus promoting the alliance's successful exit. Sorensen [49] believes that the total number of rounds of investment better represents a VC firm's investment experience. We thus employ the VC firm's maximum total investment rounds in the alliance to measure the variable of the VC alliance's investment experience.

Moreover, the round of investment (Round_i) is also highly correlated to the VC alliance's likelihood of successful exit [2]. The investee in the previous VC round is expected to be less mature. VC support is thus more important in the previous round. We choose the VC firm that has the most influence (i.e., the largest value of network centrality) in the alliance as the research subject. A dummy variable is introduced to indicate whether the VC firm with the largest centrality participates in the first-round investment, which takes the value of 1 if it is involved in the first-round financing and 0 otherwise.

Furthermore, the market depth (MarketDepth_i) at the stage of the enterprise's IPO is composed of floating capital and the market space for IPO enterprises. This type of market depth also influences the investee's IPO process. We use the total number of successfully exited VCs during the year to measure the market depth during that year.

In addition, to avoid potential omitted variable bias, we include time fixed effects and industry fixed effects in the empirical model. In the VC market, the strategies and performances of VC alliances are related to the environmental factors that are specific to different years. Therefore, we include the year dummies (Year_t) in the model to account for the time fixed effects. Since different industries may have specific environmental characteristics, such as industry competition, centralization, and growth, we also include the industry dummies (Industry_i) to control for the industry fixed effects.

4.4. Empirical Approach. Based on a Probit model, we conduct a regression analysis of the VC alliance's likelihood of choosing the IPO method of exit to analyze the impacts of network structure on the VC alliance's successful exit. The Probit model used in both the prediction and validation models is given as follows:

$$\begin{aligned}\Pr(\text{SE}_i = 1) = {} & \beta_0 + \beta_1 * \text{Heterogeneity}_i + \beta_2 * \text{Cohesion}_i \\ & + \beta_3 * \text{Compactness}_i \\ & + \beta_4 * \text{Relationship}_i + \beta_5 * \text{Size}_i \\ & + \beta_6 * \text{Experience}_i + \beta_7 * \text{Round}_i \\ & + \beta_8 * \text{MarketDepth}_i + \beta_9 * \text{Year}_t \\ & + \beta_{10} * \text{Industry}_i + \varepsilon_i,\end{aligned} \quad (6)$$

in which SE_i, Heterogeneity_i, Cohesion_i, Compactness_i, Relationship_i, Size_i, Experience_i, Round_i, and MarketDepth_i refer to the VC alliance i's successful exit through IPO, capacity for controlling information heterogeneity, network cohesion, network compactness, ties to investees, alliance size, investment experience, the round of investment, and the market depth at the stage of the enterprise's IPO, respectively. Year_t and Industry_i refer to the time and industry fixed effect. ε_i denotes the error term.

5. Results

5.1. Descriptive Statistics and Correlation. The summary statistics and correlations of key variables are reported in Table 2. The results indicate significant differences among VC alliances in terms of their network structure and other characteristics. Academic researchers have widely acknowledged that multi-collinearity is serious only when correlations are higher than the critical value of 0.70 [50, 51]. The correlations of key variables in this research are all lower than the threshold, thus indicating that serious multi-collinearity does not exist among independent variables.

Table 2: Descriptive statistics and correlations of variables.

Variable	Mean	Std.	1	2	3	4	5	6	7	8
1. SE_i	0.82	0.38								
2. $Size_i$	1.15	1.70	0.07							
3. $Experience_i$	4.48	93.05	0.09	0.19						
4. $MarketDepth_i$	5.21	81.74	0.23	0.03	0.24					
5. $Round_i$	0.72	0.45	0.04	−0.14	−0.01	−0.04				
6. $Compactness_i$	3.53	24.73	0.02	0.27	0.69	0.16	0.01			
7. $Heterogeneity_i$	−0.18	0.14	0.09	0.17	0.37	0.13	−0.01	0.72		
8. $Cohesion_i$	−1.27	0.19	−0.13	0.09	−0.29	−0.24	0.03	−0.28	−0.28	
9. $Relationship_i$	0.41	0.84	−0.12	0.35	0.13	−0.04	−0.20	0.13	0.12	0.08

5.2. Results of Prediction and Validation Models. The results of regression models on a VC alliance's successful exit are summarized in Table 3. Column 2 shows the regression results of the main estimation model. Columns 3 and 4 show the results of robustness tests which will be introduced in the next section.

5.2.1. Interorganizational Network Structure. The parameter estimate for the information heterogeneity is both significant and positive ($\beta = 1.256$, $p < 0.05$), thus supporting H1 and indicating that the VC alliance is more likely to successfully exit if it holds more heterogeneous information resources. Furthermore, in support of H2, we find that network cohesion has a negative impact on the VC alliance's successful exit ($\beta = -0.263$, $p < 0.10$), indicating that the VC firm would be more constrained if it has more connections with other firms in a small investment group. Consistent with H3, a VC alliance's network compactness negatively affects its likelihood of successful exit ($\beta = -0.679$, $p < 0.01$), indicating that, under the incentive of short-term cash through an IPO to increase market reputation, if the VC alliance has a higher capacity to influence its investee's behaviors, the incubation depth for the investee would be decreased, ultimately decreasing the likelihood of the VC alliance's successful exit.

5.2.2. Intraorganizational Network Structure. The results also indicate that the ties between the VC alliance and the investee (ties to investees) is negatively correlated with the alliance's successful exit ($\beta = -0.345$, $p < 0.10$), thus supporting H4. The intuition for the obvious negative impact is that the VC alliance cannot effectively control over-trust problems caused by a deep information-sharing relationship. Furthermore, a VC alliance's capacities to acquire implicit knowledge through an information-sharing relationship might be too weak. Usually, the enterprises supported by VC are highly innovative, and the process of technology innovation is a long, complex journey. These increase a VC alliance's difficulty in identifying high-quality projects. In addition, the VC alliance's internal information-sharing mechanism might not be perfect. VC firms thus find it difficult to transfer high-quality information and make full use of implicit knowledge that they have obtained. Therefore, the VC alliance could increase the effectiveness of information usage by enhancing internal group learning and sharing more complementary information. The results also demonstrate that the alliance size significantly and positively affects the VC alliance's likelihood of successful exit ($\beta = 0.219$, $p < 0.01$), in which H5 is supported.

Table 3: The results of regression analysis and robustness tests.

Variable	Main model	Robustness test 1	Robustness test 2
$Size_i$	0.219***	0.223***	0.220***
	(3.484)	(3.489)	(3.485)
$Experience_i$	0.005***	0.006***	0.005***
	(2.934)	(2.955)	(2.940)
$MarketDepth_i$	1.578***	1.588***	1.572***
	(3.332)	(3.333)	(3.317)
$Round_i$	0.239	0.242	0.239
	(1.256)	(1.269)	(1.258)
$Compactness_i$	−0.679***	−0.677***	−0.682***
	(−3.443)	(−3.433)	(−3.453)
$Heterogeneity_i$	1.256**	1.245**	1.263**
	(2.399)	(2.375)	(2.406)
$Cohesion_i$	−0.263*	−0.269*	−0.264*
	(−1.721)	(−1.748)	(−1.723)
$Relationship_i$	−0.345*	−0.353*	−0.365*
	(−1.762)	(−1.775)	(−1.774)
$Year_t$	Included	Included	Included
$Industry_i$	Included	Included	Included
Pseudo R^2	0.248	0.249	0.249

Notes: $N = 496$; coefficients are shown and robust t-values are in parentheses; significance level: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.10$.

5.2.3. Control Variables. The results demonstrate that the VC alliance's investment experience and market depth all significantly and positively affect the VC alliance's likelihood of successful exit. However, the round of the largest-centrality VC firm that joins the alliance does not significantly affect the VC alliance's likelihood of successful exit. The intuition is that a serious information-asymmetry problem widely exists at all stages of an enterprise's development. The VC alliance therefore should not ignore information asymmetry problems in any development stage.

5.2.4. Fixed Effects. To avoid potential endogeneity bias, we consider the fixed effects of time and industry on a VC alliance's successful exit (due to space limit, the fixed effects of time and industry are provided upon request.). Generally, a VC alliance is more likely to exit through IPO in the 2005-2006 bull market, but the difficulty of a VC alliance's successful exit has increased in the current bear market, especially in 2010-2011. Thus, a VC alliance should seize the opportunities during the rising period of a capital market to promote its successful exit. When a VC alliance refers to the fixed effects of industry, it is more likely to successfully exit in the following two types of industries: emerging markets such as financial services and clean energy technologies and industries with mature technological standards such as chains and retail, automobile manufacturing, and machine manufacturing.

5.3. Robustness Checks. In addition, to ensure effective and stable results, we develop the validation model by conducting the robustness test based on two aspects. First, the VC firm's network structures are distinct in different time windows. We establish the four-year window network structure in the main model. Therefore, we conduct the robustness test by using the five-year window of the VC firm's network structures. The results are shown in "Robustness Test 1" (column 3) of Table 3. Second, we compute the mean of the alliance members' network structure to measure the VC alliance's network structure. For instance, a VC alliance's compactness is calculated based on the average of all of its members' degree centrality. The results are summarized in "Robustness Test 2" (column 4) of Table 3. When referring to the results of the robustness checks as shown in Table 3, we find that the results in a five-year window (in Robustness Test 1) are consistent with the results in the four-year window (in main model). In addition, as shown in the results of Robustness Test 2, the results are also similar to the main model. Therefore, we conclude that our results are both effective and stable.

6. Conclusion and Discussions

In this paper, we have empirically analyzed the impacts of network structure on a VC alliance's successful exit (i.e., exit through IPO) at the initial stage of VC development. By empirically testing these hypothesized relationships through joint VC data in China for 2000–2013, we find that a VC alliance's network compactness, network cohesion, and ties to investee negatively affect its successful exit. In addition, the capacity of controlling information heterogeneity has a positive impact on its successful exit. These results indicate that, in addition to the fact that VC alliance can exert a positive effect on successful exit by obtaining heterogeneity information, there are some particularities manifested in the following aspects. First, it is not conducive to deepening the enterprise value chain to establish credibility by obtaining short-term cash during an IPO with the enhancement of a VC alliance's ability to intervene in the development of enterprises. Second, a VC alliance's independent judgment is bound by the VC market. Third, the problem of over-trust in investees reduces the likelihood of a VC alliance's successful exit. Therefore, we should pay more attention to the particularity of emerging markets such as China to improve VC performance. VC firms, entrepreneurial firms, and social planners are all guided by our results to implement better strategies and policies to promote VC development in an emerging market.

This study makes several theoretical contributions to the literature. First, we investigate a VC's successful exit from the social network perspective. Compared to previous studies that largely explore the determinants of a VC's successful exit from both the VC (including VC firm, entrepreneurial firm, VC fund, and VC market) and the macroeconomic environment perspectives [17–20], we have empirically investigated the impacts of a VC alliance's network structure on its successful exit from the social network perspective. In addition, unlike most prior studies of a single VC firm's successful exit, we explore the determinants of a VC alliance's successful exit. Given that VC alliance is beneficial for improving investment performance based on the information superiority of strategic alliances [9], joint investments are widely adopted by VC firms in the current market. Therefore, understanding the successful exit of the entire VC alliance is valuable in the context of collaborative culture. Furthermore, this research provides a more holistic understanding of a VC alliance's successful exit from the social network perspective. By investigating the influences of both interorganizational and intraorganizational networks (i.e., information heterogeneity, network cohesion, network compactness, ties to investee, and alliance size) on a VC alliance's successful exit, we contribute to related studies that only examined the impacts of VC's centrality and network density on its successful exit [17, 31, 32].

This research also has several practical implications for VC firms, entrepreneurial firms, and social planners. First, VC firms should join the VC alliance with more heterogeneous information and not select an alliance that exhibits a high level of reliance on a single VC firm. In the process of VC alliance operation, alliance members should make full use of each member's advantages, enhance their collaborative efficiency, and cultivate investees' long-term value. Meanwhile, to alleviate the over-trust problem, alliance members should further perfect the mechanism of stock option incentives and improve the principal-agent problem between investees and the VC alliance. Second, entrepreneurial firms should not only actively communicate with the VC firm with higher impact in the alliance but also strategically use the information structure of VC firm-investees-market to promote market recognition of its value. Third, from the social planner perspective, given that VC firms generally lack information on R&D capacities and the VC market system is imperfect, the VC market is quite sensitive to government policy. Government thus can guide the VC market's value orientation by supporting leading VC firms to strengthen VC's support for emerging industries.

Although this work provides a more comprehensive understanding of VC alliances' successful exit from the social network perspective, it also has several limitations. First, we have focused on the influences of network structure at the alliance level. Whether the network attributes of various roles (such as leaders, followers, and herd leaders) in the VC alliance have different impacts on a VC alliance's successful exit is not examined. Future research should investigate various alliance members' network value and its impact on a VC alliance's successful exit. Second, we hypothesized and tested the linear relationship between network structure and a VC alliance's successful exit. However, these relationships might be U-shaped [52] or inverted U-shaped [53, 54]. Therefore, we should further discuss the shapes of these relationships in future research. Third, we only considered the effects of network structure on a VC alliance's likelihood of exit through IPO. How these network structures affect a VC alliance's choice of other exit methods such as M&A should be investigated in the future.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

The Influence of Interlocking Directorates on the Propensity of Dividend Payout to the Parent Company

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An examination was performed on whether director interlocks enabled the adoption of a dividend policy for the benefit of the parent company in the ownership structure. Specifically, the study investigated the dependence of the impact of the central position in the board network on the probability of dividend payment. Based on sample of firms listed on Polish capital market, it was observed that the more central the company's position in the interlocking directorate network, the more likely it is to pay dividends to a subsidiary. This effect is related to the eigenvector centrality. The results obtained suggest that corporate financial policy can be spread across firms through the board network.

1. Introduction

The network of business connections through the interlocking directorates is a complex network. A complex network can be described as a graph that consists of vertices and edges that reveal topological properties and interrelationships [1]. The participation of a company in a network with such properties results in diversification of emerging effects whose impact on the network diffusion of multiple corporate practices is highly complex through nonlinear interactions between a large number of individual components of the entire system. The inability to explain the overall functioning of the system by determining the properties, structure, and understanding of the operation of separate components of the system constitutes a complex system.

The network perspective sees markets in the form of business networks [2]. One of the possible network connections is interlocking directorates. A relationship is created when one person sits in the boards of at least two companies. Interlocking directorates exist globally and have been studied by management scholars, economists, and organizational sociologist [3].

Pfeffer and Salancik [4] described board networks as a form of interorganizational relationship that facilitates interaction between the company over time. The links thus created between several enterprises lead to the creation of a communication network in which information flows. A communication network is a system of relationships created by the flow of data, information, knowledge, images, symbols, and other forms of messages between selected points of the network among objects in time and space [5]. Interlocking directorates are a common element of the capital market in geographical and temporal space, resulting from corporate governance. The theory of social networks suggests that interorganizational networks have the ability to influence relationships among enterprises, are also carriers of information from the external environment of organizations and are used as mechanisms of diffusion of organizational practices, including financial policies of enterprises.

The board of directors and the interlocking directorate network created through it is an important element of corporate governance. The company often consciously decides to establish relations with other companies by joining the interlocking network. This can be carried out by accepting an external board member from another organization or by delegating a director to the board of directors of another company. In this respect, the relational strategy can be discussed. Relationship strategy using interlocking directorates is the most flexible and easily implemented [4] as well as the most widely used in the external environment of the organization [6, 7]. This strategy is applied especially in cases where the enterprise operates in conditions of uncertainty, interorganizational interdependence, control of other organizations, organizational complexity, concentrated ownership structure, and inability to legalize ownership links. Access to information and organizational practices of other companies are the main benefits of interlocking, which leads to higher board of directors' effectiveness [8]. The information obtained from the network may be used by the board of directors to assess the situation of their own company and planned actions. The board of directors is therefore the key to the success of the relational strategy.

The interlocking directorate network enables the mechanism of diffusion of ideas, strategies, practices, and organizational solutions. For a company, the application of a relational strategy using its own board of directors in the creation of relationships in the interlocking network enables the launch of a channel for the adoption of business practices. In other words, participation in the board network enables the absorption of knowledge. Launching and maintaining this channel through the interlocking directorate network are achievable at low cost.

The aim of the paper was to analyze the impact of participation in the interlocking directorate network on the decision to pay dividends. The spread of dividend policy between firms in the corporate board network was examined. In particular, an attempt was made to answer the research question whether board interlocks ties in the network increase the probability of dividend payment to the parent company? In other words, is there a network diffusion of organizational practice concerning dividend policy? These questions identified a research gap in the literature, where the aim of the research was to fill this gap.

Network analysis suggests that information diffuses through networks, and firms that occupy a privileged position in the network can make more sophisticated (or informed) decision [9] in various areas of business management. It is believed that taking the central position of a company in the board interlock network increases the probability of paying dividends to the parent company. This effect relates to eigenvector centrality, i.e., centrality, which is measured by the number of relationships with other companies in the network and their level of centrality. To the best our knowledge, this research is the first to show that the dividend policy in favor of the parent company in its ownership structure may be adopted through the board interlock network. It was only at work [10] that the adoption of the interlocking network dividend policy was discussed, but the subject of the study was the payment of dividends to all the shareholders and not only to the subsidiary. The adoption of a decision to pay dividends via the interlocking network has a direct impact on the cash flow to shareholders. The results obtained in this research suggest that corporate financial policy can be spread across firms through the board network.

This study contributes to the corporate governance, corporate finance, and social network literature. Firstly, ownership structure and conflicts of interest are part of corporate governance. The results obtained show that corporate governance should be perceived not only from the point of view of strictly economic issues but also from the point of view of interorganizational relations, assuming that organizations are not isolated individuals. The conducted relational strategy determines the complex structure of the corporate network.

Secondly, this research also adds novel insights to the literature on the impact of social networks and especially the role of director networks on corporate finance. The results of the research document the impact of information flow and diffusion of organizational practices in the board network in the area of corporate finance.

Thirdly, this research contributes to the discussion on the influence of social networks in the form of interlocking directorates on behaviors and decisions made in the organization. Network analysis tools allow for the detection of network structures that are important for the organization.

The paper is organized as follows. Section 2 presents the theoretical foundations and hypotheses. Section 3 presents the research method, research sample, and process of obtaining data. It also describes the variables used in the empirical part. Section 4 is devoted to presentation of the results of the research, and the paper closes with the discussion and final conclusions.

2. Theoretical Foundations and Hypotheses

The basic assumption of the research is the observation that the enterprise network is a medium of information flow and the spread of corporate practices across companies. The literature on the subject provides many examples of diffusion of strategies and business practices through the network. One of the first studies on a platform for diffusion of organizational practices through an interlocking network concerns the adoption of financial support for election campaigns by companies in the USA [11, 12]. Further research has shown that the following organizational solutions and business practices have spread through the network: enterprise philanthropy [13]; structuring the remuneration of board members [14, 15]; the dissemination of executive compensation practices [15–18]; poison pills [19, 20]; golden parachutes [20–22]; greenmail [23]; innovations [24–27]; new product introductions [28, 29]; multidivisional form (M-form) [30, 31]; creation of an investor relations department within the organization [32]; financial restructuring [33]; diversification [34]; board independence [35]; and implementation of quality standards [36]. In addition, the network enables strategy diffusion [37–39]; its diversification [7]; international expansion [40]; management styles [41–43]; decision-making process [44, 45]; and diffusion of business practices in general [46, 47]. An important element of the relational strategy is the ability to transfer tacit knowledge between enterprises, which is impossible to produce or acquire on the market [48–53]. Forming board interlocks increase the likelihood of forming an R&D alliance with the cooped enterprise [54] and auditor choice [55, 56]. A growing body of research examined the role of board networks in corporate financial policy, such as stock option backdating [57, 58]; changes in the quotations of own shares between stock markets [59]; earnings management [60–62]; accounting method choice [63]; stock option expressing [64, 65]; venture capital investments [66]; corporate-owned life insurance as a tax shelter [67, 68]; inclination to takeover other companies [69]; the payment of bonuses for acquisitions [70]; or firms become targets in change-of-control in private equity transactions [71]. It should be mentioned that sophisticated traders made by short seller, option traders, and institutional investors are more informed when trading stocks of enterprises with more interlocked boards [72]. In the field of corporate finance, it has been shown that ties in the board network reduce the implied cost of capital [73].

One of the characteristics of the interlocking directorate network is the existence of a structure called small-world networks [74–78]. In small-world networks, the structure of relationships between vertices is different from the random network structure, according to Erdös–Renyi graphs [79], and the structure of a regular network. The literature has shown that the interlocking directorate network in different time and geographical cross sections shows the characteristics of small-world networks [78, 80–91]. Also, the interlocking network on the Polish capital market shows the characteristics of small-world networks [92]. The structure of the interlocking network in accordance with the concept of small-world networks means that relationships among organizations in the network are created in a nonrandom manner. Numerous shortcuts in such a network make the speed of information flow in the small-world network higher than in the random or regular network [92]. A network with such a structure enables fast communication between unrelated organizations, even within two opposing poles of the network. The trajectory of information transfer covers even weakly networked enterprises located on the periphery of a network with a low level of centrality.

Board of directors is a significant part of the corporate governance structure [93, 94], as a bridge between the company and other organizations. Corporate governance mechanisms are based on principles from areas such as finance, management, and law [95]. Agencies, shareholders, management, and debt providers are three main areas of potential conflicts of interest [96]. The board of directors of a company is an important element of the internal corporate governance structure, which plays an essential role in improving the financial performance of a company [97]. The board performs critical functions in the form of monitoring, advice on strategic decisions [98], services, and provision of external resources from the organization's environment [99], where these roles are performed simultaneously [100]. One of the important functions of the board of directors is to participate in shaping the company's strategy and its implementation [101]. The role of the board of directors in the aspect of scanning strategies of other companies [7], obtaining information on the applied organizational and supervisory practices [102] and their potential adoption to their own organization, is particularly emphasized within resource dependences theory. An effective board of directors can be seen as a key corporate resource [103].

Formation of connections in the interlocking directorate network is explained on the ground of the resources dependence theory [4, 104, 105]. Resource dependence theory concludes that interlocks are welfare enhancing [3]. Relationships in the network result from the demand for resources controlled by organizations in the external environment of the enterprise. The resource dependence of an organization determines the level of uncertainty, which is further increased by the asymmetry of information. The established network links provide a response to the demand for resources and the ability to access information and coordinate activities. Acquiring resources from other organizations and reducing information asymmetry through links with other enterprises in the network translates into a general benefit which is a reduction in uncertainty. Diffusion of business practices is a prerequisite for applying a network relational strategy in the area of resources dependence theory. Based on the above-mentioned consideration the following proposition can be made.

Proposition 1. *The more central the position in the network, the greater the exposure to the network information flow, increasing the possibility of adopting business practices.*

Based on the experience of the networked board member, the board of directors can recommend the payment of dividends as a distribution of the company's net profit. The recommendation to allocate part or all of the net profit to dividend payment to shareholders may be dictated by the premise of increasing the company's value. Maximizing the value of an enterprise is the primary objective of its business. In accordance with the concept of value-based management, a properly defined and consistent dividend policy contributes to the increase of the company's value for shareholders. As a result, the parent company in the ownership structure accounts for a portion of the dividend due.

Company ties can be created not only via board network but also through ownership network [106]. Nicholson et al. [107] drew attention to the parallelism of networking through interlocking directorates in relation to the concentrated ownership structure. This is due to the fact that affiliated companies in the ownership network have the possibility to delegate their directors to the company board of directors of which they are the owners or major shareholders. The positive relationship between the board network and ownership network has been demonstrated in the works [86, 108–110]. The close relationship between the two types of corporate networks also indicates a greater degree of reconstruction of accidental broken ties in the board network where both organizations have a relation in the ownership network [111]. On the contrary, interlocking links can be seen as a flexible substitute for relations in the ownership structure [112]. Interlock board network is as a result not only of resource dependence but also of corporate control and intercorporate cohesion [113].

Relationships within the interlocking directorate network are also a tool for interorganizational coordination and control of other companies. On the one hand, a company sending its director to the board of another company (initiation of relations) creates the possibility of influencing the key decisions of the related organization. It is possible for a company to participate in the decision-making process of enterprises with which a relationship is established, increasing its strength and influence over other companies [113]. On the other hand, as Schoorman et al. [114] pointed out, for a host company, the outside director (the relationship of reception) risks losing partial autonomy and its own control over the organization's affairs and flexibility in decision-making. For an enterprise, this is the cost of participating in an interlocking network, expecting a number of benefits related to the transfer of knowledge, information, or diffusion of organizational solutions. With this in mind, there is another reason for recommending the payment of dividends to owners as a policy of redistributing net profit generated by a subsidiary to its parent company. This applies to situations where there is a legal transfer of cash to the entity owning the subsidiary. Moreover, information from other companies about the applied solution of cash distribution from the subsidiary to the parent company may result in the adoption of this form of redistribution and cooperation of related companies on a larger scale. These relationships are based on agency theory. On this basis, the following proposition can be made.

Proposition 2. *Board network links increase the control of related companies by shaping the dividend policy of the subsidiary in the light of the parent company's objective in the ownership structure.*

On the basis of the above-mentioned considerations, the following hypothesis has been formulated. The higher the firm's board interlock centrality is, the higher probability that the dividend will be paid.

3. Method

3.1. Sample and Data Collection. The study was carried out on an undirected network of enterprises established on the basis of their relationship through the boards of directors. The network included 945 companies listed on the main market of Warsaw Stock Exchange (SWE) and the NewConnect market (NC), at the end of 2015. The boards of directors include the members of the management boards and the supervisory boards collectively (a total of 6,228 people). The board network is undirected and unweighted described by a matrix containing a dichotomous variable, where the value 1 means that there is a connection through a person sitting on at least two boards of enterprises and the value 0 in the opposite case. The network is shown in Figure 1. The information about the people sitting on the boards of directors, as well as the economic data, was obtained from the Notoria service, as of the 31st of December, 2015 (the preparation of financial statements). The study therefore concerned cross-sectional data where data were collected at the end of 2015. Due to missing data, the number of companies in the sample was finally limited to 678 firms. The dataset for the study is included in the supplementary material of this article in the file "Dataset.xlsx" (available (here)). Table 1 presented global network indicators.

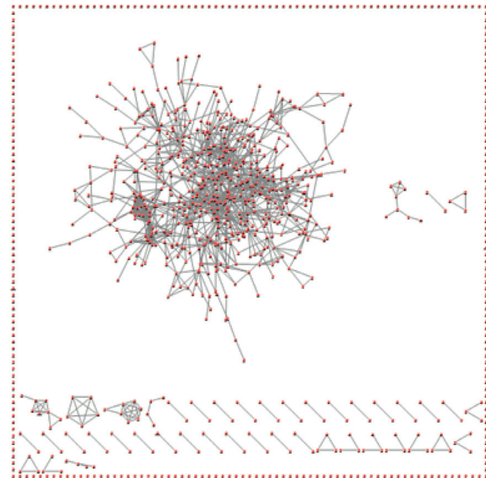

Figure 1: Network of interlocking directorates between Polish companies ($N = 945$). Visualization algorithm: stress majorization [115].

Table 1: Global indicators for the board network.

Variable	Value
Number of nodes (number of companies)	945
Number of people (members of the board of directors)	6,228
Degree for the entire network (total number of connections in the network)	2,698
Mean degree	2.86
Number of vertices in the largest component	542
Fraction of vertices in the largest component	57.4%
Number of isolated nodes	280
Number of connected nodes	665
Inclusiveness	70.37%
Network density	0.003
Network degree centralization index	2.35%
Network closeness centralization index	9.90%
Network betweenness centralization index	4.59%
Mean eigenvector centrality	0.005

3.2. Variables

3.2.1. Analytic Methods and Dependent Variable. Appropriate assessment of the impact of information flow in the interlocking network on the adoption of dividend payment practices was carried out using logistic regression. For this reason, the description of the variables adopted in the study was divided into dependent variable, independent variables, and control variables. In the logistic regression method, the dependent variable is the dichotomous variable. In the study design, a variable that determines whether the enterprise pays dividend to the parent company was adopted, taking two values, i.e.,

$$\text{Dividend} = \begin{cases} 1, & \text{when the enterprise paid dividend to the parent entity,} \\ 0, & \text{otherwise.} \end{cases} \tag{1}$$

Regression analysis for a dichotomous dependent variable can be performed using a logistic regression model, based on a logistic function, taking a general form:

$$P(Y = 1 \mid X) = \frac{e^{b_0+\sum_{i=1}^{k} b_i \cdot x_i}}{1 + e^{b_0+\sum_{i=1}^{k} b_i \cdot x_i}}, \quad (2)$$

where Y is the dichotomous dependent variable; X is the sequence of k dependent variables $(x_1, x_2, \ldots, x_k)$; b_i $(i = 0, 1, \ldots, k)$ is regression coefficients; and x_i $(i = 1, 2, \ldots, k)$ is independent variables.

The maximum likelihood method is used to maximize the likelihood function. The greater the reliability, the better the model fits the data, which means a higher probability of the dichotomous value of the independent variable appearing in the test sample. Logistic regression analysis was performed using Statistica software [116].

3.2.2. Independent Variables. The first independent variable is interlock, which determines whether a company has relationships in the interlocking network. This is a dummy variable that takes the value 1 if the company has at least one relationship in the network; 0 if otherwise.

In this study, the centrality measures were taken as network variables being a tool for measuring the degree of participation in the network structure and the possibility of absorbing information from it. The centrality measures are used to quantify the interconnection of vertices in the network [117], taking into account the network structure in the spectrum of direct and indirect connections. Centrality quantifies how important nodes are in the networked system [118]. For this reason, in this study, four measures were adopted as independent variables that measured the degree of centrality of an enterprise in the interlocking directorate network:

(1) *Degree centrality*

(2) *Closeness centrality*

(3) *Betweenness centrality*

(4) *Eigenvector centrality*

Each of the proposed measures determines the central position of the vertex in the network, although the concept of centrality is formed differently for each of them. The first three measures of centrality are the most common in the literature on social networks [117–126] and used in research [86, 127–132]. Degree is the number of edges connected to the vertex. Degree in a corporate network means the number of links with companies. *Degree centrality* is a simple centrality of network structure measured based on degree. It is computed by portion of nodes that are adjacent to each vertex. *Closeness centrality* is a measure of independence and resilience to influence [119], an index of the expected time of information flowing through the network [129]. *Betweenness centrality*, proposed in Freeman paper [117], is interpreted as the ability to control the flow of information in the network and to act as an intermediary of exchange between the other nodes [120], indicating the incidence of the vertex on the shortest path between the pairs of other nodes in the network. The *eigenvector centrality* takes into account the centrality of the nodes one is connected to, which means that the whole network model is taken into account [133]. It is a measure of the popularity and ability to transmit information through a connection with nodes that are also highly connected. This data were obtained using the NetMiner 4.4.3 [134].

3.2.3. Control Variables. In order to control the systematic variance of the impact on the payment of dividends, the following control variables have been taken into account regardless of the result in terms of the centrality of the node in the interlocking directorate network:

(1) Ln (Age), Ln (Assets), and Board size. Firm size and age were included as control variables. These variables control the firm size through the size of the board of directors, as well as the natural logarithm of the asset value and the time of listing the company on the stock exchange. It is expected that the longer the company is listed on the stock exchange and has a larger board of directors, the greater the propensity is to pay dividends.

(2) ROA, and ROA$\_{t-1}$. Return on assets in current year and lagged by one year. It should be noted that dividends are paid out of net profit (except when the company pays a privileged dividend and previous years). Return on assets as a profitability indicator is based on the net profit (net profit is divided by the value assets). The positive value of the profitability indicator, especially from the previous year, means that the net profit is higher than 0 and can therefore be transferred to the owners by the decision to pay dividend.

(3) Ln (Sales), Cash, Liquidity$\_{t-1}$*, and Ln (Leverage)*. The characteristics of the company's financial information that might affect dividend payment decision were accounted for in the logistic regressions. These control variables are the key performance indicators of the company used in the financial analysis of the company.

Table 2 presents the specification of variables used in regression models.

4. Models and Results

The descriptive statistics of the variables are presented in Table 3, and the correlation matrix with the significance coefficients are presented in Table 4.

In logistic regression analysis, the minimum size of a given group must meet the condition $N > 10(k + 1)$, where k is the number of independent variables. Therefore, the minimum group size for 14 independent variables is 151, which is fulfilled. The smallest group for companies that pay dividend is 240 cases, which is larger than the minimum group size. In addition, the total sample is 678 cases, which is much larger than the recommended sample of at least 500 elements.

The further part of the analysis presents the results of logistic regression analysis, where the dividend was adopted as the dichotomous dependent variable, and the modeling is for the dividend payment (Dividend = 1).

In the formulated hypothesis, it was predicted that the dissemination of corporate practices among board interlocks may influence a firm's dividend policy for the benefit of the

Table 2: Specification of variables used in regression models.

Type of variables	Variable	Operationalization
Dependent variable	Dividend	$\text{Dividend} = \begin{cases} 1, & \text{when the enterprise paid dividend to the parent entity} \\ 0, & \text{otherwise} \end{cases}$
Independent variables	Interlock	$\text{Interlock} = \begin{cases} 1, & \text{when the company has at least one relationship in the network} \\ 0, & \text{otherwise} \end{cases}$
	Degree centrality	The number of links with other companies in an interlocking network $DC_i = (d_i/(N-1)) = (\sum_{j=1}^{N} a_{ij}/(N-1))\,(i \neq j)$ where d_i is thedegree of vertex i, N is the number of vertices in the network, and a_{ij} is the elements of the adjacency matrix $\mathbf{A}$, where $a_{ij} = \begin{cases} 1, & \text{if there is a link between vertices } i \text{ and } j \\ 0, & \text{otherwise} \end{cases}$
	Closeness centrality	$CC_i = ((N-1)/\sum_{j=1}^{N} l_{ij})\,(j \neq i)$, l_{ij} is geodesic distance connecting i and j
	Betweenness centrality	$BC_k = (\sum_{i<j}(g_{ikj}/g_{ij})/((N-1)(N-2)/2))\,(i \neq j \neq k)$, where g_{ikj} is the number of geodesic paths connecting i and j through k and g_{ij} is the total number of geodesic paths connecting i and j
	Eigenvector centrality	$e_i = \lambda \sum_{j=1}^{N} a_{ij} \cdot e_j \ (i \neq j)$, where λ is the proportionality constant (eigenvalue), e_j is the eigenvector centrality score, and a_{ij} is the (i, j) entry of the adjacency matrix $\mathbf{A}$
Control variables	Ln (age)	The natural logarithm of the total years the company has been listed on Polish stock exchange
	Board size	Total number of persons on the board of directors
	Ln (assets)	The natural logarithm of the total assets
	ROA	Return on assets, ROA = (net profit/assets) · 100%
	ROA_$t-1$	Return on assets lagged by one year
	Ln (sales)	The natural logarithm of the revenue
	Cash	Ratio of cash flow to total assets
	Liquidity_$t-1$	Cash ratio lagged by one year (ratio of cash to payments required immediately)
	Ln (leverage)	The natural logarithm of the ratio of total long-term debt to total assets

parent company in the ownership structure. To test this prediction, we perform the following regression models:

$$
\begin{aligned}
\operatorname{logit} P &= \alpha_0 + \alpha_1 \operatorname{Ln}(Age)_i + \alpha_2 \text{BoardSize}_i + \alpha_3 \operatorname{Ln}(\text{Assets})_i + \alpha_4 \text{ROA}_i + \alpha_5 \text{ROA\_}t - 1_i + \alpha_6 \operatorname{Ln}(\text{Sales})_i + \alpha_7 \text{Cash}_i \\
&\quad + \alpha_8 \text{Liquidity\_}t - 1_i + \alpha_9 \operatorname{Ln}(\text{Leverage})_i + \varepsilon_i, \\
\operatorname{logit} P &= \alpha_0 + \alpha_1 \text{Interlock} + \alpha_2 \operatorname{Ln}(\text{Age})_i + \alpha_3 \text{BoardSize}_i + \alpha_4 \operatorname{Ln}(\text{Assets})_i + \alpha_5 \text{ROA}_i + \alpha_6 \text{ROA\_}t - 1_i \\
&\quad + \alpha_7 \operatorname{Ln}(\text{Sales})_i + \alpha_8 \text{Cash}_i + \alpha_9 \text{Liquidity\_}t - 1_i + \alpha_{10} \operatorname{Ln}(\text{Leverage})_i + \varepsilon_i, \\
\operatorname{logit} P &= \alpha_0 + \alpha_1 \text{Degree centrality} + \alpha_2 \operatorname{Ln}(\text{Age})_i + \alpha_3 \text{BoardSize}_i + \alpha_4 \operatorname{Ln}(\text{Assets})_i + \alpha_5 \text{ROA}_i + \alpha_6 \text{ROA\_}t - 1_i + \alpha_7 \operatorname{Ln}(\text{Sales})_i \\
&\quad + \alpha_8 \text{Cash}_i + \alpha_9 \text{Liquidity\_}t - 1_i + \alpha_{10} \operatorname{Ln}(\text{Leverage})_i + \varepsilon_i, \\
\operatorname{logit} P &= \alpha_0 + \alpha_1 \text{Closeness centrality} + \alpha_2 \operatorname{Ln}(\text{Age})_i + \alpha_3 \text{BoardSize}_i + \alpha_4 \operatorname{Ln}(\text{Assets})_i + \alpha_5 \text{ROA}_i + \alpha_6 \text{ROA\_}t - 1_i + \alpha_7 \operatorname{Ln}(\text{Sales})_i \\
&\quad + \alpha_8 \text{Cash}_i + \alpha_9 \text{Liquidity\_}t - 1_i + \alpha_{10} \operatorname{Ln}(\text{Leverage})_i + \varepsilon_i, \\
\operatorname{logit} P &= \alpha_0 + \alpha_1 \text{Betweenness centrality} + \alpha_2 \operatorname{Ln}(\text{Age})_i + \alpha_3 \text{BoardSize}_i + \alpha_4 \operatorname{Ln}(\text{Assets})_i \\
&\quad + \alpha_5 \text{ROA}_i + \alpha_6 \text{ROA\_}t - 1_i + \alpha_7 \operatorname{Ln}(\text{Sales})_i + \alpha_8 \text{Cash}_i + \alpha_9 \text{Liquidity\_}t - 1_i + \alpha_{10} \operatorname{Ln}(\text{Leverage})_i + \varepsilon_i, \\
\operatorname{logit} P &= \alpha_0 + \alpha_1 \text{Eigenvector centrality} + \alpha_2 \operatorname{Ln}(\text{Age})_i + \alpha_3 \text{BoardSize}_i + \alpha_4 \operatorname{Ln}(\text{Assets})_i \\
&\quad + \alpha_5 \text{ROA}_i + \alpha_6 \text{ROA\_}t - 1_i + \alpha_7 \operatorname{Ln}(\text{Sales})_i + \alpha_8 \text{Cash}_i + \alpha_9 \text{Liquidity\_}t - 1_i + \alpha_{10} \operatorname{Ln}(\text{Leverage})_i + \varepsilon_i.
\end{aligned}
\tag{3}
$$

Based on the correlation matrix, presented in Table 4, potential multicollinearity concerns can be eliminated. Because the correlation coefficients between variables separately for each model are all below 0.5, there is no potential multicollinearity issue for the variables.

Table 5 presents results of logistic regression.

Table 3: Descriptive statistics.

Variable	N	Mean	Std. dev.	Mean error	Min.	Median	Max.
Dividend	678	0.354	0.479	0.018	0.000	0.000	1.000
Interlock	678	0.709	0.454	0.017	0.000	1.000	1.000
Degree centrality	678	0.003	0.004	0.000	0.000	0.002	0.026
Closeness centrality	678	0.061	0.053	0.002	0.000	0.085	0.156
Betweenness centrality	678	0.002	0.004	0.000	0.000	0.000	0.047
Eigenvector centrality	678	0.006	0.034	0.001	0.000	0.000	0.325
Ln (age)	678	7.347	0.990	0.038	2.565	7.463	8.630
Board size	678	7.830	2.276	0.087	2.000	7.000	27.000
Ln (assets)	678	11.196	2.225	0.085	5.918	11.104	22.091
ROA	678	0.005	0.211	0.008	−1.840	0.028	1.505
ROA_$t-1$	678	0.016	0.202	0.008	−1.594	0.033	1.142
Ln (sales)	678	10.633	2.837	0.109	−2.510	10.802	22.135
Cash	678	0.018	0.119	0.005	−0.996	0.004	0.801
Liquidity_$t-1$	678	0.546	1.315	0.051	0.000	0.146	18.255
Ln (leverage)	678	0.218	1.189	0.046	−5.028	0.054	7.073

A strategy of hierarchical estimation was used. In model 1, the effect of the control variables on the dividend policy is presented. Only 3 out of 9 control variables are not statistically significant in relation to the dependent variables, Ln (Age), Ln (Assets), and Liquidity_$t-1$.

Model 2 contains the independent variable Interlock, which determines whether the company has a network strategy using interlocking directorates. The absence of statistical significance of the independent variable's regression factor means that the networking factor has no impact on the likelihood of dividend payment to the parent company. Subsequent models took into account a deeper aspect of the network structure of the analyzed phenomenon.

Models 3–6 checked the hypothesis formulated in the paper that the higher the firm's board interlock centrality, the higher the probability that the dividend will be paid. In each of models 3–6 there is a different independent variable for the measurement of the company's centralization in the board interlocks network. Independent variables for models 3–5 are not statistically significant in relation to the dependent variable. It means that degree, closeness, and betweenness centrality variables do not affect the likelihood of dividend payment to the parent company. Model 6 contains independent variables, eigenvector centrality, statistically significantly related to the dependent variable at the significance level of $\alpha = 0.01$. The final value of the loss function for model 6 is 327.415. The difference between the logarithm of reliability for model 6 compared to the model with only absolute term (B_0) is 226.40. This difference is statistically significant for $p < 0.001$, which means that the model is fitted because it differs significantly only from the model with the absolute term. This means that the eigenvector centrality and control variables significantly affected the probability of dividend payment.

Based on the assessment of the model parameters, the general form of model 6 is as follows:

$$P(Y=1|X) = \frac{e^{-7.013+8.027\text{Eigenvector centrality}+0.003\text{Ln (Age)}+0.103\text{Board size}-0.046\text{Ln (Assets)}+2.038\text{ROA}+2.926\text{ROA\_}t-1+0.52\text{Ln (Sales)}-4.214\text{Cash}+0.021\text{Liquidity\_}t-1+0.365\text{Ln (Leverage)}}}{1+e^{-7.013+8.027\text{Eigenvector centrality}+0.003\text{Ln (Age)}+0.103\text{Board size}-0.046\text{Ln (Assets)}+2.038\text{ROA}+2.926\text{ROA\_}t-1+0.52\text{Ln (Sales)}-4.214\text{Cash}+0.021\text{Liquidity\_}t-1+0.365\text{Ln (Leverage)}}}. \quad (4)$$

Considering additionally asymptotic standard errors, an equivalent form of model 6 was obtained:

$$\begin{aligned}\text{logit}\,P = &\underset{(0.939)}{-7.013} + \underset{(2.813)}{8.027}\,\text{Eigenvector centrality} + \underset{(0.102)}{0.003}\text{Ln (Age)} + \underset{(0.059)}{0.103}\text{Board size} - \underset{(0.105)}{0.046}\text{Ln (Assets)} \\ &+ \underset{(0.817)}{2.038}\text{ROA} + \underset{(0.887)}{2.926}\text{ROA\_}t-1 + \underset{(0.101)}{0.52}\text{Ln (Sales)} - \underset{(1.020)}{4.214}\text{Cash} + \underset{(0.103)}{0.021}\text{Liquidity\_}t-1 + \underset{(0.107)}{0.365}\text{Ln (Leverage)}.\end{aligned} \quad (5)$$

It should be noted that the pseudocoefficient R^2_{McFadden}, which is the equivalent of a determination coefficient for R^2 in standard regression analysis is 25.7%. Modifications of pseudo R^2 in the form of $R^2_{\text{Cox-Snell}}$ and $R^2_{\text{Nagelkerke}}$ are 28.4% and 39.0%, respectively. $R^2_{\text{Nagelkerke}}$ is a transformation of R^2_{McFadden} in such a way that its maximum value is 1. However, the calculated pseudocoefficients of R^2 in logistic

Table 4: Correlation matrix.

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
(1) Dividend	1	0.087*	0.086*	0.116**	0.096*	0.027	0.122**	0.301***	0.375***	0.209***	0.218***	0.431***	−0.061	−0.012	0.070
(2) Interlock	0.087*	1	0.534***	0.736***	0.255***	0.109**	0.068	0.122***	0.148***	−0.022	0.019	0.092*	0.044	−0.046	0.005
(3) Degree centrality	0.086*	0.534***	1	0.699***	0.722***	0.406***	0.046	0.173***	0.193***	−0.050	−0.026	0.107**	−0.051	−0.025	−0.055
(4) Closeness centrality	0.116**	0.736***	0.699***	1	0.459***	0.144***	0.114**	0.202***	0.276***	0.004	0.023	0.216***	0.029	−0.021	−0.024
(5) Betweenness centrality	0.096*	0.255***	0.722***	0.459***	1	0.089*	0.064	0.211***	0.206***	0.041	0.003	0.152***	−0.007	−0.012	−0.043
(6) Eigenvector centrality	0.027	0.109**	0.406***	0.144	0.089*	1	−0.052	−0.114**	−0.126***	−0.025	0.012	−0.130***	−0.006	0.012	−0.035
(7) Ln (age)	0.122	0.068	0.046	0.114**	0.064	−0.052	1	0.154***	0.252***	0.019	0.055	0.282***	−0.116**	−0.027	−0.098*
(8) Board size	0.301***	0.122***	0.173***		0.211***	−0.114**	0.154***	1	0.499	0.084*	0.076**	0.556***	0.037	−0.024	−0.051
(9) Ln (assets)	0.375***	0.148***	0.193***	0.276***	0.206***	−0.126***	0.252***	0.499	1	0.180***	0.136***	0.493	−0.008	−0.121**	−0.207***
(10) ROA	0.209***	−0.022	−0.050	0.004	0.041	−0.025	0.019	0.084*	0.180***	1	0.379***	0.248***	0.119**	0.042	0.148***
(11) ROA_$t-1$	0.218***	0.019	−0.026	0.023	0.003	0.012	0.055	0.076*	0.136***	0.379***	1	0.261***	0.087*	−0.047	0.078*
(12) Ln (sales)	0.431***	0.092*	0.107**	0.216***	0.152***	−0.130***	0.282***	0.556***	0.493	0.248***	0.261***	1	0.030	−0.163***	−0.160***
(13) Cash	−0.061	0.044	−0.005	0.029	−0.007	−0.006	−0.116**	0.037	−0.008	0.119**	0.087*	0.030	1	−0.031	0.138***
(14) Liquidity_$t-1$	−0.012	−0.046	−0.025	−0.021	−0.012***	0.012	−0.027	−0.024	−0.121**	0.042	−0.047	−0.163	−0.031	1	0.215***
(15) Ln (leverage)	0.070	0.005	−0.055	−0.024	−0.043	−0.035			−0.207***	0.148***	0.078*	−0.160***	0.138***	0.215***	1

$n = 678$, and ***, **, and * denote significant levels at 0.1%, 1%, and 5%, respectively.

Table 5: Logistic regression analysis results (dependent variable = Dividend).

Variable	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Constant	−6.638*** (1.003)	−6.630*** (0.790)	−6.581*** (0.953)	−6.665*** (0.902)	−6.580*** (0.856)	−7.013*** (0.936)
Interlock		0.109 (0.222)				
Degree centrality			24.357 (26.325)			
Closeness centrality				−0.408 (1.883)		
Betweenness centrality					10.960 (20.704)	
Eigenvector centrality						8.027** (2.813)
Ln (age)	0.003 (0.122)	−0.001 (0.070)	0.002 (0.110)	0.004 (0.096)	0.002 (0.086)	0.003 (0.102)
Board size	0.096† (0.058)	0.093 (0.058)	0.090 (0.058)	0.097† (0.058)	0.092 (0.058)	0.103† (0.059)
Ln (assets)	−0.035 (0.103)	−0.041 (0.104)	−0.052 (0.105)	−0.031 (0.105)	−0.043 (0.104)	−0.046 (0.105)
ROA	2.133** (0.818)	2.120** (0.815)	2.130** (0.816)	2.139** (0.818)	2.113** (0.817)	2.038* (0.817)
ROA_$t-1$	3.117*** (0.876)	3.086*** (0.877)	3.110*** (0.876)	3.123*** (0.876)	3.127*** (0.876)	2.926*** (0.887)
Ln (sales)	0.485*** (0.098)	0.487*** (0.098)	0.495*** (0.099)	0.484*** (0.098)	0.489*** (0.099)	0.520*** (0.101)
Cash	−4.187*** (1.017)	−4.182*** (1.014)	−4.182*** (1.017)	−4.194*** (1.017)	−4.177*** (1.016)	−4.214*** (1.020)
Liquidity_$t-1$	0.018 (0.101)	0.018 (0.102)	0.017 (0.102)	0.019 (0.101)	0.017 (0.102)	0.021 (0.103)
Ln (leverage)	0.333** (0.106)	0.333** (0.106)	0.337** (0.106)	0.334** (0.106)	0.334** (0.106)	0.365*** (0.107)
Total loss	331.429	331.429	331.003	331.406	331.289	327.415
$-2\log L_p$	662.859	662.617	662.006	662.812	662.577	654.830
$-2\log L_0$	881.233	881.233	881.233	881.233	881.233	881.233
Goodness of fit	617.641	617.252	610.549	618.081	616.083	596.274
χ^2	218.37***	218.37***	219.23***	218.42***	218.66***	226.40***
R^2_{McFadden}	0.248	0.248	0.249	0.248	0.248	0.257
$R^2_{\text{Cox-Snell}}$	0.275	0.275	0.276	0.275	0.276	0.284
$R^2_{\text{Nagelkerk}}$	0.379	0.379	0.380	0.379	0.379	0.390

$n = 678$, standard error in parentheses. ***, **, *, and †denote significant levels at 0.1%, 1%, 5%, and 10%, respectively.

regression do not directly inform about the goodness of fitting the model to the data, but it can be used in the analysis to determine which of the few models built is better fitted to the empirical data. It should be pointed out that all three types of coefficients of pseudo R^2 are the largest for model 6, which means that attaching a network variable to the model increases the prediction of the independent variable. In relation to model 1, which contains only control variables, pseudo R^2 coefficient are about 1 percentage point larger. The same applies to the comparison of model 6 with models 2–5.

Table 6 presents the detailed results of regression analysis for model 6.

The eigenvector centrality regression coefficient is positive, which means that higher values of centrality score correspond to a higher probability of dividend payment to the parent company. In addition, it can be concluded that with a 95% probability, the range of regression coefficients standing by independent variables is within the eigenvector centrality range $\langle 2.503 \div 13.55 \rangle$.

The odds ratio for eigenvector centrality is greater than 1, which means that the probability of dividend payment by the company increases in groups with a higher level of development of eigenvector centrality in the interlocking network. For the network variable in model 6, the odds ratio is 3,061.467. The eigenvector centrality variable takes the values in the research sample in the range of $\langle 0 \div 0.325 \rangle$, and the mean is 0.006, cf. Table 3. Based on the odds ratio, the change in probability in a group of companies whose level of eigenvector centrality is exactly 0 (companies that do not have interlocking connections, their degree = 0), and a group of companies that achieve eigenvector centrality at the average level (0.006) can be compared:

$$\left(e^{8.02664949}\right)^{0.006} = 3,061.467^{0.006} = 1.05. \quad (6)$$

This means that, for companies in the group reaching the mean level of eigenvector centrality, the probability of dividend payment to the parent company increases more than 1.05 times when compared to isolated companies whose degree and, consequently, the level of eigenvector centrality is 0. Exactly 1.5 fold increase in the probability of dividend payment (50%) compared to companies isolated in the interlocking network is achieved by a group of companies whose degree of eigenvector centrality is 0.05, which was estimated by solving the equation:

$$\begin{aligned} \left(e^{5.420357}\right)^{\text{Eigenvector centrality}} &= 1.5, \\ 225.96^{\text{Eigenvector centrality}} &= 1.5, \\ \text{Eigenvector centrality} &= 0.05. \end{aligned} \quad (7)$$

The obtained value of eigenvector centrality is close to 15% of the maximum value in the research sample (0.05/0.325).

The importance of the impact of a network variable on a dependent variable and the better fit of a model containing a network variable are important for the purpose of the study. The question is whether model 6 is better fitted by including a network variable (eigenvector centrality) in the model

Table 6: Logistic regression analysis results for model 6.

Model 6	b_i	Mean error	t (667)	95% CL lower	95% CL upper	Wald (χ^2)	Odds ratio
Constant	−7.013	0.936	−7.493***	−8.851	−5.176	56.145***	0.001
Eigenvector centrality	8.027	2.813	2.853**	2.503	13.550	8.142**	3061.467
Ln (age)	0.003	0.102	0.033	−0.196	0.203	0.001	1.003
Board size	0.103	0.059	1.750†	−0.013	0.219	3.064†	1.109
Ln (assets)	−0.046	0.105	−0.442	−0.251	0.159	0.196	0.955
ROA	2.038	0.817	2.495*	0.434	3.642	6.227*	7.675
ROA_$t-1$	2.926	0.887	3.300***	1.185	4.667	10.888***	18.648
Ln (sales)	0.520	0.101	5.152***	0.322	0.719	26.539***	1.683
Cash	−4.214	1.020	−4.130***	−6.218	−2.211	17.055***	0.015
Liquidity_$t-1$	0.021	0.103	0.204	−0.181	0.223	0.042	1.021
Ln (leverage)	0.365	0.107	3.401***	0.154	0.576	11.565***	1.440

$n = 678$, and ***, **, *, and †denote significant levels at 0.1%, 1%, 5%, and 10%, respectively.

Table 7: Difference between models 6 and 1.

Maximum likelihood	Loss = $-2\log L_p$				
	Model $-2\log L_p$	Number of variables	Change in $-2\log L_p$	Change in k variables	p
Value	654.830	11	8.029	1	0.005

when compared to model 1? Table 7 provides a relevant summary.

The value of the likelihood ratio (LR) test as the difference of the loss function ($-2\log L_p$) between models 6 and 1 (662.859–654.830) as a result of the addition of the eigenvector centrality variable is 8.029, which has a distribution close to χ^2. This statistic tests the hypothesis.

H_0: $b_1 = 0$, meaning that the regression coefficient for the eigenvector centrality variable is 0, so there is no statistically significant difference between the two models.

As the significance is $p = 0.01$, which means that the H_0 hypothesis is rejected and the assumption that the eigenvector centrality variable attached to model 6 leads to a statistically significant difference when compared to model 1 is adopted. In other words, the eigenvector centrality variable significantly improves the fit of the model to empirical data, where a higher level of centralization in the interlocking network makes it more likely that dividends will be paid to the parent entity.

Table 8 shows the classification correctness coefficient and odds ratio for models 1 and 6. On the basis of model 6, better results of classification correctness of enterprises to a given group due to a dependent variable were obtained. The classification correctness for model 6 is 73.45%. The odds ratio is the ratio of the product of correctly classified cases to the product of incorrectly classified cases ($368 * 125/115 * 70$) for model 1 and ($369 * 129/111 * 69$) for model 6, respectively.

Table 9 presents the results of permutation test for logistic regression for model 6. Permutation significance test randomly permuted vectors from original vector with 2,034,000 number of iterations (3,000 permutation per observation). The expected value of the regression coefficient (b_i, $i = 0, 1, \ldots, k$), as the average value in randomly permuted vectors is computed and then compared with the observed value. The original observed value of the regression coefficient is higher than the expected value for network variable, eigenvector variable, and the probability of such an occurrence is estimated to be 0.999. Therefore, this is a strong position to state that the observed value of the regression coefficient is statistically significant.

Similarly, in the case of control variables—Board size, ROA, ROA_$t-1$, Ln (sales), Cash, and Ln (leverage)—the original observed values of the regression coefficients are statistically significantly different from the expected value.

Figure 2 shows the receiver operating characteristic (ROC) curve for model 6. The model shows a better assessment of the predictive capability if the ROC curve is close to the upper left corner of the coordinate system, as a result the area under the ROC curve is larger and the ROC index higher. A line inclined at 45° means a reference line indicating the expected result of the classification of the model based on random prediction.

The ROC index, defined as AUC (area under the ROC curve), was 0.813. The values of this index are in the range of $\langle 0 \div 1 \rangle$, where the higher the ROC index values, the better the model rating. In probabilistic terms, the ROC index means the probability that the model determines a higher rank for randomly selected cases from positive target levels (variable Dividend = 1) than for randomly selected cases from negative target levels (Dividend = 0). ROC index values below 0.6 mean that the model is weak, and above 0.7, it means that it is strong [135].

5. Discussion

The study showed that not all network variables, including centrality measures, are statistically significant in relation to the dependent variable. This applies to independent variables such as interlock, degree centrality, betweenness centrality, and closeness centrality. Centrality can be seen as a node's position that is as a source of opportunities and

Table 8: Case classification for models 1 and 6.

Model	Original dividend	Predicted dividend = 0	Predicted dividend = 1	Percentage correct	Odds ratio	Classification correctness
Model 1	**0**	368	70	84.02	5.714	72.71
	1	115	125	52.08		
Model 6	**0**	369	69	84.25	6.215	73.45
	1	111	129	53.75		

Table 9: Permutation significance test for logistic regression.

(Model 6) variable	Observed	Expected (mean)	Std. dev.	p (mean ≥ Obs.)	p (mean = Obs.)	p (mean ≤ Obs.)
Constant	**−7.013**	−0.619	0.705	1	0	0
Eigenvector centrality	**8.027**	−0.265	2.808	0.001	0	0.999
Ln (age)	**0.003**	0.003	0.088	0.491	0	0.509
Board size	**0.103**	−0.001	0.047	0.012	0	0.988
Ln (assets)	**−0.046**	−0.002	0.067	0.747	0	0.253
ROA	**2.038**	0.014	0.464	0	0	1
ROA_$t-1$	**2.926**	0.016	0.482	0	0	1
Ln (sales)	**0.52**	0.002	0.053	0	0	1
Cash	**−4.214**	−0.006	0.738	1	0	0
Liquidity_$t-1$	**0.021**	−0.006	0.074	0.362	0	0.638
Ln (leverage)	**0.365**	−0.003	0.076	0	0	1

$n = 678$.

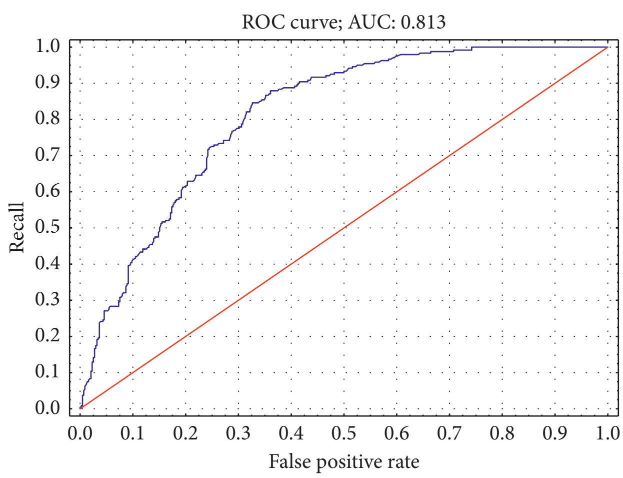

Figure 2: ROC curve for model 6.

advantage. Different centrality measures have different characteristics and capture various aspects of vertex position properties in the network. These measures also bring different information about the structure of the network.

The lack of dependence of participation in the interlocking network (interlock variable) on dividend payment results from insufficient information about the position in the network. In other words, the indication of the interlock network links does not guarantee an increase in the likelihood of dividend payments to the parent company. A similar result was obtained for the degree centrality, which takes into account the number of links in the network.

This means that neither a larger number of network relationships nor the mere indication of such relationships is significantly indistinguishable due to the modelled dependent variable. Although the better-connected directors are more experienced, powerful and competent in supervising firms, companies with more interlocked directors are not found to be more likely to payout dividends to the parent company in the ownership structure. More importantly is the position of the company in the board network structure. Degree centrality covers networked information flow only in an ego network structure. The degree of centrality does not take into account further connections beyond the company's closest neighbors in the network. It does not indicate the value of the relationship in the information flow network. Degree centrality is a standardized degree category, one of the basic network measures, which directly informs about the number of relationships with other companies in the network. However, it is a measure that covers ego network and does not allow for a wider context of indirect relationships within a wider network spectrum that includes pathway trajectory. In other words, degree does not take into account the network structure beyond the direct links. It is of limited application to the assessment of the interlocking strategy used by the undertaking. It does not indicate the value of a link in the information flow network. Many links to vertices on the periphery of the network cannot provide a substitute for a single link to a centrally networked company. Degree centrality should be seen as a measure of impact, enabling it to influence other companies to achieve their own goals [136], not the possibility of information transmission over the network. In this context, it was concluded that simply increasing the number of interlock network relationships leading directly to an increase in degree centrality does not significantly increase the flow of information on the network. This explains the lack of a statistically significant impact of demonstrating relationships in board interlock network (variable interlock) and changes in degree centrality in the modeled relationship.

Closeness centrality and betweenness centrality are measures of centralities that are based on the trajectory of connections of any nodes along the shortest paths in the network. Betweenness centrality indicates the frequency of occurrence of the vertex on the geodesic paths between pairs of other nodes in the network, while centrality closeness is directly dependent on the geodesic distance between the vertex and other nodes in the network. As a result, the first of these measures should be interpreted more in terms of intermediation and control of information flow in the network, and the second measure in terms of the speed of information flow, depending on the distance from other nodes in the network only along the geodesic paths. Closeness centrality indicates the time of access to information appearing in nodes. The high position of closeness centrality enables the exchange of information in a shorter time and quick access to other enterprises on the network. This is not a key aspect for adopting the practice of paying dividends to the parent company. Contrary to a lot of information available through the network regarding market opportunities, the decision on dividend policy does not have to be made under time pressure. For these reasons, the relationship between the above measures of centralities and the payment of dividends to the parent company is not statistically significant. Considering only the connections along the shortest paths, the time of information flow (closeness centrality) as well as control and intermediation of information flow (betweenness centrality) are less important. The position of the company in the interlock network determined by means of centrality measures such as degree, closeness, or betweenness centrality is not sufficient to correctly assess the network diffusion of dividend payment practices to the parent company.

It has been shown that eigenvector centrality significantly influenced the propensity of paying dividend. Eigenvector centrality is a measure of the ability to transmit information in a network, taking into account all paths. The centrality of a node in the network is greater not only because of the number of links but also because of the centrality of the connected nodes. In other words, greater centrality results from relationships with vertices in a network with a high level of centrality. This makes it possible to shape the central position of an enterprise in the network from its structure, where the shortest paths are of equal importance to other possibilities of indirect links between companies. Eigenvector centrality is a measure of the ability to transmit information due to the existence of relationships with also highly connected enterprises. In this light, the panoramic context of the flow of information in the network, passing through a wider network structure than just the shortest paths in the network, is more important. This justifies the statement that the measure of eigenvector centrality is a more appropriate instrument for the measurement of organizational practices diffusion in social networks such as a dividend payment to the parent company in the ownership structure. The results of logistic regression indicate that the centrality of an enterprise in the network is important if its source comes from derived and reflected centrality, taking into account all paths in the network and not just the shortest. However, the number of relationships, closeness, and betweenness in the network resulting from the connection along the geodetic paths is irrelevant.

6. Conclusions

This study explored the link between the information flow within the board network and corporate financial decisions. In this study, information transmission between boards of directors was examined by studying the opportunity to adopt business practices through the interlock network. Specifically, the investigation was whether the various dimensions of a firm's centrality network affect corporate dividend policy. Board of directors seems to rely on social networks when making corporate policy decisions [9]. As corporate organizations form interlocking directorates, they create a social network of direct and indirect links with each other. This network can influence the information and corporate practices diffusion among enterprises [26]. This report provides evidence that corporate financial decisions can be adopted from other firms through board of directors and their connections in social networks. Consistent with the hypothesis of this study, it was observed that eigenvector centrality as a measure of network centrality within the interlock network, and it increases the probability of dividend payment to the parent company in the ownership structure.

Establishing links in the interlocking directorate network is associated with several benefits for the organization. One of them is the possibility of adopting organizational practices used in other companies. It is important to be able to establish such connections in order to ensure an appropriate level of centrality in the network, ensuring the implementation of the process of diffusion of organizational practices.

This study contributes to the literature in two primary ways. Firstly, it provides new evidence that contributes to the literature on the effect of social networks and the role of director networks on diffusion of practices in the field of corporate finance. Secondly, this study also contributes to the literature on the corporate governance. Findings of this study may have implications for board of directors, investors, and regulators.

Further research may focus on issues related to a wide range of corporate financial decisions and can be spread across firms through the influence of social networks including equity issuance, share repurchase, bond buyback, debt management strategy, or shaping of the capital structure.

Data Availability

The data that support the findings of this study are available in the supplementary material of this article.

Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this article.

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Supplementary Materials

Dataset. (*Supplementary Materials*)

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Research Article

Research on Information Spillover Effect of the RMB Exchange Rate and Stock Market Based on R-Vine Copula

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This paper studies the dependence structure and information spillover effect between the RMB exchange rate and the Chinese stock market based on the R-vine copula model and spillover index model. The results show that due to the occurrence of the trade war, the correlation between the three RMB exchange rate indicators and the two stock market indicators increases in varying degrees. In the intensity of spillover, the information spillover of the stock market to the RMB exchange rate is significantly enhanced, and the information spillover intensity of the RMB Index to the stock market increases, but the information spillover of the US dollar and Hong Kong dollar exchange rates to the stock market is significantly weakened. In the direction of spillover, the spillover of the RMB Index and stock market shows the characteristics of alternating transformation, while the exchange rate of a single currency and the stock market shows a one-way transmission from the stock market to the exchange rate. Additionally, the information spillover between the RMB exchange rate and the stock market is closely related to the degree of market openness. The RMB Index contains more information than the exchange rate of a single currency.

1. Introduction

With the financial globalization and complex environment, not only the RMB foreign exchange market fluctuates abnormally but also the Chinese stock market fluctuates violently and the exchange rate market fluctuates frequently. China's economy has suffered as a result of the successful implementation of supply-side reforms and financial deleveraging. The current economy has gradually recovered, but there is still a huge difference compared with the launch of the US tax reform policy and the full recovery of the economy. The serious economic differentiation between the two countries has led to the fluctuation of the RMB exchange rate to a certain extent. In addition, in recent years, in order to reduce the trade deficit and environmental domestic deficit pressure, the United States has directly referred to China as a "currency manipulator." A trade war broke out between the United States and China, and although the first phase of the trade agreement between the two countries has been agreed, the escalating "tariff war" has caused some damage to the economies and financial markets of the two countries, the profits of related industries, and the average price-to-earnings ratio.

Regarding the Sino-US trade war as a typical shock, this paper studies the correlation and information spillover effects between the RMB exchange rate and stock markets to show the dynamic changes of their relationship. The process of domestic exchange rate system reform and RMB internationalization has improved the degree of marketization and openness of the exchange rate, and its relationship with the stock market is becoming more and more complex. Studying the impact of trade conflict on information transmission between the two markets is helpful to supplement or support previous conclusions. Further exploration of the path and direction of potential risk transmission can provide a basis for risk management and control for national authorities and investors.

The structure of the paper is as follows. Section 2 is a review of the related literature. The selected model specifications and related methodology are provided in Section 3. We apply the model specifications to study the information overflow of the RMB exchange rates and the stock market in Section 4. Finally, the main conclusions are drawn in Section 5.

2. Literature Review

The research on the RMB exchange rate and stock market mainly focuses on their correlation and spillover effect. Traditional measurement methods included the correlation coefficient method, Granger causality test, GARCH family model, and so on. With the development of the theory, more models have appeared and been popularized. Copula function has become a widely used tool to measure the correlation of variables because it did not limit edge distribution and can capture nonlinear asymmetry and tail relation effectively. With the deepening of research and the increase of research variables, binary copula function can no longer meet the needs of research. Joe and Hu [1] proposed the vine copula model, which can flexibly describe the dependence structure between multiple variables. In recent years, Diebold and Yilmaz [2] proposed a new method, which is based on traditional orthogonal variance decomposition to characterize multivariate information spillovers, enriching the research method system of spillovers. After that, they [3] improved this method again, using the generalized VAR framework to overcome the problem of variable ranking and proposed a method to calculate directional overflow index, net overflow index, and pair of net overflow indexes. With the help of constantly improving and perfecting measurement methods, the research on the exchange rate and the stock market is also advancing. As foreign markets are relatively open, cross-market research was relatively mature. The research focused on two issues. The first issue was whether and how exchange rates are related to the stock market. Nieh and Lee [4] found that in the long run, there was no significant correlation between stock prices and exchange rates in G-7 countries. Tudor and Popescu-Dutaa [5] compared 13 developed and emerging financial markets and found that there was a significant Granger causality between stock price and exchange rate. Andreou et al. [6] studied 12 emerging markets; it was found that the two markets have significant two-way impacts. Blau [7] studied the influence of euro on relevant stock markets; he found that a stable exchange rate was conducive to the stability of stock markets and reduced the possibility of stock market bubbles. Blau [8] found that the US exchange rate and stock market were linked through fluctuations in US depositary receipts. The second issue was whether there were time-varying effects and structural changes in the correlation between the exchange rate and the stock market. Relevant studies showed that such changes were usually related to market conditions and external shocks. Śmiech and Papież [9] found that during the financial crisis and high market volatility, the correlation between exchange rates and stock markets in European countries has increased. Sui and Sun [10] also supported that the crisis will also strengthen the link between stock and foreign exchange markets in emerging countries. Reboredo et al. [11] studied the different states of exchange markets and stock markets in eight emerging economies and found that the correlation shows asymmetric effects in the upward and downward phases of the market.

In China, research on the exchange rate and stock market revolves around four aspects. The first was the correlation between the exchange rate and stocks in different sectors. Yin [12] focused on the study of the interconnection between specific industries and the RMB exchange rate. It was found that the exchange rate has a positive impact on the marginal risk spillover of related industries at any risk level, and the impact degree of each industry was different. Zhao and Shi [13] improved their research on various sectors of the stock market, including Shanghai Stock, Shenzhen Stock, and small and medium-sized stocks. It was found that the three markets were affected by exchange rates to different degrees. The research of Yu et al. [14] also found that there were industry differences in the relationship between the stock market and exchange rate (Supplementary Materials available here). The second was the correlation between different exchange rate indexes and the stock market. Previous studies have mostly focused on onshore RMB and were lacking focus on offshore RMB. Zhou and Han [15] and Que and Li [16] have made improvements in this aspect. Among them, Zhou's research made the comparison between onshore and offshore RMB's spillover effects on stock market risks, while Que's research paid attention to the spillover effects of interest rate spread on the stock market. The third was cross-market correlation research. Chen et al. [17] expanded the market and studied the relationship among the foreign exchange market, bond market, and stock market to fill the gap of a cross-market investment portfolio. It was found that among the interaction of the three, the stock market and foreign exchange market were more closely linked. Xiao and Yin [18] believed that the foreign exchange market was relatively separated from the bond market, but it has a significant fluctuation effect with the stock market. Zhang's research [19] showed that the impact of the stock market on the exchange rate was more in the long term, while the impact of the exchange rate on the "triple paradox" mechanism of the stock market through interest rate transmission was limited. The fourth was the study of the exchange rate and stock market under different market conditions and external shocks. Wang et al. [20] found that the relationship between the two markets was related to market conditions. There was a significant asymmetric two-way volatility spillover effect under bull market conditions. In the bear market, there was the only one-way overflow of the stock market to the foreign exchange market. Important events such as financial crisis and policy reform usually lead to structural changes in the relationship between the two. Yan and Li [21] found that the crisis changed the spillover of the exchange market to the stock market into the stock market to the exchange market, and there were no significant mean spillover and volatility spillover effects during the crisis. Hao and Li [22] focused on studying the impact of the international stock market and the RMB exchange rate on China's stock market through the analysis of plummeting events. The results showed that the impact of the RMB exchange rate on China's stock market in the context of devaluation has only weak supporting evidence. Research by Chen and Liu [23] showed that RMB's accession to the SDR basket will lead to the expected appreciation of the exchange rate, thus having a positive effect on the A-H share premium. Liang and Zhang [24] found that the A-share market was increasingly affected by RMB under the background of the trade war. The devaluation of RMB will lead to the decline of the stock market and affect the safety of capital. Li et al. [25] believed that the influence of the RMB exchange rate on the stock market comes from the short-term arbitrage capital flow caused by investor expectations.

In the complex international environment, this paper did improvements and innovations in the following three aspects. Firstly, from the perspective of the research background, we select the data of the Sino-US trade war period, which is different from mature research under the background of the subprime mortgage crisis and economic crisis. The aim is to explore the dynamic changes of the relationship between the exchange rate and stock market, providing a scientific basis for national risk transmission prevention and investor hedging measures. Secondly, from the perspective of research content, previous studies have mostly focused on the correlation or spillover effect, while there are few works of literature that combine the two sides. Using the vine copula model to explore the correlation structure between the two sides and studying the direction and intensity of information spillover can make the research more extensive. Thirdly, from the perspective of research methods, vine copula and spillover index models are relatively advanced research technologies, which are more effective in depicting the dependency relationship and spillover structure of multidimensional variables. They complement and support each other to obtain more reliable and rigorous conclusions.

3. Model Building

3.1. GARCH (1,1) Model of the Marginal Distribution. Before vine copula modeling, the edge distribution of each sequence should be fitted. The sequence is tested by autocorrelation and ARCH effect. Considering the fluctuation aggregation effect of variables, GARCH (1,1) model and t distribution are introduced to fit variables. The specific mathematical formula is as follows:

$$\begin{aligned} r_t &= \mu + a_t, \\ \sigma_t^2 &= \omega + \alpha a_{t-1}^2 + \beta \sigma_{t-1}^2, \\ a_t &= \sigma_t \varepsilon_t, \\ \varepsilon_t &\sim i.i.d.t. \end{aligned} \quad (1)$$

Among them, r_t represents the rate of return, σ_t represents the conditional variance, a_t is the residual sequence, and ε_t is the standardized residual, where t is the standard distribution with mean 0 and variance 1. The parameters to be evaluated are μ, ω, α, and β.

3.2. The Vine Copula Model. Copula theory was first proposed by Sklar in 1959 and has been widely used in the financial field since then. Its essence is a connection function, which combines the joint distribution function with the edge distribution of variables. According to Sklar's theorem, if X is an n-dimensional random vector like $X = (X_1, X_2, \ldots, X_n)$, then $F(x_1, x_2, \ldots, x_n) = C(F(x_1), F(x_2), \ldots, F(x_n))$, where $F(x_1, x_2, \ldots, x_n)$ is a joint distribution function. $F(x_n)$ is an edge distribution function of the nth variable, and C is a copula connection function. If the edge distribution function is continuous, then the copula function is unique. Common copula functions include Gaussian copula, t copula, Archimedes copula (including Gumbel copula and Clayton copula).

With the constant increase of variables, the original copula technology cannot be satisfied. In 1996, Joe proposed a vine structure to connect the pairwise dependencies of multiple variables and expand the scope of application of copula, which is called the vine copula model. The first two vine structure copulas proposed are C-vine copula and D-vine copula. The difference between the two is that the form of C-vine takes one of the variables as the root node, and the other variables are connected to it, while D-vine is connected in two by two according to the order between the variables. Subsequently, a new vine structure, called R-vine, was developed on the basis of C-vine and D-vine. It combines the characteristics of C-vine and D-vine and can have more than one root node. Its advantage is that when the number of variables is large, the R-vine copula model is more effective.

The concept of R-vine was proposed by Bedford and Cooke. Kurowicka and Cooke gave a detailed description that an n-variable R-vine consists of $(n-1)$ trees and is denoted as $T_1, T_2, \ldots, T_{n-1}$, the node set of tree T_i is N_i, and the edge set is $E_i\,(i = 1, \ldots, n-1)$, which satisfy the following conditions:

(i) Node set $N_1 = \{1, \ldots, n\}$ and edge set E_1 of tree T_1.

(ii) The node set $N_i = E_{i-1}\,(i = 2, \ldots, n-1)$ of tree T_i; it means that the node set of tree i is the edge set of tree $i-1$.

(iii) If two edges in the tree T_i are connected by edges in the tree T_{i+1}, then the two edges must have a common node in the tree T_i.

The R-vine with 5 variables and 4 trees constructed according to the above conditions is shown in Figure 1.

In order to establish R-vine copula model for N variables, we mark the node as $N = \{N_1, \ldots, N_{n-1}\}$, the edge is $E = \{E_1, \ldots, E_{n-1}\}$, and one of the edges in E_i is $e = j(e), k(e) \mid D(e)$, where $j(e)$ and $k(e)$ are two conditional nodes associated with edge e, $D(e)$ is the conditional set, and $c_{j(e),k(e)|D(e)}$ is the corresponding copula density function. Suppose that an n-dimensional random variable $X = (X_1, \ldots, X_n)$, $X_{D(e)}$ is a subvector of X determined by condition set $D(e)$, and the marginal density of the k-th variable X_k is $f_k\,(k = 1, \ldots, n)$. Then, an R-vine distribution can be defined as the joint probability density function $f(x_1, \ldots, x_n)$ of the random vector $X = (X_1, \ldots, X_n)$, as shown in the following formula:

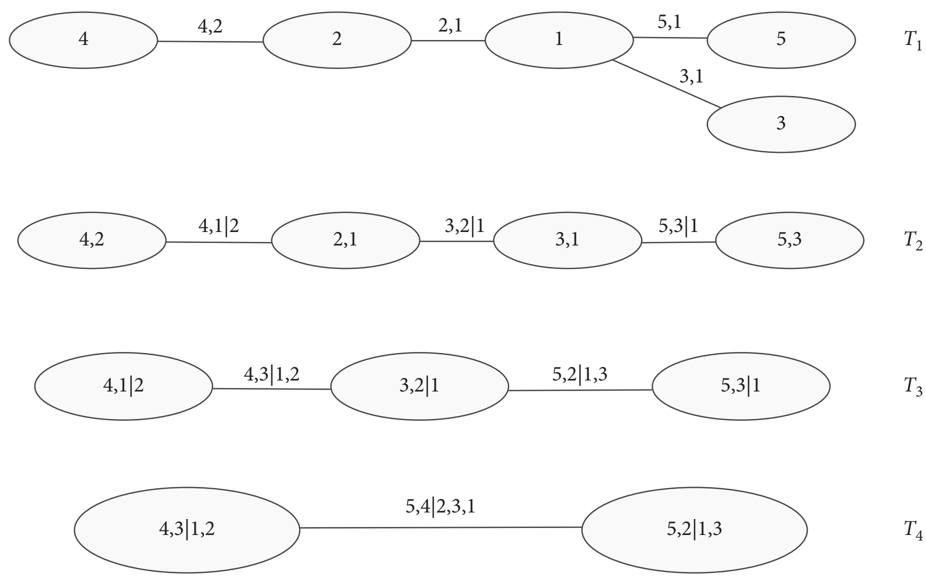


Figure 1: R-vine structure with five variables.

$$f(x_1, x_2, \ldots, x_n) = \prod_{k=1}^{n} f_k(x_k) \cdot \prod_{i=1}^{n-1} \prod_{e \in E_i} c_{j(e),k(e)|D(e)} \cdot \left(F\left(x_{j(e)} \mid x_{D(e)}\right), F\left(x_{k(e)} \mid x_{D(e)}\right)\right). \quad (2)$$

3.3. Information Spillover Index Model. The information spillover index model proposed by Diebold and Yilmaz is constructed as follows. Firstly, we construct an n-dimensional VAR(P) model with stable covariance: $X_t = \sum_{i=1}^{p} \Phi_i X_{t-i} + \varepsilon_t$, where $\varepsilon_t \sim (0, \Sigma)$ is an independent and identically distributed vector. Its moving average process is $X_t = \sum_{i=0}^{\infty} A_i \varepsilon_{t-i}$; here A_i is the coefficient matrix of $N * N$ and satisfies the recurrence formula: $A_i = \Phi_1 A_{i-1} + \Phi_2 A_{i-2} + \cdots + \Phi_p A_{i-p}$, where A_0 is the n-order unit matrix. If $i < 0$, then $A_i = 0$. The coefficient of the moving average equation is the determining factor of the system change and the variance decomposition result.

Diebold and Yilmaz define their variance decomposition as the part of the H-step prediction error variance of the variable X_i that is impacted by themselves and volatility spillover as the part of the H-step prediction error variance of the variable X_i that is impacted by other variables. According to the above theory, the H-step prediction error variance under the generalized VAR framework is decomposed into

$$\theta_{ij}^{g}(H) = \frac{\sigma_{jj}^{-1} \sum_{h=0}^{H-1} \left(e_i' A_h \Sigma e_j\right)^2}{\sum_{h=0}^{H-1} \left(e_i' A_h \Sigma A_h' e_i\right)}, \quad (3)$$

where $H = 1, 2, \ldots, \Sigma$ is the variance matrix of the error vector ε, σ_{jj} is the standard deviation of the error term of the j-th equation, e_i is the selection vector, and the other elements are zero except the value of the i-th element which is 1. Since the information impact of variables under the generalized VAR framework is not orthogonal, it is necessary to standardize each variance decomposition matrix. The standardized formula is

$$\tilde{\theta}_{ij}^{g}(H) = \frac{\theta_{ij}^{g}(H)}{\sum_{j=1}^{N} \theta_{ij}^{g}(H)}. \quad (4)$$

According to the method of calculating volatility contribution by difference decomposition under the generalized VAR framework, the total volatility spillover index can be constructed to characterize the contribution of the volatility spillover effect of each variable to the variance of total prediction error. The calculation formula is

$$S^{g}(H) = \frac{\sum_{\substack{i,j=1 \\ i \neq j}}^{N} \tilde{\theta}_{ij}^{g}(H)}{\sum_{i,j=1}^{N} \tilde{\theta}_{ij}^{g}(H)} \cdot 100 = \frac{\sum_{\substack{i,j=1 \\ i \neq j}}^{N} \tilde{\theta}_{ij}^{g}(H)}{N} \cdot 100. \quad (5)$$

In addition to the total spillover index, the generalized VAR model can also analyze the direction of the spillover effect of each variable. The standardized formula for calculating the directional spillover effect of the variable j on the variable i is

$$S_{i\cdot}^{g}(H) = \frac{\sum_{\substack{j=1 \\ j \neq i}}^{N} \tilde{\theta}_{ij}^{g}(H)}{\sum_{i,j=1}^{N} \tilde{\theta}_{ij}^{g}(H)} \cdot 100 = \frac{\sum_{\substack{j=1 \\ j \neq i}}^{N} \tilde{\theta}_{ij}^{g}(H)}{N} \cdot 100. \quad (6)$$

Correspondingly, the directional fluctuation overflow of the variable i to the variable j is

$$S_{\cdot i}^{g}(H) = \frac{\sum_{\substack{j=1\\ j\neq i}}^{N} \tilde{\theta}_{ji}^{g}(H)}{\sum_{i,j=1}^{N} \tilde{\theta}_{ji}^{g}(H)} \cdot 100 = \frac{\sum_{\substack{j=1\\ j\neq i}}^{N} \tilde{\theta}_{ji}^{g}(H)}{N} \cdot 100. \tag{7}$$

According to the above two-directional spillover effects, the net fluctuation spillover effect can be calculated. The net fluctuation spillover effect of the variable i on other variables is

$$S_{i}^{g}(H) = S_{\cdot i}^{g}(H) - S_{i\cdot}^{g}(H). \tag{8}$$

In actual application, the fluctuation spillover effect between the two variables is often more important. Diebold and Yilmaz [3] define it as

$$\begin{aligned} S_{ij}^{g}(H) &= \left(\frac{\tilde{\theta}_{ji}^{g}(H)}{\sum_{i,k=1}^{N} \tilde{\theta}_{ik}^{g}(H)} - \frac{\tilde{\theta}_{ij}^{g}(H)}{\sum_{j,k=1}^{N} \tilde{\theta}_{jk}^{g}(H)} \right) \cdot 100 \\ &= \left(\frac{\tilde{\theta}_{ji}^{g}(H) - \tilde{\theta}_{ij}^{g}(H)}{N} \right) \cdot 100. \end{aligned} \tag{9}$$

4. Results and Discussion

In this section, we select the representative variables of the RMB exchange rate and the Chinese stock market. Based on R-vine, the variables construct a vine copula model to obtain the dependence structure. The dynamic and static analysis method of the information overflow index model is used to obtain the overflow direction and intensity between variables, especially between two variables. Based on the above two methods, this paper describes the interdependence and information spillover structure between the RMB exchange rate and the stock market during the Sino-US trade war and draws reliable research conclusions.

4.1. Data Description. As the study was carried out against the background of the Sino-US trade war, the USD/CNY index was directly affected by it. The PEG linked exchange rate system has been closely linking the Hong Kong dollar and the US dollar. After several major reforms, the mainland of China has formed a managed floating exchange rate system with reference to a basket of currencies. The exchange rate will be affected by more currencies. Besides, as the connection between the mainland and Hong Kong is gradually established, the combination of the two could better reflect the comprehensiveness and integrity of the study. Based on the above background, we will select the variables of USD/CNY, HKD/CNY, RMB Index, Shanghai and Shenzhen 300 Index, and Hong Kong Hang Seng Index. The data come from the Choice database. The research period is from July 4, 2016, to January 17, 2020. Inconsistent factors such as holidays are eliminated and relevant pretreatment is carried out. The logarithmic rate of return of the variable is calculated as follows:

$$r_{i,t} = \ln\left(\frac{p_{i,t}}{p_{i,t-1}}\right), \tag{10}$$

where $r_{i,t}$ is the logarithmic rate of return of variable i on day t and $p_{i,t}$ is the price of the variable i on day t.

Table 1 shows the descriptive statistics of variables. According to the maximum, minimum, and standard deviation, the stock market fluctuates most strongly, the RMB Index fluctuates second, and USD/CNY and the HKD/CNY fluctuate the least. Among them, the volatility of the mainland stock market is higher than that of the Hong Kong stock market. Judging from skewness and kurtosis, we find that all sequences have a peak and thick tail. In addition, the ADF test shows that the sequences are stationary, and we can conduct further modeling and analysis.

4.2. Fitting Result of Edge Distribution. Autocorrelation test, ARMA modeling, and the ARCH test are carried out on the sequences. It is found that the sequences have an ARCH effect. Therefore, the GARCH model can be constructed. GARCH (1, 1) is selected here for a fitting. The results are shown in Table 2. The value of $\alpha + \beta$ of CSI300 Index and Hong Kong Hang Seng Index is very close to 1, which shows that the fluctuation of the Chinese stock market has a continuous effect. In contrast, the volatility of the exchange rate market, especially the RMB Index, is relatively low. The normalized residual series all passed the KS test. The sequences can be modeled and analyzed by vine copula.

4.3. Analysis of the Result of the R-Vine Copula Model. The data obtained by edge distribution fitting are used to make a matrix scatter plot of the dependence between the RMB exchange rate and the stock market. Among them, the triangular area in the lower-left corner of the matrix is the contour line of each variable, and the upper right corner is the variable scatter plot area and Kendall value between the two variables. A subsample analysis is conducted on March 8, 2018, as an important time point before and after the Sino-US trade war. The scatter plot of the exchange rate and stock market before and during the trade war is shown in Figure 2. Before the trade conflict occurred, the exchange rate and the stock market operated relatively smoothly. The correlation between the USD/CNY and the HKD/CNY is 0.91, which shows the exchange rate market is closely linked internally. The two currencies' exchange rate and RMB Index have a correlation coefficient of 0.12. As a result of the two-market accommodation policy in recent years, the mainland stock market has a strong positive correlation with the Hong Kong stock market. There is a weak correlation between the RMB exchange rate and the stock market, and the correlation between the single currency and the stock market is slightly stronger. With the occurrence of the Sino-US trade war, the USD/CNY frequently fluctuates under pressure. At the same time, the stock market also fluctuates violently, and thus the internal correlation between the exchange rate and the stock market changes. The internal correlation of the RMB exchange rate is weakened, especially the correlation between

Table 1: Descriptive statistics.

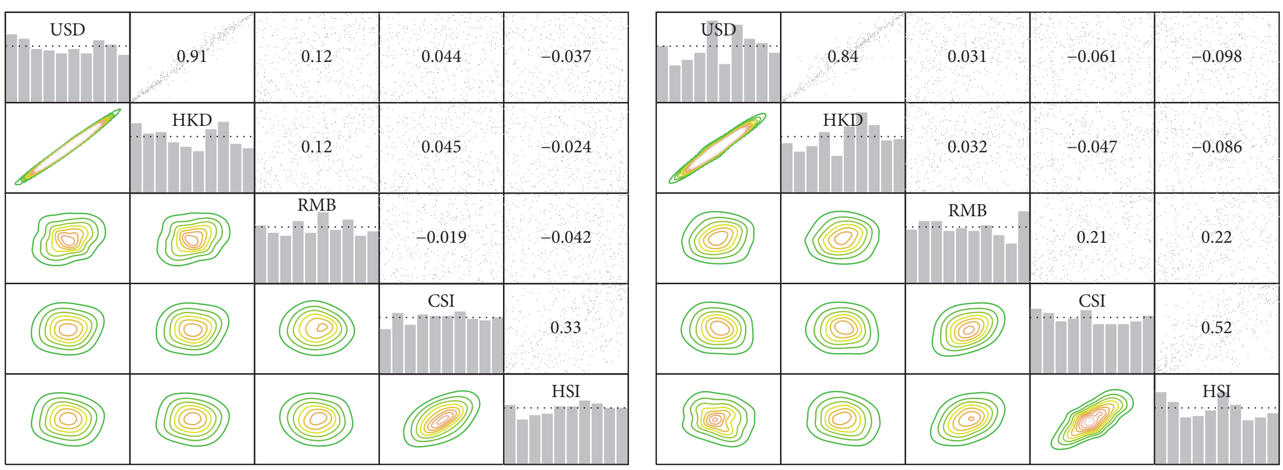
	USD/CNY	HKD/CNY	RMB	CSI	HSI
Mean	$5.65E-05$	$5.65E-05$	$-2.19E-05$	0.000399	0.000440
Maximum	0.008981	0.008855	0.014529	0.057775	0.041251
Minimum	−0.009263	−0.009330	−0.019322	−0.060192	−0.052519
Standard deviation	0.002234	0.002228	0.002308	0.010724	0.009895
Skewness	−0.141791	−0.099961	−0.690067	−0.017957	−0.298325
Kurtosis	4.577832	4.447624	13.49380	6.493369	4.736612
JB statistics	84.381***	70.118***	3678.1***	400.73***	110.71***
ADF value	−26.667***	−26.856***	−29.432***	−27.979***	−27.216***

Note. USD/CNY, HKD/CNY, RMB, CSI, and HSI represent US dollar against RMB, Hong Kong dollar against RMB, RMB Index, Shanghai and Shenzhen 300 Index, and Hong Kong Hang Seng Index, respectively **, *** Rejection of the null hypothesis at the 5% and 1% levels, respectively.

Table 2: Estimation results of edge distribution.

	USD/CNY	HKD/CNY	RMB	CSI	HSI
μ	$6.827e-05$	$5.4192e-05$	$-3.5219e-06$	$6.4296e-04$**	$8.0386e-04$**
ω	$9.142e-08$	$1.0005e-07$	$3.1738e-06$***	$5.6308e-07$	$4.9549e-07$
α	$1.056e-01$***	$8.7701e-02$***	$2.9990e-01$***	$4.6354e-02$***	$2.2418e-02$***
β	$8.889e-01$***	$8.9905e-01$***	$2.1124e-01$	$9.5012e-01$***	$9.7275e-01$***
Shape	$4.998e+00$***	$6.1725e+00$***	$3.1192e+00$***	$5.7682e+00$***	$6.8393e+00$***
KS test	0.394145	0.180304	0.932194	0.805889	0.810711

Note. **, *** Rejection of the null hypothesis at the 5% and 1% levels, respectively.



(a) (b)

Figure 2: Scatter diagram of dependence matrix. (a) Scatter diagram of two markets before trade war. (b) Scatter diagram of two markets during trade war.

single currency and RMB Index weakened to 0.03 after the trade war. The correlation between the RMB exchange rate and the stock market increased significantly. In addition, the correlation between the US dollar exchange rate, Hong Kong dollar exchange rate, and Shanghai and Shenzhen 300 Index changes from positive to negative, while the correlation between the RMB Index and the stock market changes from negative to positive. Due to the occurrence of external uncertainties, the RMB exchange rate depreciates rapidly and fluctuates abnormally. In order to maintain the smooth operation of the exchange market, the central bank comprehensively uses various exchange rate tools to deal with the existing unilateral expectation phenomenon. Our governments start the countercyclical adjustment and moderately hedge the procyclical sentiment of currency devaluation. Under such comprehensive adjustment, the correlation between RMB exchange rates is weakened. Due to the persistence of abnormal fluctuations in one market caused by the trade war, signals are released to other markets, resulting in a significant increase in the correlation between the exchange rate and the stock market. Normally, due to the limited degree of financial market opening, cross-market links are relatively weak. However, under the impact of extreme events, abnormal fluctuations in one market will generate signals and hints to other markets. Market participants will form psychological expectations and change their participation behaviors, leading to market fluctuations. In this process, the correlation between markets will be strengthened. During the Sino-US trade war, the RMB was under devaluation pressure, and the decline in the value of the RMB would reduce investor confidence, leading to the outflow of cross-border capital. Coupled with the herding effect, the stock market has a tendency to decline.

Table 3 shows the decomposition results of the "first tree" of R-vine copula, including copula function selection between two variables, parameter value, Kendall value, and tail correlation coefficient. Copula functions include elliptic copula, Archimedes copula, and nonlinear copula functions. It is difficult to accurately describe the different dependency relationships between financial markets with only one specific copula function. Due to the different dependence structures of the two markets, it is necessary to choose the appropriate copula function to describe the correlation between the markets. According to the AIC criterion to judge the effect of the fitting, R-vine chooses the best copula function, including student t copula, Joe copula, Gaussian copula, and Survival BB1 copula function. Gaussian copula could not characterize the tail, while student t-copula has symmetrical upper and lower tails. Joe copula is Archimedes copula function, which is suitable for describing the correlation of the upper tail. Before the Sino-US trade war, Joe copula function was used to study the Shanghai and Shenzhen 300 Index and HKD/CNY. The upper tail is 0.13. It indicates that during the market rise, the correlation between CSI300 and HKD/CNY shows a strong positive spillover effect. During this period, the exchange rate has become more market-oriented and internationalized through reform. The Shanghai-Hong Kong Stock Connect and Shenzhen-Hong Kong Stock Connect mechanisms provide funds for the stock market. Both markets are in a relatively positive condition, so they respond to good news more obviously. Survival BB1 copula is a two-parameter copula model, which combines Clayton copula and Gumbel copula and rotates 180°. It can capture many types of asymmetric dependent structures of upper and lower tails between variables. During the Sino-US trade war, the upper tail between Hong Kong's Hang Seng Index and RMB Index is 0.01, and the lower tail is 0.21. The lower-tail coefficient is greatly higher than the upper-tail coefficient, indicating that the correlation between Hong Kong stocks and the RMB Index is stronger in the period of market decline than in the period of market rise. The uncertainty of the relationship between the two countries enables the upper and lower tails to show obvious asymmetry and is more sensitive to bad news. The implementation of relevant policies directly leads to abnormal fluctuations in the exchange rate market and the stock market. Bad news can easily lead to investor panic and risk contagion.

The vine copula model is constructed for variables, and different copula functions are used for fitting to obtain a corresponding tree structure diagram, as shown in Figure 3. R-vine contains a series of trees, and each side of each tree corresponds to a (conditional) pair-copula. The transition of the central node based on R-vine is used to analyze the dependence structure between the RMB exchange rate and the stock market. The results are shown in Figures 3(a) and 3(b), respectively. Before the trade war, the HKD/CNY was at the center of linking the exchange rate market and the stock market, which was directly related to the USD/CNY, the RMB Index, and the Shanghai and Shenzhen 300 Index. If the HKD/CNY fluctuates sharply, the USD/CNY will also fluctuate because the correlation between them is 0.91. According to Table 3, the upper tail correlation between the Shanghai and Shenzhen 300 Index and the HKD/CNY is relatively high, so the fluctuation of the HKD/CNY will also lead to the fluctuation of the Shanghai and Shenzhen 300 Index. During the trade war, the central variable changes into Hong Kong's Hang Seng Index, which indicates that it plays a leading role in the market linkage. It has a strong lower tail correlation with the RMB Index. If there is a crisis in the Hong Kong stock market, risks will spread from the Hong Kong stock market to the RMB Index, further leading to a decline in the value of the RMB.

4.4. Analysis of Spillover Index Model Result. Subsamples are used to analyze the information spillover effect of variables by the spillover index model. VAR framework is constructed, and the variance of prediction error is calculated by generalized variance decomposition, as shown in Table 4. The results are consistent with the dependency structure under the vine copula model. Before the trade war, there was a relatively strong information spillover within a single financial market, specifically between the USD/CNY and HKD/CNY, while the cross-market information spillover was weak. The Sino-US trade war not only led to an increase in information spillover within the stock market but also strengthened the information spillover between the stock market and the exchange rate. The information overflow of the USD/CNY and the HKD/CNY to other indicators has obviously been weakened. When external shocks occur, the exchange rate fluctuates directly and violently, which is very easy to have adverse effects on other markets. Therefore, the government will implement macro adjustment policies to maintain market stability. Under the effect of countercyclical adjustment, the impact of the exchange rate on the stock market is significantly reduced. However, the fluctuation caused by the impact on the stock market will be transmitted to the exchange rate market uncontrollably.

Static analysis can only describe the overall state of information overflow between the two markets. It cannot show the time-varying effect and direction change of information overflow dynamically. Therefore, we use a 200-day rolling window period to calculate the error variance under the 10-day forecast period and carry out generalized variance decomposition. Finally, we obtain the dynamic changes in the two markets' information spillover effect.

First is the information overflow of the mainland stock market and RMB exchange rate, as shown in Figure 4. Overall, the net spillover between the RMB exchange rate and the mainland stock market is roughly within 7%. Compared with the exchange rates of the US dollar and Hong Kong dollar, the directional changes of the RMB Index and Shanghai and Shenzhen stock markets are more frequent. Specifically, the net spillover of the USD/CNY and the mainland stock market tends to be consistent with the HKD/

Table 3: R-vine copula estimation result of Sino-US trade war.

	Tree 1	Copula function	Par1	Par2	Kendall	Upper TD	Lower TD
Before the trade war	HKD/CNY, USD/CNY	Student t	0.99	2	0.91	0.91	0.91
	HKD/CNY, RMB Index	Student t	0.19	5.24	0.12	0.08	0.08
	CSI300, HKD/CNY	Joe	1.11	—	0.06	0.13	—
	HSI, CSI300	Gaussian	0.52	—	0.35	—	—
During the trade war	USD/CNY, HKD/CNY	Student t	0.98	2	0.86	0.86	0.86
	HSI, USD/CNY	Gaussian	−0.16	—	−0.1	—	—
	HSI, RMB Index	Survival BB1	0.14	1.19	0.21	0.01	0.21
	HSI, CSI300	Gaussian	0.71	—	0.51	—	—

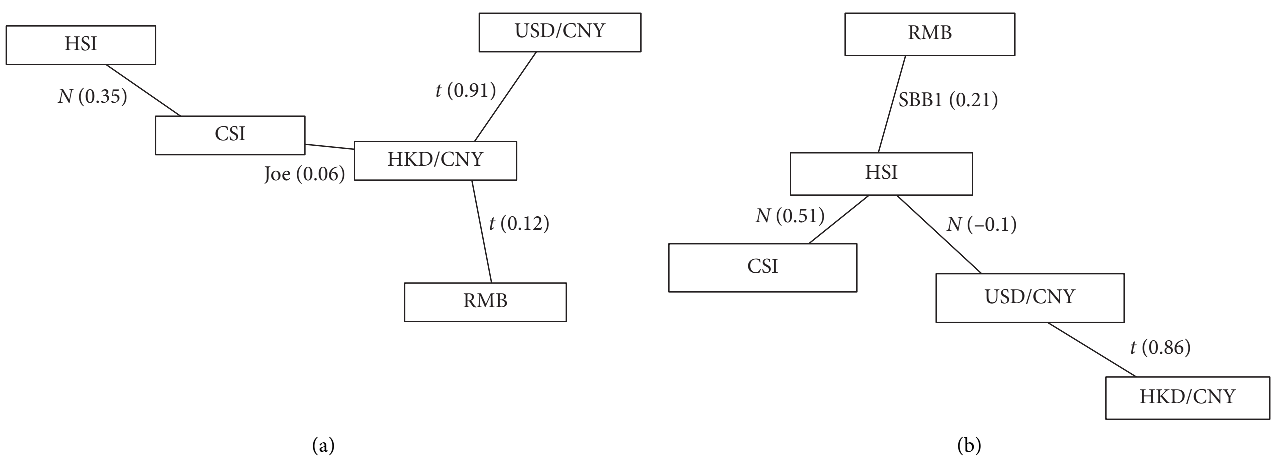


Figure 3: Tree structure diagram based on R-vine copula. (a) "Tree 1" of R-vine structure before the trade war. (b) "Tree 1" of R-vine structure during the trade war.

Table 4: Information spillover values of subsample under static conditions.

	Before the trade war							During the trade war					
	USD	HKD	RMB	CSI	HSI	From		USD	HKD	RMB	CSI	HSI	From
USD	43.54	42.56	9.06	2.06	2.77	56.5	USD	38.31	35.99	15.51	2.99	7.20	61.7
HKD	42.37	43.68	9.52	1.80	2.62	56.3	HKD	37.65	40.68	14.33	2.20	5.14	59.3
RMB	1.86	2.41	91.64	1.89	2.19	8.4	RMB	0.87	0.91	82.52	6.85	8.85	17.5
CSI	0.88	0.69	1.50	73.38	23.56	26.6	CSI	0.33	0.36	5.27	63.19	30.85	36.8
HSI	0.93	0.72	1.70	23.16	73.48	26.5	HSI	0.66	0.68	6.73	29.96	61.98	38.0
To	46.1	46.4	21.8	28.9	31.1	174.3	To	39.5	37.9	41.8	42.0	52.0	213.3
Total contribution	89.6	90.1	113.4	102.3	104.6	34.9%	Total contribution	77.8	78.6	124.4	105.2	114.0	42.7%

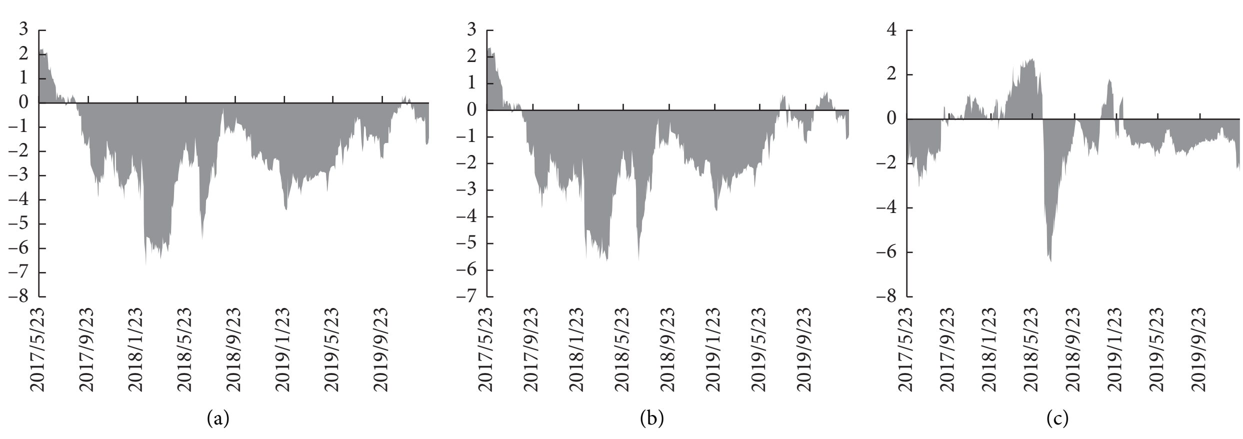


Figure 4: Dynamic changes of net spillover on the exchange rate and mainland stock market. (a) Net spillover of US dollar to RMB and Shanghai and Shenzhen 300 Index. (b) Net spillover of Hong Kong dollar to RMB and Shanghai and Shenzhen 300 Index. (c) Net spillover of RMB Index and Shanghai and Shenzhen 300 Index.

CNY and the mainland stock market. Before the Sino-US trade war broke out, the USD/CNY had a stronger spillover effect on the stock market. However, the Sino-US trade dispute became prominent and information overflow gradually shifts from the stock market to the exchange rate. The spillover intensity increases significantly. As the Sino-US trade war gradually subsides, the net spillover intensity of the two gradually is weakened. The information spillover is highlighted with the escalation of conflicts and the “tariff war” during the Sino-US trade war. From March to September 2018 and from the beginning of 2019 to May 2019, the two sides impose tariff repression due to trade conflicts and incomplete negotiations. Related industries suffered losses, profits fell, stock prices fell, and stock market fluctuations were transmitted to the exchange rate market. During this period, the information spillover intensity of the stock market to the USD/CNY and HKD/CNY is greatly strengthened and reaches its peak. At the same time, the RMB Index and the stock market overflow are more directional; especially during the trade war, there are many rounds of alternate conversion. In the change of net spillover, the information spillover from the stock market to the RMB Index is more intense. As the RMB tends to be more market-oriented after many reforms, a specific currency cannot fully and effectively reflect market information. The RMB Index is an index formed by referring to the fluctuations of various international currencies and giving different weights, which can reflect the comprehensive changes in the exchange rate market and the strength of the RMB value.

Second is the information overflow of the Hong Kong stock market and RMB exchange rate, as shown in Figure 5. The net spillover of the RMB exchange rate and the Hong Kong stock market is within 7% except for USD/CNY and the stock market reaching 11%. The information spillover of the USD/CNY and Hong Kong stock market is highly similar to the HKD/CNY and the Hong Kong stock market. Both of them have weak net spillover to the stock market before the Sino-US trade war broke out, while in the whole period of the trade war, especially in the first half of 2019, there was the high-frequency spillover from the Hong Kong stock market to USD/CNY and HKD/CNY. Excluding the difference in coordinates, the net spillover strength of Hong Kong stocks to the US dollar exchange rate is higher than that to the Hong Kong dollar exchange rate, indicating that Hong Kong stocks are relatively more sensitive to changes in US dollar exchange rate. In the alternate overflow between Hong Kong stocks and RMB Index, the net overflow intensity of the RMB Index to Hong Kong stocks is higher than that of Hong Kong stocks to the RMB Index. The spillover from the RMB Index to the Hong Kong stock market mainly occurred at the stage of expansion and escalation of the Sino-US trade war. As the contradiction between the two parties could not be eased, the value of the RMB was unstable. Hong Kong Hang Seng Index is mainly composed of large companies in Hong Kong and the mainland, whose businesses are mainly in the mainland and are greatly influenced by mainland policies. Moreover, more than half of the performance of the Hang Seng Index comes from listed companies disclosed in RMB, with companies disclosed in US dollars and Hong Kong dollars accounting for 20% each. The absolute advantage in quantity causes the Hang Seng Index to be strongly influenced by the RMB exchange rate, especially in the high-frequency period of exchange rate fluctuations, which will be significantly strengthened. The information overflow from Hong Kong stocks to the RMB Index mainly occurs in the second half of 2019. Influenced by the violence in Hong Kong, as a social disorder is caused by the nuisance actions of activists such as rallies, marches, and strikes, the large-scale shutdown of enterprises damages the economic vitality. The falling fluctuation of the stock price is bound to affect the RMB exchange rate.

The third is to consider the spillover effect of both changes mentioned above. The intensity of net information spillovers across markets is floating within 10%. The intensity of spillovers during the Sino-US trade war is significantly enhanced. The direction of information spillover between the USD/CNY, HKD/CNY, and the stock market is basically from the stock market to the exchange rate. There is also a spillover effect from the exchange rate to the stock market before the trade war. The direction of the information overflow between RMB Index and the stock market has the feature of alternating conversion. Whether it is the mainland stock market or Hong Kong stock market, the overflow direction and period are the same. However, the information overflow between the exchange rate and the mainland stock market is also different from that of the exchange rate and the Hong Kong stock market. Firstly, in terms of spillover intensity, the net information spillover intensity of the RMB Index to Hong Kong stocks is higher than that of mainland stock markets, and the net spillover of mainland stock markets to the RMB Index is higher than that of Hong Kong stocks to RMB Index. The capital of the Hong Kong stock market mainly comes from the mainland capital, outward capital, and local capital, which are related to the RMB exchange rate. Therefore, Hong Kong stocks are greatly affected by the RMB Index, but the influence of Hong Kong stocks on the RMB exchange rate is relatively limited. Secondly, in the direction of spillover, the causality between the exchange rate and the stock market is uncertain. Specifically, there is a net information spillover from the HKD/CNY to the mainland stock market in the second half of 2019. But there is also a reverse situation, and the net spillover direction is from the Hong Kong stock market to HKD/CNY in this period. This is due to the agreement reached in the first phase of the trade agreement between China and the United States. The domestic market gradually gets rid of the pressure and influence, and the stock market gradually shows a stable trend. However, Hong Kong is in a semiparalyzed state due to riots. The stock market fluctuated sharply when the economy was hit hard, becoming the source of potential risk transmission.

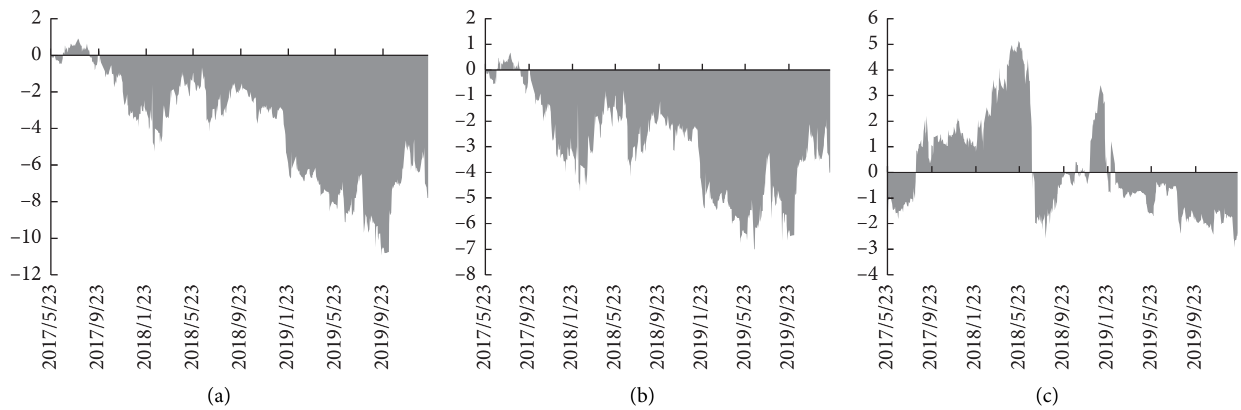


Figure 5: Dynamic changes of net spillover on the exchange rate and Hong Kong stock market. (a) Net overflow of US dollar against RMB and Hong Kong Hang Seng Index. (b) Hong Kong dollar against RMB and Hong Kong Hang Seng Index. (c) Net overflow of RMB Index and Hong Kong Hang Seng Index.

5. Conclusions

The vine copula model based on R-vine is constructed for the five representative indexes of the RMB exchange rate and China's stock market in different periods, obtaining the characteristic changes of the dependence structure between RMB exchange rate and the stock market. The information spillover index model is used to explore the transmission direction and intensity of information spillover between the two markets. It can show the changes in information spillover under the Sino-US trade war comprehensively and dynamically.

First, during the Sino-US trade war, the correlation between RMB exchange rates is decreased and the information spillover of USD/CNY and HKD/CNY is weakened. At the stage of accelerating RMB devaluation, in order to prevent the risk spread caused by its continuous devaluation, the state restarts the countercyclical factor and risk reserve to effectively alleviate the procyclical fluctuation of the exchange rate. In this process, the information spillover effect of the RMB exchange rate on the stock market is weakened to prevent the large-scale spread of potential risks. Therefore, the regulatory authorities should choose the opportunity to use foreign exchange management tools. When the foreign exchange fluctuation is abnormal or the market exhibits irrational behavior, the adjustment tools of foreign exchange regulation such as countercyclical factors will be used to restrain the procyclical sentiment of the market. However, the "herding effect" is not a normal feature of the foreign exchange market, and the irrational behavior of investors will not always exist. Regulators should always pay attention to the changes in the exchange rate market. The essence of countercyclical regulation and macroprudence is that the government participates in the management of the intermediate price, which will restrict the free flow of capital to a certain extent and be used timely and reasonably. When the market returns to rationality, we should adjust or cancel these regulatory measures and restore the market-led mechanism.

Second, the Sino-US trade war will enhance the correlation and information spillover between the stock market and the RMB exchange rate. The results of R-vine structure show that the central Hong Kong stock market has a strong tail correlation with the RMB Index, which means that risk transmission becomes easier when the market is faced with negative external shocks. When external shocks occur, the market in the central position will shift, and the uncertainty among the financial markets as a whole will increase. The key center position causes the change of the related market through high correlation and asymmetric tail effect. In this process of transmission, international capital flows, foreign trade, psychological expectations, and interest rates are important channels to influence market changes. Therefore, investors and management departments need to pay attention to tail risks. Extreme events such as the trade war and the financial crisis may cause a superimposed effect between the two markets. Establishing a risk prevention and control system between markets could effectively monitor changes in the market under external shocks and predict the future situation in advance. It achieves the purpose of preventing risk spillover and is used to reduce the risk of contagion, avoiding unnecessary losses caused by the decline in investor confidence and market expectations due to problems such as information asymmetry.

Third, the spillover effect of the RMB Index and the stock market is stronger than the single currency exchange rate. It more comprehensively reflects various factors and information such as the actual supply and demand of RMB. From the perspective of spillover intensity, the correlation between the Chinese stock market and the RMB Index is significantly higher than that between the stock market and the single currency exchange rate. From the perspective of spillover direction, the information spillover from the RMB Index to the stock market shows the feature of alternating transformation, while the information spillover from the stock market to USD/CNY and HKD/CNY shows a single direction during the high tide of the trade war. Under the process of market-oriented reform and internationalization, the exchange rate system no longer focuses on a single currency but refers to a basket of currencies, which can better reflect its comprehensive value. Therefore, it is necessary to promote the reform of the RMB exchange rate market mechanism. Reasonable selection of macroeconomic indicators improves the selection of the weight of "a basket of currencies" and further reduces the impact of government intervention and policy adjustments on the market. Expanding the rise and fall of foreign exchange and stock markets increases the flexibility of China's financial market. Investors should fully consider the stability and strength of currencies when changing their investment direction.

Fourth, the Hong Kong stock market is more closely linked with the RMB exchange rate due to its higher degree of openness. Comparing the mainland stock market and the Hong Kong stock market, it is found that the correlation and spillover effects of the RMB exchange rate on the Hong Kong stock market are generally higher than those on the mainland stock market. Although the degree of financial market opening in mainland China has improved in recent years, it is still relatively closed compared with the Hong Kong market. As a mature and open market, the Hong Kong stock market has great advantages in absorbing foreign capital, introducing management methods, and promoting market integrity. However, it is also vulnerable to fluctuations in other markets and becomes an emission area for external risks. Therefore, we should emphasize on macroprudential supervision while increasing the degree of openness. Dynamic financial regulation through the market fills the gaps in overseas assets and strengthens the necessary review and restriction of international capital. It can prevent the impact of speculative capital, promote long-term stable capital entry into the market, and reduce the vulnerability of overseas capital markets.

The information spillover between the RMB exchange rate and the stock market is closely related to the degree of market openness. There is a positive relationship between the opening of the market and the ability to receive external information. The occurrence of external shocks is easy to accelerate the information transmission of the market, and the risk will continue to spread in this process, which will endanger the stability of the entire financial system. Therefore, while promoting the internationalization of the financial market, it is also necessary to establish a "risk firewall" to effectively avoid risk contagion and control risk spread. Investors timely adjust the allocation of different assets and investment strategies to improve risk tolerance, which involves factors such as the rate of return, liquidity, and transaction costs.

Data Availability

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

Conflicts of Interest

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

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Supplementary Materials

The attached data file is the logarithmic return rate of the stock market and exchange rate. (*Supplementary Materials*)

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