Journal of Mathematics

Data-Driven Operations Research in Supply Chain Management

Lead Guest Editor: Shaojian Qu
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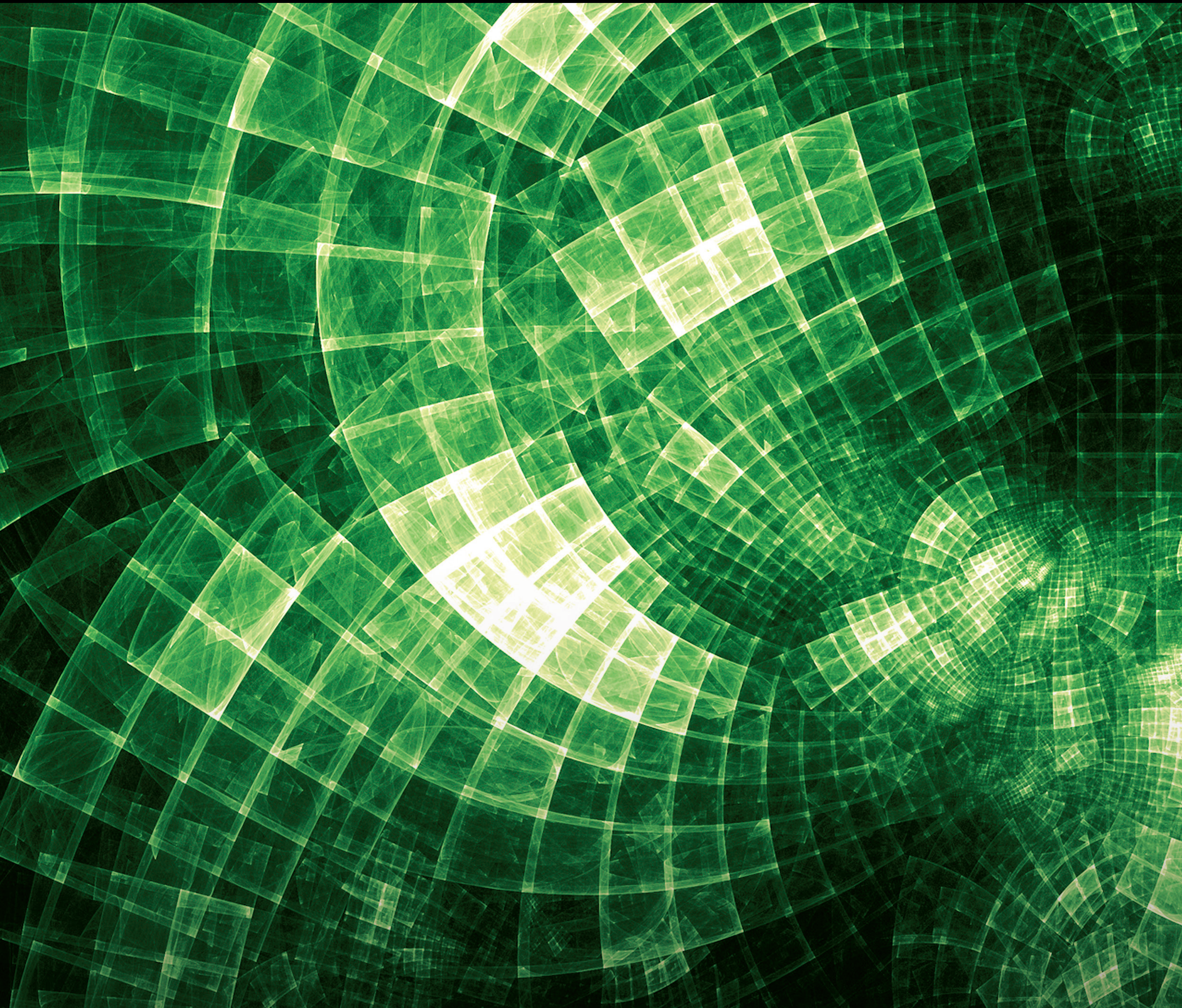

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Research Article

Resource Configuration Efficiency and Influencing Factors of Elderly Care Services Based on a Data-Driven DEA-Tobit Approach

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Efficient resource configuration is critical to providing sustainable aged care services. Empirical studies are conducted with a two-stage data-driven method of DEA-Tobit. First, the BCC model of data envelopment analysis is employed, to determine whether the values obtained from the three efficiency aspects (namely technical, pure technical, and scale) are situated in the frontiers of production, whether DEA is effective, and whether the problems of uneconomical scale or low technical level are available. Next, the causes of these problems are analyzed. Then, the regression analysis is performed using Tobit with the influencing factors including GDP, the number of institutions engaged in elderly care, the number of day service centers in the communities, the number of medical service institutions for the elderly, and the density of the elderly population. Known as a city with a severely aging population, Shanghai will be selected for a case study to propose countermeasures from the three dimensions of the elderly group, the elderly care industry, and the market environment.

1. Introduction

Global aging has a large and profound impact on society's long-term growth [1]. In the coming twenty years, the number of elderly people will undoubtedly rise in China [2]. Because of falling birth rates and rapidly growing life expectancy, rapid aging, which has serious economic consequences, has become a critical issue in China. As the population of the elderly grows, so will the demand for health services and aged care [3]. Against the background of active aging, the continuous improvement of the security and quality of the livelihoods of elderly people is not only an urgent requirement for continuous economic development and the further promotion of social civilization but also the accelerated promotion of economic and social stability.

Accordingly, properly configuring the resources required to provide senior care services would be a critical issue. There are several articles on this subject in the literature. Reference [4] conducted an efficiency analysis of the elderly care sector in Norway, revealing substantial variation in efficiency. Inefficient configuration of elderly resources may result in various issues besides increased costs. Reference [5] considered the correlation of clinical quality and productive efficiency in institutional long-term elderly care. Reference [6] presented the inequalities of elderly population in Germany based on morbidity-related and socioeconomic inequalities and the resulting financial burden.

From another perspective, understanding the determinants of resource configuration efficiency of elderly care service is essential to illuminate the potential improvement for better efficiency. The researchers used various methods from different perspectives to investigate the problem. For example, [7] adopted logistic regression to explore potential determinants in using those services. Reference [8] investigated quality of care and efficiency in nursing homes through DEA with an Italian example. Reference [9] explored decisive factors of long-term care and compared features of the community/home-based and of institution-based service users. Reference [10] provided a three-stage data envelopment analysis to investigate the efficiency of provincial social elderly care among 148 Councils in Britain. Reference [11] proposed an evaluation method with 33 indicators and compared the performance of community-based elderly care service centers with that of home-based ones in six dimensions.

As is the growing trend in elderly care, there is a significant waste of elderly care resources due to the lack of highly efficient management. Efficient resource configuration is an essential goal and needs to be evaluated well. Reference [12] introduced and performed the second-stage DEA efficiency analysis in the generating process of censoring data, with an empirical study to evaluate the configuration efficiency and explore the impacting factors. Reference [13] mentioned that Tobit regression is often encountered in second-stage DEA and concluded that the Tobit approach will in most cases be sufficient in representing second-stage DEA models. A similar approach has been taken in other areas, such as energy or medical services [14–16]. Reference [17] proposed a two-stage DEA model for efficiency assessments of wind powers. Reference [18] aimed to evaluate the technical efficiency of public and private hospitals in Beijing, China, and analyze the influencing factors of hospitals' technical efficiency.

The rest of the paper is constructed as follows. Section 2 discusses the theories of DEA analysis. Section 3 provides DEA results using Shanghai as an example. The results of the efficiency determinants are presented in Section 4. Concluding remarks are given in Section 5.

2. DEA Formulation and Preliminaries

2.1. Adoption of DEA Model. Data envelopment analysis (DEA) provides an insight to evaluate the relative efficiency demonstrated by a set of decision-makers with sufficient inputs and outputs.

There are two fundamental models: the CCR model, which is proposed by Charnes, Cooper, and Rhodes in 1978 and the BCC model proposed by Bankers, Charnes, and Cooper in 1984 [19–21].The difference between the two models lies in the fact that the CCR model has the premise of constant return to scale (CRS), while the BCC model has the premise of variable return to scale (VRS). Thus, the former can only be used to evaluate the decision-making units (DMUs) with constant returns to scale. This model can only compute technical efficiency value, instead of being decomposed to scale and pure technical efficiency value and directly evaluating the effectiveness of DUM. By adding a constraint to the CCR model, the BBC model ameliorates the problems noted above. The technical efficiency value can therefore be broken down into a pure technical efficiency value and a scale efficiency value, the formula CRSTE = VRSTE ∗ SCALE being fulfilled.

In the study on the evaluation model of input-output efficiency, the input-oriented BBC model is mainly adopted to evaluate the efficiency of the resource configuration. In other words, the input is reduced as much as possible under the condition of a fixed output. First, the resource configuration of the elderly care services is subjected to not only the influence imposed by the external environment (such as related policies and the mechanism of market competition) but also some internal environments. Hence, the guidance over the input of elements under the fixed output is explored in this study to decrease the factors. On this basis, the input-oriented type is selected. Furthermore, in comparison with the BCC model, the CCR model can only be employed to calculate the technical efficiency value of the resource configuration of the elderly care services. It is unable to decompose pure technical efficiency value and scale efficiency value. On the other hand, the BCC model works for technical efficiency value, pure technical efficiency, and scale efficiency. Therefore, the BBC model is more conducive to comprehensively analyzing the key issues surrounding the resource configuration of the elderly care services.

2.2. The Inputs and Outputs of DEA Model. To simplify, when defining the resource configuration of the elderly care services, the input of the resource associated with the aged care services is divided by the output. From another perspective, it can be understood as a comparison of the technical efficiency values obtained from the resource configuration of the elderly care services to determine which is larger.

From an input perspective, there are different types of resources available to aged care services. According to the principle in the selection of indexes and the availability to the statistics, the pension from the retired personnel is first selected because it is the main financial source of the aged. Additionally, a large amount of literature review demonstrated that the indexes frequently used to evaluate the resource configuration of the elderly care services contain the number of the institutions engaged, the number of senior care beds, the number of institutions possessed by every one thousand seniors, and the number of beds possessed by every one thousand seniors. According to the evaluation indexes of elderly care services conducted in institutions and communities and the accessibility of the statistics data, institution-based elderly care services and the number of daycare institutions caring for the elderly in communities are taken as the indexes.

From an output perspective, the paper adopts the number of yearly served seniors and the population of the seniors over 60 years old as the output indexes for the evaluation over the resource configuration of the elderly care services. It is revealed that it conforms to the requirement for the correlation between input indexes and output of the DEA model and can comprehensively reflect the connection between the resource configuration efficiency and the growth rate of the elderly.

2.3. Data Source. Shanghai is already one of the cities with the highest degree of aging in China. The steadily growing population of the aged has presented great demand for economic supply, medical care, basic daily care, and spiritual relief. A typical meaning can be demonstrated in the research on the resource configuration of the elderly care services in Shanghai.

The statistics of the study come from the Shanghai Statistical Yearbook and the Shanghai Municipality's Elderly Population and Elderly Career Monitoring Statistics from

2010 to 2019. This ensures that the statistics are meaningful to a certain extent. Given the accessibility of statistics, the resource about the elderly care services in Shanghai is selected as the evaluation sample in this paper to compare and analyze the efficiency of the resource configuration in different years, as shown in Table 1.

Given that there are differences in the dimension of different indexes, the treatment of nondimensionalization is conducted for different indexes and statistics before the analysis on DEA to ensure the results obtained from the analysis. The formulas are

$$\begin{aligned} x_{ij}' &= 0.1 + \frac{x_{ij} - \min_j}{\max_j - \min_j} \times 0.9, \quad 0.1 \le x_{ij}' \le 1, \\ y_{ij}' &= 0.1 + \frac{y_{ij} - \min_j}{\max_j - \min_j} \times 0.9, \quad 0.1 \le y_{ij}' \le 1, \end{aligned} \tag{1}$$

where x_{ij} indicates various original data of the inputs; y_{ij} denotes the original data of the outputs; $\min_j$ represents the minimum value in the statistics of indexes; and $\max_j$ denotes the maximum value in the index statistics. The statistics after the treatment of nondimensionalization offset the influence imposed by dimension. The range of values is $0.1 \le x \le 1$, as shown in Table 2.

3. The Results of the DEA Analysis

With the software of DEAP2.1, a DEA calculation for the resource configuration efficiency of the elderly care services in Shanghai from 2010 to 2019 is carried out in this study. Under the condition of variable scales, CRSTE, VRSTE, and Scale are obtained from the resource configuration of the elderly care services in Shanghai, including the scale effect from 2010 to 2019.

In the DEA analysis, IRS and DRS indicate ascending returns to scale and descending returns to scale, respectively; "—" denotes constant returns to scale. In addition, CRSTE, VRSTE, and SCALE represent technical efficiency, pure technical efficiency, and scale efficiency, respectively. Technical efficiency is equal to pure technical efficiency multiplied by scale efficiency. The final efficiency results are shown in Table 3.

Regarding the resource configuration of the elderly care services in Shanghai from 2010 to 2019, the graphic of changes for technical efficiency, pure technical efficiency, and scale efficiency of input-output are depicted using Excel. The horizontal axis and the vertical axis indicate years and the efficiency values obtained from DEA computation in different years, respectively. The line chart reflects the changes in the technical efficiency, pure technical efficiency, and scale efficiency, as illustrated in Figure 1.

3.1. Technical Efficiency. Technical efficiency refers to the production efficiency generated by input factors, under the prerequisite of a comprehensive measurement and evaluation of the resource configuration capability and resource usage for DUM. According to the DEA calculation, the average technical efficiency score from 2010 to 2019 is 0.864, which suggests that the resource of the elderly care services in Shanghai plays a role of 86.4%. From the previous part, it can be seen that if the value of technical efficiency in a certain year is 1, the efficiency of the resource of the elderly care services in that year reaches production limit. This demonstrates that the resource configuration of the elderly care services reaches the level is relatively effective.

Figure 1 indicates that the technical efficiency reached 1 in 2014, while both pure technical efficiency and scale efficiency reached 1, realizing the relative efficiency of DEA. The variation trend of technical efficiency can be divided into three stages. (1) The stage of increasing from 0.757 to 0.990 from 2010 to 2012 demonstrates that resource configuration in Shanghai during this period. (2) The stage of fluctuation from 2012 to 2014 (first decreasing and then increasing to the efficiency value of 1, then holding it constant) shows that the situation of wasting resources can exist, and the effective value was realized in 2014 through constant structural adjustment. (3) The stage of decreasing has appeared since 2014. The rule exhibited by efficiency value is gradually decreasing, and the efficiency value of 1 drops to 0.757. In combination with the status quo analysis of the resource configuration of the elderly care services in Shanghai, it can be revealed that a conflict in the resource configuration or the waste of resources after 2014 can be identified.

3.2. Pure Technical Efficiency. Pure technical efficiency denotes the efficiency brought to DMU by reforming systems and management levels within the framework of the input scale of a specific resource. It reflects the management level in the resource configuration of the elderly care services in Shanghai. If the pure technical efficiency is equivalent to 1, the resource configuration utilization rate is currently effective based on the current systems and management level.

The analysis results show that the average value obtained from pure technical efficiency of resource configuration of the elderly care services in Shanghai reached 0.990 from 2010 to 2019. With the exception of 2011, 2015, and 2016, the effective purely technical efficiency was achieved with a share of 70%. According to the general level of the years examined, the pure technical efficiency of resource configuration of the elderly care services in Shanghai was relatively high, suggesting a high level of system and management level. Therefore, the resources input can be effectively used at the current level of technical management.

3.3. Scale Efficiency. According to the DEA calculation, scale efficiency reflects the difference between actual scale and optimal scale of the present resource configuration of the elderly care services under the premise of the system and management at a certain level. When the scale efficiency of DMU is equivalent to 1, the resource has achieved the optimal scaling configuration.

From 2010 to 2019, the average scale efficiency of resource configuration of the elderly care services in Shanghai was 0.872 and thus remained a relatively excellent state. The change of scale efficiency was almost the same as that of technical efficiency, implying that the influence of pure

Table 1: Evaluation index of the efficiency of pension resources allocation.

Year	Input index		Output index
	X_1: pension for retired personnel (100 million yuan)	X_2: number of pension resource institutions per 1,000 elderly people (number)	Y_1: population receiving annual service (10,000 persons)
2010	783.42	0.369	331.02
2011	912.71	0.360	347.76
2012	1018.79	0.341	367.32
2013	1192.33	0.330	387.62
2014	1377.17	0.328	413.98
2015	1658.44	0.335	435.95
2016	1957.76	0.331	457.79
2017	2265.11	0.330	483.60
2018	2469.00	0.334	503.28
2019	2690.27	0.345	518.12

Table 2: Input-output data for dimensionless process.

Year	Pension for the retired	Number of institutions possessing pension resource per thousand elders	Population of the elderly receiving service annually
2010	0.100	0.916	0.100
2011	0.161	0.775	0.181
2012	0.211	0.269	0.276
2013	0.293	0.100	0.375
2014	0.380	0.100	0.502
2015	0.513	0.409	0.609
2016	0.654	0.353	0.715
2017	0.799	0.438	0.840
2018	0.896	0.663	0.936
2019	0.100	0.100	0.100

Table 3: Efficiency results of Shanghai pension service.

Year	CRSTE	VRSTE	SCALE	Returns to scale
2010	0.757	1.000	0.757	irs
2011	0.851	0.938	0.907	irs
2012	0.990	1.000	0.990	irs
2013	0.969	1.000	0.969	irs
2014	1.000	1.000	1.000	—
2015	0.899	0.989	0.909	drs
2016	0.828	0.977	0.847	drs
2017	0.796	1.000	0.796	drs
2018	0.791	1.000	0.791	drs
2019	0.757	1.000	0.757	irs
mean	0.864	0.990	0.872	

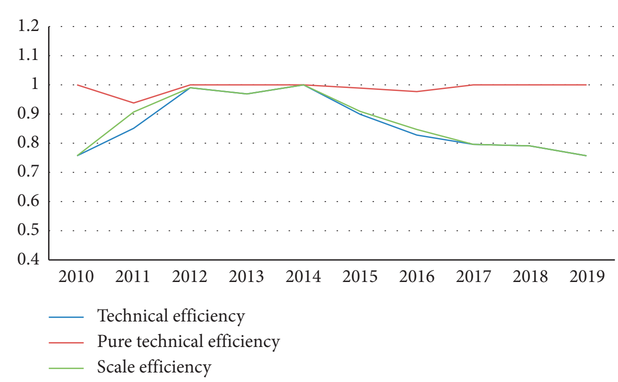

Figure 1: Line graph of technical efficiency, pure technical efficiency, and scale efficiency.

technical efficiency on technical efficiency was small due to a high level of pure technical efficiency approaching 1. Hence, the scale efficiency is the key factor for the technical efficiency of resource configuration of the elderly care services in Shanghai.

The total change in returns to scale can be broken down into three stages as follows. First of all, the stage of increasing returns to scale from 2010 to 2013 suggests that the input of resource and the scale of resource configuration should be enlarged during this period. Second, the stage of constant return to scale was only achieved in 2014. Third, the stage of decreasing returns to scale from 2015 to 2018 indicates that the input was unable to obtain the output of the same level, and the input structure about the resource configuration of the elderly care services in Shanghai was not reasonable. In addition, there was a trend towards economies of scale up to 2019, which shows that the configuration of the resources for elderly care in Shanghai has been continuously optimized and further developed.

4. Explaining Variations in Efficiency with Tobit

In the previous sections, the input-output efficiency of the resource configuration of the elderly care services in Shanghai was measured. The analysis results verified that effective and invalid DEA are available in different years. However, the introduction of the Tobit model facilitates the measurement of the efficiency value obtained from DMU with the DEA model to examine the factors influencing the resource configuration efficiency of various other care services for elderly in Shanghai.

The resource configuration of elderly care services is the result caused by the role played by many parties together, mainly including input, output, and social environment. Regarding the social environment, the factors influencing resource configuration of elderly care services exhibit characteristics of diversity and complexity. Other researchers suggested that it is majorly composed of economic level, industry level, and social environment.

4.1. Introduction of Tobit. The Tobit model was proposed by Tobin in 1958 [22]. It is a model with a limited dependent variable. Since the value range of the efficiency value through DEA computation is [0, 1], derivation will exist in the result during the estimation if the least square method is adopted. However, in the finite dependent model, the expected error is not zero. The maximum likelihood method, the Tobit model, is therefore used for the calculation in order to effectively avoid the above-mentioned derivation [23]. It can be further illustrated using a formula.

The maximum likelihood method is applied to parameter estimation of the Tobit model. The maximum likelihood function is expressed as follows:

$$L = \prod_{y_i=0} \left(1 - F_i\right) \prod_{y_i>0} \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{1}{2\sigma^2}\left(y_i - \beta x_i\right)^2\right], \quad F_i = \int_{-\infty}^{\beta_x/\sigma} \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{t^2}{2}\right] \mathrm{d}t. \tag{2}$$

In the above formula, the first part represents the product obtained from the probability of the effective DMU; the second part expresses the product obtained from the probability of the ineffective DMU. Fi denotes the standard normal distribution on the interval. In this paper, the value range of the resource configuration of the elderly care services is [0, 1], and the analysis using Tobit regression is reasonable. The Tobit model can deliver relatively concrete results to the degree of influence imposed by different influencing factors on efficiency. In addition, derivation and inconsistency in the results are not available. The Tobit regression analysis is better suited to the limited dependent variable situation. Thus, the Tobit model in this study is finally written as follows:

$$\begin{aligned} Y_i^* &= \beta_0 + \beta_i X_i + \varepsilon_i, \\ Y_i &= \begin{cases} 0, & \beta_0 + \beta_i X_i + \varepsilon_i \in (-\infty, 0], \\ Y_i^*, & \beta_0 + \beta_i X_i + \varepsilon_i \in (0, 1], \\ 1, & \beta_0 + \beta_i X_i + \varepsilon_i \in (1, +\infty], \end{cases} \end{aligned} \tag{3}$$

where $\varepsilon_i \sim N(0\sigma^2)$; Y_i^* presents the potential vector quantity of dependent variable; Y_i denotes the vector quantity of limited dependent variable; X_i indicates the vector quantity of variable vector, that is, the influencing factors of efficiency; β_0, β_i and ε_i designate the constant term, the vector quantity of regression coefficient, and the random error term, respectively.

4.2. Determinants Analysis of Resource Configuration. The reasons for the micro factors influencing the resource configuration efficiency of the elderly care services in Shanghai are complicated. It is difficult to obtain all the relevant information. In this paper, the influence of macro factors on the resource configuration efficiency is mainly explored based on the three dimensions of economy, industry, and society. In addition, when selecting input-output indicators, the analysis of various controllable influencing factors on the resource configuration efficiency of geriatric care services is carried out from different perspectives in order to comprehensively understand various factors. The Tobit model is further employed to analyze the interfering factors of resource configuration efficiency of the elderly care services. Based on the existing studies and the actual situation about resource configuration of the elderly care services in Shanghai, the specific factors influencing efficiency are selected and exhibited in Table 4.

Therefore, regression analysis is performed in this study with the technical efficiency of resource configuration of the elderly care services in Shanghai from 2010 to 2019 as the dependent variable and five indexes as the explanatory variables of the Tobit model. The five indexes include Shanghai GDP (100 million RMB) from 2010 to 2019, institutions engaged in the elderly care (number), day service institutions in the community (number), medical service institutions engaged in the elderly care (number), and the density of the elderly Population. As stated, the statistics are collected from the Shanghai Statistical Yearbook and Shanghai Municipality's Elderly Population and Elderly Career Monitoring Statistics from 2010 to 2019, as well as the analysis previously performed in the paper. Relevant descriptive statistics of the data are offered in Table 5.

4.3. Hypothesis and Research Questions. Based on the studies carried out by other scholars, the factors influencing resource configuration efficiency of elderly care services in Shanghai are explored from the aspects of the economic

Table 4: Factors influencing efficiency.

	Analysis dimension	Index	Unit	Description	Signs
Factors and indicators influencing efficiency	Economic level	GDP of Shanghai	RMB100 million	Regional economic development level	Y_1
	Industrial level	Institutions engaged in the elderly care	Number	Development level of the elderly care industry	Y_2
		Day service institutions in the community	Number		Y_3
		Medical service institutions engaged in the elderly care	Number		Y_4
	Social environment	Population density of the elderly	Persons/square kilometers	Objective environment of elderly care service resources	Y_5

Table 5: Descriptive statistics of factors influencing resource allocation efficiency of the Shanghai pension service in 2010–2019.

Name of variable	Average value	Standard deviation	Minimum value	Maximum value
Technical efficiency value	0.86	0.95	0.757	1.00
GDP of Shanghai	27157.07	6912.82	17915.41	38155.32
Number of institutions engaged in the elderly care	671.90	39.73	625	724
Day service institutions in the community	451.40	147.42	303	720
Medical service institutions engaged in the elderly care	30.4	11.46	18	55
Density of the senior population	669.73	103.92	522.07	817.16

level, industrial level, and social environment level. The analysis starts from the element framework of comprehensive and systematic influencing factors.

Hypothesis 1. There is a positive correlation between Shanghai GDP and the technical efficiency of the resource configuration of elderly care services.

From an economic point of view, regional economic development level with the GDP of Shanghai as the representative is the fundamental influencing on the resource configuration efficiency of elderly care services. The economy serves as the root of social development. The higher the GDP, the better the economic development in this area and the higher the level of economic development. The rapid development of society at all levels promotes the high resource configuration efficiency of elderly care services to some extent.

Hypothesis 2. There is a positive correlation between the level of industry development and the technical efficiency of resource configuration of elderly care services.

At the industry level, the level of sophistication of geriatric care facilities, community day care, and elderly medical service facilities could affect the efficiency of the resource configuration of geriatric care services in an area. The higher the level of development in an area, the richer the industry experience and experience. It makes a positive contribution to the resource configuration of geriatric care services.

Hypothesis 3. There is a positive correlation between the density of the elderly population and the technical efficiency of the resource configuration of elderly care services.

At the level of social environment, the density of the elderly population denotes the reflection of the elderly population per unit land area. It can effectively measure the degree of accessibility to the resource of elderly care services. We believe that there is a positive correlation between the elderly population density and the population obtaining the resource of elderly care services. The higher the population density of the elderly, the greater their access to resources for care for the elderly. To some extent, the cost of administration and monitoring per unit area will decrease, resulting in an increase in the economies of scale and efficiency of the resource configuration of geriatric care services.

According to the three hypotheses, the multiple regression model is established in this study with the technical efficiency as the dependent variable and the five previously discussed indices as explanatory variables.

$$Y = \beta_0 + \beta_a P_1 + \beta_b P_2 + \beta_c P_3 + \beta_d P_4 + \beta_e P_5 + \varepsilon, \quad (4)$$

where Y refers to the value of resource configuration efficiency of elderly care services in Shanghai; β_0 denotes the constant term; $\beta_a, \beta_b, \beta_c, \beta_d,$ and β_e represent the GDP, institutions engaged in the elderly care, day service institutions in the community, medical service institutions engaged in the elderly care, and the density of the elderly population, respectively; and ε indicates the random disturbance term.

4.4. Regression Results and Analysis. The factors influencing the resource configuration efficiency of elderly care services are measured using the Stata 15.0 software. The regression results are obtained, as shown in Table 6.

5. Discussion

Findings of this study shed some light on the current efficiency evaluation of the resource configuration and the future development for both practitioners and policy makers. It is also noted that, when establishing the

Table 6: Analysis of factors influencing the efficiency of pension resources allocation.

Dimensions	Economic level	Industrial level			Social environment level
Indicators	GDP of Shanghai	Institutions engaged in the elderly care	Day service institutions in the community	Medical service institutions engaged in the elderly care	Density of the senior population
Technical efficiency	0.0000804 (2.04)	0.0031597** (3.85)	0.0030568** (3.66)	0.0006829** (0.66)	0.0013795* (0.81)

Note. The value of t is in parentheses; "*", "**", and "***" indicate the significance levels at 10%, 5%, and 1%, respectively.

evaluation indexes, the policy environment and other related indicators were not included due to the complexity and data accessibility, and accordingly the study was unable to reflect the overall picture of the resource allocation efficiency issue. Also, in future research, the nature of the various resources available for elderly care services can be further subdivided, and the factors that affect the efficiency of different types of resources can be examined separately.

5.1. Conclusions. The overall resource configuration efficiency of elderly care service in Shanghai is not high. The technique efficiency about the resource configuration efficiency of elderly care service in Shanghai "first increases and then decreases". Among all the ten years' studies, valid DEA was only realized in 2014, accounting for 10% of the total. Then, it shows a decreasing trend. However, from the point of view of purely technical efficiency, the average value obtained from pure technical efficiency of the resource configuration of elderly care service reached 0.990, suggesting that the system and management of resource configuration are at a high level. At the current technical level, the resource can be input to promote its effective utilization.

Scale efficiency is the key factor influencing the technical efficiency of the resource configuration of elderly care services in Shanghai. The average value of the resource configuration efficiency of elderly care service in Shanghai from 2010 to 2019 was 0.888, which is slightly above 0.872 (the average value of technical efficiency). Over the 10-year study, pure technical efficiency was achieved in the first six years, accounting for 70% of the total. Moreover, the average value obtained from pure technical efficiency was as high as 0.990, approaching 1. The technical efficiency of the resource configuration of the geriatric care services in Shanghai is therefore heavily influenced by the economies of scale.

Complexity and diversity are reflected in the influencing factors of resource configuration efficiency of elderly care services in Shanghai. Regarding the regression analysis on the influencing factors of resource configuration efficiency of elderly care services in Shanghai, there is a positive correlation between resource configuration efficiency of elderly care services and the four indexes (the institutions engaged in the elderly care, day service institutions in the community, medical service institutions engaged in the elderly care, and the density of the elderly population). To sum up, the factors influencing resource configuration efficiency of elderly care services are diverse. Hence, the evaluation is supposed to start from the multidimensional perspective and comprehensively consider various influencing factors such as technical efficiency and resource utilization. Specifically, objective and comprehensive results can be obtained to explore the effective path for improving the resource configuration efficiency of elderly care services.

5.2. Management Implies. In the view of the empirical analysis on the status quo, efficiency evaluation, and influencing factors related to resource configuration of elderly care services in Shanghai, corresponding countermeasures are proposed from the three dimensions of the elderly group, the elderly care industry, and market environment. In this way, the study may improve resource configuration efficiency of elderly care services in Shanghai and enable the industry to develop efficiently.

First, value the willingness of the elderly in old age to engage in social activities. From the viewpoint of long-term development, the resource of elderly care services offered by the government uniformly is limited to some extent. Hence, it should be first supplied to the elderly who are in great demand of such safeguard to maximize the marginal utility, instead of providing all the elderly with basically the same elderly care services under the lowest conditions. Thus, the social role of the healthy seniors of low ages is transformed from a single consumer to producer. They would conduct production and consumption concurrently and are transformed to the positive creators of the resource relevant to elderly care services rather than the passive recipients of the resource [24].

Second, guide the elderly care industry to improve itself reasonably. The capital employed is to be increased; the flow of capital should be appropriately directed; and the subsidy received on the basis of the policy should be distributed appropriately. In addition, although government spending in various areas of the elderly care industry has grown rapidly, the resource should be used wisely. Simultaneously, the capital supervision should be strengthened, accompanied by improved corresponding regulatory institutions and systems [25].

Third, the efficiency of resource configuration in the geriatric care industry needs to be emphasized to realize the optimal resource configuration. Moreover, the elderly care sector in different regions should be developed by adapting the measures to local conditions and taking full account of the economic level, social development characteristics, and the objective environment of the specific areas. It should be combined with an appropriate map of the geographic location where the elderly care facilities are located.

Fourth, the promotion of consumption in the elderly care market. Market demand serves as the key factor pulling resource configuration. The market requirement in the elderly care market should be further subdivided to improve the resource configuration level of elderly care services. The government must take the initiative to overcome the negative obstacles affecting social capital participation in elderly care in order to continually attract social capital to the elderly care sector.

Finally, the key role of the market in shaping the market resource should be exerted. It points to a more important responsibility of the government than to the deprivation of government responsibility [26]. This is because elderly care services are within the range of activities falling in the scope of governmental public function, which is a distinctive feature.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

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

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Research Article

Two-Stage Robust Optimization Model for Uncertainty Investment Portfolio Problems

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Investment portfolio can provide investors with a more robust financial management plan, but the uncertainty of its parameters is a key factor affecting performance. This paper conducts research on investment portfolios and constructs a two-stage mixed integer programming (TS-MIP) model, which comprehensively considers the five dimensions of profit, diversity, skewness, information entropy, and conditional value at risk. But the deterministic TS-MIP model cannot cope with the uncertainty. Therefore, this paper constructs a two-stage robust optimization (TS-RO) model by introducing robust optimization theory. In case experiments, data crawler technology is used to obtain actual data from real websites, and a variety of methods are used to verify the effectiveness of the proposed model in dealing with uncertainty. The comparison of models found that, compared with the traditional equal weight model, the investment benefits of the TS-MIP model and the TS-RO model proposed have been improved. Among them, the Sharpe ratio, Sortino ratio, and Treynor ratio have the largest increase of 19.30%, 8.25%, and 7.34%, respectively.

1. Introduction

Investment portfolio means that investors invest their own assets in stocks, funds, bonds, and other securities at the same time, in order to achieve higher or more stable profits under lower risk conditions. In the early research, many scholars constructed the mean-variance model and the portfolio effective boundary model, which opened a new era of investment portfolio. Among them, since Markowitz founded the portfolio theory, the development of portfolio theory has been extremely rapid [1,2]. Risks persist due to poor risk management and uncertainty in the market environment. Portfolio theory is one of the important financial theories that discuss the profits and risks in the investment process. In the management of risk, many scholars believe that the research of investment portfolio can effectively measure uncertainty and avoid risk. The investment portfolio mainly embodies the idea of investment diversification. By screening different types of risk asset projects, the purpose of reducing investment risks is achieved. The investment portfolio optimization method provides a powerful tool for risk management [3,4]. Using the model method of investment portfolio optimization to find a reasonable allocation of funds can help investors balance safety and profitability and ensure that they achieve maximum profits within the acceptable risk range. Whether it is the securities and finance industry or other academic fields such as research institutes and universities, how to effectively formulate appropriate investment strategies has always been the focus of research [5,6]. It is found that the game between investment and risk is always accompanied by investors. Continuously improving investment risk management capabilities is a top priority for regulatory authorities, financial institutions, and even individual investors.

Some investors tend to avoid risks by looking for the law of risk distribution, so that they can modify their strategies in a timely manner in the face of unexpected situations. In the application process of investment portfolio optimization, there are few or even missing historical data. How to accurately measure risk in the absence of historical data and how to reasonably estimate possible losses taking into account a variety of factors is also a huge challenge. In addition, the study found that financial risk measurement is based on a basic distribution assumption. The selection of appropriate distribution assumptions has a significant impact on the accurate measurement of risk, which in turn affects the efficiency of the overall investment plan. How to choose an appropriate distribution hypothesis is also a pain point in portfolio research. In the research on the uncertainty of portfolio risk distribution, researchers focus on how to incorporate the uncertainty of loss into the investment decision-making process and then improve the problem of portfolio optimization. In addition to the existing research on the specific distribution probability of hypothetical risks, many scholars have tried to conduct research from the risk itself. It is found that the loss is affected by many factors. In an economic environment that is rising frequently, the distribution of losses may be similar to a normal distribution. In a flat economic environment, the risk loss distribution may be similar to a certain distribution [7–9]. In a recessionary economic environment, the risk loss distribution may be similar to a certain Pareto distribution [9,10]. Under different distribution models, the choice of portfolio strategy often leads to significant differences in expected results. How to effectively screen the probability distribution of risks and how to effectively determine the investment portfolio plan are a hot topic in the research.

In addition to the research on the probability of risk distribution, many scholars have conducted multidimensional research on the inherent uncertainty by citing models in cross-domains. Garlappi et al. (2007) constructed a portfolio model by estimating the confidence interval of the expected profit. The study found that the fuzzy aversion portfolio only performed stably for a period of time [11]. Tu and Zhou (2010) proposed a method that allows Bayesian Priors to reflect the objectives of economic problems. In terms of measurement of out-of-sample loss function, the model of portfolio strategy based on the objective priori can be significantly superior to the model developed in the classical framework [12]. Bayraktar and Zhou (2017) studied the fundamental theorem of asset pricing and option hedging prices under discrete-time nondominated model uncertainty and portfolio constraints. Research has discovered the duality of superhedging prices in a market where stocks are dynamically traded and options are statically traded [13]. The research of Golosnoy and Okhrin (2008) found that there is general uncertainty in the asset allocation model, and the optimal belief degree can be determined by developing a case-based decision-making method [14]. Some scholars use the linear loss aversion function to construct the model and obtain the optimal solution. This function assumes that the marginal utility of investors' gains and losses is constant. Investor's loss aversion degree and reference profit will vary with market conditions and relative wealth. The assumption that the loss aversion coefficient and the reference point remain unchanged does not conform to the true psychology of investors [15,16]. Huang and Qiao (2012) discussed a multiperiod securities investment portfolio selection problem and proposed an uncertain risk index adjustment model. The goal of optimal investment portfolio adjustment is to maximize the total incremental wealth under the constraints of accumulating risk index values during the control investment period and satisfying the constraints of self-raised funds in each period [17]. When analyzing the optimal investment decision of loss aversion investors, the dynamic change characteristics of loss aversion coefficient and reference point should be considered. At present, when building loss aversion models, scholars assume that the expected profit of assets is determined, and the average profit and profit distribution of risky assets in the market are both uncertain. Using the uncertainty of asset profit distribution for reference, the assumption of unknown profit distribution is introduced into robust optimization to describe the fuzzy aversion characteristics of investors, which is more in line with the real psychology of investors. Uncertainties are particularly prominent, and the economy has been affected. In this case, reasonable investment decisions are particularly important. For multiperiod investments, the experience and wisdom of investors are extremely important, where investing, profits, risks, and liquidity are often involved. These three are interrelated and restrict each other. This relationship is in the relationship between profit and risk. The performance is more prominent in time. High risk means high returns, and risk and profit are often proportional, but investors hope to obtain higher profits with less risk, which poses a big problem for investors and researchers. Therefore, it is still necessary to continue to study multistage investment under uncertain conditions.

In recent years, with the steady optimization theory and methods being gradually accepted and recognized by scholars, the uncertainty of using robust optimization to study the portfolio has become particularly novel. The robust optimization theory simply expresses the uncertain parameters in a specific interval and can flexibly control the degree of uncertainty. The robust optimization theory proposed by Bertsimas and Sim (2004) and Ben Tal et al. (2007) to deal with the uncertainty in the model is now a commonly used research method [18,19]. Huang et al. (2010) studied how to use robust optimization to analyze uncertain parameter problems and proved the effectiveness of the robust optimization model [20]. Dai and Wen (2014) proposed a robust optimization theory for minimizing the CVaR of the investment portfolio under the general affine data perturbation uncertainty set. Their research uses numerical experiments with real market data to illustrate the practicality of robust optimization models [21]. In venture capital, investors pay more attention to the right-leaning loss distribution risk, and then it is of practical significance to introduce information entropy into risk measurement research in the financial field. Through the review of the above literature, diversification of investment demand and uncertainty of risk preference are also hot issues in investment portfolio research in recent years. Many scholars have conducted in-depth investigations on the uncertainty of risk appetite. Information entropy can be used to measure the degree of deviation from uniform distribution. The deviation corresponds to a point that reflects the uncertainty of the probability distribution over the entire range of values. At the same time, information entropy can express more information about the distribution, more accurately reflect the risk of loss distribution, and then serve as an ideal means of measuring risk. It can be found from the above-mentioned literature that robust optimization, CAaR, and information entropy, as tools to measure stock investment risk, can be well applied in the symmetric and asymmetric distribution of probability. However, although most of the existing algorithms have played a certain role in improving the accuracy of the model solution, the convergence speed is often slow due to the complexity of the solution algorithm.

In the research of portfolio optimization, the mean-risk model usually assumes that the expected profit on risky assets is subject to a known probability distribution and that the number of transactions is infinitely divided, which is not consistent with the actual situation. In this paper, a two-stage robust portfolio optimization model is constructed, and the optimal solution in the worst case is found in the uncertain set. Based on the analysis and comparison of the above related literature, the research in this paper mainly includes the following innovations:

(i) This paper summarizes the research results of related scholars, analyzes the classical portfolio problems in depth, and proposes a deterministic TS-MIP model considers the risk and diversity of investment problems.

(ii) On the basis of deterministic model, the research content is further extended to uncertainty, and the mechanism of influence of uncertainty parameters on portfolio efficiency is analyzed in depth.

(iii) In the research of dealing with uncertainty interference, this paper introduces the theoretical method of robust optimization, constructs a TS-RO model, and applies it to the research field of investment portfolio.

(iv) In the numerical case analysis part, this paper uses data crawling technology to obtain the latest real data from real-time websites as the input part of the model and uses real data for a large number of case studies and parameter comparisons, to obtain practical investment advice.

The rest of this framework is as follows: Section 2 lists related basic theories and methods. In the third section, based on the basic deterministic TS-MIP model, we analyze the problem under uncertain parameters and further construct the TS-RO model. Section 4 obtains relevant data through data crawling technology and constructs numerical cases for analysis. Section 5 compares the key parameters of the model and puts forward some management investment recommendations.

2. Basic Theory and Model

2.1. Information Entropy. Information entropy can be defined as the possibility of discrete random events [22–24], and the specific expression is shown in

$$S = -\sum_{i=1}^{n} p_i \ln\, p_i. \tag{1}$$

Among them, the function of p_i is to measure the probability of occurrence of the situation i. In the current stage of theoretical research, information entropy has been widely used to measure the uncertainty of information, and there is a positive correlation between entropy and uncertainty. In addition, the information entropy function also has the following three special properties:

(i) Continuity: S is a continuous function of p_i, $(p_i \in [0,1])$

(ii) Nonnegativity: $S(p_1, p_1, p_1, \ldots, p_n) \geq 0$

(iii) Extreme value: if and only if the condition is $p_1 = p_2 = \cdots = p_n$, the information entropy achieves the maximum value

2.2. Value-Added Entropy and Actual Entropy. Value-added entropy is a kind of generalized entropy [25,26], which can be defined as

$$H = \sum_{i=1}^{W} p(x_i) \log \sum_{i=1}^{N} x_i r_i. \tag{2}$$

Suppose there are N types of stocks or securities in the market, and the k type contains n_i possible prices $(i = 1, 2, 3, \ldots, N)$. The number of all possible value combinations is $W = n_1 \times n_2 \times n_3 \times \cdots \times n_N$. $\mathbf{X}$= $(x_1, x_2, x_3, \ldots, x_k; i = 1, 2, \ldots, W)$ refers to the investment ratio of the k securities, and $\mathbf{R}$= $(r_1, r_2, r_3, \ldots, r_k)$ is the output ratio in the i price combination. In addition, R_i = $1 + r_i$ and r_i represent the rate of profit, assuming that short selling is not allowed, that is, $r_k \geq 0, k = 1, 2, \ldots, N$. The above formula (2) can be further transformed into

$$\begin{aligned} H &= \log \prod_{i=1}^{W} R_i^{p(x_i)}, \\ R_i &= \sum_{k=1}^{N} q_k R_{ik}. \end{aligned} \tag{3}$$

Actual entropy: in the actual financial market, investment transactions require costs, and an investment portfolio that ignores transaction costs will often have a great impact on actual profits and may make investments invalid. Introduce typical transaction costs into the portfolio and define linear transaction costs. However, linear transaction costs rarely appear in investment costs, so the improved transaction cost function $C(\mathbf{X}) = [c(x_1), c(x_2), c(x_3), \ldots, c(x_n)]$ can be expressed as

$$c(x_i) = \begin{cases} r\sqrt{x_i}, & 0 \le x_i \le a, \\ r\left(kx_i^2 + hx_i + q\right), & a \le x_i \le b, 0 \le k \le 1, \\ rx_i^3, & b \le x_i \le 1. \end{cases} \quad (4)$$

This paper draws on the improved typical transaction cost function and establishes a dual-objective portfolio model with the largest profit expectation and the smallest risk expectation. Set $\mathbf{X} = (x_1, x_2, x_3, \ldots, x_n)$ as the investment ratio in n stocks, $\mathbf{R} = (r_1, r_2, r_3, \ldots, r_n)$ as the expected rate of profit, and $M(\mathbf{X})$ as the actual rate of profit of stocks and securities, and the portfolio model based on the CVaR measurement is expressed as

$$\Pi = \sum_{i=1}^{n} r_i x_i - \sum_{i=1}^{n} c_i x_i. \quad (5)$$

Among them, $f(\mathbf{X}, \overline{Y}_j) = -X'\overline{Y}_j$, $x_i \ge 0$ means that short selling is not allowed, if and only if $\omega(\mathbf{X}) > \omega(\mathbf{Y})$ and $\widetilde{F}_\beta(\mathbf{X}, \delta, \mu) < \widetilde{F}_\beta(\mathbf{Y}, \delta, \mu)$. Actual entropy can reflect the speed of appreciation and the cumulative profit of funds. Compared with the mean function that cannot directly reflect the cumulative profit of the fund, the combination of actual entropy and actual entropy can be more effective and more appropriate to reflect the investment profit.

2.3. CVaR. VaR can usually be defined as value at risk [27,28], that is, the maximum loss of an investment portfolio in a normal market in a specific period under a specific confidence level of α. Set $f(\mathbf{X}, \mathbf{Y})$: $\mathbf{R}^m \times \mathbf{R}^n \longrightarrow \mathbf{R}^{mn}$ as the loss function of the investment portfolio, and the specific meaning is the expected loss of the investment portfolio. Among them, $\mathbf{X}$ is the investment decision vector, which specifically means the proportion of risky securities in the investment portfolio. $\mathbf{Y}$ is a 0–1 variable of value at risk, which represents the profit rate of securities stocks. Then, there is $f(\mathbf{X}, \mathbf{Y}) = -X'\mathbf{Y}$. When $\mathbf{X}$ is fixed, $f(\mathbf{X}, \mathbf{Y})$ is a function of $\mathbf{Y}$. Assuming that $\mathbf{Y}$ is a continuous random variable, the probability density function of $\mathbf{Y}$ is $\varphi(\mathbf{Y})$, then $\forall \delta \in \mathbf{R}$, and the distribution function is $\psi(\mathbf{X}, \delta) = \int_{f(\mathbf{X},\mathbf{Y})} \varphi(\mathbf{Y}) d\mathbf{Y}$, which represents the probability that the loss $f(\mathbf{X}, \mathbf{Y})$ does not exceed δ, δ is the upper limit of risk, and $\psi(\mathbf{X}, \delta)$ is the nonincreasing right continuous function of δ. Assuming that $\beta (0 \le \beta \le 1)$ is used to represent the confidence level, $\mathbf{X}$ of VaR is expressed as

$$\mathrm{VaR}_\beta(\mathbf{X}) = \min\{\delta \in \mathbf{R}\colon \psi(X, \delta) \ge \beta\}. \quad (6)$$

However, because VaR is only a quintile within a certain confidence level, the left-tail risk beyond this quintile cannot be measured by VaR, which leads to failure in assessing the overall risk of the portfolio and makes investors may ignore huge losses in some small probability events. At the same time, VaR cannot measure the risks in some extreme situations, such as financial crises. Based on this, VaR under certain CVaR was proposed. CVaR can be defined as the conditional average value of losses exceeding under a certain confidence level, which is used to measure the average excess level of losses [29,30]. According to the research of related scholars, CVaR is more sensitive to the shape of the loss distribution at the tail of the distribution [31,32]. According to the definition of CVaR, we can get

$$\mathrm{CVaR}(\mathbf{X}) = E\left[f(\mathbf{X}, \mathbf{Y}) | f(\mathbf{X}, \mathbf{Y}) \ge \mathrm{VaR}_\beta(\mathbf{X}) = (1-\beta)^{-1}\right] \int_{f(\mathbf{X},\mathbf{Y}) \ge \mathrm{VaR}_\beta(\mathbf{X})} f(\mathbf{X}, \mathbf{Y}) \varphi(\mathbf{Y}) d\mathbf{Y}. \quad (7)$$

It is found that VaR must be used in the process of solving equation (7), and the mathematical expression is extremely complicated, and it is difficult to calculate the result. In order to solve this problem, Rockafellar and other scholars constructed an auxiliary function $F_\beta(\mathbf{X}, \delta)$ and effectively connected CVaR and VaR [33,34]. The auxiliary function is

$$F_\beta(\mathbf{X}, \delta) = \delta + (1-\beta)^{-1} \int_{\mathbf{Y} \in \mathbf{R}^n} \max[f(\mathbf{X}, \mathbf{Y}) - \delta, 0] \varphi(\mathbf{Y}) d\mathbf{Y}, \quad (8)$$

where $\mathrm{VaR}_\beta(\mathbf{X}) = \min F_\beta(\mathbf{X}, \delta)$. Due to the diversity and complexity of the market environment, the loss caused is also uncertain, and the probability density function $\varphi(\mathbf{Y})$ is not easy to calculate. Therefore, the method of using historical data to simulate calculations is selected, and historical data is used to predict the specific future random vector. Assuming that the random variable $\mathbf{Y}$ in the past trading day represents m scenarios, the value of each scenario is $\overline{Y}_j$, $j = 1, 2, \ldots, m$, and the probability of any one scenario is $1/m$. So, it exists that

$$\widetilde{F}_\beta(\mathbf{X}, \delta) = \delta + m^{-1}(1-\beta)^{-1} \sum_{j=1}^{m} \{\max[f(\mathbf{X}, \overline{Y}) - \delta], 0\}. \quad (9)$$

Because of the existence of function max in equation (9), and because function $\widetilde{F}_\beta(\mathbf{X}, \delta)$ is usually not continuous and differentiable, general algorithms cannot be solved. Here, the aggregation function proposed by related scholars is used to smooth the max function [35,36]. For any $\mu > 0$, the above function can be expressed as

$$\widetilde{F}_\beta(\mathbf{X}, \delta, \mu) = \delta + m^{-1}(1-\beta)^{-1} \sum_{j=1}^{m} \mu \ln\left[\exp \frac{f(\mathbf{X}, \overline{Y}) - \delta}{\mu} + 1\right]. \quad (10)$$

2.4. Two-Stage Mixed Integer Programming (TS-MIP) Model. A diversified investment portfolio has lower volatility risk than personal assets, and increasing the diversification of the investment portfolio can help investors reduce the variance of the investment portfolio. Not only can the risk in the investment portfolio be effectively and accurately measured, but also the investment portfolio can evaluate diversity. According to investment portfolio theory, diversity G can be used to reduce nonsystematic risks. Specifically, the greater the value, the more diversified the investment portfolio. Based on the above theory, in the model proposed in this paper, CVaR is used to adjust the direct function to determine the new objective function to measure the risk of the investment portfolio. The value-added entropy combined with the real entropy function M is used to measure the statistical profit of investment. Skewness function is used to measure investment increment. Based on the above analysis and combined investment portfolio strategy research, this paper proposes the following TS-MIP model, the structure of which is shown in Figure 1. The problem of outer layer maximization benefit planning mainly analyzes the maximization of income and the maximization of investment diversity and the maximization of skewness. Corresponding to it is the problem of internal minimization of risk, which mainly includes the minimization of information entropy and the minimization of investment risk. The investment risk here is measured by the CVaR.

The stage of maximizing the benefit of the outer layer is the overall stage, and the specific form is as follows:

$$\begin{aligned}
\max \quad & Z = \left\{\alpha(R'\mathbf{X}) + \beta(S'\mathbf{X}) + \gamma E_{\delta} \min \widetilde{F}_{\beta}(\mathbf{X},\mathbf{Y})\right\} \\
\text{s.t.} \quad & \sum_{i=1}^{M} \alpha r_i x_i - \sum_{i=1}^{M} c_i x_i \geq \Pi^{\min}, \quad \forall r_i \in \mathbf{R}, i = 1,2,3,\ldots,M, \\
& \sum_{i=1}^{M} x_i = 1, \quad \forall x_i \in \mathbf{X}, \\
& \sum_{i=1}^{M} \beta x_i \ln x_i \leq G^{\max}, \quad i = 1,2,3,\ldots,M, \\
& \sum_{i=1}^{M} s_i x_i \leq U^{\max}, \quad \forall s_i \in \mathbf{S}, i = 1,2,3,\ldots,M, \\
& \alpha, \beta \in \{0,1\}, \\
& x_i \in [0,1], \quad i = 1,2,3,\ldots,M.
\end{aligned} \tag{11}$$

The objective function is combinatorial optimization problem, which maximizes the profit under the condition of the lowest risk. The first line of constraint indicates the lower bound of profit. The second line of constraint indicates the maximum investment ratio, short selling is not allowed, and there is no additional capital inflow. The third line of constraints indicates the upper limit of investment diversity. The fourth line of constraints indicates the upper limit of the investment increment. The fifth and sixth lines of constraints are related variable constraints; the purpose is to ensure the feasibility. The inner minimization problem is second stage, and the form is as follows:

$$\begin{aligned}
& E_{\delta} \min \widetilde{F}_{\lambda}(\mathbf{X},\mathbf{Y},K,\gamma,\delta,\mu), \\
& \text{s.t.} \; -\sum_{i=1}^{M}\sum_{j=1}^{N} x_i p_j \ln\left|\frac{r(\text{CVaR})_i}{\sum_{i=1}^{M} r(\text{CVaR})_i}\right| \geq K^{\min}, \\
& \delta + \frac{1}{m(1-\lambda)} \sum_{i=1}^{M}\sum_{j=1}^{N} \mu \ln\left\{\exp\frac{\gamma[f(\mathbf{X},\mathbf{Y})-\delta]}{\mu} + 1\right\} \leq r_{\text{CVaR}}^{\max}, \\
& f(\mathbf{X},\mathbf{Y}) = \sum_{i=1}^{M}\sum_{j=1}^{N} x_i y_j, \quad \forall x_i \in \mathbf{X}, \forall y_i \in \mathbf{Y}, \\
& \sum_{i=1}^{M} x_i = 1, \quad \forall x_i \in \mathbf{X}, \\
& \sum_{i=1}^{M}\sum_{j=1}^{N} x_i p_j = 1, \quad p_j \geq 0, \forall x_i \in \mathbf{X}, \\
& \gamma \in \{0,1\}, \\
& x_i \in [0,1], \quad \forall x_i \in \mathbf{X}, i = 1,2,3,\ldots,M, \\
& y_j \in [0,1], \quad y_j \in \mathbf{Y}, j = 1,2,3,\ldots,N.
\end{aligned} \tag{12}$$

The specific meaning: the objective function is to minimize information entropy, the risk. The first line of constraints represents that the lowest value of information entropy is higher than the limit threshold. The second line of constraint represents that the risk that investors can bear is lower than the upper bound of the maximum tolerance. The third line of constraints describes the calculation strategy for cumulative risk. The fourth line of constraints indicates the maximum investment ratio and no remittance of external funds. The fifth line of constraints indicates that the probability of all scenarios is 1. The sixth, seventh, and eighth lines of constraints are related variable constraints. In order to calculate CVaR with r_{VaR}, assuming that the rate of profit on investment shows a normal distribution, r_{VaR} can be expressed as $r_{\text{VaR}} = r_q + \sigma_q z_\alpha$ according to the law of large numbers, where r_q measures the maximum loss of the investment portfolio. Then, we obtained that

$$r(\text{CVaR}) = \frac{1}{1-\alpha}\partial(z_\alpha)\sigma_q - r_q. \tag{13}$$

Among them, $\partial(z_\alpha)$ is the probability density function of the standard normal distribution, which can be expressed as

$$\partial(z_\alpha) = \frac{1}{\sqrt{2\pi}} e^{-(z_\alpha^2/2)}. \tag{14}$$

In addition, because p_i cannot directly predict and is extremely difficult to calculate, this paper uses a computer program to assist in the solution of the model. In order to introduce the two-stage optimization model and its application in the risk-considering investment portfolio problem,

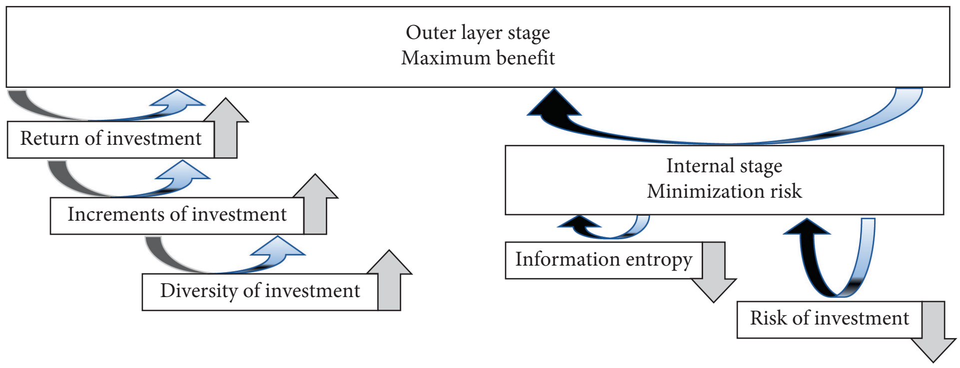

FIGURE 1: The theoretical framework of the TS-MIP model.

the relevant decision variables and parameters are summarized in Table 1.

3. Two-Stage Robust Optimization (TS-RO) Model with Uncertainty

3.1. Portfolio Optimization Problem with Uncertainty. The real capital market environment is full of instability and randomness, and it is extremely difficult or even impossible to obtain the accuracy of data parameters. In the research of dealing with uncertain information, many scholars have cited the theory of robust optimization. Robust optimization model can effectively provide an effective measure of uncertainty. Studies have found that it plays an extremely restrictive role in dealing with uncertain information parameters. In this section, by citing the theory of robust optimization, a two-stage robust optimization model for solving portfolio problems under uncertain conditions is constructed [37]. Based on the analysis of real securities and stock markets, this paper takes the two-stage basic model as the research object to explore the impact of uncertainty in depth. In the actual market analysis process, the upper bound of the expected risk probability is not always certain. In other words, in a complex capital market environment, investors' risk attitudes are not always consistent. As investors' risk attitudes change, the original assumptions of expected risk probability as deterministic will not reflect the reality. Therefore, this section extends the expected risk probability from certainty to uncertainty. According to the relevant theory of robust optimization, the assumptions are as follows. Set the expected risk probability that $\delta_i \longrightarrow \widetilde{\delta}_i$ is $\widetilde{\delta}_i = \delta_i^0 + \widehat{\delta}_i$, where δ_i^0 is the nominal demand, $\widehat{\delta}_i = \varepsilon\delta_i^0$ and ε are the disturbance items [38]. Based on the above problem description and feasibility assumptions, this paper builds the TS-RO model. The expected risk of uncertainty in the model is $\widetilde{\delta}_i$, and the uncertainty set is the most commonly used ellipsoid set E_E [39]. The l_2 norm is used to define the uncertain ellipsoid sets $\{\cup_E\}$, $\{\cup_E|\varepsilon_j\colon \|\varepsilon_j\|_2 \le \Omega \Longleftrightarrow \varepsilon_j \sqrt{\sum_J \varepsilon_j^2} \le \Omega\}$, and Ω_j as adjustable safety parameters, as well as the spherical diameter of the uncertain set. It means that at most Ω_j disturbance items deviate from the nominal set $\{\cup_E\} = \{\widetilde{\delta}_j \in \mathbb{R}, \sum_{\mathcal{J}}[(\widetilde{\delta}_j - \delta_j^0)/\widehat{\delta}_j]^2 \le \Omega_j^2\}$ [40,41].

Theorem 1. *For the given condition that $\widetilde{\delta}_i$ is closed and convex, when the parameter $\varepsilon = 0$ is uncertain, the constraint adjustment of the second stage part of the TS-RO model under uncertain conditions is equivalent to TS-MIP model, that is,* $\max\{\widetilde{\delta}_i + H(\mathbf{X}, \mathbf{Y}, \widetilde{\delta}_i)\} \le r_{CVaR}^{\max} \Longleftrightarrow \sup\{\widetilde{\delta}_i + [\varepsilon]_{\varepsilon=0} \mathrm{H}(\mathbf{X}, \mathbf{Y}, \varepsilon, \widetilde{\delta}_i)]\} \le r_{CVaR}^{\max}$, *in which, in order to simplify the expression, set* $H(\mathbf{X}, \mathbf{Y}) = (1/m(1-\lambda)) \sum_{i=1}^{M} \sum_{j=1}^{N} \mu \ln\{\exp(\gamma[f(\mathbf{X}, \mathbf{Y}) - \delta]/\mu) + 1\}$.

Proof. The conventional ellipsoid uncertainty set $\{\cup_E\}$ is $\{c_i \in R^n\colon c_i = \overline{c}_i + \Delta\xi, \xi \le \Omega\}$, where $\Delta = \sum^{1/2}$, and its constraints $\max c_i^T X \le B$ can be translated as $\max\{c_i^T X\colon (c_i - \overline{c}_i)^T \Sigma^{-1}(c_i - \overline{c}_i) \in \Omega^2\}$. For $\forall\Sigma$ is positive and closed, it is a convex problem. Therefore, convex problem can be solved by Karush-Kuhn-Tucher condition. $\min \mathscr{F}(c_i^*) = -c_i^{*T} X$ with s.t. $g(c_i^*) = (c_i^* - \overline{c}_i)^T \Sigma^{-1}(c_i^* - \overline{c}_i) - \Omega^2 \le 0$. Therefore, the meaningful solution to deal with uncertain problems is its robust feasible solution. In all robust feasible solutions, how to interpret the value of the target (and possibly uncertain) still needs deeper analysis. When applied to the target problem, it is natural to quantify the quality of the solution through the guaranteed value $\sup_{E_E} E[\widetilde{\delta}_i\colon c]$ (i.e., the maximum value) with the help of the "worst case-oriented" concept of robust theory. Thus, the best possible robust feasible solution is the one that solves the TS-MIP model $\max\{\widetilde{\delta}_i + H(\mathbf{X}, \mathbf{Y}, \widetilde{\delta}_i)\} \le r_{\mathrm{CVaR}}^{\max}$, or which is the same, the optimization problem $\sup\{\widetilde{\delta}_i + [\varepsilon]_{\varepsilon=0} H(\mathbf{X}, \mathbf{Y}, \varepsilon, \widetilde{\delta}_i)]\} \le r_{\mathrm{CVaR}}^{\max}$ in the TS-RO model. The latter problem is called the robust counterpart of the original TS-MIP problem. Above all, Theorem 1 can be proved. □

3.2. Two-Stage Robust Optimization (TS-RO) Model with Uncertainty. Based on the above analysis and combined investment portfolio strategy research, this paper proposes the following TS-RO model. Under uncertain conditions, the expression form of the outer maximization stage is the same as the TS-MIP model, and the specific form is as follows:

$$\begin{aligned}
&\sup_{\varepsilon\in\mathbb{E}_E}\mathscr{Z}=\left\{\alpha\left(R'\mathbf{X}\right)+\beta\left(S'\mathbf{X}\right)+\gamma_\delta\mathbb{E}\inf_{\varepsilon\in E_E}\widetilde{F}_\beta\left(\mathbf{X},\mathbf{Y},\widetilde{\delta}_j\right)\right\},\\
&\text{s.t.}\ \sum_{i=1}^{M}\alpha r_i x_i-\sum_{i=1}^{M}c_i x_i\geq\Pi^{\min},\quad\forall r_i\in\mathbf{R},\quad i=1,2,3,\ldots,M,\\
&\sum_{i=1}^{M}x_i=1,\quad\forall x_i\in\mathbf{X},\\
&\sum_{i=1}^{M}\beta x_i\ln\,x_i\leq G^{\max},\quad i=1,2,3,\ldots,M,\\
&\sum_{i=1}^{M}s_i x_i\leq U^{\max},\quad\forall s_i\in\mathbf{S},i=1,2,3,\ldots,M,\\
&\alpha,\beta\in\{0,1\},\\
&x_i\in[0,1],\quad i=1,2,3,\ldots,M.
\end{aligned}\tag{15}$$

Since the risk attitude of investors is considered, the expression form of the second stage inner minimization problem is significantly different from the basic model. The specific form is as follows:

$$\begin{aligned}
&\mathbb{E}_\delta\inf_{\varepsilon\in\mathbb{E}_E}\widetilde{F}_\lambda\left(\mathbf{X},\mathbf{Y},K,\gamma,\widetilde{\delta}_j,\mu\right),\\
&\text{s.t.}\ -\sum_{i=1}^{M}\sum_{j=1}^{N}x_i p_j\ln\left|\frac{r\,(\mathrm{CVaR})_i}{\sum_{i=1}^{M}r\,(\mathrm{CVaR})_i}\right|\geq K^{\min},\\
&\delta_j^0+\Omega_j\left\{\frac{1}{m(1-\lambda)}\sum_{i=1}^{M}\sum_{j=1}^{N}\mu\,\ln\left\{\exp\frac{\gamma\left[f\,(\mathbf{X},\mathbf{Y})-\widehat{\delta}_j\right]}{\mu}+1\right\}\right\}\leq r_{\mathrm{CVaR}}^{\max},\\
&f\,(\mathbf{X},\mathbf{Y})=\sum_{i=1}^{M}\sum_{j=1}^{N}x_i y_j,\quad\forall x_i\in\mathbf{X},\forall y_i\in\mathbf{Y},\\
&\sum_{i=1}^{M}x_i=1,\quad\forall x_i\in\mathbf{X},\\
&\sum_{i=1}^{M}\sum_{j=1}^{N}x_i p_j=1,\quad p_j\geq 0,\forall x_i\in\mathbf{X},\\
&\gamma\in\{0,1\},\\
&x_i\in[0,1],\quad\forall x_i\in\mathbf{X},i=1,2,3,\ldots,M,\\
&y_j\in[0,1],\quad y_j\in\mathbf{Y},j=1,2,3,\ldots,N.
\end{aligned}\tag{16}$$

It is worth noting that, in the inner minimization problem with uncertainty, the objective of the objective function is rewritten to solve the infimum problem due to the heterogeneity of investors' risk attitudes. The meaning of the second term of the constraint is the risk probability scenario under the worst scenario. When the disturbance term of the uncertain parameter fluctuates within the range of the ellipsoid set, the adjustable safety parameter reflects the decision under the worst scenario. Its purpose is to solve the most stable investment income scenario, that is, the most stable income. In the process of calculation, the planning problem is more difficult due to the solution of multiple quadratic functions. Therefore, in the follow-up study, in the program involving a large number of calculations, computer

Table 1: Description of parameters and variables.

Annotation	Description
x_i	Continuous variables, $x_i \in [0,1]$ $\mathbf{X} = \{x_1, x_2, \ldots, x_i\}$, represent the investment ratio;
y_j	Continuous variables, $y_j \in [0,1]$ $\mathbf{Y} = \{y_1, y_2, \ldots, y_j\}$, represent the risk ratio;
α	0–1 variable, $\alpha \in \{0,1\}$, indicates the existence or nonexistence of the return;
β	0–1 variable, $\beta \in \{0,1\}$, indicates whether the skewness be evaluated;
γ	0–1 variable, $\gamma \in \{0,1\}$, indicates whether the risk measure is selected or not;
p_i	Measure the probability of the i th combination, $i = 1, 2, \ldots, M$;
$r(\text{CVaR})_i$	Measure the CVaR combination of the investment ratio;
R	Measure the output ratio of in portfolio, $R = 1 + r$;
r	The profit rate;
s_i	Indicative stock skewness, $s_i \in \mathbf{S}$;
$G^{\max}$	Indicates the maximum number of combinations that can be selected;
$U^{\max}$	Indicates the maximum acceptable skewness;
$K^{\min}$	Indicates the lowest acceptable information entropy;
$r_{\text{CVaR}}^{\max}$	Indicate the maximum acceptable risk value;
r_q	Measure the maximum loss of the portfolio;
σ_q	Standard deviation of portfolio;
z_α	The quintile of normal distribution at the confidence level of α;
δ	Indicates acceptable expected risk value;
M	$i = 1, 2, \ldots, M$;
N	$i = 1, 2, \ldots, N$;

software and existing commercial software are used to solve the problem. The package is used for solving calculations to ensure the accuracy of the obvious results.

4. Numerical Experiment

Suppose that an investor conducts investment activities on a stock exchange and selects 10 securities stocks as alternatives through multiple comparisons in multiple securities markets. After rigorous data comparison and advantage analysis, the best investment plan combination is screened out in order to achieve the purpose of maximizing the comprehensive benefits. In the process of selecting securities and stocks, the following factors and principles need to be considered comprehensively. First, the ultimate goal of investors is to maximize profits, but, at the same time, they must also take into account their risk tolerance. In other words, investors are pursuing the maximization of profits on the basis of certain risk expectations. Second, the investor's investment assets are fixed, and the initial investment proceeds will be used again for investment. Third, the investment process is rational. When investors face the risk of resisting the initial threshold, the investment quota will no longer be added. According to the above basic elements and principles, this paper first uses data crawling technology to obtain the relevant database, then uses the computer to simulate and check the model, and finally obtains investment management recommendations and research enlightenments through a large number of comparisons.

4.1. Data Collection. In this section, we use actual financial securities market data to conduct simulation experiments to verify the effectiveness of the model. In the data acquisition stage, this section uses python to write the technical framework, *Python* 3.6, requests, math, time, pandas, matplotlib, pyecharts, statsmodels, scipy, jieba, and pylab. Figure 2 describes the calculation steps of the data crawling technology. First, log in to the target web page, browse the relevant web page information (Eastern Fortune.com), and search for the online information of the target web page. Secondly, analyze the web page structure, view the source code of the web page, and click on the next page to observe the change of the url in the search bar of the browser. Thirdly, use the dictionary method to read the data directly, and save the read data to the preset file database. Next, use a loop strategy to crawl the data step by page, jump to the next page after completing the crawling of one page of data, and repeat the same data collection process. Finally, when the acquired data is stored in the database, the crawling process is terminated.

This section obtains historical data of historical stocks from a real website (Eastern Fortune.com). The data is obtained from the period from July 24, 2020, to December 20, 2020, about 1,000 statistical data generated by 100 exchanges of 10 stocks on the next day. Since the trading of stocks is only carried out on the trading day, the data sequence is sorted by time, but the time sequence is not continuous. In order to facilitate statistical calculations, this section sorts them according to the order of the trading days, which are 1 to 100 trading days. Table 2 describes the initial part of the data form of the obtained stock information. Before the numerical simulation, we conducted a simple statistical analysis of the historical profits of 10 stocks. Table 2 lists the average profit, standard deviation, skewness, and kurtosis of a single stock.

The relevant parameter settings in this section are as follows: when investors sell securities in the securities market, the ratio of securities lending margin shall not be less than 50%, so $k = 0.5$. In the process of stock trading, the transaction cost includes commission, stamp duty, and transfer fee, which is generally 0.3% of the transaction amount. Due to the existence of transaction fees, stock

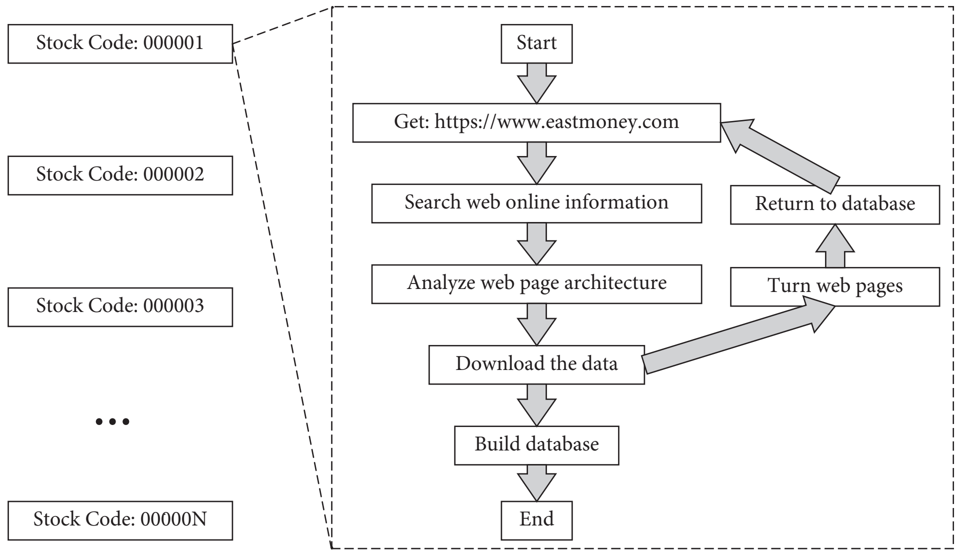

Figure 2: Data crawling process steps.

Table 2: Original stock data table (partial data).

Code	Date	Closing point	Opening.P	Highest.P	Lowest.P	Ups and downs	Quote	Volume
000001.SH	0724	3196.7684	3310.6449	3319.1268	3184.9645	128.3418	−3.8598	427054026
000001.SH	0723	3325.1102	3306.1489	3336.3002	3257.8269	−8.0533	−0.2416	407042499
000001.SH	0722	3333.1635	3315.1816	3381.9757	3311.7862	12.2688	0.3694	393335335
000001.SH	0721	3320.8947	3330.5467	3336.6791	3300.5719	6.7457	0.2035	359252029
000001.SH	0720	3314.149	3243.9105	3314.149	3220.684	100.0203	3.1119	418555306
000001.SH	0717	3214.1287	3214.4022	3252.7786	3181.2745	4.0301	0.1255	359652413
000001.SH	0716	3210.0986	3356.359	3373.5317	3209.7272	151.2058	−4.4984	490613123
000001.SH	0715	3361.3044	3422.0778	3432.4506	3345.7488	−53.3142	−1.5614	492030542
000001.SH	0714	3414.6186	3435.0237	3451.2224	3366.0828	−28.6677	−0.8326	543211492
000001.SH	0713	3443.2863	3379.3867	3458.7914	3369.0378	59.9641	1.7723	558006875
000001.SH	0710	3383.3222	3418.9347	3433.1085	3372.5066	−67.2713	−1.9496	556120011
...	...	...	...	...	...	...	...	...

trading should not be too frequent. This paper studies wind as three levels; one is based on a 30-day cycle, another is based on a 60-day cycle, and the third is based on a 90-day cycle. Analyze the relevance and influence of various indicators of stock trading. The profit rate of the stock is fitted according to historical parameters, and the fitted value of the historical data is used as the profit rate for analysis. On the assumption of the confidence interval, this paper, respectively, assumes 85%, 90%, 95%, and 99% confidence intervals and analyzes the parameters of each confidence interval.

Figure 3 depicts the volatility of the profit rate of the selected 10 stocks 100 times. It can be seen that the fluctuation of stocks is relatively large, which shows that the volatility of investment income is relatively large. It can also be found that there is no obvious law for the fluctuation of stocks, so there are no algorithms and tools that can accurately predict stock investment profits. Overall, the volatility of individual stocks is affected by objective economic factors, which is manifested in the overall change trend of the macro. From the above figure, it can be seen that the volatility of stocks has a certain time regularity; that is, there are overall ups and downs. The trend of. Therefore, in the investment process, it is necessary to take into account the various factors of the investment, as well as to make a reasonable plan in combination with objective conditions and risk tolerance.

Figure 4 depicts the overall (100 trading days) average amount of fluctuations in 10 stocks. Only from the perspective of the average value, among the 10 stocks, the average value of volatility of 8 stocks is higher than 0, and the average value of volatility of 2 stocks is lower than 0. This shows that the overall stock market at this stage shows a good development trend. Stockholders showed a positive attitude towards the improvement of economic conditions and actively invested funds in the stock market.

4.2. Model Algorithm Design. In this paper, based on the Matlab (R2016a) platform, the algorithm framework is designed, and the algorithms of the two-stage basic model and the TS-RO model under uncertain conditions are constructed, respectively. Solve by calling the solver Gurobi (9–1–0). In order to ensure the rigor and scientificity of the experiment, all algorithms are operated in the same computing environment (Windows 10, Intel (R) Core (TM) i5-8300H CPU @2.3 GHz, RAM 8 GB, 512 G SSD). The

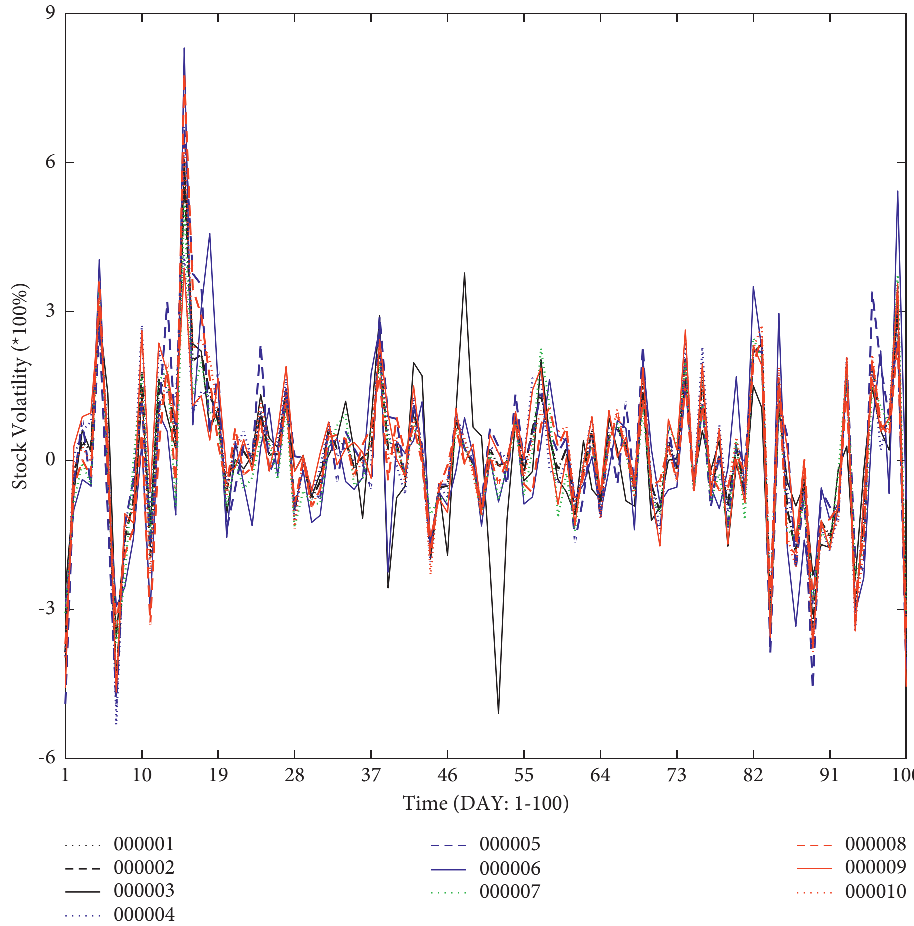

Figure 3: Volatility of stocks (100 Trades).

algorithm framework and calculation steps of the model are shown in Algorithm 1.

5. Sensitivity Analysis

5.1. The Computational Efficiency of the Model. In the same computing environment and the same computing scale, this section analyzes the factors affecting the running time of the model. After fixing the relevant parameters, the investment cycle is the only variable. We divide the time period (L/DAY) into 30, 60, and 90 trading days and compare the differences in the running time of the model. The calculation results are shown in Table 3. The analysis found that the length of the time period has a positive correlation with the calculation time; that is, the longer the time, the longer the calculation time of the model. Secondly, the calculation time of different models is slightly different. Among them, the calculation time of the equal-weight model is the shortest, the calculation time of the TS-MIP model is in the middle, and the calculation time of the TS-RO model is the longest. The increase in computing time reflects the increase in computing volume, which means that the computing volume and complexity of the TS-RO model are also the largest.

5.2. Autocorrelation Analysis. The long memory of financial securities asset profits refers to the significant autocorrelation of distant time intervals in the time series of profits; that is, historical events will continue to affect the future. Since stock securities data has obvious long memory, historical data information can be used to predict future profits and other related parameters. In this section, the parameters obtained are normalized, and the correlation effects can be compared more clearly. In this section, using the autocorrelation coefficient method, research and analysis found that the income of the industrial average index has significant long memory, as shown in Figures 5 and 6. The autocorrelation function is a measure of correlation, that is, a measure of similarity, which is the correlation between the function and the function itself. When there are periodic components in the function, the maximum value of the autocorrelation function can well reflect this periodicity. Cross-correlation is the similarity between two functions. When both functions have the same periodic component, the maximum value can also reflect this periodic component. From the perspective of linear space, correlation operation is actually an inner product operation, and the inner product of two vectors in linear space represents the projection of one vector to another vector, indicating the similarity of the

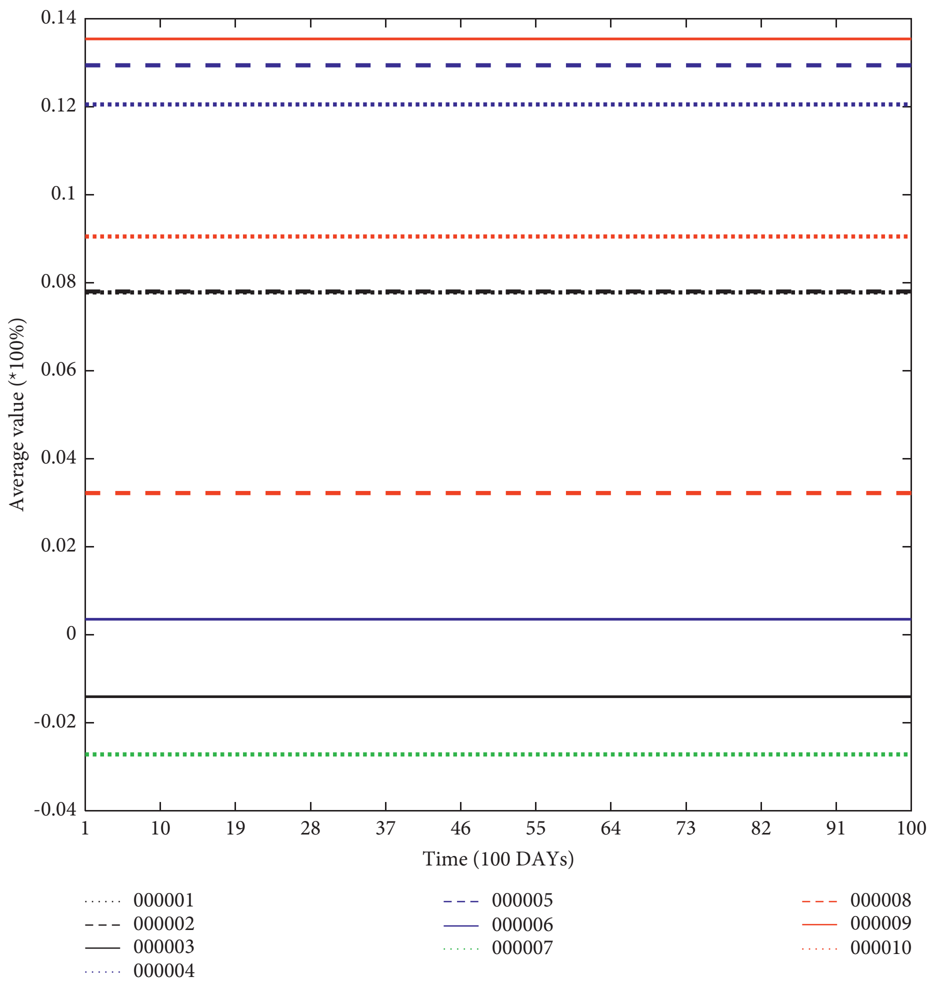

Figure 4: Average value of stock volatility.

Input Measurement data
Initialization: Input the initial value; Setting parameter value boundary;
Step 1:
For TS-MIP model: Define variable type; Set probability function;
else TS-RO model
Define the variable type; Generate random number; Set the safety parameters;
End
Step 2: **While**
Input $\{\varepsilon, \xi\} \in \left\{\mathbb{U}_{Bj}, \mathbb{U}_{Bj}\right\}$, do step 3; Otherwise: re-step 1;
End while
Step 3: Initialize
Input Parameter constraints; Variable constraints;
End
Step 4: **Do for:** Set the solution environment; Solved by Gurobi;
If met step 3: Out the result and time
Else: profit step 2;
End do
Profit $\{\mathbf{X}^*\}$

Algorithm 1: Specific steps of models algorithm.

Table 3: CPU calculation time of three models under different time windows.

Period (L/DAY)	30 (s)	60 (s)	90 (s)
Equal weight method	1.983	3.781	8.093
TS-MIP model	2.081	4.234	7.781
TS-RO model	2.145	4.689	8.071

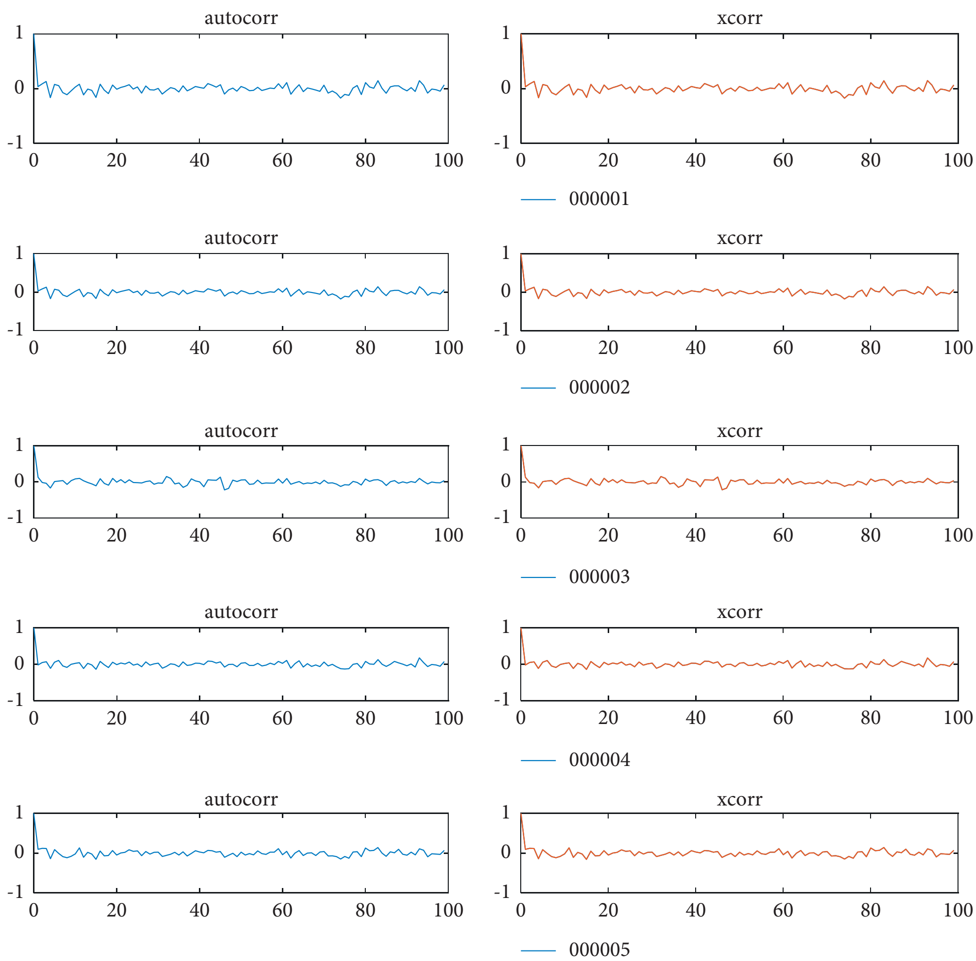

Figure 5: Autocorrelation analysis (Stocks 1–5).

two vectors, so the correlation operation reflects this kind of similarity.

From Figures 5 and 6, we can find that the fluctuation of the curve tends to be flat. For the autocorrelation graph test, stationary series have short-term correlation. This property indicates that, for stationary series, only recent series values usually have a more obvious influence on the current value. The farther apart the past value, the smaller the influence on the current value. As the number of delay periods increases, the autocorrelation coefficient of a stationary series will decay relatively quickly to zero and fluctuate randomly around zero, while the autocorrelation coefficient of a nonstationary series decays slowly. This is the use of autocorrelation graphs, the standard for the stationarity test.

5.3. Influence of Safety Parameters. To ensure the unbiased and scientific nature of the experiment, the parameters are fixed. The model under the condition of deterministic information is the TS-MIP model. With the increase of security parameters, the parameters in the model such as rate of profit, diversity, skewness, information entropy, and CVaR are not affected. In the environment of uncertain risk preference, the model is the TS-RO model. The parameter diversity, skewness, and information entropy are not disturbed by uncertainty. Under the environment of uncertain risk appetite, the risk attitude of investment has changed. Here, through the method of robust optimization, the relevant risk preference range and boundary are constructed with the help of uncertain sets. The benefits of important parameters, CVaR, and total revenue are significantly affected by safety parameters.

Figure 7 describes the impact of security parameters on A: revenue and B: diversity. It can be seen from Figure 7 that, under deterministic information conditions, changes in

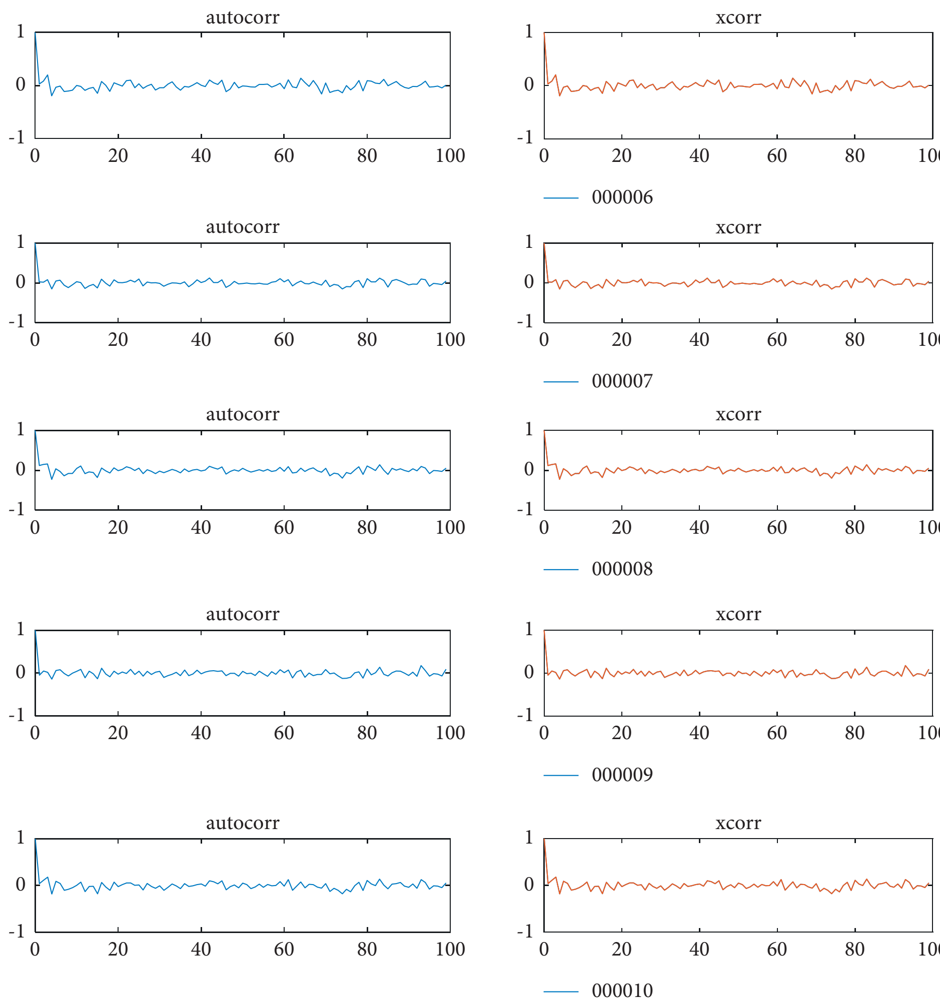

Figure 6: Autocorrelation analysis (Stocks 6–10).

security parameters will not have an impact on revenue and diversity. The figure shows that the influence curve of the TS-MIP model is a horizontal straight line. Of course, the deterministic TS-MIP model cannot cope with the problem of portfolio optimization under uncertain conditions. Under conditions of uncertain information, changes in security parameters have a positive impact on profits, but not on the diversity of investment portfolios. Specifically, as the level of security parameters increases, investors' investment income also shows an increasing trend. That is, when the risk is controllable, the rate of profit on investment is higher, and the investment ratio is larger.

Figure 8 describes the impact of security parameters on C: skewness and D: information entropy.

It can be seen from Figure 8 that, under deterministic information conditions, changes in security parameters will not have an impact on skewness and information entropy. The figure shows that the influence curve of the TS-MIP model is a horizontal straight line. Of course, the deterministic TS-MIP model cannot cope with the problem of portfolio optimization under uncertain conditions. Under uncertain conditions, changes in security parameters will not have an impact on skewness and information entropy. This shows that it is not the controllability of risk that affects investor confidence, but other deeper factors.

Figure 9 describes the impact of safety parameters on E: CVaR and F: total benefits. From the change trend of the curve in Figure 9, it can be found that, under certain information conditions, changes in safety parameters will not have an impact on CVaR and overall benefits. The figure shows that the influence curve of the TS-MIP model is a horizontal straight line. Under uncertain conditions, changes in safety parameters will have a significant impact on CVaR and overall benefits. As the security parameters increase, the risk of investment shows an increasing trend, which is often referred to as a robust price, which is the price paid to resist risks. But, at the same time, the increase in safety parameters also makes the overall benefit show an increasing trend, which can increase investors' investment confidence when they choose investment.

5.4. Testing the Effectiveness of the Portfolio. For comparison, three financial ratios are listed below to measure the pros and

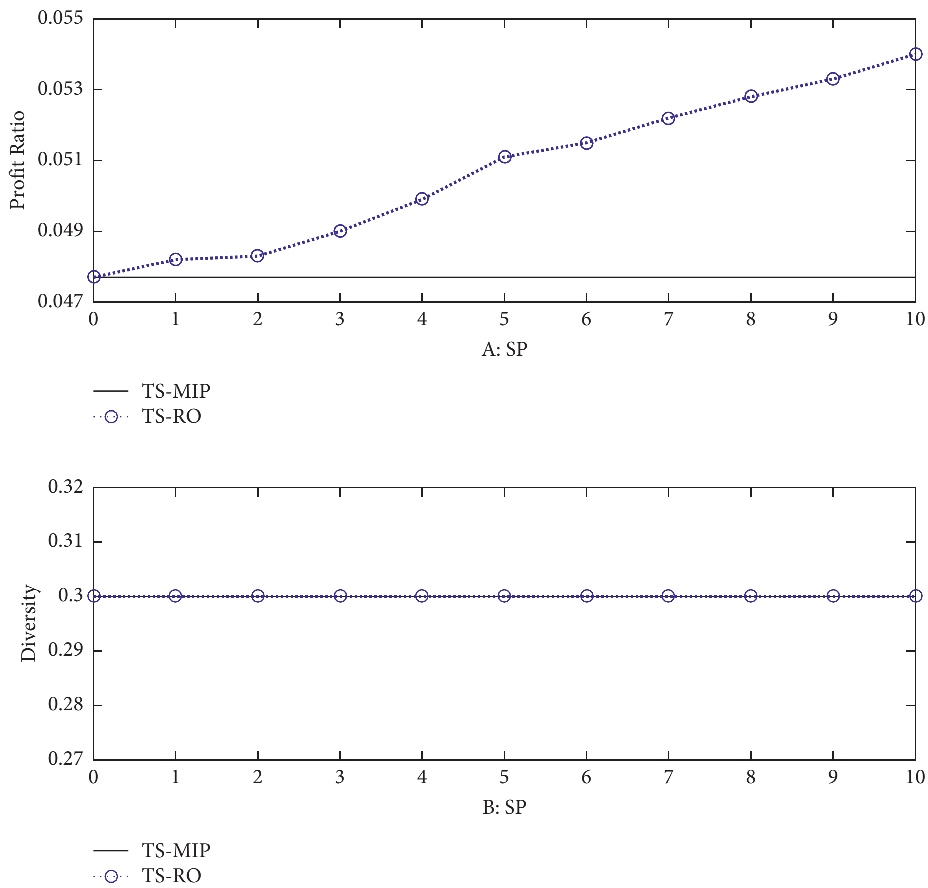

Figure 7: Revenue and diversity in SP.

cons of stocks and securities. The Sharpe ratio (ShR) is used to help investors understand the profit on investment related to their risk. Unlike the ShR, the Sortino ratio (SoR) is used to evaluate the excess profit of a portfolio given a downside risk. The Treynor ratio (TrR) represents a risk-adjusted profit based on systemic risk. Generally speaking, the greater the value of the Sharpe/Sortino/Treynor ratio, the greater the risk-adjusted profit, and the more attractive the risk-adjusted profit for rational investors.

ShR is an indicator proposed by William to research and measure fund performance [42]. This indicator is not only a standardized indicator for fund performance evaluation, it has been successfully applied in many fields as well. The purpose of the ShR is to calculate how much excess profit will be generated per unit of total risk assumed by the portfolio. When all assets in the portfolio are risk assets, the Sharpe ratio applies. The formula for calculating the ShR is

$$\text{ShR} = \sum_i \frac{E(Rp_i) - R_f}{\sigma p_i}, \quad i \in I. \tag{17}$$

Among them, $E(Rp_i)$ is the expected annualized profit of the investment portfolio, R_f is the annualized risk-free interest rate, and σp_i is the standard deviation of the annualized profit of the investment portfolio. The Sharpe ratio represents how much excess profit investors can get for each additional risk point. If it is greater than 1, it means that the fund's profit is higher than the volatility risk; if it is less than 1, it means that the operational risk of the fund is greater than the rate of profit.

In this way, the Sharpe ratio of each investment portfolio can be calculated, that is, the ratio of investment profits to more risks.

The higher the Sharpe ratio, the better the portfolio. Through experimental verification, it is found (Table 4) that when $L = 30$, the equal weight method is the lowest (11), the TS-MIP model is in the middle (ShR = 0.5004), and the TS-RO model is the best (ShR = 0.5407). Compared with the equal weight method, the Sharpe value of the TS-RO model increased by 18.97%. In addition, in each model, as the time period increases ($L = 30 \longrightarrow L = 60 \longrightarrow L = 90$), the Sharpe ratio gradually increases. This law shows that long-term investment is due to short-term investment, which can provide decision-making suggestions for investors' investment cycle planning.

SoR is the standard for quantitatively dealing with the trade-off between the profit and risk of investment plans and

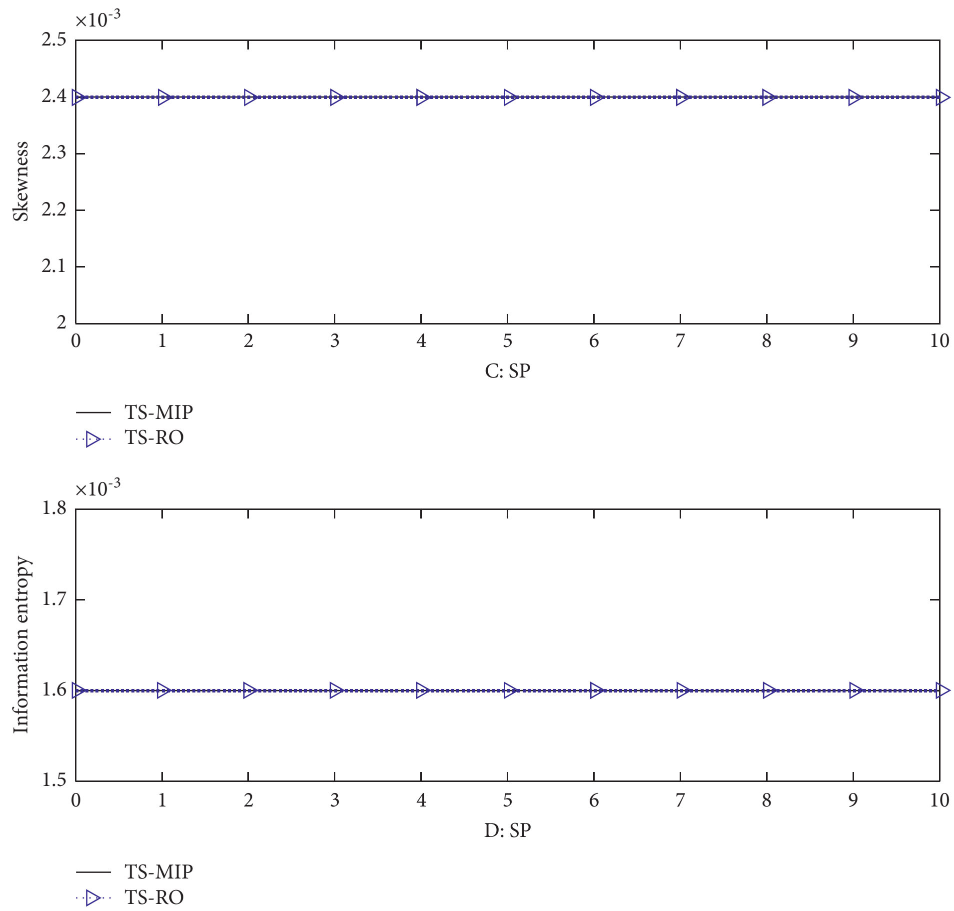

Figure 8: Information entropy and skewness in SP.

the final selection of investment plans. Its calculation formula is as follows:

$$\begin{aligned} \mathrm{SoR} &= \sum_i \frac{R_{pi} - r_i}{\delta_i (R, \mathrm{MARR})}, \\ \delta_i (R, \mathrm{MARR}) &= \sqrt{E\left\{[\min (R - \mathrm{MARR}, 0)]^2\right\}}, \quad i \in I. \end{aligned} \tag{18}$$

Among them, R_{pi} is the profit rate of the investment portfolio, which is replaced by the average value of the profit rate of the investment plan obtained by the simulation. r_i is the minimum profit required by investors of 2%. $\delta_i (R, \mathrm{MARR})$ is the risk that the actual rate of profit is lower than the average value, that is, the downside risk of the rate of profit, MARR is the lowest acceptable rate of profit, and MARR can be the risk-free rate or 0. The SoR is a measure that is more in line with investors who are more sensitive to the decline in asset value. The higher the ratio, the higher the profit rate by the fund if it bears the same unit of downside risk.

The result verification in Table 5 found that, taking $L = 60$ as an example, the equal weight method is the lowest (SoR = 0.4758), the TS-MIP model is in the middle (SoR = 0.5012), and the TS-RO model is the best (SoR = 0.5578). Compared with the equal weight method, the SoR of the TS-RO model has an increase of 8.20%. In addition, in each model, as the time period grows ($L = 30 \longrightarrow L = 60 \longrightarrow L = 90$), the SoR is gradually increasing, further verifying the conclusions obtained by the Sharpe Ratio. It should be pointed out that risk is the uncertainty of the result. This uncertainty includes situations where the actual rate of profit is lower than expected and situations where the actual rate of profit is higher than expected. From the perspective of project investors, it is undoubtedly beneficial for the actual rate of profit to be higher than the expected value (i.e.,

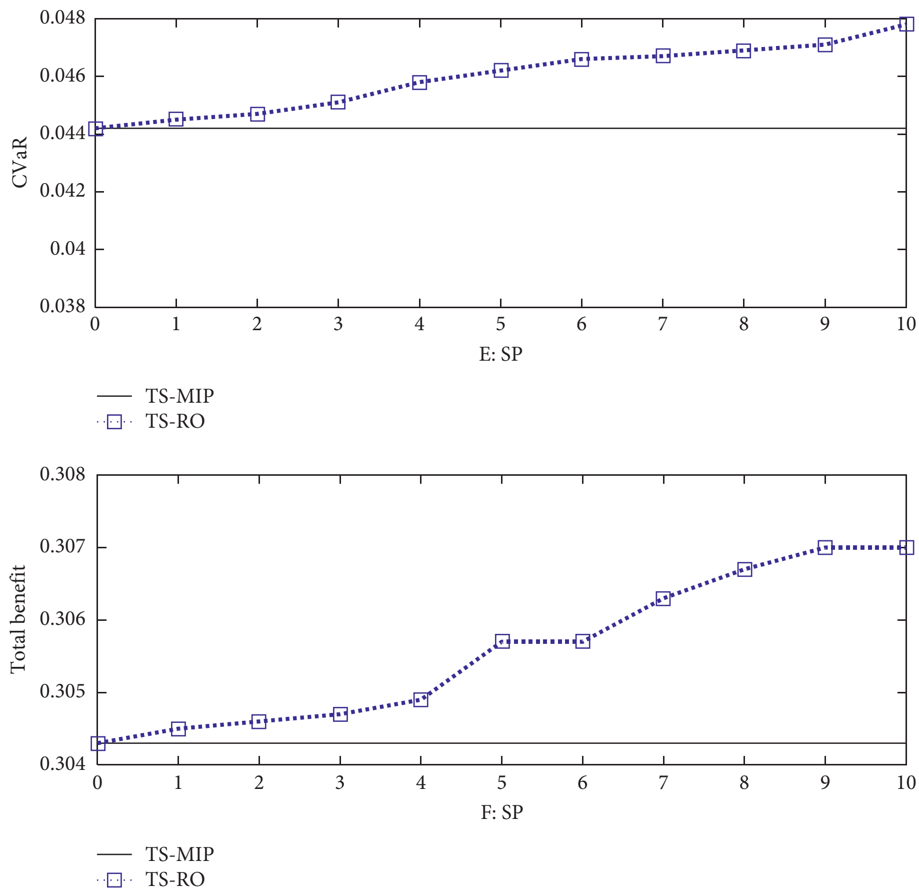

Figure 9: The impact of SP on CVaR and presidential benefits.

Table 4: Sharpe ratio under different time window lengths.

Period (L/DAY)	30	Increase	60	Increase	90	Increase
Equal weight method	0.3510	0	0.3654	0	0.3789	0
TS-MIP model	0.5004	0.1494	0.5137	0.1483	0.5245	0.1456
TS-RO model	0.5407	0.1897	0.5546	0.1892	0.5719	0.1930

Table 5: SoR of the model under different time window lengths.

Period (L/DAY)	30	Increase	60	Increase	90	Increase
Equal weight method	0.4514	0	0.4758	0	0.4985	0
TS-MIP model	0.4904	0.0390	0.5012	0.0254	0.5176	0.0191
TS-RO model	0.5397	0.0883	0.5578	0.0820	0.5810	0.0825

average) when making investment decisions. This uncertainty brings unexpectedly high profits to investors. Therefore, we should not pay attention to these risks in the investment but should pay attention to the risk that the actual rate of profit is lower than the expected value of the investment decision.

TrR is the ratio of the value of the fund's profit rate exceeding the risk-free interest rate to the systemic risk. TrR measures the excess profit that the fund receives from the systemic risk of the unit. The larger the TrR, the higher the risk-adjusted profit. The TrR is based on the fact that nonsystematic risks have been completely diversified; that is, it is believed that the portfolio of assets held by the fund has fully diversified the risks of individual stocks or industries. TrR is suitable for evaluating nonsystematic risk of completely diversified funds, such as large-cap index funds.

$$\mathrm{TrR} = \sum_i \frac{E\left(R_p\right) - R_f}{\beta_{pi}},$$
$$\beta_{pi} = \frac{\mathrm{Cov}\left(r_i, r_m\right)}{\sigma_m^2}, \quad \forall i \in I. \tag{19}$$

The numerator of the Treynor ratio is still the excess profit of the asset portfolio, $E(Rp_i)$ is the expected

Table 6: The TrR of different models.

Period (L/Day)	30	Increase	60	Increase	90	Increase
Equal weight method	0.3514	0	0.3758	0	0.3985	0
TS-MIP model	0.4187	0.0673	0.4256	0.0498	0.4367	0.0382
TS-RO model	0.4260	0.0746	0.4635	0.0877	0.4719	0.0734

annualized profit of the portfolio, R_f is the annualized risk-free interest rate, and the denominator becomes systemic risk β_{pi}. Its economic meaning is that every unit of systemic risk is assumed. For risk, r_i represents the profit of a single stock, r_m represents the market profit, and σ_m^2 represents the variance of the market profit.

As shown in Table 6, through experimental verification, when $L = 90$, the equal weight method is the lowest (TrR = 0.3985), the TS-MIP model is in the middle (TrR = 0.4367), and the TS-RO model is the best (TrR = 0.4719). Compared with the equal weight method, the TrR of the TS-RO model increased by 7.34%. In addition, in each model, as the time period increases ($L = 30 \longrightarrow L = 60 \longrightarrow L = 90$), TrR is gradually increasing, which further verifies the conclusions obtained by ShR and TrR. Regarding the excess profit the investment portfolio can get, the greater the value of the TrR, the stronger the ability of the fund manager. The TrR applies to a fully diversified investment portfolio, at which time nonsystematic risks have been completely diversified, and only systemic risks in the market are considered [43,44].

6. Conclusion

Research on investment portfolio issues can provide investors with more robust investment plans, and the uncertainty in it is a key factor affecting investment performance. Aiming at the investment portfolio problem, this paper comprehensively considers the five dimensions of profit, diversity, skewness, information entropy, and conditional risk value and constructs a two-stage mixed integer programming (TS-MIP) model. However, the deterministic TS-MIP model cannot cope with the problem of uncertain information. Therefore, this paper constructs a two-stage robust optimization (TS-RO) model by introducing robust optimization theory.

In terms of case experiments, this paper uses data crawler technology to obtain actual data from real websites for analysis and verifies the effectiveness of the proposed model in dealing with uncertain problems. The comparison of models found that, compared with the traditional equal weight model, the investment benefits of the TS-MIP model and the TS-RO model proposed in this paper have been improved. Among them, the Sharpe ratio, Sortino ratio, and Treynor ratio have the largest increase of 19.30%, 8.25%, and 7.34%, respectively. Combined with the results of empirical analysis, this paper analyzes the investment decisions of investors and puts forward some suggestions to investors.

The content and contributions of this paper mainly include the following: first, in response to the uncertainty of the rate of profit, this paper uses historical data as the basis to predict the rate of profit and express the uncertainty scenario. Second, after the analysis of the mean-variance model, this paper uses the two-stage integer programming theory to establish a portfolio model that maximizes profits, minimizes risks, and considers both profits and risks. Third, the empirical analysis of the model using the data of 10 stock indexes in my country's stock market shows that the model is feasible and effective, giving investment decision-makers a simple, clear, and intuitive guidance. Fourth, relevant suggestions are made to investors. Investors should strengthen their ability to obtain relevant information and be able to identify and analyze the information and then use relevant technologies to predict stock profits. Moreover, conservative, prudent, and aggressive investors must consider their own circumstances when investing and should not invest blindly.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Simulation Study on the Evolutionary Game Mechanism of Collaborative Innovation in Supply Chain Enterprises and Its Influencing Elements

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Collaborative innovation between companies is critical for increasing supply chain value. However, as a dynamic game process, the collaboration between manufacturer, provider, and seller in the supply chain is influenced by a range of elements. This paper is set out to investigate the collaborative innovation strategy adopted by manufacturer, supplier, and distributor (the "three players"). To meet this end, an analytical framework was built to study the evolutionary game of collaborative innovation in supply chain enterprises. Based on the analysis, this research further studied the dynamic evolutionary mechanism and influencing elements through four different simulation cases. The research showed the following. (1) When the three players have equal innovative capability, they are more willing to contribute to innovation if the projected revenue is higher reflecting an increasing coefficient of collaborative innovation gains. As a result, the three players are more likely to agree on their cooperation approach. (2) When the three players have different independent and innovative capabilities, they are more willing to innovate if the collaborative innovation gain coefficient increases, but supply chain players with stronger capability are more active to innovate than their peers. In other words, strong innovators attach particular attention to innovation. (3) When any collaborative innovation could generate profits for all players in the supply chain, the player who enjoys the benefit but lacks innovative capability will be unwilling to cooperate with others if additional gains rise. Thus, better maintenance of the stability of the collaborative innovation system requires a strictly implemented coordination mechanism.

1. Introduction

Chinese enterprises have entered a critical stage of transformation and reform, while innovation could be the main source of sustainable development. Some agents may find it difficult to engage in innovation alone due to limited resources. Luckily, the emerging economic model provides more opportunities for innovation linkages and collaboration in the supply chain industry. Facing development, governments should guide enterprises to strengthen collaborative innovation. The aim of this paper has therefore been to review key elements that are decisive to the collaborative innovation strategy for different circumstances, which will serve as a reference to policy-makers. This article explores how environment elements and innovation gains influence the innovation strategies based on simulation analysis of supply chain bodies in the mechanism of game evolution. These findings have laid a theoretical foundation for the government to guide and strengthen collaborative innovation and will greatly improve the overall collaborative innovation capability of the industry.

Innovation has been proposed as the national development strategy as the Chinese public has a stronger awareness of innovation. Meanwhile, more scholars have paid particular attention to this topic. In recent years, there has been an increasing amount of literature on collaborative innovation, particularly its application in the supply chain. To date, there are two primary research objects of collaborative innovation studies.

1.1. The Influencing Elements of Supply Chain Synergy. According to the concept of open innovation proposed by Chesbrough [1], enterprises should integrate internal and external resources in the process of innovation research and development for sharing economy and expand the source to partners and competitors in the industry, thus creating a friendly environment for performing collaborative innovation in the supply chain. In their empirical study on the service industry and manufacturing industry in the United States, Tamer Cavusgil et al. [2] pointed out that the synergy effects between supply chain enterprises are positively correlated with tacit knowledge transformation. In an investigation into the role of trust in the process of supply chain collaboration, Nyaga et al. [3] found that the trust and commitment between supply chain members support collaborative innovation, which generates a higher profit than the cost incurred by the collaboration, leading to better collaborative performance and satisfaction. To analyze how information sharing affects competition and cooperation in the supply chain industry, Albert and Tong [4] addressed two retailing companies receiving symmetrical demand signals. The analysis of Majumder and Srinivasan [5] on competing supply chains discovered that cost network structure and leadership are the two elements affecting the competition status of the supply chain.

Du and Shao [6] established a game model to compare the profits earned by core and supporting enterprises through independent innovation with the profits made by collaborative innovation. The research proved that in the market environment, enterprises would get better innovation results through collaboration than working individually. An empirical study by Trigo and Vence [7] measured the positive correlations between innovation level and collaboration. In 2017, Skippari et al. [8] studied cognitive barriers preventing supply chain players from collaborative innovation and suggested that market players' different viewpoints would affect collaborative innovation activity.

1.2. An Evolutionary Game Model for the Collaborative Innovation by Supply Chain Enterprises. Over the past decade, most research in collaborative innovation has emphasized the use of evolutionary game theory. In 2016, Bai and Sarkis [9] used game theory to study supplier's development situations and analyze how collaborative and noncooperative decisions between manufacturers and suppliers influence the latter's investment directly. To better understand the contract design made in different collaborative situations between manufacturers and suppliers, Friedl and Wagner [10] established a systematic innovation model covering supply chain players, which showed that suppliers would produce the maximum value when receiving cooperative incentives. In another research on collaboration and cooperation, Feng et al. [11] used the evolutionary game to analyze the mechanism between prefabricated component producers under punishment and incentive conditions. When manufacturers and suppliers try to solve problems in a complex collaborative system, the evolutionary game theory helps analyze how the problem scale and handling mechanism impact the decision-making process [12].

In a discussion of profit allocation mechanism, Ma and Wang [13] discussed and modified the Shapley value model with the innovation incentives, which may enhance the competitiveness of the supply chain. In another modified Shapley value model, Li et al. [14] extensively studied innovation resource investment, innovation profits, and potential risks when redistributing the gains from collaborative innovation among supply chain players. In the evolutionary game model of collaborative innovation built by Wu et al. [15], the government plays the guide, the university is the pioneer, while enterprises are the major participant, demonstrating distinct strategic decision-making process of different market players. The evolutionary game model can also be used to depict enterprises' decision behavior. Ji et al. [16] found that enterprises, universities, and research institutes invested resources differently as their preferences towards cooperation fairness, output, and profit allocation ratio diversify.

The above literature has attempted to explain the formation and influencing elements of the collaborative innovation mechanism. In addition, a considerable amount of literature has used the game model to study the dynamic evolution path of collaborative innovation, the profit allocation among the three players in a game, or elements of game strategy choice. However, few studies have researched how collaborative innovation gain, as an influencing element, impacts industrial players' strategic choice of collaborative innovation.

As all the previous collaborative innovation research studies were cross-sectional in design, this article combines the three spiral model with game analysis as a major research methodology to analyze the influencing coefficient of collaborative innovation gain. The simulation analysis focused on the three-layer supply chain body made up of individual manufacturers, suppliers, and distributors and studied the key elements influencing the gain coefficient under three different circumstances. The research results will make a contribution to the theory which governments could refer to when making policies encouraging collaborative innovation.

2. Evolutionary Game Framework for the Analysis of Collaborative Innovation by Supply Chain Enterprises

More than half a century ago, Ansoff [17] formulated his synergy effect theory, centered around how enterprises achieve mutual growth through collaboration and resource sharing. According to Baidu Encyclopedia, collaboration refers to the process of two or more individuals working jointly to achieve their common goal or the capability to do so. Economic slowdown intensified competition between enterprises and even between supply chains. Such competitions are usually reflected in business ecosystems, such as

Alibaba, Tencent, and Baidu. In the Internet economy, more resources are available to share on the World Wide Web, enabling supply chain enterprises (manufacturer, supplier and distributor) to pursuit collaborative innovation at low cooperation cost. Thus, a new development model emerges. Anthony Jnr [18] revealed that the internal and external characteristics influence an enterprise's sustainable innovation capability.

The collaborative innovation in the supply chain is evolved in the game theory framework, leading to the earning equilibrium and rationalization. The three players in the game, among others, are the manufacturer (m) who produces products, supplier (s) who delivers products, and distributor (d) who sells products. The three players form a closed-loop of game theory (Figure 1), enabling enterprises in the supply chain to make the best decisions [19].

(1) *Collaborative Strategy*. In the collaborative innovation in the supply chain, the three players (manufacturer, supplier, and distributor) enjoy equal status, which means they can freely choose strategies according to their gains and losses. The strategy set (engagement and no engagement in collaborative innovation) was denoted as (Y, N).

(2) *Collaborative Cost*. Assuming that there is no enterprise playing the leading role in the collaborative innovation and the government does not control the system with punitive and rewarding regulations, enterprises are allowed to make strategy choices according to the market cycle [20, 21]. The costs paid by manufacturer, supplier, and distributor for collaborative innovation are thus denoted as C_m, C_s, and C_d, respectively.

(3) *Collaborative Gains*. Almost all enterprises are forced to and will inevitably carry out innovative research and development in today's market [22–24]. Assuming that an enterprise has independent innovation capability, the gains thus generated are independent innovation gains. The independent innovation gains obtained by manufacturer, supplier, and distributor are denoted as W_m, W_s, and W_d, respectively. When two of the three players participate in collaborative innovation and share knowledge and technology, their gains will increase. The collaborative innovation gain is denoted as coefficient k_1, representing the increase from the independent innovation gains. The collaborative innovation gain coefficient is k_2 if all the three players participate in collaborative innovation. Based on the scale effect, $k_2 > k_1$, which conforms to the actual situation.

(4) *Additional Gains*. The supply chain players are closely linked in the production cycle. When the player engaging in collaborative innovation shares its technological and knowledge innovations, other external parties may obtain an increase in gains without costs or risks [25].

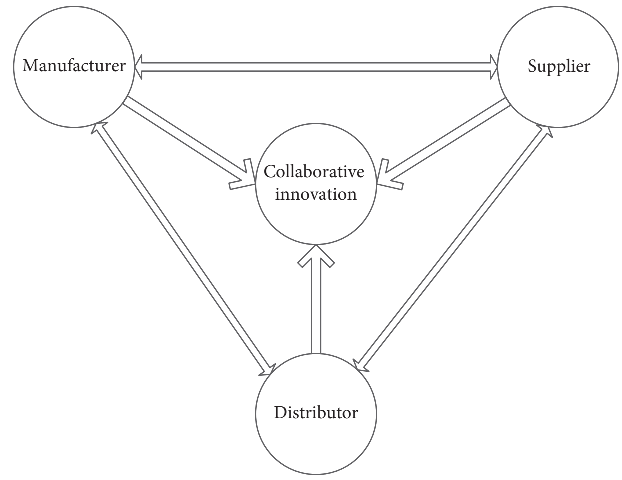

Figure 1: Manufacturer supplier distributor collaborative innovation.

If one of the three players engages in collaborative innovation, while the other two players do not, those who do not innovate may also record gains generated by innovative achievements in the supply chain. The additional gains received by the manufacturer, supplier, and distributor are denoted as $\Delta W_m^+ (\Delta W_m^+ \geq 0)$, $\Delta W_s^+ (\Delta W_s^+ \geq 0)$, and $\Delta W_d^+ (\Delta W_d^+ \geq 0)$, respectively. When two of the three parties engage in collaborative innovation, the other party (be the manufacturer, the supplier, or the distributor) would also enjoy additional gains. The additional gains of the three players in this condition are denoted as $\Delta W_m^{++} (\Delta W_m^{++} \geq 0)$, $\Delta W_s^{++} (\Delta W_s^{++} \geq 0)$, and $\Delta W_d^{++} (\Delta W_d^{++} \geq 0)$, respectively.

3. Analysis of the Evolution Mechanism of Collaborative Innovation Game of Supply Chain Enterprises

3.1. The Payoff Matrix in the Game. According to the game theory, supply chain enterprises adjust their game strategy according to their gains. We assume that the probability of a manufacturer's engagement in collaborative innovation is x $(0 \leq x \leq 1)$ and no engagement is $1 - x$; the probabilities of a supplier's engagement and not engagement are y $(0 \leq y \leq 1)$ and $1 - y$, respectively; and the probabilities of the distributor are z $(0 \leq z \leq 1)$ and $1 - z$, respectively.

The manufacturer (m), supplier (s), and distributor (d) have two strategic choices, i.e., engagement and no engagement in collaborative innovation. Table 1 demonstrates the game payoff matrix of eight strategy combinations.

3.2. Analysis on the System of Replicator Dynamic Equation and Stability of Collaborative Innovation. The manufacturer, supplier, and distributor are determined to engage in collaborative innovation based on the results of multiple games. The system of replicator dynamic equation represents the dynamic evolution of their decision-making process.

Table 1: The payoff matrix of supply chain players.

Strategy combination	Manufacturer (m)	Supplier (s)	Distributor (d)
(N, N, N)	W_m	W_s	W_d
(N, Y, N)	$W_m + \Delta W_m^+$	$W_s - C_s$	$W_d + \Delta W_d^+$
(N, N, Y)	$W_m + \Delta W_m^+$	$W_s + \Delta W_s^+$	$W_d - C_d$
(N, Y, Y)	$W_m + \Delta W_m^{++}$	$W_s(1+k_1) - C_s$	$W_d(1+k_1) - C_d$
(Y, N, N)	$W_m - C_m$	$W_s + \Delta W_s^+$	$W_d + \Delta W_d^+$
(Y, Y, N)	$W_m(1+k_1) - C_m$	$W_s(1+k_1) - C_s$	$W_d + \Delta W_d^{++}$
(Y, N, Y)	$W_m(1+k_1) - C_m$	$W_s + \Delta W_s^{++}$	$W_d(1+k_1) - C_d$
(Y, Y, Y)	$W_m(1+k_2) - C_m$	$W_s(1+k_2) - C_s$	$W_d(1+k_2) - C_d$

The manufacturer's (m) expected gains for engagement in collaborative innovation are E_m^H, while the expected gains for not engaging in collaborative innovation are E_m^L, and the average expected gains are $\overline{E}_m$; therefore,

$$\begin{cases} E_m^H = (1-y)(1-x)(W_m - C_m) + y(1-z)[W_m(1+k_1) - C_m] + (1-y)z+ \\ (1-y)z[W_m(1+k_1) - C_m] + yz[W_m(1+k_2) - C_m], \\ E_m^L = (1-y)(1-x)W_m + y(1-z)(W_m + \Delta W_m^+) \\ +(1-y)z(W_m + \Delta W_m^+) + yz(W_m + \Delta W_m^{++}) \\ \overline{E}_m = xE_m^H + (1-x)E_m^l. \end{cases} \tag{1}$$

The supplier's (s) expected gains for engagement in collaborative innovation are denoted as E_s^H, while the expected gains for not engaging in collaborative innovation are denoted as E_s^L, and the average expected gains are denoted as $\overline{E}_s$; therefore,

$$\begin{cases} E_s^H = (1-x)(1-z)(W_s - C_s) + (1-x)z[W_s(1+k_1) - C_s]+ \\ x(1-z)[W_s(1+k_1) - C_s] + xz[W_s(1+k_2) - C_s], \\ E_s^L = (1-x)(1-z)W_s + (1-x)z\left(W_p + \Delta W_p^+\right)+ \\ x(1-z)(W_s + \Delta W_s^+) + xz(W_s + \Delta W_s^{++}), \\ \overline{E}_s = yE_s^H + (1-y)E_s^L. \end{cases} \tag{2}$$

The distributor's (d) expected gains for engagement in collaborative innovation are denoted as E_d^H, while the expected gains for not engaging in collaborative innovation are denoted as E_d^L, and the average expected gains are denoted as $\overline{E}_d$; therefore,

$$\begin{cases} E_d^H = (1-x)(1-y)(W_d - C_d) + (1-x)y[W_d(1+k_1) - C_d]+ \\ x(1-y)[W_d(1+k_1) - C_s] + xy[W_d(1+k_2) - C_d], \\ E_d^L = (1-x)(1-y)W_d + (1-x)y(W_d + \Delta W_d^+)+ \\ x(1-y)(W_d + \Delta W_d^+) + xy(W_d + \Delta W_d^{++}), \\ \overline{E}_d = zE_d^H + (1-z)E_d^L. \end{cases} \tag{3}$$

In the evolutionary game theory, we reach the imitation dynamic equations of the manufacturer (m), supplier (s), and distributor (d) according to the imitation dynamic equation:

$$\begin{cases} f(x) = \dfrac{\mathrm{d}x}{\mathrm{d}t} = x\left(E_m^H - \overline{E}_m\right) = x(1-x)\left(E_m^H - E_m^L\right), \\ f(y) = \dfrac{\mathrm{d}y}{\mathrm{d}t} = y\left(E_s^H - \overline{E}_s\right) = y(1-y)\left(E_s^H - E_s^L\right), \\ f(z) = \dfrac{\mathrm{d}z}{\mathrm{d}t} = z\left(E_d^H - \overline{E}_d\right) = z(1-z)\left(E_d^H - E_d^L\right). \end{cases} \tag{4}$$

If $f(x)$, $f(y)$, and $f(z)$ are 0, the equilibrium points of the three replicator dynamic equations are (0,0,0), (0,1,0), (0,0,1), (0,1,1), (1,0,0), (1,1,0), (1,0,1), and (1,1,1), respectively. Based on the three replicator dynamic equations, we made the Jacobian matrix as follows:

$$J = \begin{bmatrix} \dfrac{\partial f(x)}{\partial x} & \dfrac{\partial f(x)}{\partial y} & \dfrac{\partial f(x)}{\partial z} \\ \dfrac{\partial f(y)}{\partial x} & \dfrac{\partial f(y)}{\partial y} & \dfrac{\partial f(y)}{\partial z} \\ \dfrac{\partial f(z)}{\partial x} & \dfrac{\partial f(z)}{\partial y} & \dfrac{\partial f(z)}{\partial z} \end{bmatrix}. \tag{5}$$

By placing the eight equilibrium points into the Jacobian matrix, respectively, their eigenvalues are as shown in Table 2.

Through the local analysis on the Jacobian matrix, we obtain the evolutionarily stable strategy of the system of replicator dynamic equations. The point would be stable only when the eigenvalues are all nonpositive.

4. Simulation Analysis on the Influencing Factors of Collaborative Strategy

The equilibrium points (0,0,0), (0,1,1), (1,1,0), (1,0,1), and (1,1,1) could be stable points with the change of undetermined parameters of the 3D helical model. This paper only discussed how the coefficient of collaborative innovation gain affects the evolution of collaborative innovation game. To this end, other parameters have to be determined before observing the changes in the coefficient of collaborative innovation gains.

Table 2: Eigenvalues of the Jacobian matrix.

Equilibrium point	Eigenvalue T_1	Eigenvalue T_2	Eigenvalue T_3
$E_1\,(0,0,0)$	$-C_m$	$-C_s$	$-C_d$
$E_2\,(0,1,0)$	$k_1W_m - C_m - \Delta W_m^+$	C_s	$k_1W_d - C_d - \Delta W_d^+$
$E_3\,(0,0,1)$	$k_1W_m - C_m - \Delta W_m^+$	$k_1W_s - C_s - \Delta W_s^+$	C_d
$E_4\,(0,1,1)$	$k_2W_m - C_m - \Delta W_m^{++}$	$-(k_1W_s - C_s - \Delta W_s^+)$	$-(k_1W_d - C_d - \Delta W_d^+)$
$E_5\,(1,0,0)$	C_m	$k_1W_s - C_s - \Delta W_s^+$	$k_1W_d - C_d - \Delta W_d^+$
$E_6\,(1,1,0)$	$-(k_1W_m - C_m - \Delta W_m^+)$	$-(k_1W_s - C_s - \Delta W_s^+)$	$k_2W_d - C_d - \Delta W_d^{++}$
$E_7\,(1,0,1)$	$-(k_1W_m - C_m - \Delta W_m^+)$	$k_2W_s - C_s - \Delta W_s^{++}$	$-(k_1W_d - C_d - \Delta W_d^+)$
$E_8\,(1,1,1)$	$-(k_2W_m - C_m - \Delta W_m^{++})$	$-(k_2W_s - C_s - \Delta W_s^{++})$	$-(k_2W_d - C_d - \Delta W_d^{++})$

4.1. Influence of Collaborative Innovation Gain Coefficient on the Evolution Process of Collaborative Innovation Strategy. In the changing economy, enterprises' economic scale and innovation ability in the supply chain are thus different. We studied how the coefficient of collaborative innovation gains influences the strategic evolution from the perspective of the independent innovation gains, collaborative innovation costs, and additional gains of the manufacturer, supplier, and distributor [26].

Situation 1. Where the manufacturer, supplier, and distributor engaging in collaborative innovation have similar economic scale, gains, and costs, we observe how the coefficient of collaborative innovation gains impacts its strategic evolution when the three players have the same level of willingness. The parameters' setting is as follows: $W_m = W_s = W_d = 30$, $W_m^+ = W_s^+ = W_d^+ = 5$, $W_m^{++} = W_s^{++} = W_d^{++} = 6$, $C_m = C_s = C_d = 8$, and $x = y = z = 0.5$.

According to the simulation by Matlab software (Figure 2), the three players' strategies follow the same evolving paths due to their similarities in economic scale. The line in Figure 2 represents the evolution of collaborative innovation strategy of the three players. As shown in Figure 2, as k_1 and k_2 increase by the same ratio, the strategies of the three players gradually changed from (N, N, N) to (Y, Y, Y). Simulation results showed that the manufacturer, supplier, and distributor would choose similar strategies when they have an equal economic scale and enjoy a relatively fair allocation of collaborative innovation gains. Moreover, as the coefficient of collaborative innovation gains grows, they are more willing to engage in collaborative innovation. Finally, the three players would also devote themselves to collaborative innovation driven by the market margin. The evolution of collaborative innovation strategy aligns with the market law of enterprises' nature of "profit-seeking."

Situation 2. We suppose the independent innovation gains recorded by the three players are different, but their costs for collaborative innovation and additional gains are the same. When the three players have the same level of initial willingness to engage in collaborative innovation, we observe the influence of the coefficient of collaborative innovation gains on the evolutionary game of collaborative innovation strategy. The parameters' setting is as follows: $W_m = 30$, $W_s = 40, W_d = 50, W_m^+ = W_s^+ = W_d^+ = 5, W_m^{++} = W_s^{++} = W_d^+$ $+ = 6, C_m = C_s = C_d = 8$, and $x = y = z = 0.5$.

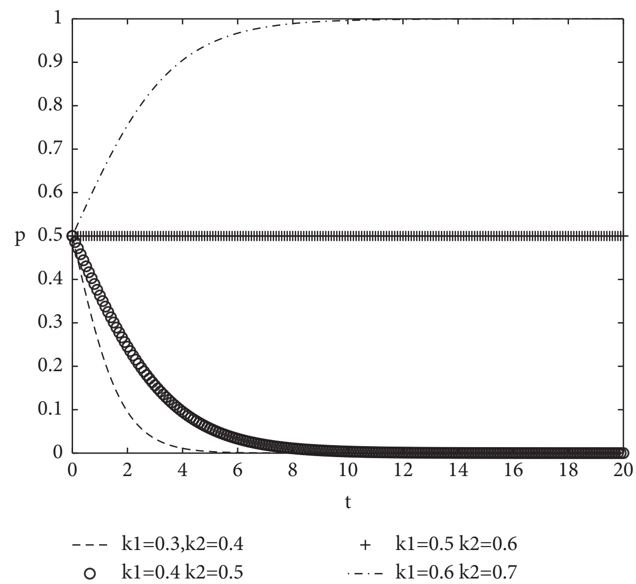

Figure 2: Strategy evolution paths under different gain coefficients.

Matlab software simulated the model and produced the results, as shown in Figures 3–5. The strategies of the three players follow different evolving paths as they have inconsistent independent innovation gains. According to Figures 3–5, the strategy of the three parties gradually changed from (N, N, N) to (Y, Y, Y) as k_1 and k_2 increase. Simulation results showed that the three players are inclined to choose the same strategy when the collaborative innovation gains are fairly distributed despite their different independent innovation gains. However, the entity with greater independent innovation gains is more likely to make better achievements in collaborative innovation, and the player with stronger independent innovation capability would be more willing to engage in collaborative innovation as the coefficient of collaborative innovation gains rises. The bottom line is that enterprises with stronger independent innovation capability are likely to leverage and transform the production means of other market players to enhance their productivity through collaborative innovation.

The enterprises with greater independent innovation gains arouse other market players' enthusiasm for collaborative innovation. In the actual economic environment, the "Internet + traditional enterprise" have been driving the transformation of traditional enterprises and promoting the traditional enterprises to pursue innovation, which is consistent with the simulation results [27].

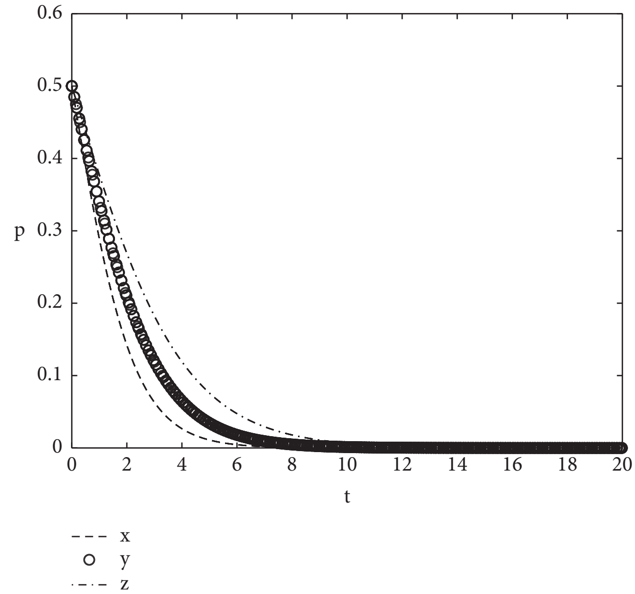

Figure 3: $k_1 = 0.3$ and $k_2 = 0.4$.

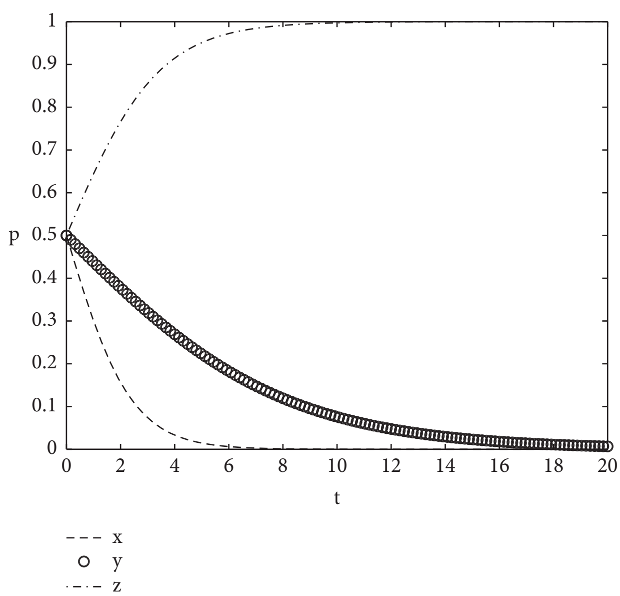

Figure 4: $k_1 = 0.35$ and $k_2 = 0.45$.

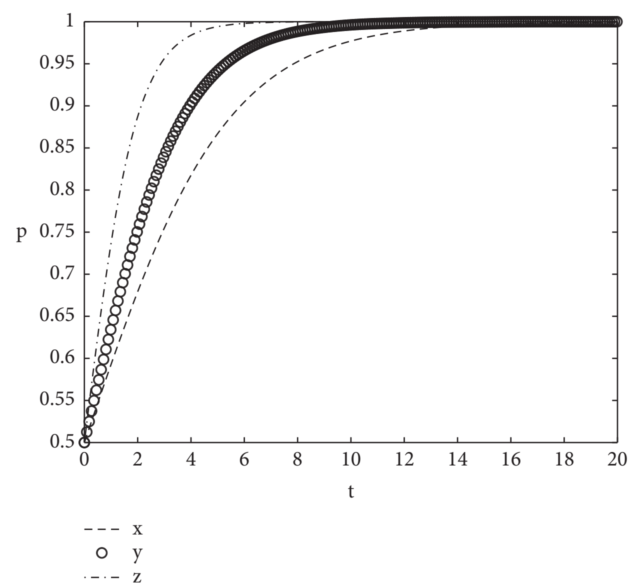

Figure 5: $k_1 = 0.5$ and $k_2 = 0.6$.

Situation 3. We suppose the additional gains of the three parties are different. There are few areas in the real economic environment for market players to carry out collaborative innovation activities because they are not complementary to each other. Therefore, players refusing to engage in collaborative innovation may gain additional gains from those engaging in collaborative innovation. The parameters' setting is as follows: $W_m = 30, W_s = 30, W_d = 30, W_m^+ = 10, W_s^+ = 8, W_d^+ = 6, W_m^{++} = W_s^{++} = W_d^{++} = 6, C_m = C_s = C_d = 8$, and $x = y = z = 0.5$.

Figures 6–9 show the Matlab software simulation results. The strategies of the three players follow different evolving paths due to differences in additional gains. As shown in Figure 6, the strategies selected by the three players are not hugely different in terms of the evolving paths when the coefficient of collaborative innovation gains is small. As a result, enterprises are generally unwilling to engage in collaborative innovation when the benefits of collaborative innovation are not apparent.

In Figure 7, as the coefficient of collaborative innovation gains increases, the effect of collaborative innovation becomes more apparent. However, the player receiving greater additional gains is less willing to engage in collaborative innovation than the party with lower additional gains. Additional gains attenuated enterprises' willingness to benefit from other players' innovative achievements though such additional gains gained without costs reduce the risk that the loss of the player exceeds its gains.

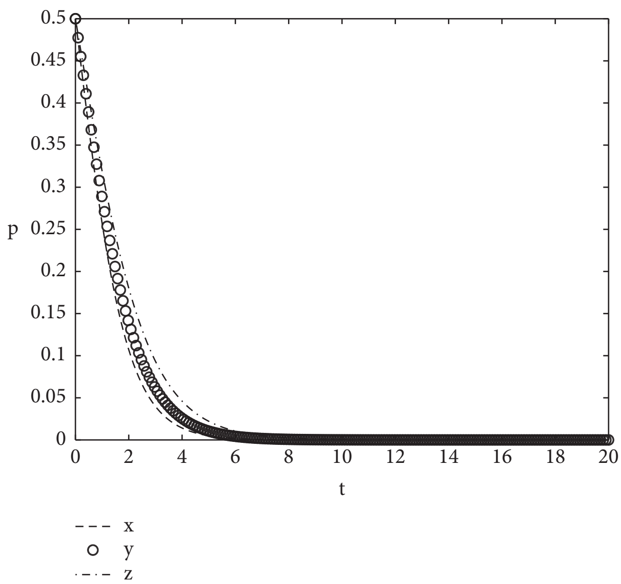

Figure 6: $k_1 = 0.3$ and $k_2 = 0.4$.

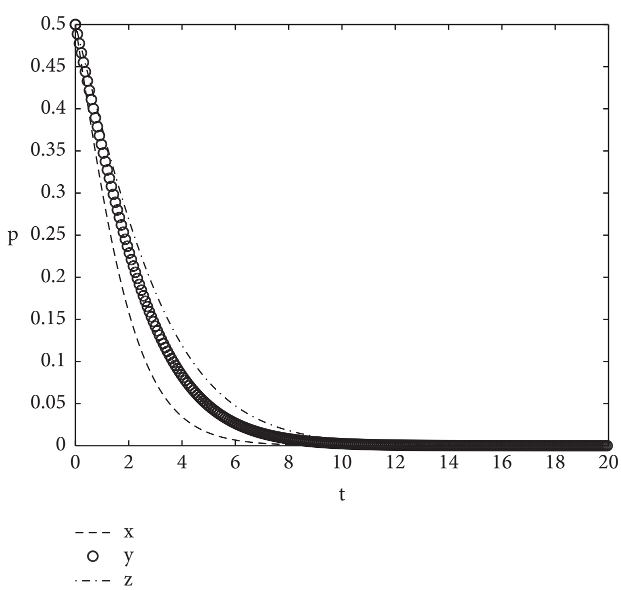

Figure 7: $k_1 = 0.5$ and $k_2 = 0.6$.

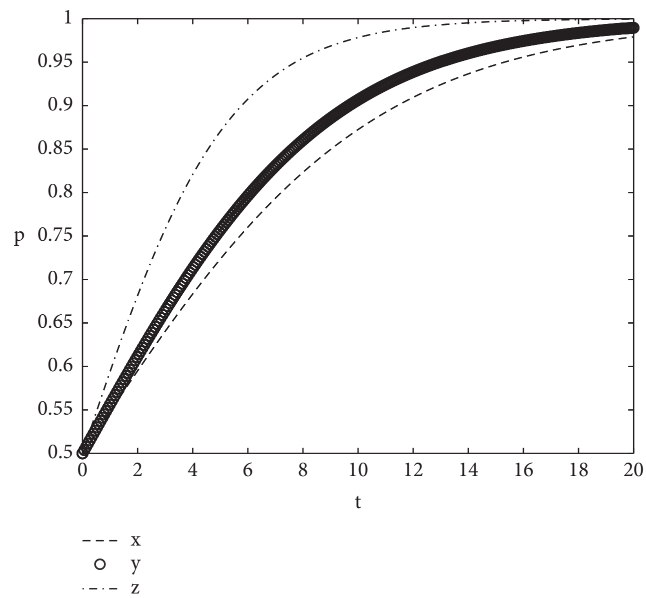

Figure 8: $k_1 = 0.6$ and $k_2 = 0.7$.

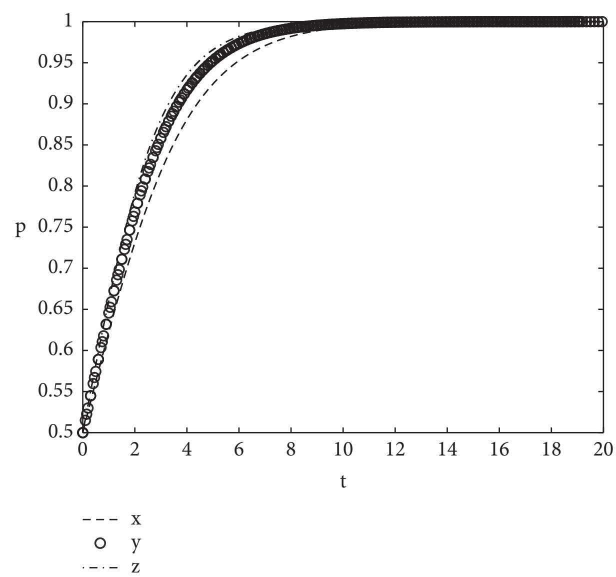

Figure 9: $k_1 = 0.7$ and $k_2 = 0.8$.

As shown in Figures 8 and 9, as the coefficient of the collaborative innovation earning grows higher, collaborative innovation shows a noticeable effect. The weakening effect of additional gains on enterprises' willingness to engage in collaborative innovation is waning. When the collaborative innovation earning coefficient increases to a certain level, the evolving paths of the three players converge. In general, the enterprise will choose to engage in collaborative innovation when the effect of collaborative innovation is favorable to self-development.

Situation 4. We suppose that the three players record different additional gains. Players not engaging in collaborative innovation may receive different additional gains from those engaging in collaborative innovation. The parameters' setting is as follows: $W_m = 30, W_s = 30, W_d = 30, W_m^+ = 5, W_s^+ = 5, W_d^+ = 5, W_m^{++} = 10, W_s^{++} = 8, W_d^{++} = 6, C_m = C_s = C_d = 8$, and $x = y = z = 0.5$.

Figures 10–13 show the Matlab software simulation results. The strategies of the three players follow different evolving paths due to different additional gains.

As shown in Figures 10–13, additional gains may attenuate the enterprises' willingness to engage in collaborative innovation, a similar result to Situation 3. By comparing the coefficients of consistent collaborative innovation gains in Situations 3 and 4, double shares of additional gains have a more substantial impact on enterprises' willingness to engage in collaborative innovation than a single share of additional gains. In the real situation, if more enterprises participate in

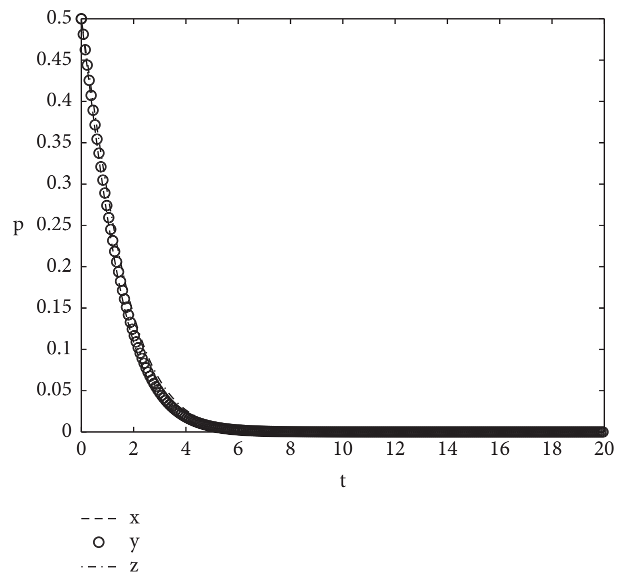

Figure 10: $k_1 = 0.3$ and $k_2 = 0.4$.

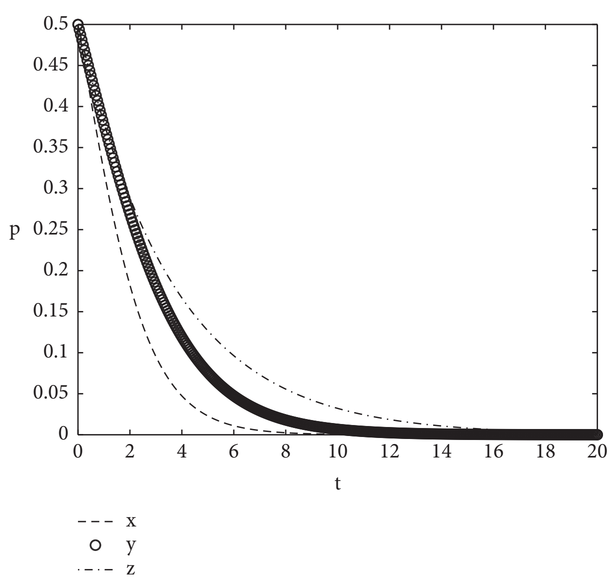

Figure 11: $k_1 = 0.5$ and $k_2 = 0.6$.

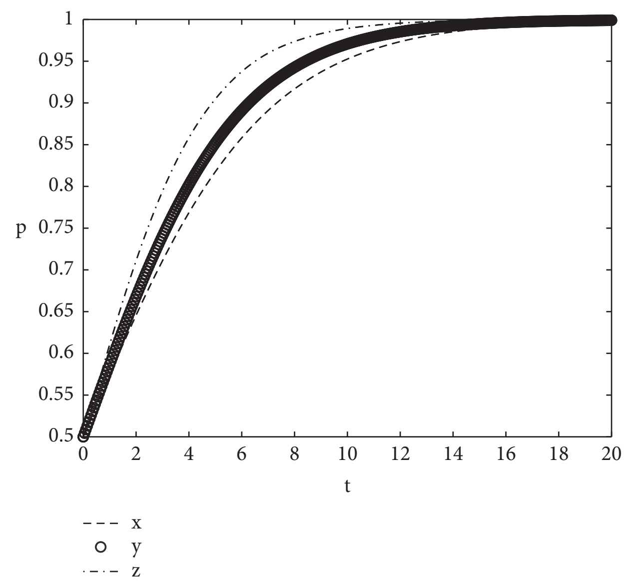

Figure 12: $k_1 = 0.6$ and $k_2 = 0.7$.

collaborative innovation, those who do not engage in collaborative innovation are less willing to do so when they enjoy higher additional gains. China has found it challenging to encourage the conventional manufacturing industry to innovate. Moreover, long-time dependence on innovation achievements owned by foreign companies also undermines Chinese companies' innovation vitality since such dependence on European and American peers has brought in high profits at the cost of losing innovation willpower. The fierce China-US trade frictions create an opportunity for domestic enterprises to pursue innovation and development despite the adverse influences.

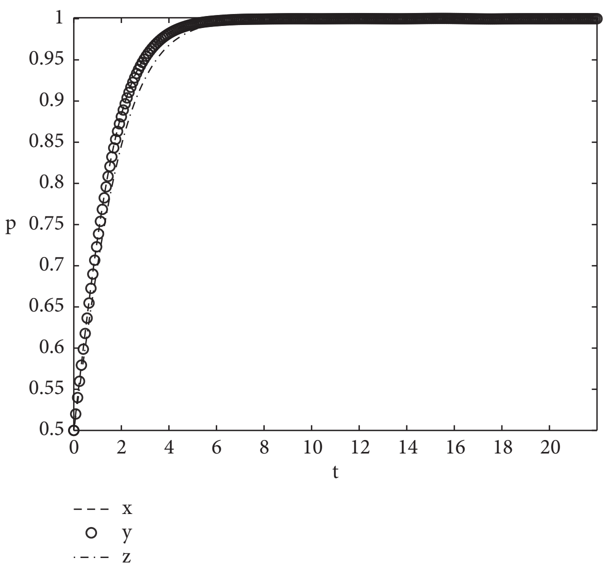

Figure 13: $k_1 = 0.7$ and $k_2 = 0.8$.

5. Conclusion

This paper established a simple supply chain model simulating the innovation behaviors of manufacturer, supplier, and distributor. To simulate the real situation, the model used simplified parameters of collaborative innovation gains to be distributed among the three players. Based the simulation results, this paper discussed the effect of collaborative innovation gains under different economic conditions and analyzed how different economic conditions influence the collaborative innovation strategy based on evolutionary game theory. The research has showed the following. (1) For manufacturer, supplier, and distributor who have the same level of initial willingness, if they have the same independent innovation capability, they are more willing to innovate and more likely to agree on cooperation approach as the coefficient of collaborative innovation gain increases and higher gains are created from collaborative innovation. (2) For manufacturer, supplier, and distributor with different independent innovation capabilities, if the coefficient of collaborative innovation gains is higher, they are more willing to cooperate, but supply chain players with stronger innovation capability are more active than their peers, indicating that stronger innovators are more likely contribute more into innovation and also in a collaborative way. Therefore, governments should cultivate and encourage innovative pioneers in the supply chain of different industries, thus driving the healthy development of the business ecosystem. (3) If all players in the supply chain could enjoy gains generated by any collaborative innovation activities, the three players are more likely to work collaboratively for innovation. As the gains increase, the willingness to cooperate grows stronger. In conclusion, as more gains are shared in the supply chain, market players are more willing to engage in collaborative innovation, accelerating the cooperation between enterprises for innovation.

Overall, the evolutionary game simulation of the collaborative innovation strategy in this paper provides insights for collaborative innovation management in the supply chain. However, these findings are limited by the simplicity of the model, the uncertainties in the actual economy, and the complex and changing government policies. In the future, it will be important to introduce policy guidance into this model of collaborative innovation in the supply chain.

Data Availability

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

Conflicts of Interest

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

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Research Article

A Network Evolution Model of Credit Risk Contagion between Banks and Enterprises Based on Agent-Based Model

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Credit risk contagion between banks and firms is one of the important triggers of financial crisis, and the credit linkage network is the way of systemic risk contagion triggered by external shocks. Considering the heterogeneity of behavioral rules, learning rules, and interaction rules, this paper constructs a bank-firm credit matching network model based on ABM (agent-based model) model and reinforcement learning algorithm to analyze the interaction behavior and credit risk network contagion mechanism. The results show that (1) macroeconomic cycles are the result of the interaction between banks and enterprises and the interaction of microentities under complex financial conditions; (2) enterprises are heterogeneous and the asset size follows a power-law distribution; (3) the greater the sensitivity of banks and enterprises to market performance, the lower the bank failure rate and enterprise default rate; and (4) shocks to the largest banks and enterprises in terms of assets and entry can all intensify the risk contagion between banks and enterprises. Therefore, the regulation of financial institutions that are "too big to fail" is not sufficient but should be a comprehensive regulation of the banking system.

1. Introduction

The global economic integration has deepened the close connection among economic agents, and the association between banks and enterprises, as two important support subjects of the modern economic system, has become increasingly close, forming a supernetwork with credit as the main credit connection, and the credit network of banks and enterprises can easily become the transmission channel of the risk of external shocks. Related studies have shown that bank-credit networks have the role of "financial gas pedals" and can amplify the spread of bank-enterprise credit risks. The subprime mortgage crisis and its risk contagion in the United States in 2007 are a very typical example. In China, there is a strong risk correlation between banks and enterprises in the capital chain. External shocks leading to corporate credit defaults will inevitably impact the stability of the banking system, which in turn affects the supply of credit from the banking system to the rest of the real economy, causing a vicious circle and exacerbating the credit risk contagion effect between banks and enterprises.

The existing studies on credit risk contagion between banks and enterprises mainly explore the mechanisms and laws of risk contagion between banks and enterprises from the perspectives of considering single subjects of banks and enterprises and dual subjects of banks and enterprises. First, in terms of considering only the bank subject, Giulia et al. [1] constructed an interbank lending network to study the risk contagion among banks in the presence of volatile liquid assets. Li [2] studied the impact of intersubject network structure of banks and behavioral rules of bank subjects on risk contagion. Krause and Giansante [3] concluded with the help of logit regression analysis that the topology of the credit network among bank subjects is an important factor influencing risk contagion. Lux [4] constructed an interbank credit correlation network model based on reinforcement learning algorithms, and the results showed that the interbank market has a core-periphery structure. Anand et al.

[5] and Simone and Tedeschi [6] showed that network topology and high leverage are responsible for the formation of interbank market risk. Chen et al. [7] construct a network model of credit risk contagion in the interbank lending market based on time series and incomplete information. It investigates how the contagion effect of credit risk accumulates and spreads in the interbank market network and the evolutionary characteristics of credit risk contagion triggered by initial default of creditor banks in the interbank market. Tedeschi et al. [8] studied the impact of systemic risk as well as risk sharing on the interbank market based on the ABM model. Chen et al. [9] incorporate the average fitness for credit risk contagion, risk aversion, and the risk resistance of credit risk holders into an evolutionary network model of credit risk contagion. The impact of these factors on credit risk contagion in financial markets is investigated. However, the drawback of this type of model is that it only studies the risk evolution in the interbank market and does not consider the impact of bank default and bankruptcy on the corporate side. Secondly, in terms of considering only corporate subjects, Battiston et al. [10] introduced supply chain networks and showed that the risk of corporate default bankruptcy is transmitted from downstream to upstream firms and that the main cause is the commercial credit of the firm. Barro and Basso [11] constructed an interfirm business linkage interaction network and studied the credit risk contagion between firms. Chen and Wang [12] constructed a SIRS model of counterparty credit risk contagion. The effects, mechanisms, and evolutionary features of counterparty credit network structure and its heterogeneity, counterparty behavioral preferences, counterparty suitability, and regulatory bailout strategies on counterparty credit risk contagion are investigated. Hou et al. [13] studied the risk contagion effect between upstream and downstream firms based on a network of upstream and downstream firms. This literature mainly focuses on business linkages and risk contagion among firms, while ignoring the interaction behavior between banks and firms and the impact of corporate bankruptcy default on the banking system. Finally, considering banks and enterprises at the same time, Riccetti et al. [14]; Bargigli et al. [15]; and Giri et al. [16] studied the evolution of risk contagion in banking firms based on the financial gas pedal mechanism. Catullo et al. [17] argue that interbank risk contagion is related to the structure of the credit network of the bank and the leverage of the subject. Delli Gatti et al. [18] analyzed the characteristics of the banking firm credit network economy and showed that differences in financial positions and interactions between subjects contribute to the development of macroeconomic cycles and that the bankruptcy of one subject can generate a chain reaction of bankruptcies. He et al. [19] constructed an endogenous credit network between firms and banks and studied the distribution characteristics of simulation-generating variables such as the topology of interbank and interbank networks. Chen et al. [20] constructed a two-tier credit network model between banks and corporate counterparties by considering the impact of corporate credit defaults on their counterparties under a credit link. The mechanisms affecting the evolution of the bank-firm partnership were analyzed and the evolutionary characteristics of credit risk contagion between banks and corporate counterparties under a two-tier network. Li et al. [21] constructed a systemic risk measurement model for banking enterprises based on debt ranking and studied the contagion effect of risk between banks and enterprises from a risk feedback perspective. This literature does not analyze in depth the macroeconomic characteristics of subject interactions and the impact of uncertainty shocks on risk contagion between banks and firms.

In summary, existing studies have conducted theoretical and qualitative research on interbank risk. However, the heterogeneity and interaction of the behavioral rules of banking and corporate entities have not been investigated in depth, and how the macroeconomic characteristics of the banking and corporate system affect credit risk contagion and its evolution has not been analyzed in depth. This would make the existing research not very adequate to guide the practice of credit risk management between banks and enterprises. In view of this, in this paper, with the help of ABM (agent-based model) and reinforcement learning algorithm, considering in depth the behavioral rules, strategic choices, and interaction rules of banking and business subjects and their heterogeneity, construct a bank-enterprise credit matching network model and study in depth the mechanism of macroeconomic characteristics between banks and enterprises and their network structure on credit risk contagion between banks and enterprises. The research in this paper will be helpful to grasp the interaction mechanism of credit risk contagion among subjects at the microlevel and will also be helpful to control the evolution law of credit risk contagion among banks and enterprises at the macrolevel, which is of great significance to prevent systemic financial risks.

2. ABM Model of Bank-Enterprise Endogenous Credit Matching Network

The endogenous credit network contains corporate subjects and bank subjects, and the credit association between banks and enterprises forms the edge of the credit network. Companies invest in the production of perishable products, and they finance production with their own assets and loans provided by banks. At the same time, both banks and firms choose their respective target levers to maximize profits through enhanced learning mechanisms. It is assumed that the credit agreement has only two periods and that both consumer and credit markets are considered, but with a greater focus on the banking and corporate credit market, simplifying the consumer market.

2.1. Enterprise Subject Behavior Model

2.1.1. Enterprise Output. Considering the enterprise system as a discrete evolutionary system, in the period each enterprise produces using its own capital ($K_{i,t}$). Under the premise of full capacity utilization, the firm produces based on the ideal output of capital as shown in the following equation:

$$Y_{i,t} = \rho K_{i,t}, \tag{1}$$

where $Y_{i,t}$ is the output of the firm $i = 1, \ldots, M (M = 500)$ in the time period $t = 1, \ldots, T (T = 500)$ and ρ is the coefficient of production technology of capital, $0 < \rho < 1$.

According to the balance sheet constancy equation, the capital of the enterprise is shown in the following equation:

$$K_{i,t} = L_{i,t} + \phi L_{i,t-1} + E_{i,t}. \tag{2}$$

Capital is equal to the sum of net equity ($E_{i,t}$) and loans. Firm loans include loans assumed in time $t(L_{i,t})$ and the part of the loans borrowed at time $t-1$ that is repaid at time $t(\phi L_{i,t-1})$, where $\phi (0 < \phi < 1)$ represents the repayment ratio of the previous loan in the current period. Since the enterprise can obtain loans from multiple banks, the final loan amount of the enterprise is equal to the sum of the loans obtained from all the banks, namely:

$$L_{i,t} = \sum_z L_{i,z,t}. \tag{3}$$

2.1.2. Enterprise Loan Demand and Decision. It is assumed that at the beginning of the period each firm determines a target leverage level $\beta_{i,t}$ of its own, which is equal to the ratio of the firm's loans to its own net equity. Loans include the current period's loan demand and the previous period's loans that need to be repaid, so that there are

$$\beta_{i,t} = \frac{\left(L_{i,t}^d + \phi L_{i,t-1}\right)}{E_{i,t}}. \tag{4}$$

According to formula (4), the current loan demand of enterprises can be obtained as follows:

$$L_{i,t}^d = \beta_{i,t} E_{i,t} - \phi L_{i,t-1}. \tag{5}$$

It is assumed that the target leverage of an enterprise is determined by the leverage strategy ($\eta_{i,t}$) chosen in each period, $\beta_{i,t} = 1/\eta_{i,t} - 1$. Because loans are risky, companies will consider their own bankruptcy and risk aversion. To incorporate these factors into the model, a risk appetite coefficient is given $\psi_f \in [0, +\infty)$, where $\psi_f = 1$ is risk neutral. Therefore, the impact of an enterprise's risk appetite on its actual target leverage ratio is

$$\beta_{i,t} = \psi_f \left(\frac{1}{\eta_{i,t}} - 1\right). \tag{6}$$

Combining formula (5) and formula (6), the loan demand of enterprises is updated as follows:

$$L_{i,t}^d = \psi_f \frac{E_{i,t}}{\eta_{i,t}} - \psi_f E_{i,t} - \phi L_{i,t-1}. \tag{7}$$

Enterprises use reinforcement learning algorithms to select their leverage strategies ($\eta_{i,t}$) from a set of limited strategy sets G. The lower the $\eta_{i,t}$, the higher the target leverage ($\beta_{i,t}$) and, thus, the higher the risk taken by the firm.

The enterprise loan interest rate ($r_{i,t}$) is the function of the enterprise's current target leverage ratio and the benchmark deposit interest rate (r) set by the bank:

$$r_{i,t} = r \exp\left(\alpha \beta_{i,t}\right). \tag{8}$$

In formula (8), the parameter α is the sensitivity of the bank to the corporate target leverage ratio, which reflects the sensitivity of the bank to the corporate total debt.

2.1.3. Marginal Revenue and Net Value of the Enterprise. Assuming that the interest rate paid by the enterprise and the bank on their respective equity is equal to the prime rate, the change in the profit of the business entity is affected by sales revenue ($u_{i,t} Y_{i,t}$), dividend payments ($r E_{i,t}$), interest payments on bank loans, and other fixed costs (F_f). Therefore, the marginal income of the enterprise i is

$$\pi_{i,t} = u_{i,t} Y_{i,t} - r E_{i,t} - r_{i,t} L_{i,t} - \phi r_{i,t} L_{i,t-1} - F_f, \tag{9}$$

where $u_{i,t}$ is the actual price of a unit product of an enterprise, including the marginal cost price m related to loans and a random component ($\varepsilon_{i,t}$), which represents the unpredictable fluctuation of demand in the consumer market. Therefore, every business wants $\varepsilon_{i,t}$ the expected value to be zero and meets

$$\begin{aligned} u_{i,t} &= m + \varepsilon_{i,t}, \\ \varepsilon_{i,t} &\sim N(0, \sigma). \end{aligned} \tag{10}$$

Proposition 1. *If the marginal cost pricing of any enterprise satisfies $m > r_{\max}/\rho$, the enterprise subject can operate well without the fluctuation of consumer market demand.*

Proof. Only considering that enterprises use loans for production, so as long as the price is higher than the variable cost, enterprises can obtain marginal revenue to cover the fixed cost, and the surplus is profit:

$$m\rho\left(L_{i,t} + \phi L_{i,t-1}\right) > r_{i,t} L_{i,t} + \phi r_{i,t} L_{i,t-1}. \tag{11}$$

Formula (11) can be simplified as follows:

$$m > \frac{r_{i,t}}{\rho}, \tag{12}$$

$r_{i,t}$ is different between enterprises. Therefore, as long as $m > r_{\max}/\rho$ is used, the larger the marginal cost price m is, the more the profits the enterprise will make and the better its operation will be. Proposition 1 is proved.

As mentioned above, from Proposition 1, assuming that$\delta$is a real number greater than zero, then the marginal cost price m of an enterprise is

$$m = r_{\max}/\rho + \delta, \delta > 0. \tag{13}$$

Assuming that part of the profits is not accumulated ($\tau \pi_{i,t}, 0 < \tau < 1$) for enterprises, the net equity of the enterprise i is accumulated as follows:

$$\begin{cases} E_{i,t} = E_{i,t-1} + (1-\tau)\pi_{i,t}, & \pi_{i,t} > 0, \\ E_{i,t} = E_{i,t-1} + \pi_{i,t}, & \pi_{i,t} \leq 0. \end{cases} \tag{14}$$

2.2. Behavior Model of Banks. According to credit rating in reality, banks tend to learn repeatedly to update credit strategy based on corporate loan repayments and their own assets and liabilities. So the mechanism for banks' behavior is divided into three stages.

The first stage is to update the level of credit supply. The bank entity provides loans ($L_{z,t}$) through its own equity ($E_{z,t}$) and deposits ($D_{z,t}$), and the bank entity has a balance sheet of $L_{z,t} = D_{z,t} + E_{z,t}$, $z = 1, \ldots, N$, ($N = 50$). Similarly, the bank uses the learning algorithm to select $\eta_{z,t} \in G$ to establish the level of credit supply. The bank's potential credit supply level is reduced by the total amount of loans outstanding to the firm i, as shown in the following equation:

$$L^s_{z,t} = \frac{E_{z,t}}{\eta_{z,t}} - \sum_{I_{z,t-1}} \phi L_{i,z,t-1}. \tag{15}$$

For firms, a riskier leverage strategy corresponds to a lower level of $\eta_{i,t}$. The smaller $\eta_{i,t}$ is, the more loans that banks need to provide, which indirectly makes them more dependent on external funds. Thus, the lower $\eta_{i,t}$ increases the leverage of the bank, increasing the risk of the bank entity.

The second stage is to update the marginal revenue of the banking entity. The marginal revenue consists of the sum of the interest on the borrower's loan for two periods, the bad debt of the associated enterprise in bankruptcy for two periods ($B\ D$), interest payments on deposits, dividend payments, and fixed costs (F_b). Therefore, the marginal revenue of the banking entity is

$$\begin{aligned} \pi_{z,t} = {} & \sum_{I_{z,t-1}} r_{i,z,t-1} L_{i,z,t-1} + \sum_{I_{z,t}} r_{i,z,t} L_{i,z,t} - BD_{t-1} \\ & - BD_t - r\left(E_{z,t} + D_{z,t}\right) - F_b. \end{aligned} \tag{16}$$

The third stage is to update the net value of the bank. Assuming that part of the profits is not accumulated ($\tau\pi_{z,t}, 0 < \tau < 1$), the net value of banks is accumulated according to the following formula:

$$\begin{cases} E_{z,t} = E_{z,t-1} + (1-\tau)\pi_{z,t}, & \pi_{z,t} > 0, \\ E_{z,t} = E_{z,t-1} + \pi_{z,t}, & \pi_{z,t} \leq 0. \end{cases} \tag{17}$$

2.3. Bank-Enterprise Credit Matching Mechanism. Firms and banks determine their respective loan demand and supply at the beginning of the period. On the one hand, each firm can borrow from different banks until its own loan demand is met. On the other hand, each bank lends to firms with demand until the supply of loans is exhausted.

Because banks can reject loan applications from firms considered too risky, the probability (p_R) of accepting a loan demand for firm i is related to the firm's current choice of leverage strategy, namely:

$$p_R = \frac{1}{e^{\xi\left(1-\eta_{i,t}\right)}}, \tag{18}$$

where ξ is a constant.

Proposition 2. *The higher the target leverage ratio a firm chooses, the lower the probability that the firm's loan demand will be accepted by the bank.*

Proof. Formula (18) derivates the leverage strategy of the enterprise as follows:

$$\frac{dp_R}{d\eta} = \frac{\xi}{e^{\xi(1-\eta)}}. \tag{19}$$

From equation (19), we can know that $dp_R/d\eta > 0$. Therefore, the probability that the enterprise loan is accepted by the bank is an increasing function of the enterprise's choice of strategy.

According to $\beta_{i,t} = 1/\eta_{i,t} - 1$, leverage strategy and leverage ratio are inverse functions of each other. Therefore, the higher the corporate target leverage ratio, the lower the probability that the corporate loan demand will be accepted by the bank. Proposition 3 is proved. □

Proposition 3. *This shows the sensitivity of banks to corporate leverage. In addition to the requirement for banks to hold deposit reserves under Basel III, setting a maximum corporate leverage ratio acceptable to banks can prevent the spread of systemic risk in banks and enterprises.*

2.4. Bank and Enterprise Strategy Selection. Banks and firms choose the strategies ($\eta_{z,t}$ and $\eta_{i,t}$) to determine their target leverage levels at the beginning of the period. The strategies $\eta_{z,t}$ and $\eta_{i,t}$ are selected in a finite countable set G. The selection mechanism is a simple generalization of the learning algorithm of Tesfatsion [22]. At the beginning of the period, banks and firms measure the effectiveness of each leverage strategy based on the profits of the previous period, namely:

$$q\left(\eta_s\right)_{i,t} = (1-\chi) q\left(\eta_s\right)_{i,t-1} + \pi_{i,s,t-1}, \tag{20}$$

where $\eta_s = (\eta_{z,t}, \eta_{i,t})$. Banks and firms evaluate each leverage strategy against $q(\eta_s)_{i,t}$ and update it at the beginning of the period when the strategy is selected. The parameter χ value is chosen to limit the impact of past value of strategy effectiveness to allow agents to rapidly adapt to the changing conditions of the economic system, $0 < \chi < 1$. Therefore, the higher the profit associated with a strategy, the higher the effectiveness of that strategy and the higher the probability of choosing that strategy. The effectiveness of the strategy choice at the beginning of the period is reduced by $\zeta(0 < \zeta < 1)$, namely: $q(\eta_s)_{i,t-1} = (1-\zeta) q(\eta_s)_{i,t-1}$.

Since business loans are divided into two periods, companies must consider their own past debts. If a company's business mismanagement in the previous period causes its own net asset value to decline and it appears that its own leverage level is higher than the specified maximum leverage level, then the company will not apply for a loan and the bank will not provide credit to the company. Thus, once the effectiveness of each strategy is evaluated, each strategy corresponds to a probability value that determines how likely the subject is to choose that strategy. The probability of each strategy (η_s) is given by $p(\eta_s)_{i,t}$:

$$X_{i,s,t} = \left(\frac{q(\eta_s)_{i,t}}{c}\right)^{\nu}, \quad p(\eta_s)_{i,t} = \frac{e^{X_{i,s,t}}}{\sum_{G_a} e^{X_{a,t}}}, \tag{21}$$

where $X_{i,s,t}$ is the relative strength of the firm's i selection strategy s in period t, depending on the effectiveness of the strategy, and c and υ are model parameters. The index value of each strategy strength $(X_{i,s,t})$ is used to calculate its probability of being selected for that strategy $p(\eta_s)_{i,t}$.

However, in the basic learning mechanism, it is not considered that different strategies generate different profits in each period, and it may bring positive or negative returns. Therefore, using the improved reinforcement learning algorithm of Ermanno Catullo et al. [17], subjects are assumed to correct their strategy choices according to the standard deviation of profits (σ_π) over multiple periods for a given strategy. The standard deviation of profit is calculated based on the profit value of each strategy for the most recent multiple periods. That is, strategy effectiveness $\nu(\eta_s)_{i,t}$ is updated using profit fluctuations.

$$\nu(\eta_s)_{i,t} = (1-\chi)\nu(\eta_s)_{i,t-1} + \sigma_\pi. \tag{22}$$

From the above $\nu(\eta_s)_{i,t-1} = (1-\zeta)\nu(\eta_s)_{i,t-1}$, the probability of each strategy being selected is

$$X_{i,s,t} = \left(\frac{q(\eta_s)_{i,t}}{c + \omega\nu(\eta_s)_{i,t}}\right)^{\upsilon}, \tag{23}$$

$$p_\sigma(\eta_s)_{i,t} = \frac{e^{X_{i,s,t}}}{\sum_{G_a} e^{X_{a,t}}}, \tag{24}$$

where the probability $p_\sigma(\eta_s)$ describes the magnitude of the likelihood of a particular strategy choice. The parameter ω indicates the sensitivity of banks and firms to past market performance. $\omega\nu(\eta_s)_{i,t}$ reduces the probability that strategies with high profit volatility will be selected.

Proposition 4. *The greater the sensitivity of banks and firms to past market performance, the lower the bank failure rate and the lower the default rate of firms.*

Proof:. The first-order derivative of the sensitivity of equation (23) to the past performance of the market is

$$\frac{dX}{d\omega} = -\upsilon\left(\frac{q(\eta_s)}{c + \omega\nu(\eta_s)}\right)^{\upsilon-1} \frac{q(\eta_s)\nu(\eta_s)}{(c + \omega\nu(\eta_s))^2}. \tag{25}$$

As shown in equation (25), the intensity of strategy selection decreases as the sensitivity of banks and firms to past market performance ω rises. That is, in the reinforcement learning algorithm mechanism, the probability of each policy being selected will be fairer. Combined with the simulation results in Figure 1, as the sensitivity of banks and firms to past market performance rises, the bank failure rate and firm default rate both decrease, and the bank failure rate and firm default rate decrease. Proposition 4 is proved. □

3. Computational Simulation of Credit Risk Contagion in Banking Enterprises

Given the complexity of the model in this paper and the unavailability of real data, numerical computational simulation analysis with the help of MATLAB becomes relatively the most effective test method. According to the related research results of Riccetti et al. [14], Catullo et al. [17], and other scholars, the number of bank nodes in the banking system is assumed to be 50 and the number of enterprise nodes is 500, and the simulation is simulated for 500 cycles. At the beginning of the calculation simulation, the net value of each firm is set to 1 and the net value of each bank is set to 3. When the banking firm becomes insolvent, it will be replaced by a new banking firm, with the new bank and the firm's initial ownership interest being random numbers in the interval (0,3) and (0,1), respectively. Other important parameters are set as shown in Table 1. Drawing on the parameters in related work by Catullo et al. [17], in this paper we set the set of strategies to $G = \{1.0, 1/1.5, 1/2, 1/2.5, 1/3, 1/3.5, 1/4, 1/4.5, 1/5, 1/5.5, 1/6, 1/6.5, 1/7, 1/7.5, 1/8\}$.

3.1. Emergence Characteristics of Bank-Enterprise System. Based on the parameter values in Table 1, each simulation run was calculated for 500 periods. The first 250 periods of each simulation are omitted because the model needs to be initialized. Meanwhile, for the reason of stability of simulation results, all the results of this paper are the average of 100 Monte Carlo simulations of the corresponding variables. Figure 2 illustrates the time series evolution of total firm output. As can be seen from Figure 1, the fluctuations in total firm output are irregular, with amplitudes and periods varying considerably from subcycle to subcycle. This is due to the fact that, in a complex adaptive system, each firm's decisions and its own assets vary from period to period, resulting in different total outputs. Figure 3 illustrates the time series evolution of the number of credits in the banking and corporate credit network. As can be seen from Figure 3, the overall fluctuations in the volume of credit are largely consistent with the overall fluctuations in total firm output. From equation (1), it can be seen that the firm's own assets and the amount of credit determine the firm's output.

Combining Figures 2 and 3, we can obtain that, during the expansionary phase of the economy, banks provide more credit and firms' output increases, but they also face the risk of high debt crisis. The high debt crisis backfired on banks' earnings; as the amount of credit provided by banks became less, the total output of firms decreased, causing the economy recession.

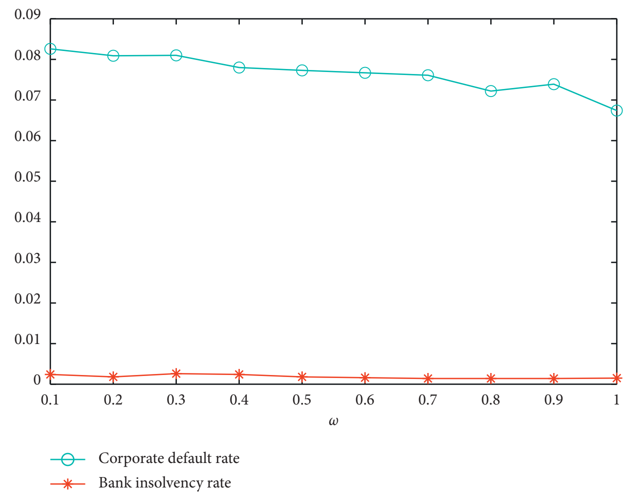

Figure 1: Evolutionary characteristics of corporate default rate and bank insolvency rate with sensitivity.

Table 1: Model baseline parameter values.

Parameter	Parameter meaning	Base case
$i = 1, \ldots, M$	Number of firm agents	500
$z = 1, \ldots, N$	Number of bank agents	50
$t = 1, \ldots, T$	Number of model periods	500
E_i	Initial net value of the firm	1
E_z	Initial net value of the bank	3
ρ	Firm capital production factor	0.1
ϕ	Firm loan repayment ratio	0.5
r	Base rate	0.1
ψ_f	Risk appetite factor of firm agents	$U \sim (0.9, 1.1)$
α	Sensitivity of banks to corporate target leverage	1/300
σ	The variance	1
δ	Real numbers	0.001
τ	Profit share that is not accumulated	0.4
F	Fixed costs	0.01
ξ	Constants	0.05
χ	Validity of past values of strategies	0.2
ζ	The "forgetting" parameter	0.05
c	The model of constant	0.01
υ	The model of constant	1

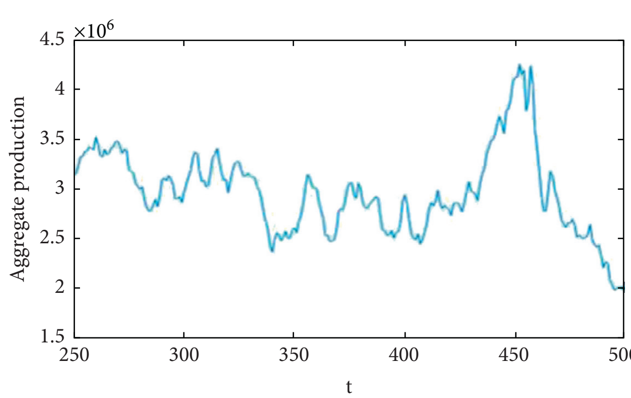

Figure 2: Time series evolution of aggregate production.

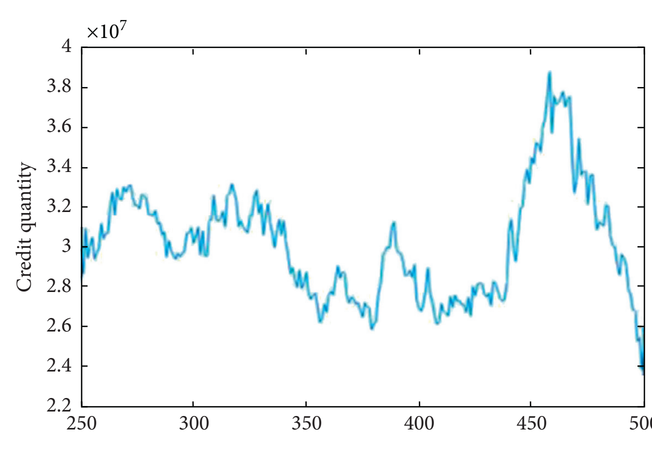

Figure 3: Time series evolution of credit quantity.

Figure 4 illustrates the strong heterogeneity of the 500 firms as the simulation progresses under the same initial conditions and the power-law distribution of firm asset size. This is due to the fact that, in each period, each firm is subject to market uncertainties resulting in different prices for its products, and therefore each firm has a different rate of net asset accumulation.

Figure 5 shows that the bank node degree distribution has a double power-law characteristic. A few banks have a node degree greater than 30, which indicates a core-edge structure of the banking enterprise credit network. This also means that only a few bank nodes in the bank-enterprise credit network are at the center of the network, have a high level of activity, and form an intensive loan association with the enterprise. In general, financially sound banks are better able to provide credit and thus increase their market share, so they can attract more connections. As a result, both the corporate and banking sectors become polarized and the degree distribution becomes asymmetric. This polarization increases the vulnerability of the banking and corporate credit network to shocks, due to the fact that defaults by highly connected institutions, even if relatively rare events, can create risk contagion between banks and enterprises. And the possibility of this occurrence depends on the network structure.

As can be seen in Figure 6, bad debts are always present in the banking and corporate credit network. The bankruptcy of a single firm has a significant impact on the net asset value of the banks, potentially creating the tide of bankruptcy. The scale depends on the amount of bad debts. At the same time, the banks and enterprises network are weak robust and the banks have absorbed those bad debts, so there will not be a massive bankruptcy. In addition, the distribution of the growth rate of total firm output is far from Gaussian and is characterized by positive and negative fluctuations around zero (Figure 7).

Based on the above calculation and analysis, this paper further analyzes the credit matching mechanism between banks and enterprises. As can be seen from Figure 8, the higher the target leverage of the firm, the higher the interest rate on the loan and the lower the probability that the firm's loan demand will be accepted by the bank. In other words, highly leveraged companies face higher interest rates on loans, more debt, and more difficult loan financing, with some potential for bankruptcy. Therefore, real-time regulation of highly leveraged companies is essential.

The above computational simulations show how the presence of uncertainties affect the financial position of firms and banks. Financial vulnerability can amplify the impact of these uncertainties in the banking and corporate credit network.

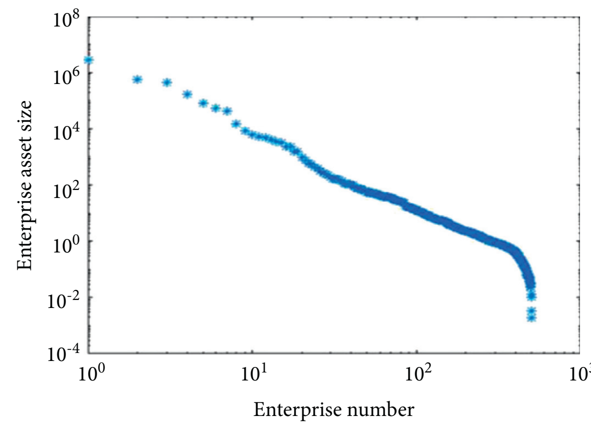

Figure 4: Asset size distribution of firms (double logarithmic coordinates).

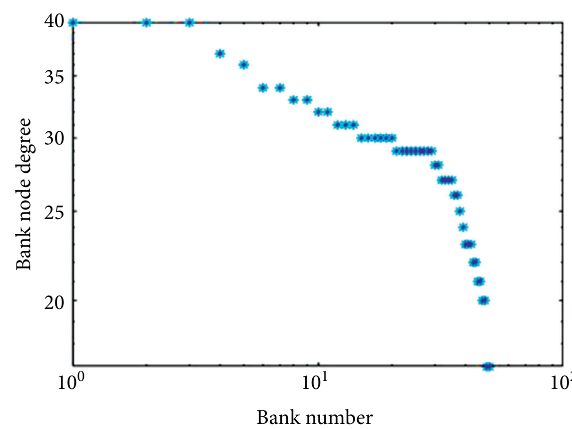

Figure 5: Degree distribution of bank nodes (double logarithmic coordinates).

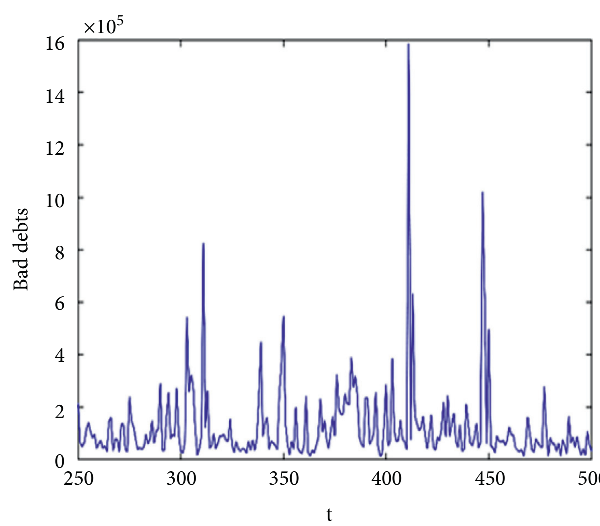

Figure 6: Time series evolution of the number of bad debts.

3.2. Impact of Uncertainty Shocks on Risk Contagion between Banks and Enterprises

3.2.1. Impact of Shocks to Asset-Largest Banks on Risk Contagion between Banks and Enterprises. With the development of financial innovation and economic globalization, an increasing number of large-scale financial institutions have emerged. Its impact will inevitably bring systemic risk to the entire banking system and even the

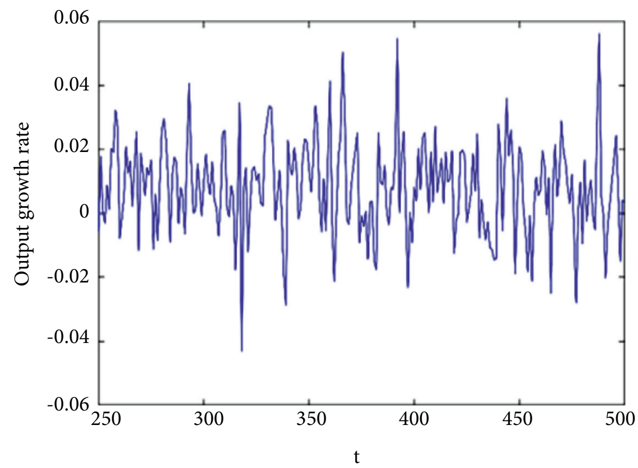

Figure 7: Time series evolution of output growth rate.

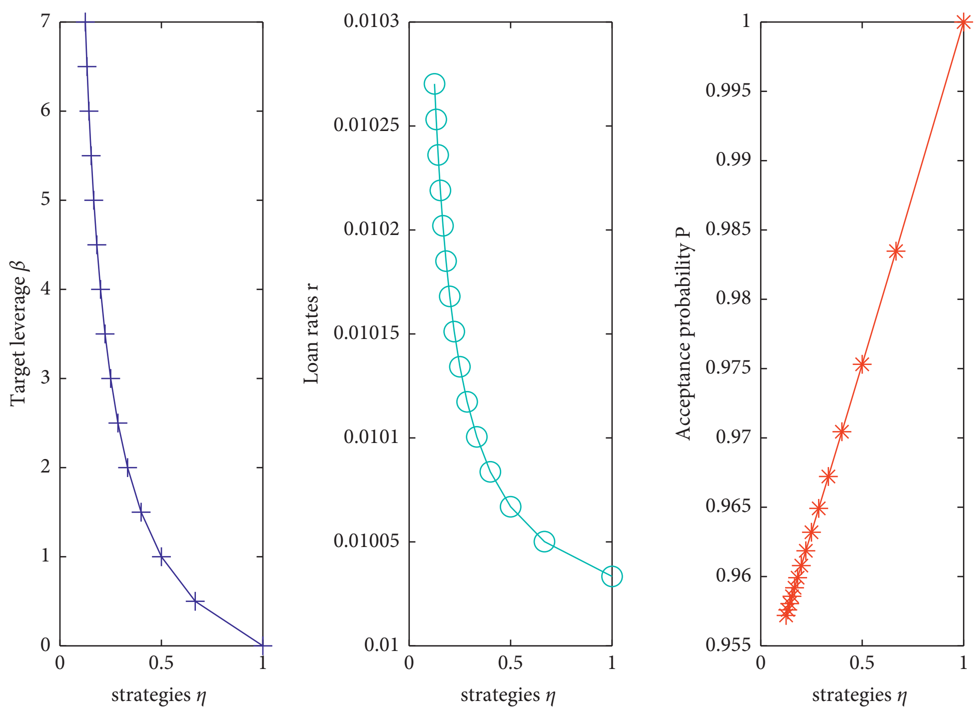

Figure 8: Evolutionary characteristics of target leverage, loan interest, and acceptance probability with strategy.

entire economic system [23]. Since the subprime crisis in 2007, regulators have adopted various policies to ensure the safety and stability of large financial institutions. Therefore, this section analyzes the impact of external risk shocks to the largest asset banks on the entire banking system (as shown in Figure 9). It is assumed that the external risk shock of the bank with the largest assets is, respectively, implemented in $t = 250$, $t = 300$, $t = 350$, $t = 400$, $t = 450$, and $t = 500$ periods. Figure 9 illustrates the evolutionary path of the corporate default rate, bank insolvency rate, and the number of bad loans following external shocks to asset-max banks in each period, where the solid asterisk line represents the evolutionary characteristics of the corporate default rate, bank insolvency rate, and the number of bank bad loans after a shock to the largest asset banks. The solid circle line represents the evolutionary characteristics of the default rate of banking firms and the number of bad loans of banks before the shock. As can be seen in Figure 9, the external shocks to the most capitalized banks exacerbate the degree of risk contagion among banking firms. Moreover, for the whole bank and enterprise network, the external shock of the bank with the largest assets leads to a significant increase in the number of bad debts in each period, which intensifies the systemic risk of banks and enterprises. Based on this, the reality is that regulators should strengthen the supervision of banks with large assets in order to prevent the contagion of banking risks caused by their bankruptcy.

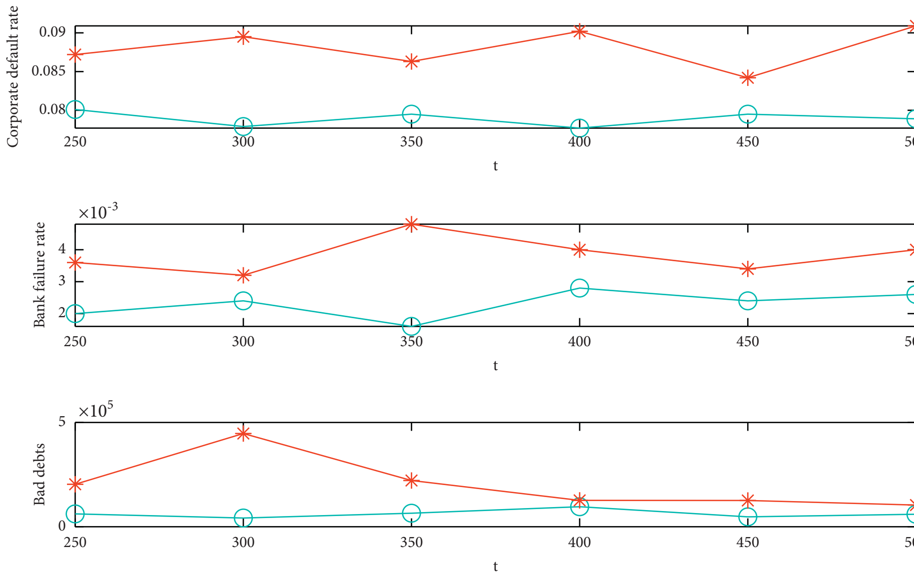

Figure 9: Evolution of risk contagion between banks and enterprises due to shocks to the largest banking entities in terms of assets.

3.2.2. Impact of Shocks on Interbank Risk Contagion for the Largest Banks in the Entry Degree. In fact, the regulation and protection of "too big to fail" banks are not enough to eliminate the risk of contagion from banking enterprises. Battiston et al. [24] point out that when regulating "too big to fail" institutions, "too connected to fail" institutions should also be included. Miranda and Tabak [25] show that the largest degree of entry, the default of financial institutions that borrow from a large number of other economic agents, will trigger large-scale negative effects. Catullo et al. [17] emphasize the importance of shifting policy attention from "too big to fail" to "too relevant to fail." Based on previous studies, this section will focus on the risk contagion between banks and firms due to shocks to the largest banks in the entry degree. It is assumed that the external risk shock of the bank with the largest exposure is, respectively, implemented in $t = 250$, $t = 300$, $t = 350$, $t = 400$, $t = 450$, and $t = 500$ periods. Figure 10 illustrates the evolution of the corporate default rate, bank insolvency rate, and the number of bad loans following external shocks to the largest banking entities in each period of entry, where the solid asterisk line represents the evolutionary path of the corresponding variable after a shock to the bank with the largest entry degree. The solid circle line represents the evolutionary path of each variable before the shock. From Figure 10, it can be seen that the external shock to the largest bank in the entry degree leads to a significantly higher bank insolvency rate per period than the bank insolvency rate per period before the shock. Firms' default rate per period is relatively higher than the preshock firm default rate per period. But compared with before the shock, the number of bad debts has not significantly increased. As a result, the impact on the largest banks has exacerbated the risk contagion between banks and enterprises. It also reaffirms that it is not enough to regulate "too big to fail" financial institutions without going bankrupt. Attention should also be shifted to the regulation of "too connected to fail" financial institutions. Financial institutions with large assets and large entry degrees should be monitored in a focused manner to prevent the domino effect resulting from their bankruptcy.

3.2.3. Impact of Consumer Market Shocks on Risk Contagion between Banks and Enterprises. This section will focus on exploring the impact of consumer market shocks on risk contagion between banks and firms. Assume that consumer market shocks are implemented in periods $t = 250$, $t = 300$, $t = 350$, $t = 400$, $t = 450$, and $t = 500$. Figure 11 illustrates the evolutionary path of corporate default rates, bank insolvency rates, and the number of bad bank loans following shocks to consumer markets in each period, where the solid asterisk line represents the evolutionary path of the corresponding variable after a shock to the consumer market. The solid circle line represents the evolutionary path of each variable before the shock. As can be seen from Figure 11, the default rate of firms per period is significantly higher than the default rate of firms per period before the shock, which increases exponentially. However, the bank failure rate is slightly higher than the preshock bank failure rate. For the whole network of banks and enterprises, the impact of the consumer market leads to a significant increase in the number of bad debts in each period, which intensifies the systemic risk of banks and enterprises. That is, consumer market shocks have severely exacerbated corporate default bankruptcies. Significant increase in the number of bad debts thus affects banks' earnings. However, most of the bad loans were absorbed by the banks due to the accumulation of precapitalization of the banks, without creating a large-scale bank failure. Therefore, banks act as financial stabilizers in the banking and enterprises credit network. This is consistent with the findings of Braun and Larrain [26], Raddatz [27], and Ashraf [28].

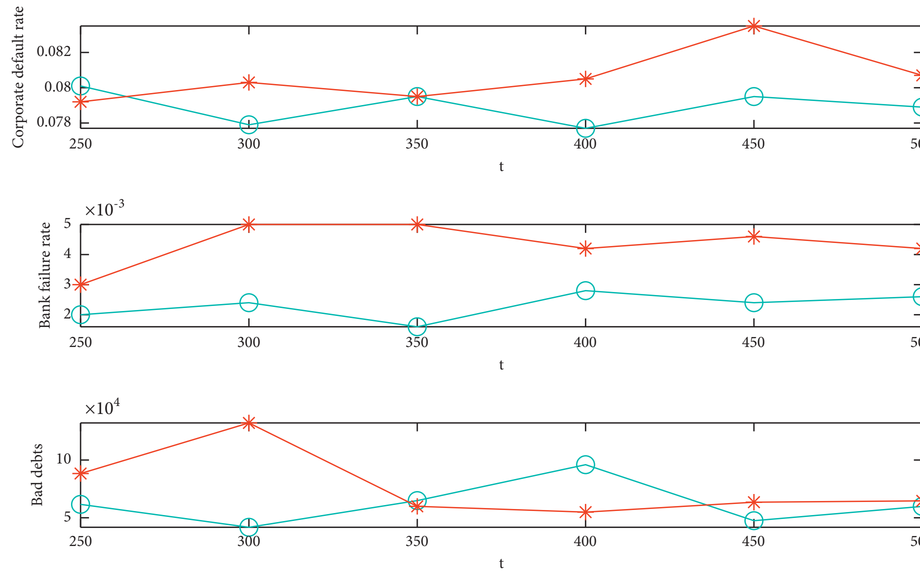

Figure 10: Evolution of risk contagion between the largest banks in terms of entry shocks and banking firms.

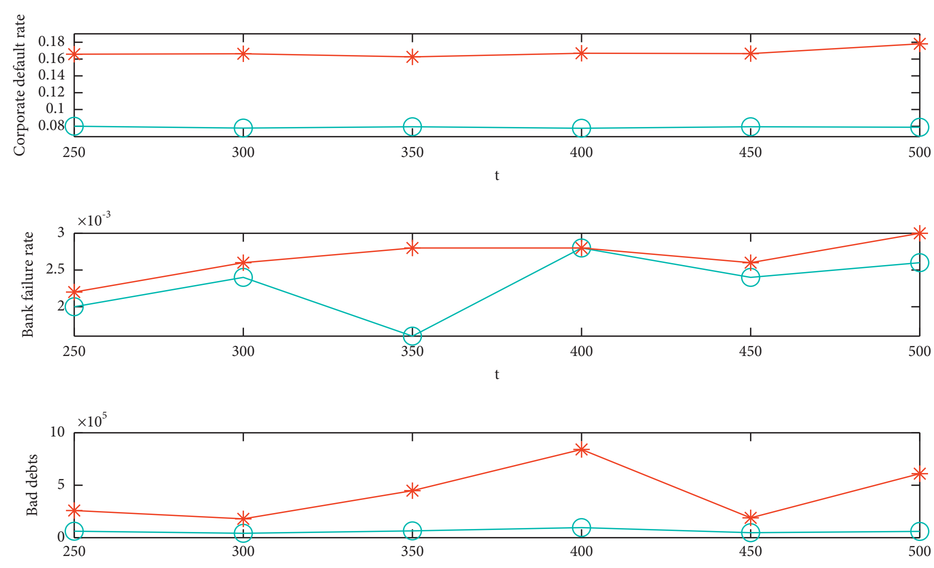

Figure 11: Consumer market shocks and the evolution of risk contagion between banks and enterprises.

3.2.4. Impact of Shocks to the Largest Asset Companies on Risk Contagion between Banks and Enterprises. Since the subprime crisis in 2007, regulators have focused on the regulation of "too big to fail" financial institutions. But for the corporate body "too big to fail" is also a regulatory focus. Therefore, this paper analyzes the impact of external risk shocks to the largest asset companies on the entire banking network through computer simulation (as shown in Figure 12). It is assumed that the external risk shock of the enterprise with the largest assets is, respectively, implemented in $t = 250$, $t = 300$, $t = 350$, $t = 400$, $t = 450$, and $t = 500$ periods. Figure 12 illustrates the evolutionary path of firm default rates, bank insolvency rates, and the number of bad debts following external shocks to asset-max firms in each period, where the solid asterisk line represents the evolutionary path of the corresponding variable after a shock to the bank with the largest assets. The solid circle line represents the evolutionary path of each variable before the shock. From Figure 12, it can be seen that the default rate of firms per period is slightly higher than the default rate of firms per period before the shock. And bank insolvency rates are significantly higher than preshock bank insolvency rates. At the same time, for the whole network of banks and enterprises, the external shock of enterprises with the largest assets leads to a significant increase in the number of bad debts in each period, which intensifies the systemic risk of banks and enterprises. This is due to the default bankruptcy of the largest asset companies, which has led to a spike in the number of bad debts due to the size of their assets, causing banks to be unable to fully absorb

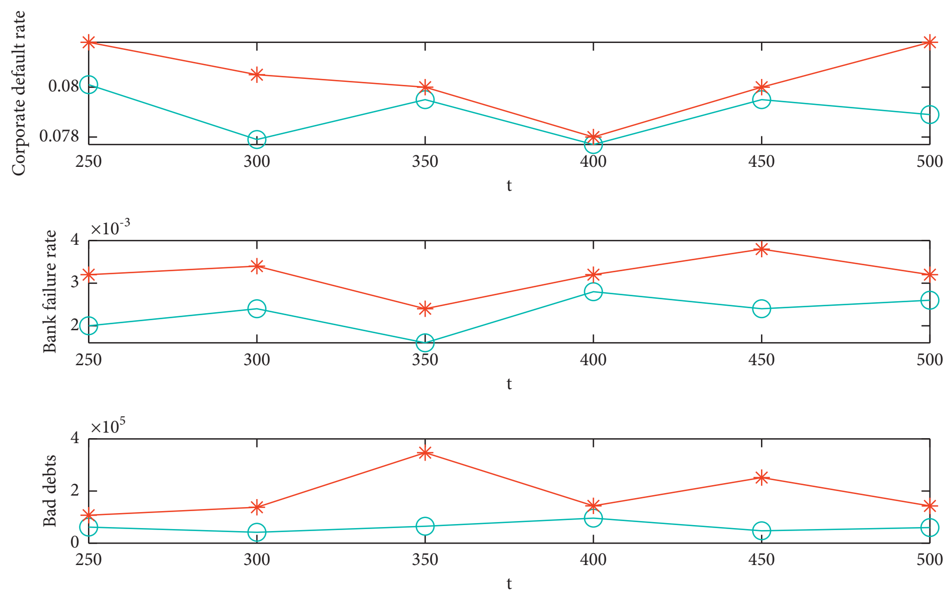

Figure 12: Shocks to the largest asset firms and the evolution of risk contagion between banks and enterprises.

the negative shock, making bank failures significantly higher. As a result, external shocks to the largest capital firms exacerbate the degree of risk contagion between banks and firms. This means that the regulator should do the supervision of financial institutions that are "too big to fail" and enterprises that are "too big to fail" to prevent the contagion of banking risks caused by their bankruptcy.

4. Conclusion

Considering the heterogeneity of interaction behaviors in the credit matching between banks and enterprises, in this paper, we construct an endogenous credit matching association network model that includes firms and banks. It also introduces production, decision-making, and learning mechanisms to portray the behavior and interaction rules of the two types of economic agents. The network evolution and its influencing factors of bank and enterprise credit risk contagion are explored. Based on the above study, we further consider the impact of various types of shocks on the evolution of risk contagion between banks and enterprises and conduct computational simulation analysis to substantially expand the existing study. The results of the study showed that the macroeconomic business cycle of the bank and enterprise system is the result of the interaction of bank and enterprise subjects under complicated financial conditions. The behavior rules, learning mechanism, and interaction of banks and firms lead to the heterogeneity of firms and their asset scale obeys the power-law distribution. The bank node degree distribution has a double power-law feature. The risk contagion between banks and enterprises is exacerbated by shocks to the largest banks with the largest assets, shocks to the largest banks with the largest revenues, shocks to the consumer market, and shocks to the largest enterprises with the largest assets. Banks play the role of financial stabilizers.

Based on the results of the study, the practical implications of this paper's research are that, in actual supervision, one cannot focus only on financial institutions with larger assets. Shocks to financial institutions with greater access, sharp fluctuations in the consumer market, and shocks to enterprises with larger assets can still bring about nonnegligible chain risks, which can spread through the banking and enterprises credit network. Therefore, in the daily supervision, a full range of supervisory policies should be formulated to effectively prevent the negative chain reaction that various shocks may bring to the entire banking system.

Data Availability

The method in this article is computer mathematical simulation. Numerical simulation analysis is the most effective way to test real-time dynamic data without a large number of empirical validations. The authors consider the heterogeneity of behavioral rules, learning rules, and interaction rules and construct a bank-firm credit matching network model based on ABM (agent-based model) model and reinforcement learning algorithm to analyze the interaction behavior and credit risk network contagion mechanism by using Matlab2016b software. This paper does not have the data that can be obtained because they directly use the plot function of Matlab2016b software to make the images.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Differences in the Values of the Senior Management Team, Antirisk Ability, and Innovation Performance by the Data-Driven Approach: Evidence from 841 Listed Companies in China

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This study explores the mechanism of corporate antirisk capabilities on corporate innovation performance by using a data-driven method. The data are from China's Shanghai and Shenzhen A-share listed companies from 2013 to 2018. The value differences between the senior management team's ability to resist risk and innovation performance are discussed. The results show that the antirisk ability of an enterprise will improve the efficiency of the utilization of enterprise resources and promote the formation of competitive advantage so that enterprises have a more stable internal and external environment, so as to improve the innovation performance of the enterprise. Risk capability improves corporate innovation performance; from the perspective of the value difference of the senior management team, a smaller value difference has a more significant effect on enhancing the enterprise's antirisk ability and improving corporate innovation performance than a larger value difference. While improving their own antirisk capabilities, companies should further promote and improve the consistency of senior management team values, thereby improving corporate innovation performance.

1. Introduction

Since the 19th National Congress of the Communist Party of China, the Party Central Committee has formulated and issued a series of policies and measures to accelerate my country's economic transformation and upgrading [1]. In particular, on March 30, 2020, the Central Committee of the Communist Party of China and the State Council issued the "Opinions on Building a More Complete System and Mechanism for Factor Market Allocation," which clearly stated that the decisive role of the market in resource allocation should be fully utilized and the reform of factor market allocation should be deepened [2]. To promote the independent and orderly flow of factors, improve the efficiency of factor allocation, and further stimulate the creativity of the whole society and the vitality of the market, it is necessary to analyze the influent factors for enterprise innovation. Enterprise innovation performance is a comprehensive evaluation of the level of technological innovation of an enterprise [3], which embodies the effectiveness of the enterprise's innovation activities [4]. Examining and understanding the problems existing in the process of enterprise innovation and further mastering the relevant theories and methods of enterprise innovation performance evaluation will not only help the government to improve the enterprise innovation promotion policy but also help innovative enterprises conduct self-examination and self-correction and continue to improve [5].

Existing research believes that the main body of enterprise innovation is "entrepreneur," and the core function of entrepreneur is innovation [6]. Different entrepreneurs have different strategic choices for corporate innovation due to differences in knowledge, experience, abilities, values, and concepts [7]. Therefore, the consistency of values of the corporate senior management team is an important factor affecting corporate innovation performance. When a company is faced with major strategic innovation decisions, the more consistent values of the corporate senior management team, often determine the efficiency and direction of the innovation strategy selection, thereby affecting the company's development. The achievement of innovation performance has a significant impact [8]. In addition, under the common influence of many internal and external environments of the enterprise, through a series of decision-making behaviors of the enterprise's senior management team, the enterprise's risk-bearing ability is gradually formed and strengthened in the daily business activities of the enterprise [9]. On the one hand, the difference in values of corporate executive teams and their ability to resist risks are the two most basic internal and external factors that affect corporate operations [10]; on the other hand, when corporate ownership and management rights are separated, the conflict of interest shown by differences in the values of the corporate senior management team may lead to different business results in dealing with external market risks. The specific manifestation is the company's strong antirisk ability and insufficient antirisk ability [11]. The different antirisk abilities shown by companies will affect the company's innovation decision-making, thereby affecting the company's innovation performance [12]. According to the above literature, differences in the values of the senior management team have an important impact on the innovation behavior of the enterprise. The antirisk ability of the enterprise is the result of a series of decision-making behaviors of enterprise senior management, and the antirisk ability of the enterprise will eventually affect the innovation performance of the enterprise.

In recent years, with the continuous strengthening of the support of my country's corporate innovation policy, the impact of corporate executive team characteristics on corporate innovation has attracted great attention from the academic community [13–16]. These studies mainly take corporate innovation performance as the research object. On the basis of measuring the innovation performance of enterprises, the relationship between the educational background, professional background, demographic characteristics, and social capital of corporate executives and the relationship between corporate innovation performances have been actively discussed. However, the above-mentioned research mainly focuses on the influence of external characteristic factors of the senior management team on corporate innovation behavior or performance, ignoring the role of internal characteristic factors such as values and behavioral cognition, and does not reveal deeply the differences in the values of the senior management team. The relationship and influence mechanism with enterprise innovation performance have been discussed.

At present, relevant research on the ability of senior management team to bear corporate risks has gradually emerged. Scholars have studied the impact of the characteristics of the senior management team on the corporate risk-taking ability [17, 18] and the characteristics of the senior management team and corporate innovation performance [19]. A lot of research studies have been carried out from different perspectives. It is particularly noteworthy that when enterprises take risks, they will have management effects. Managers are the direct decision-making subjects of enterprise investment behavior, which is significantly influenced by individual characteristics. Therefore, the heterogeneity of individual executives and the executive team will have a certain impact on an enterprise's ability to resist risks. However, there is still a lack of theoretical explanation and strict measurement test on how the difference in values of senior management team affects the enterprise's antirisk ability. Hao and Sun [20] have empirically examined the impact of the characteristics of senior management and their risk appetite on corporate innovation performance, but this research regards the characteristics of the senior management team and their risk appetite as a closely connected whole and does not consider the possible influence relationship between them. Scholars mainly use empirical methods to test the impact of enterprise antirisk ability on enterprise innovation performance. For example, Liu and Liang [21] proved that strong risk-bearing ability helps to achieve innovation performance and Bi and Li [22] proved that improving enterprise risk-taking ability in the market competition environment promotes enterprise innovation performance. These previous publications have laid a foundation for this article to carry out related research. However, how the value difference of top management team affects the risk resistance ability of the enterprise and the enterprise's innovation performance and what effect is still worthy of further study are questions. More importantly, the current research does not bring the differences between the values of the senior management team and the enterprise's ability to resist risks into a unified analysis framework to comprehensively examine its impact on enterprise innovation performance. Therefore, this paper is to reveal the coordination and performance of enterprise innovation more comprehensively.

In view of this, from the perspectives of the differences between the values of the senior management team and the enterprise's ability to resist risks, it analyzes the influencing factors behind the achievement of corporate technological innovation performance and explores the impact of the enterprise's antirisk ability on corporate innovation from two different dimensions: the smaller value difference and the higher value difference. The adjustment effect of the difference between performance mechanism and the senior management team will help us correctly understand the internal connection between the values of the corporate senior management team and innovation performance and provide certain theoretical reference and practical guidance for the improvement of corporate innovation performance.

The rest of this paper is organized as follows. Section 2 presents literature review and research hypothesis. Section 3 is the research and design. Section 4 proposes the empirical results and discussion. Section 5 concludes.

2. Literature Review and Research Hypothesis

2.1. Enterprise's Antirisk Ability and Innovation Performance. The theory of corporate behavior believes that organizational redundancy is the basic driving factor of corporate behavior, and it is necessary to incorporate it into the framework of the research on the relationship between corporate risk-taking and performance. When domestic and foreign scholars study the impact of corporate risk-taking ability on innovation performance, the representative view is that corporate risk-taking ability affects the efficiency of corporate capital allocation. John et al. [23] and Yu et al. [24] believe that risk-taking means more choices of high-risk and high-return projects, indicating that managers can more fully identify and utilize investment opportunities and can significantly improve the capital allocation efficiency of the enterprise. Li et al. [25] believe that the venture capital department is an external Research and Development (hereinafter referred to as "R&D") organization of a company, and performance is an important driving force for corporate venture capital. When the innovation performance of a company is close to social expectations, the company will not stop venture capital. The research of Wu and Yang [1] shows that when new companies need specialized complementary assets, compared with new companies that need general complementary assets, the funding of corporate venture capital will be more conducive to the performance of new companies. Zhang et al. [26] also pointed out that the participation of venture capital can reduce the uncertainty of technological innovation, increase the risk appetite of technology enterprises, and thus stimulate technological innovation performance. Yu et al. [27] found that there is a significant positive correlation between the level of risk-taking and corporate performance. Properly improving the risk-taking level of enterprise can promote the improvement of enterprise performance.

However, some scholars hold the opposite view. From the perspective of hidden costs of risk, we believe that it is the higher risk-taking of enterprises and the greater fluctuations in performance that lead to the conservative strategies of stakeholders and the decline in business performance. We believe that companies with good business performance are willing to take small risks, and they are unwilling to take risks to invest too much in R&D activities, and it is difficult for them to achieve significant improvement in innovation performance. There is a nonlinear relationship between corporate risk-taking and innovation performance. The level of enterprise risk-taking has a reasonable range and does not exceed the optimal level of risk-taking. Appropriately increasing enterprise risk-taking can promote enterprise innovation performance. He et al. [28] believe that entrepreneurs' overconfidence can promote corporate risk-taking. This effect is limited to a modest range of corporate risk-taking. With the increase in entrepreneur's self-confidence, the enterprise's risk-taking is beyond reasonable scope. Not only does it fail to bring innovation performance to the enterprise, it may even lead to bankruptcy. Based on this, the following competitive research hypotheses are proposed.

Hypothesis 1a: assuming that other conditions remain unchanged, the more risk-resistant the enterprise is, the better the innovation performance

Hypothesis 1b: assuming that other conditions remain the same, the stronger the enterprise's ability to resist risk, the worse the innovation performance

2.2. The Values of the Senior Management Team and the Company's Antirisk Ability. In the 1980s, the Upper Echelons Theory proposed by Hambrick and Mason believed that the economic and political environment of a manager's birth affects his or her values, cognitive risks, and behavioral decisions. For enterprises, the formulation and implementation process of strategic management is not an easy task. First, senior management personnel are required to have high professional quality and other qualities and abilities. The direction of strategic decision-making will also be affected by their entrepreneurs and senior executives and the influence of managers' cultural level and values [29]. At the same time, affected by the response of stakeholders as well as the corporate value and image perceived by the corporate executive team, the executive team will make strategic decisions based on their own experience, values, and personality characteristics, and the environment in which the company is located [30]. On the one hand, from the perspective of the personal characteristics of senior management team members, the background characteristics of corporate executives, including gender, age, education, service years, and professional experience have an impact on the decision-making behavior of senior management team and team organization process and affect the company's strategic choices and corporate performance [31]; on the other hand, from the perspective of the overall structural characteristics of the executive team, the composition of the corporate executive team generally consists of about ten people. There are inevitably differences in power and attitudes towards risk, and each has its own characteristics, which affects the decision-making process of the senior management team and the strategic choice of the company [32]. In fact, although the cognitive environment is the same, the cognitive abilities of corporate executives are affected by their cognitive willingness, knowledge, technology, information, and other factors, mainly including entrepreneurial attitudes, subjective norms (personal values and knowledge structure), and personal behavior. The difference in values composed of efficacy (personal background and risk meaning), etc., will lead to completely different decisions, behaviors and results [26]. As far as senior managers are concerned, they mainly make business decisions and strategic planning, which will be affected by their own perceptions, risk preferences, experience level, values, professionalism, innovation capabilities, etc. In addition to the impact of flexibility and communication skills, it is directly reflected in the company's ability to resist risks.

Studies have shown that the top managers in the senior management team tend to be different from other managers on the team due to factors such as their own educational background, length of service, and age, leading them to have opinions about cognitive structure, values, and risk awareness. Disagreement may also increase the interactive exchange of diversified information within the team, and this vertical difference will inevitably have an important impact on the company's innovative strategic decision-making, and different strategic choices will have an important impact on the company's ability to resist risks [33]. High-quality corporate executives and qualified employees should establish internal controls and risk values, which will help identify corporate strategy, operations, finance, legal, and other risk information and contribute to the occurrence of risk internal control imbalances within the company. At the same time, there are early warnings and strategies at the first time, so as to effectively enhance the enterprise's market risk-bearing capacity [34]. Ultimately, the psychological characteristics of managers, such as cognitive basis, values, and risk appetite, will affect the organization's strategic choices and company performance and then affect the company's ability to resist risks. Based on this, the following research hypotheses are proposed.

> Hypothesis 2: assuming that other conditions remain the same, the greater the difference in the values of the senior management team is, the more helpful it is for the company to formulate innovation strategies and the stronger the company's ability to resist risks.

2.3. Value Differences and Innovation Performance of the Senior Management Team. Innovation is one of the most important tasks of the corporate executive team. Sun et al. [35] first proposed the theory of high-level echelon, which caused an in-depth study of the relationship between corporate executive team and innovation performance in academia. In the theory of technological innovation, technological innovation needs to be reflected through human behavior, and the senior management team, as the decision maker of corporate strategy, has an important influence on the strategic choices of corporate technology research and development and product innovation. Chen et al. [36] pointed out that although the senior management team is not directly involved in the company's technological innovation, as the highest headquarters of the company, the process of corporate strategic decision-making is inherently creative, and the innovation of the company's management mechanism also mainly comes from the senior management team, creative views, and ideas of members. Zhao et al. [37] showed that the senior management team of innovative enterprises and the management team members of the company's performance innovative enterprises have unique knowledge and skills, broad international vision, and strong learning ability. Only in this way can they have the awareness of innovation and guarantee and the ability to carry out innovation activities smoothly. Xiao et al. [38] proposed that the emergence of corporate innovation behavior is largely determined by the senior management team's awareness of innovative behavior. The stronger the senior management team's awareness of innovation is, the more innovation investment may be, thereby promoting the future of the company's growth and development. The differences in the values of corporate senior management teams have an important impact on strategic change, corporate performance, and whether to use corporate venture capital. In the existing research, scholars basically follow the "consistency assumption" of the values of the senior management team and replace cognition with easily observable demographic characteristics (such as gender, age, education level, professional background, and tenure). Subjective factors such as characteristics and values are used to predict the R&D investment activities and innovation performance of the senior management team. Yu [39] pointed out that once the senior management team with high value consistency truly recognizes the value of the management innovation plan; they decide to implement the plan within the enterprise and personally participate in the plan to coordinate the deployment and allocation of resources. The implementation team led by the senior manager coordinates the work of various departments, reduces the resistance in the implementation process, organizes learning, trains employees, and forms a consistent understanding of the innovation plan, which can more effectively promote the implementation of the enterprise innovation plan, to better achieve "problem solving" and then to a greater extent to promote the improvement of enterprise innovation performance.

As the participants in the company's major decision-making and the director of daily work, the senior executives of the company are the core and soul of the company. Their decision-making behaviors and even their own quality directly affect the long-term development of the company, which is closely related to the company's performance and risk. Therefore, in the research of enterprise risk, it is often discussed from the perspective of the consistency of senior managers' values. Rong et al. [40] believe that Chinese people have always been influenced by Confucianism, the concept of the golden mean is deeply rooted, and the consistent value tendency makes risk aversion behaviors often appear, and executives hope to obtain long-term benefits from prudent investments. In [41], the fulfillment of corporate social responsibility focuses on the judgment standards of corporate executives' values. Corporate social responsibility can effectively improve the ability of the company to resist risks, attract outstanding employees, and increase the productivity of employees, thereby improving the company's performance and economic performance. Based on this, the following research hypotheses are proposed.

> Hypothesis 3: assuming that other conditions remain unchanged, the consistency of the differences in the values of the senior management team will enhance the company's innovation performance by enhancing the ability to resist risks.

3. Research and Design

3.1. Data Source and Description. Select the 2013–2018 China Shanghai and Shenzhen A-share listed companies as the research object. The native place data of the main members of the senior management team are partly derived from the senior executive profile database of Guotai'an (CSMAR), but only about 30% of the listed company chairman and general manager's provincial (municipal) nationality data can be found in this database. We manually check the resumes and relevant news reports of the chairman and general manager through the Internet and manually supplement about 60% of the chairman and general manager's provincial (municipal) native place. If the hometown information of the chairman and general manager is missing, we will replace them with the province (city) where they were born.

The cultural dimension data of China's provinces (municipalities) come from the score data of cultural characteristics of all provinces (municipalities) across the country measured by the value measurement system based on the "Empirical Study on the impact of organizational identity on employee behavior effectiveness." reported by Wang et al. [42]. We use the cultural characteristics score of each province (city) across the country to measure the cultural scores of the provincial (city) where the chairman and general manager of listed companies are located to measure their personal values.

In order to ensure the validity of the sample, try to eliminate the influence of abnormal data on empirical research; data processing is mainly as follows: (1) exclude the data of the company's listing year and previous years; (2) exclude the data of financial companies; (3) exclude data abnormal data value and Winsor, processing the data. Finally, 5916 observation data were selected, and the related data processing and measurement analysis used stata14.0 software.

3.2. The Explained Variable

3.2.1. Innovation Performance. Existing documents mainly use the number of R&D personnel, R&D expenditure, the number of patents, and the number of registered trademarks as corporate innovation indicators [43, 44]. Among them, the number of R&D personnel and R&D expenditure indicators belong to the input indicators of enterprise innovation. Due to the long-term and risky nature of innovation input, such indicators cannot truly reflect the achievement of enterprise innovation performance, and the number of registered trademarks is used as an indicator of innovation output. The content of its reflection is quite different from that of the enterprise innovation performance studied in this article. Therefore, this article selects the cumulative number of patents (Inv) owned by a company as a measure of the size of the company's innovation performance.

3.2.2. Explaining Variables

(1) *Differences in Values of the Senior Management Team* (Detv). Based on the measurement based on the Globe cultural model reported by Liu et al. [45], this model contains a total of 9 dimensions: uncertainty avoidance, future orientation, power gap, socially-oriented collectivism, small-group collectivism, interpersonal care orientation, performance orientation, gender equality, and dominance [46]. We use Euclidean distance to measure the difference between the chairman and general manager in these 9 cultural dimensions, and the calculation formula is as follows:

$$\sqrt{\sum_{i=1}^{9} (V_{i1} - V_{i2})^2}, \quad (1)$$

where V_{i1} represents the chairman's score on the GLOBE cultural model dimension 1 and V_{i2} represents the general manager's score on the GLOBE cultural model dimension 1. Assume a company with a chairman from Guangdong and a general manager from Heilongjiang. According to the cultural model of Zhao and Wei [47], Guangdong Province is in terms of uncertainty avoidance, future orientation, power gap, socially oriented collectivism, interpersonal care-oriented, performance-oriented, small-group collectivism, gender equality, and dominance 9. The scores of each dimension are 4.37, 4.37, 4.42, 4.72, 4.51, 4.66, 5.05, 3.61, and 4.15, while the scores of Heilongjiang Province in the corresponding 9 dimensions are 4.38, 4.22, 4.52, 4.59, 4.38, 4.65, 5.00, 3.49, and 4.01, and the value difference between the two is $\sqrt{((4.37\text{-}4.38)^2 + (4.37\text{-}4.22)^2 + (4.42-4.52)^2 + (4.72\text{-}4.59)^2 + (4.51\text{-}4.38)^2 + (4.66\text{-}4.65)^2 + (5.05\text{-}5.00)^2 + (3.61\text{-}3.49)^2 + (4.15\text{-}4.01)^2)} = 0.32$.

Finally, in order to further analyze the specific impact mechanism of different degrees of executive values on the corporate innovation performance, according to the results of relevant literature research, the difference in executive values is 1.500 as the boundary, and the differences in executive values are divided into low differences. Degree has a score value less than or equal to 1.500, and high degree of difference has a score value greater than 1.500. Using this as a standard, in the total sample of 5916 observational data, there are 1626 data with low value differences and 4290 data with high value differences.

(2) *Antirisk Ability* (ART). Antirisk ability refers to the ability of enterprises and organizations to cope with crises. It can measure the health, capital, and industry status of an organization and enterprise. "Risk" is a very common term, which is often used around our lives. T.A. Kletz, a famous British industrial safety expert, pointed out human ignorance of risks at the 150th anniversary meeting of the British Society for scientific development. With the continuous change of the environment, the connotation and extension of risk management have been greatly expanded, and the risk management activities have become increasingly rich. Risk management has become the focus of the management activities of many international large companies.

Because the study of enterprise risk tolerance is less and there are few measurement indicators that can be used for reference, this study refers to the research framework of the corporate risk-bearing level. Firstly, enterprise risk-taking behavior and its economic consequences are used as alternative variables of enterprise antirisk ability, specifically for the three different levels of indicators of the company's market share, operating gross profit margin, and cash ratio. Then, referring to the steps of principal component analysis comprehensive evaluation summarized by Lin and Sun [48]; the principal component analysis was performed on the above three corporate risk tolerance indicators, and the principal component comprehensive evaluation function was constructed and the sample value of the comprehensive function was calculated. Obtain the index value of the enterprise's antirisk ability.

3.2.3. Control Variables. In this paper, referring to previous studies (such as [49–51]), we controlled a series of variables at the enterprise level and corporate governance level. The enterprise level controls the enterprise size (Ens), asset-liability ratio (Fle), and enterprise performance (ROA). At the corporate governance level, we control the size of the board of directors (Bsi) and board independence (Bin).

3.3. Model Construction and Variable Definition. The following basic model is constructed to analyze the impact of corporate antirisk capabilities on innovation performance:

$$\mathrm{Inv}_{i,t} = \beta_0 + \beta_1 \mathrm{ART}_{i,t} + \mathrm{Controls}_{i,t} + \sum \mathrm{year} + \sum \mathrm{Ind} + \varepsilon_{i,t}. \tag{2}$$

Model (2) takes $\mathrm{Inv}_{i,\ t}$ as the dependent variable, $\mathrm{ART}_{i,\ t}$ as the main explanatory variables, and particularly selects the enterprise scale (Ens), asset-liability ratio (Fle), and enterprise performance (ROA) as the control variables from the enterprise management level to explore the enterprise. The impact of antirisk ability on enterprise innovation performance is determined. Enterprise size (Ens) is an important indicator to evaluate the business ability of an enterprise, reflecting whether the enterprise has the basis for future development. The larger the size of the enterprise, the better the innovation performance of the enterprise. The debt-to-asset ratio (Fls) is an important indicator to evaluate the solvency of a company, and it can reflect the size of the company's financing ability. Only by keeping the debt-to-asset ratio at a reasonable level can companies improve the likelihood of achieving innovative performance. Among them, the return on total assets (ROA) is an important indicator to evaluate the profitability of a company. The higher the return on total assets, the more likely it is that the company's innovation performance will improve. In model (2), it is expected that $\beta 1 > 0$, that is, the enterprise's antirisk ability will increase the possibility of achieving innovation performance.

In order to verify the impact of differences in senior management values on the enterprise's ability to resist risks, a model (3) is constructed:

$$\mathrm{ART}_{i,t} = \beta_0 + \beta_1 \mathrm{Detv}_{i,t} + \mathrm{Controls}_{i,t} + \sum \mathrm{year} + \sum \mathrm{Ind} + \varepsilon_{i,t}. \tag{3}$$

Model (3) uses $\mathrm{ART}_{i,\ t}$ as dependent variables and $\mathrm{Detv}_{i,\ t}$ as the main explanatory variables. Especially, from the governance level of listed companies, the enterprise scale (Ens) and asset-liability ratio (Fle) are selected as control variables from the corporate management level to explore the impact of differences in senior management values on corporate antirisk capabilities. Enterprise size (Ens) is an important indicator to evaluate the business ability of an enterprise, reflecting whether the enterprise has the basis for future development. The larger the company, the stronger the ability to resist risks. The debt-to-asset ratio (Fls) is an important indicator for evaluating the solvency of a company, and it can reflect the size of the company's financing ability. Only when the company's debt-to-asset ratio remains at a reasonable level is the company more likely to withstand risk. In model (3), it is expected that $\beta 1 < 0$, that is, differences in corporate executive values will reduce the company's ability to resist risks.

In order to verify the impact of differences in senior management values on corporate innovation performance, model (4) is constructed:

$$\mathrm{Inv}_{i,t} = \beta_0 + \beta_1 \mathrm{Detv}_{i,t} + \mathrm{Controls}_{i,t} + \sum \mathrm{year} + \sum \mathrm{Ind} + \varepsilon_{i,t}. \tag{4}$$

Model (4) uses $\mathrm{Inv}_{i,\ t}$ as the dependent variable and $\mathrm{Detv}_{i,\ t}$ as the main explanatory variable. Especially, from the level of listed company governance, it selects the board size (Bsi) and board independence (Bin) as the control variables to explore executives. The impact of differences in values on corporate innovation performance is determined. The size of the board of directors (Bsi) is an important indicator to evaluate the management level of an enterprise, reflecting the level of the establishment of a modern enterprise shareholding system. The larger the board of directors is, the more the company will focus on its long-term development and the better its innovation performance is. The independence of the board of directors (Bin) is an important indicator for evaluating the scientificity and rationality of corporate internal governance. It can reflect the level of decision-making ability of the company. Only by setting up the position of independent director scientifically can the company make relevant major decisions to ensure its scientificity and rationality. Therefore, companies are more likely to achieve higher innovation performance. In model (4), it is expected that $\beta 1 > 0$, that is, differences in corporate executive values will increase the possibility of achieving innovation performance.

In order to further verify the moderating effect of the differences in corporate executive values and their different degrees of differences on the relationship between corporate antirisk capabilities and innovation performance, model (5) is set up:

$$\begin{aligned}\mathrm{Inv}_{i,t} = {} & \beta_0 + \beta_1 \mathrm{Detv}_{i,t} + \beta_2 \mathrm{Detv}_{i,t} \times \mathrm{ART}_{i,t} + \beta_3 \mathrm{ART}_{i,t} \\ & + \mathrm{Controls}_{i,t} + \sum \mathrm{year} + \sum \mathrm{Ind} + \varepsilon_{i,t}.\end{aligned} \tag{5}$$

Model (5) introduces the interaction terms between the differences in values of senior management and the ability to resist risks to study whether the differences in values of senior management can further enhance the impact of the ability to resist risks on enterprise innovation performance. In model (5), it is expected that $\beta 2 > 0$, that is, differences in the values of senior management can improve the possibility of enterprise innovation performance by enhancing the enterprise's antirisk ability.

The settings and definitions of variables in each model are shown in Table 1:

4. Empirical Results and Analysis

4.1. Descriptive Statistics. The descriptive statistical results of each variable are shown in Table 2. There are 5916 observations in total. Among them, 1626 had observational data with a low degree of difference in executive values, accounting for 27.48%; 4,290 had observational data with a high degree of difference in executive values, accounting for 72.52%. The proportion of executives in Shanghai and Shenzhen A-share listed companies with high value difference is much higher than that in companies with low value difference, indicating that the geographical and cultural characteristics of executives in China's Shanghai and Shenzhen A-share listed companies are indicative. The phenomenon of large differences in values is even more obvious. The standard error of the cumulative number of patents owned by the entire sample of companies is 33.664, and the minimum and maximum values are 0 and 455, respectively, indicating that there is a large degree of difference in the achievement of corporate innovation performance. Even listed companies also have the number of patents. The average value difference score of the senior management team of the full sample is 2.42, indicating that the difference in values of the senior management team of China's Shanghai and Shenzhen A-share listed companies is relatively large; the standard error of the difference in the values of the senior management team is 1.259, indicating the internal values of the senior management team of the listed company. There are obvious differences. The minimum and maximum antirisk capabilities of the full-sample companies are 0.0147 and 0.0522, respectively, and the average and standard errors are 0.0337 and 0.0120, respectively, indicating that the overall performance of China's Shanghai and Shenzhen A-share listed companies' antirisk capabilities is relatively weak, and the difference is not the same, big. The minimum and maximum sizes of the full sample companies are 2.7665 and 4.6052, respectively, and the average and standard errors are 3.9989 and 0.3814, respectively, indicating that the scale of China's Shanghai and Shenzhen A-share listed companies has maintained a certain level, and the difference is not obvious. The average asset load ratio of the entire sample is 0.4613, indicating that the overall debt level of China's Shanghai and Shenzhen A-share listed companies is relatively large. The average return on total assets of the full sample is 1.99%, indicating the overall profitability of A-share listed companies in Shanghai and Shenzhen, China; the standard error of the return on total assets is 3.27%, indicating that there is a significant difference in the profitability of listed companies. The minimum and maximum board sizes of the full sample are 1.693 and 13.526, and the average and standard errors are 2.355 and 8.345, respectively, indicating that the size of the board of directors of China's Shanghai and Shenzhen A-share listed companies has maintained a certain level and the difference is obvious. From the perspective of the proportion of independent directors, the average value is 36.78%, the standard error is 9.84%, the structure is more reasonable, the independence is good, and the difference between samples is not obvious.

4.2. Correlation Analysis. Correlation analysis of the main variables (Table 3) lists the Pearson correlation test results. It can be seen from Table 3 that the Pearson coefficient of enterprise antirisk ability and enterprise innovation performance is 0.025, and there is a significant positive correlation at the 1% statistical level, indicating that there is a correlation between enterprise antirisk ability and innovation performance; enterprise antirisk ability, innovation performance, and differences in the values of the senior management team are all significantly related, indicating that there is a certain connection between the differences in the values of the senior management team and the enterprise's ability to resist risks, and there is a certain connection between the two and the achievement of enterprise innovation performance. Except for individual control variables, the correlation coefficients of other control variables are all less than 0.6, so there is no co-linearity problem in regression analysis.

4.3. Antirisk Ability and Innovation Performance. Two models of OLS estimation and fixed effects are used to test the relationship between the enterprise's antirisk ability and innovation performance. The regression results are shown in Table 4. From the full-sample regression results, it can be seen that the coefficient of inefficient investment under the OLS estimation method is 0.027, and the coefficient of inefficient investment under the fixed effects model is 0.023, both of which are greater than 0, indicating that the firm's ability to resist risks is positively correlated with innovation performance. That is, the enhancement of the enterprise's antirisk ability will directly improve the enterprise's innovation performance so that hypothesis 1a is verified and hypothesis 1b should be discarded.

The difference in values of senior management team of an enterprise can be divided into two situations: low difference and high difference. Is there any difference in the positive impact of enterprise's antirisk ability on the innovation performance of the two forms? To this end, two subsamples with low and high degrees of difference were regression tested. It can be seen from Table 4 that the coefficients of the antirisk ability of the low degree of difference subsample under the OLS estimation and the fixed-effect model are 0.005 and 0.018, respectively, and the coefficients of the high degree of difference subsample have the antirisk ability under the OLS estimation and the fixed effect model, respectively, are 0.035 and 0.038. Through comparison, it can be found that whether it is an OLS estimation or a fixed-effect model, the coefficient of the antirisk ability of the subsamples with a high degree of difference is much larger than the coefficient of the antirisk ability of the subsamples with a low degree of difference. The greater the difference in

Table 1: Variable settings and definitions.

Variable type	Variable name	Variable symbol	Variable description
Explained variable	Number of patents	Inv	Number of invention patents owned by the company
Explanatory variables	Differences in the values of the senior management team	Detv	Based on the "empirical study on the impact of organizational identity on employee behavior effectiveness." reported by Wang et al. [42]; the Euclidean distance is then used to measure the difference between the chairman and the general manager in these 9 cultural dimensions
	Antirisk ability*	ART	The comprehensive function value obtained after the principal component analysis of the enterprise risk-bearing ability index
Control variable (enterprise level)	Enterprise size	Ens	The natural logarithm of the company's total assets
	Assets and liabilities	Fle	Total liabilities at the end of the year/total assets at the end of the year
	Business performance	ROA	Total profit at the end of the year/(total assets at the end of the year + total assets at the beginning of the year)
Control variable (corporate governance level)	Board size	Bsi	The total number of board members takes the natural logarithm
	Board independence	Bin	Number of independent directors/total number of board of directors
Control variable (others)	Year	Year	Annual dummy variable
	Industry	Ind	Industry dummy variables defined based on the industry classification of the China securities regulatory commission

*, in Model (3), is the explained variable.

Table 2: Descriptive statistical results of main variables.

Variables	N	Minimum	Maximum	Mean	Standard deviation
Inv	5916	.0000	455.0000	24.6357	33.6641
Detv	5916	.0000	4.0800	2.4202	1.2592
ART	5916	.0147	.0522	.0337	.0120
Ens	5916	2.7665	4.6052	3.9989	.3814
Fle	5916	.0108	0.8477	.4613	.2118
ROA	5916	−7.2530	26.5761	1.9913	3.2738
Bsi	5916	1.6931	13.5264	2.3551	8.3447
Bin	5916	.0667	.8333	.3678	.0984

Table 3: Pearson correlation analysis.

	Inv	Detv	ART	Ens	Fle	ROA	Bsi	Bin
Inv	1							
Detv	.039**	1						
ART	.025**	.046**	1					
Ens	.030*	.055**	.042**	1				
Fle	−.023	−.068**	−.057**	−.035**	1			
ROA	.021	.058**	.041**	.173**	−.093**	1		
Bsi	−.007	.021	−.003	.006	−.011	.012	1	
Bin	.003	.023	.018	.003	−.012	.006	−.331**	1

**, significantly correlated at the 0.01 level (two-sided); *, significantly correlated at the 0.05 level (two-sided).

management values is, the more a company's ability to resist risks can promote its innovation performance.

As shown in Table 4, the regression coefficient between antirisk ability and innovation performance under different degree has obvious difference. This is because when enterprises have strong antirisk ability, they will continue to increase the investment in R&D expenses, and more research literature shows that a higher level of R&D investment will lead to an increase in enterprise innovation performance.

4.4. Differences in Values of the Senior Management Team and Antirisk Ability. Two models of OLS estimation and fixed effects are used to test the relationship between the differences in the values of the senior management team and the enterprise's ability to resist risks. The regression results are shown in Table 5. From the full-sample regression results, it can be seen that the coefficient of the difference in the values of the executive team under the OLS estimation method is −0.039, and the coefficient of the difference in the values of the executive team under the fixed effects model is −0.051,

Table 4: Regression analysis results of antirisk ability and innovation performance.

Variable name	Full sample		Low degree of difference		High degree of difference	
	(1)	(2)	(3)	(4)	(5)	(6)
Antirisk ability	.027**	.023**	.005*	.018*	.035**	.038***
Enterprise size	−.043*	.026**	.001	.022	−.021**	.026**
Assets and liabilities	−.010	−.019*	−.007*	.008	.003	−.026**
Business performance	−.074*	.014*	−.030	.022*	−.013*	.010
Board size	.021	−.009	.017	−.006**	−.002	−.011*
Board independence	.056	−.004*	−.011*	.036	.008	−.017
Year fixed	NO	YES	NO	YES	NO	YES
Industry fixed	NO	YES	NO	YES	NO	YES
N	5916	5916	1626	1626	4290	4290
R^2	0.0360	0.0460	0.0312	0.0458	0.0390	0.0452

Table 5: Regression analysis results of differences in the values of the senior management team and the ability to resist risks.

Variable name	Full sample		Low degree of difference		High degree of difference	
	(1)	(2)	(3)	(4)	(5)	(6)
Differences in the values of the senior management team	−.039***	−.051***	.033*	−.051	.008	−.011**
Enterprise size	.033	.047**	.012	.022*	.042***	.058**
Assets and liabilities	−.051***	−.034	−.058*	−.041	−.047***	−.039*
Business performance	.028*	.033**	.044*	.053**	.022	.031
Year fixed	NO	YES	NO	YES	NO	YES
Industry fixed	NO	YES	NO	YES	NO	YES
N	5916	5916	1626	1626	4290	4290
R^2	0.0670	0.0850	0.0334	0.0471	0.0290	0.0352

both of which are less than 0, indicating the values of the executive team. The difference is negatively related to the enterprise's antirisk ability, that is, the increase of the difference in the values of the senior management team will reduce the enterprise's antirisk ability, thus verifying Hypothesis 2.

The difference in the values of the senior management team is divided into two situations: low difference and high difference. The level of difference in the values of the senior management team has a greater impact on the enterprise's antirisk ability or the difference between the two levels of executive value. Are there differences in the negative impact of corporate innovation performance? It can be seen from Table 5 that the coefficients of the differences in the values of the executive team under the OLS estimation and the fixed-effect model for the low degree of difference subsample are 0.033 and −0.051, respectively. The coefficients of the difference in values are −0.008 and −0.011, respectively. Through comparison, it can be found that whether it is an OLS estimation or a fixed-effect model, the absolute value of the coefficient of the difference in values of the senior management team of the subsample with a high degree of difference is much smaller than the absolute value of the coefficient of the difference in values of the executive team of the subsample with a low degree of difference, which indicates that the smaller the difference in team values is, the more consistent the difference in values of the corporate executive team and the better the ability of enterprises to resist risks.

4.5. Differences in Values of Senior Management Teams and Innovation Performance. Two models of OLS estimation and fixed effects are used to test the relationship between the differences in the values of senior management team and the innovation performance of the enterprise. The regression results are shown in Table 6. From the full-sample regression results, it can be seen that the coefficient of the difference in the values of the executive team under the OLS estimation method is −0.040, and the coefficient of the difference in the values of the executive team under the fixed effects model is −0.036, both of which are less than 0, indicating the values of the executive team. Differences are negatively related to corporate innovation performance, that is, increasing differences in the values of the senior management team will reduce corporate innovation performance, thus enabling Hypothesis 3 to be verified.

The difference in values of senior management team can be divided into two situations: low difference and high difference. To what extent do the differences in the values of the senior management team have an impact on the innovation performance of the enterprise or to what extent do the differences in the values of the two-level senior management have an impact on the innovation performance of the enterprise? Is there a difference in the positive impact? It can be seen from Table 6 that the coefficients of the differences in the values of the executive team under the OLS estimation and the fixed-effect model for the low-level difference subsample are −0.022 and 0.063, respectively. The coefficients of the difference in values are 0.010 and −0.043,

Table 6: Regression analysis results of differences in the values of the senior management team and innovation performance.

Variable name	Full sample		Low degree of difference		High degree of difference	
	(1)	(2)	(3)	(4)	(5)	(6)
Differences in the values of the senior management team	−.040***	−.036***	−.022**	.063	.010	−.043**
Enterprise size	−.013	.025**	.001	.021*	−.019*	.027***
Assets and liabilities	.000	−.018*	−.007	.009	.002	−.027***
Business performance	−.018**	.013	−.032*	.021*	−.012*	.010
Board size	.004	−.010	.015	−.006	−.001	−.011
Board independence	.003	−.005*	−.011	.035**	.009	−.017**
Year fixed	NO	YES	NO	YES	NO	YES
Industry fixed	NO	YES	NO	YES	NO	YES
N	5916	5916	1626	1626	4290	4290
R^2	0.0260	0.0382	0.0300	0.0408	0.0363	0.0478

respectively. Through comparison, it can be found that whether it is an OLS estimation or a fixed-effect model, the absolute value of the coefficient of the difference in values of the senior management team of the subsample with a high degree of difference is much smaller than the absolute value of the coefficient of the difference in values of the executive team of the subsample with a low degree of difference, which indicates the executives. The smaller the difference in team values, the more consistent the differences in the values of the corporate executive team and the better the innovation performance of the enterprise.

4.6. Tests on the Moderating Effect of Differences in Senior Management Values. Two models of OLS estimation and fixed effects are used to test the moderating effect of the differences in the values of the senior management team against risk and innovation performance. The regression results are shown in Table 7. From the regression results of the full sample, it can be seen that the coefficients of the company's antirisk ability under the OLS estimation and the fixed effects model are 0.002 and 0.005, respectively, which are both greater than 0, indicating that the enhancement of the company's antirisk ability will improve the company's innovation performance; the coefficients of the interaction term between value difference and antirisk ability under OLS estimation and fixed-effect model are 0.052 and 0.049, respectively, which are both greater than 0, indicating that the difference in values of the senior management team can enhance the enterprise's antirisk ability, thereby improving the innovation performance of the enterprise.

Is there any difference in the moderating effect of the difference in values between the top management team and the bottom management team on the enterprise's ability to resist risks? It can be seen from Table 7 that the coefficients of the interaction term between the corporate antirisk ability and the differences in the values of the senior management team under the OLS estimation and the fixed effect model of the low degree of difference subsample are 0.118 and 0.104, respectively, and the high degree of difference subsample is estimated and fixed in the OLS. Under the effect model, the coefficients of the interaction terms between the corporate antirisk ability and the difference in the values of the senior management team are 0.120 and 0.146, respectively, which are both greater than 0, indicating that the difference in the values of the senior management team can play an effective moderating effect regardless of whether it is a low or a high degree of difference to enhance the innovation performance of the enterprise. At the same time, through comparison, it can be found that whether it is OLS estimation or fixed-effect model, the value of the interaction term coefficient of corporate antirisk ability and the value difference of the senior management team under the high degree of difference subsample is smaller than that of the low degree of difference subsample, indicating the difference in management team values has a greater moderating effect on the enterprise's ability to resist risks.

4.7. Robustness Test. In order to obtain a more robust regression result, the research model was further used as a substitute variable for corporate innovation performance to conduct regression analysis on corporate R&D expenditure. The test results showed that the coefficients of antirisk ability were all positive and reached a statistically significant level; the interaction terms between the corporate antirisk ability and the differences in the values of the senior management team are both positive and reach a statistically significant level; this is consistent with the previous results so that the conclusions of this article are supported to a certain extent. In addition, considering that the problems of innovation and transformation of China's Shanghai and Shenzhen A-share manufacturing industries from 2011 to 2016 are more prominent, and the selected sample size is relatively large; manufacturing data are selected for robustness testing. In order to alleviate the endogenous problems caused by sample selection bias and the two-way influence of variables, the industry average of enterprise antirisk ability is taken as the instrumental variable of enterprises' antirisk ability. The conclusion is further supported (limited to space, the specific process and results of robustness test will not be reported).

The success of any business depends on the senior management team. Team members have to work together, and sometimes there are differences of team members' opinions. We can understand the issue of differences in the values of the senior management team from two perspectives [52]. One perspective is that executives have different backgrounds and values, which can make corporate

Table 7: Tests on the moderating effects of the differences in senior Management's values against risks and innovation performance.

Variable name	Full sample		Low degree of difference		High degree of difference	
	(1)	(2)	(3)	(4)	(5)	(6)
Antirisk ability	.002*	.005*	.055	.026**	−.065	.072**
Antirisk ability × differences in values of the senior management team	.052**	.049***	.120***	.146*	.118*	.104**
Differences in the values of the senior management team	.001*	.003*	.144**	.098**	−.058**	.044**
Enterprise size	−.014**	.024***	.001	.023*	−.021**	.026***
Assets and liabilities	.001	−.017**	−.006	.009	.004	−.025*
Business performance	−.019***	.013*	−.032**	.022*	−.013	.010
Board size	.004*	−.010	.015	−.007	−.002*	−.012
Board independence	.002	−.005	−.011	.035**	.008	−.017*
Year fixed	NO	YES	NO	YES	NO	YES
Industry fixed	NO	YES	NO	YES	NO	YES
N	5916	5916	1626	1626	4290	4290
R^2	0.0300	0.0410	0.0331	0.0460	0.0390	0.0501

decisions more scientific and effective. Another perspective is that differences within the executive team can also be beneficial. This is mainly because differences can enhance creativity, which can improve the team's decision-making level. More important, when there are differences in values in the senior management team, relationship conflicts are more likely to bring more negative effects. One explanation is that differences in values make senior management team members sensitive to differences. When members of the executive team find that their values are inconsistent, they will drift away. Therefore, when the senior management team lacks consensus and sense of belonging, the company's working atmosphere and spirit of collaboration will be damaged.

One of the worst examples is Enron. They listed the company's core values in the mission statement: respect, integrity, communication, and excellence. When Enron's late former CEO, Kenneth Lay, conducted a survey of Enron's executives and asked them "what is the company's core values;" they thought "what does he value as a CEO." Not only that, Neilman did not accuse the two employees of leaking flight records, but took responsibility for their mistakes because "management obviously did not guide them correctly." Some task conflicts can lead to constructive arguments, but relationship conflicts can hinder effective decision-making [53]. Therefore, the company should minimize the relationship conflicts within the senior management team, while encouraging the ultimate improvement of decision-making behavior and company operations.

5. Conclusions

This article uses my country's 2013–2018 Shanghai and Shenzhen listed companies as a sample. Based on the measurement data of cultural value system of various provinces (municipalities) across the country and the hometown data of chairman and general manager, this article measures the difference of their values and makes an empirical analysis on the values of senior executives. Differences and enterprise antirisk ability have an impact on enterprise innovation performance and further test the role of differences in executive values. The empirical results show that the following. (1) The enterprise's antirisk ability is positively correlated with its innovation performance, that is, the stronger the enterprise's antirisk ability is, the better its innovation performance is. (2) The difference in the values of the senior management team is negatively correlated with innovation performance. That is, only when the values of the corporate executive team have a certain consistency can the enterprise have better innovation performance. (3) The consistency of the differences in the values of the senior management team can effectively enhance the enterprise's antirisk ability and enhance its innovation performance. Moreover, the lower level of differences in the values of the senior management team has a more significant moderating effect on corporate innovation performance. The research in this paper enriches and expands the existing research in the following aspects.

Firstly, it discusses the impact mechanism of corporate antirisk capability on corporate innovation performance and conducts an empirical test by using data from Chinese listed companies. The empirical results show that corporate antirisk ability has a positive impact on corporate innovation performance, which is consistent with the research results of some domestic scholars [54]. There may be two reasons. One is that strong corporate antirisk capabilities will increase the efficiency of corporate resource utilization, promote the formation of competitive advantages, and enable companies to have a more stable internal and external environment, thereby improving corporate innovation performance. Second, strong corporate antirisk capabilities will encourage the senior management team to favor investment in high-risk projects, actively seek and seize innovation opportunities, and promote the improvement of corporate innovation performance.

Secondly, it focuses on the impact mechanism of the difference of senior management team values on innovation and innovation performance. It is found that the better the consistency of the differences in the values of the corporate senior management team, the more scientific the corporate decision-making is, especially the strategic investment decision, so the corporate strategy is. The choice of direction, strategic objectives, and strategic route will be further optimized, enabling enterprises to quickly adapt to the environment of internal and external innovation transformation of the enterprise and ultimately improve the innovation performance of the enterprise. This is not discovered in previous research. This may be because previous studies have used more executive team overconfidence to examine the impact of the executive team on innovation performance [55]; the overconfidence of the executive team is difficult to accurately reflect the differences in the values of the executive team and the level of difference, which makes it difficult to draw accurate research conclusions. This article uses the differences in the values of the senior management team to analyze the mechanism of the differences in the values of the senior management team on innovation performance and expands the relevant research on the impact of the differences in the values of the senior management team on corporate innovation.

Thirdly, China has a profound cultural heritage and an extremely diverse variety, forming a rich and complex regional culture. This article uses regional cultural differences to measure the difference degree of senior management team values and investigates the moderating effect of the differences in the values of the senior management team in the process of the enterprise's antirisk ability affecting the enterprise's innovation performance from a microperspective. The research results show that the better the consistency of the values of the senior management team is, the better the company's ability to resist risks, and the promotion of its corporate innovation performance is also more obvious. This is also the content less involved in previous studies. Previous studies have mainly explored the impact of the differences in the values of the senior management team on the innovation strategy of the company, or they are controlling the environmental factors of different countries and analyzing the impact of the company's antirisk ability on the innovation performance of the company or the difference in the values of the senior management team. The impact of corporate risk-taking cannot clearly reveal the moderating mechanism that is truly caused by the differences in the values of the senior management team or their consistency [56]. Therefore, the existing related research is further improved and enriched.

It can be seen that an important aspect to solve the problem of improving enterprise innovation performance is to effectively improve the antirisk ability of enterprises, and the consistency of values of the senior management team can enhance the enterprise's antirisk ability. Therefore, companies must improve the corporate governance system from the perspectives of board structure and board governance, especially the geographical and cultural differences of corporate executives, improve the selection and incentive mechanism of corporate executive teams, and strengthen the consistency of corporate executive team values. Secondly, it is necessary to further improve my country's market competition mechanism and continue to maintain and enhance the enterprise's strong antirisk ability. Finally, it is necessary to optimize the value consistency structure of the senior management team and further exert the promotion effect of the consistency of the values of the senior management team on the enterprise's antirisk ability.

Of course, this study also has some shortcomings: Firstly, given that China's regional culture is rich and complex, there have been few previous studies on China's regional cultural differences. Currently, only Zhao [57] has measured the different regional cultures of China for the first time. The measurement of executive values is measured by using their regional cultural data, but the current research has not verified the accuracy of their regional cultural measurement. Future research can revise and enrich the measurement indicators of executive values to further examine the impact of differences in executive values on corporate strategy.

Secondly, this article not only focuses on the impact of corporate antirisk capabilities on corporate innovation performance but only uses corporate financial indicators to measure corporate antirisk capabilities. However, corporate antirisk capabilities are diverse and complex. The resistance measured under other types of indicators' risk capability may have a certain impact on enterprise innovation performance. Future research can extend this research indicator to some nonfinancial indicators of enterprises to further test the more objective and comprehensive impact of antirisk ability on enterprise innovation performance.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Data-Driven Repeated-Feedback Adjustment Strategy for Smart Grid Pricing

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Applying the optimal problem, we get the optimal power supply and price. However, how to make the real power consumption close to the optimal power supply is still worth studying. This paper proposes a novel data-driven inverse proportional function-based repeated-feedback adjustment strategy to control the users' real power consumption. With the repeated-feedback adjustment, we adjust the real-time prices according to changes in the power discrepancy between the optimal power supply and the users' real power consumption. If and only if the power discrepancy deviates the preset range, the real power consumption in different periods will be adjusted through the change of the price, so the adjustment times is the least. Numerical results on real power market show that the novel inverse proportional function-based repeated-feedback adjustment strategy brought forward in the article achieves better effect than the linear one, that is to say, the adjustments times and standard error of the residuals are less. Meanwhile, profit and whole social welfare are more. The proposed strategy can obtain more steady and dependable consumption load close to the optimal power supply, which is conducive to the balanced supply of electric energy.

1. Introduction

More and more research has focused on environmental protection and energy conservation. Due to the nonrenewable and high pollution of traditional energy, people are more and more inclined to use clean and renewable energy [1]. The rapid development of new energy vehicles may increase the power demand. We need to do more to balance the power supply to ensure the safety and dependability of the power grid.

As the abovementioned problems need to be solved urgently, many countries have extensively researched and applied the smart grid (SG). SG solves energy problems through superior electronic communication technology and power grid system [2]. Smart meter, one of the essential nodes in SG, has a real-time interaction function and can realize interactive communication between consumers and power suppliers at any time, due to the scientific and technological progress of intelligent algorithms and energy networks.

As the demand response mechanism of the smart grid controller, combined with smart meters, shows us a picture of real-time pricing (RTP) [3, 4], RTP can realize real-time price and load interaction between consumers and power suppliers more elastically and cleverly. This is an advantage that other traditional pricing strategies do not have. Hu et al. proposed a distributed algorithm to solve the power dispatching strategy between a power company and multiple power users [5]. Goudarzi et al. put forward a game theory method considering both incentive and price in reducing power consumption and improving users' benefit [6]. Zhao et al. developed a model to obtain dynamic pricing and lead the consumers' power consumption mode and update the power load [7].

The prime intent of implementing RTP in SG is to obtain optimal power consumption, power supply, and electricity price. When power suppliers implement the optimal electricity price, users can use electricity according to the optimal electricity consumption, which can run steadily. However, the reality is the real power consumption alters radically and reduces the grid's steadiness and dependability. Up to now, the researchers have seldom paid attention to how to keep the real load steady. Kb and Ms brought forward a bidirectional converter, providing more optimized control strategies for controlled power consumption administration [8]. Yildirim and Khooban studied a controller of noninteger order for the stable LFC of the MGs [9].

For the above reasons, we want to research a strategy that changes the real-time price to control the real power consumption within a specific boundary. He et al. studied an automatic process control (APC) strategy in a smart grid to get steady power consumption [10, 11]. Dennis et al. developed a diminutive biomass energy combustor for process heat generation, which is on the basis of "maximum combustion current" technology and has repetitive feedback APC [12]. Efheij and Albagul presented a comprehensive repeated-feedback process controller that is a neural network to maintain stability [13]. In fact, it is still a challenge to choose which controller to control the power consumption process by using the repetitive feedback regulation method, and there is little literature on this.

In this paper, we propose a novel data-driven inverse proportional function-based repeated-feedback adjustment strategy to control the discrepancy between the users' real power consumption and optimal power supply. The repeated-feedback adjustment strategy is incorporated into the pricing algorithm to adjust real-time pricing by minimizing the deviation from an objective, which is that the real power consumption equals the optimal power supply. The discrepancy is a discrete-time series, for it changes at fixed intervals, say, every hour. For SG, experience has shown that frequent changes in electricity prices are not feasible, driving away customers [14]. To solve these problems, we forecast power consumption and optimal power supply discrepancy of the next period from historical data with an exponentially weighted moving average (EWMA) controller [15, 16]. During different periods, we set an EWMA forecast for the discrepancy as the controller. If and only if the controller exceeds the established range, can we adjust the price. Because the EWMA of historical data is used as the controller, the adjustment does not depend on the abnormality in a certain period, but the development trend in this period. Thus, the adjustment times can be reduced while obtaining more stable power consumption and maintaining the balance between supply and demand. With the help of the smart meters for automatic monitoring the next period, an optimal data-driven repeated-feedback adjustment strategy is given. Among the strategies forecasting the future value in the moving average time series, the EWMA method is efficiently minimises the mean square error. In recent years, many kinds of literature have studied how to use EWMA controllers to form control charts to monitor future data [10, 11, 17, 18]. To monitor carbon emissions, Shamsuzzaman et al. integrated a Shewhart control chart with an EWMA scheme to reduce costs [19]. Zhang et al. focused on detecting the anomalous changes by Wilcoxon rank-sum statistics based on distributed-free EWMA [20].

The specific structure of the remainder of this article is as follows. Section 2 describes the system model and knowledge reserve. We demonstrate the problem formulation and solutions in Section 3. Section 4 offers numerical tests and analysis. In Section 5, we conclude this research.

2. System Model and Preliminary Knowledge

2.1. System Model. Suppose that the smart grid includes a power supplier, a lot of power users with smart meters, and some rules to be followed by both parties. Smart meters monitor and adjust power load through the price adjustment and can harmonize every user with the power supplier and the other users. Power users and the power supplier exchange information such as electricity price and power load every hour through communication facilities such as the network. The notations and variables are summarized in Table 1. The cycle time in our system is separated into $\mathscr{H}$ periods, and the set is $\Lambda = \{1, 2, \ldots, \mathscr{H}\}$. Let ϖ denote the number of users, and the set of power users is $\Xi = \{1, 2, \ldots, \varpi\}$. Let d_n^τ denote the power consumption used by every user $n \in \Xi$ in period $\tau \in \Lambda, l_n^\tau \le d_n^\tau \le L_n^\tau$, where l_n^τ and L_n^τ are explained in Table 1.

2.1.1. Profit Function and Benefit Function. Let $S^\tau \in [S_{\min}^\tau, S_{\max}^\tau]$ denote the power supply of power supplier in period τ and $g(S^\tau)$ represent the cost providing S^τ in period τ. Assuming that supply can meet consumption, $S^\tau \in [S_{\min}^\tau, S_{\max}^\tau]$, $S_{\min}^\tau = \sum_{n=1}^{\varpi} l_n^\tau$ and $S_{\max}^\tau = \sum_{n=1}^{\varpi} L_n^\tau$ are explained in Table 1. According to [10, 11], the power supplier's power supply cost function in period τ is

$$g(S^\tau) = \alpha (S^\tau)^2 + \beta S^\tau + \gamma, \tag{1}$$

where $\alpha > 0, \beta, \gamma \ge 0$ are shown in Table 1. The power supplier's profit function in period τ is

$$\hbar(S^\tau) = \rho^\tau S^\tau - g(S^\tau), \tag{2}$$

where ρ^τ is defined in Table 1.

In economics, experts used to characterize the degree of happiness generated from power consumption with a utility function. In this paper, it is assumed that the utility increases with user power consumption and will not increase when it increases to a certain amount and will not grow when it increases to a certain amount. Let $\vartheta_n^\tau > 0$ denote the user n's preference. We model a logarithmic function as the utility function [11]:

$$U(d_n^\tau, \vartheta_n^\tau) = \begin{cases} \vartheta_n^\tau \ln(d_n^\tau + 100), & \text{if } d_n^\tau \ge 0, \\ 0, & \text{if } d_n^\tau < 0, \end{cases} \tag{3}$$

where user n's benefit function in period τ is

$$f(d_n^\tau, \vartheta_n^\tau) = U(d_n^\tau, \vartheta_n^\tau) - \rho^\tau d_n^\tau. \tag{4}$$

2.1.2. The Optimal Problem. From (2) and (4), the whole social welfare function is [10]

$$\Phi(d_n^\tau, S^\tau) = \sum_{\tau=1}^{\mathscr{H}} \left(\sum_{n=1}^{\varpi} U(d_n^\tau, \vartheta_n^\tau) - g(S^\tau) \right). \tag{5}$$

We assume that the power supplier's power supply is not less than power consumption in total in each period τ,

Table 1: List of notations and variables.

n/τ	Index of user/period
$\varpi/\mathscr{H}$	Amount of users/periods
Ξ/Λ	Set of users/periods
ϑ_n^τ	User n's preference in period τ
$\alpha/\beta/\gamma$	Parameters of cost function
d_n^τ	The amount of user n's power consumption in period τ
l_n^τ/L_n^τ	User n's minimum/maximum power consumption in period τ
S^τ	Power supplier's power supply in period τ
$S_{\min}^\tau/S_{\max}^\tau$	Power supplier's minimum/maximum power supply in period τ
ρ^τ	Electricity price in period τ
θ^τ	Variation of electricity price in period τ

$$\sum_{n=1}^{\varpi} d_n^\tau \le S^\tau, \quad \forall n \in \Xi, \forall \tau \in \Lambda. \tag{6}$$

The optimal problem is depicted as [10]

$$\max_{\substack{l_n^\tau \le d_n^\tau \le L_n^\tau \\ S_{\min}^\tau \le S^\tau \le S_{\max}^\tau}} \sum_{\tau=1}^{\mathscr{H}} \left(\sum_{n=1}^{\varpi} U\left(d_n^\tau, \vartheta_n^\tau\right) - g\left(S^\tau\right) \right), \tag{7}$$

$$\text{s.t.} \sum_{n=1}^{\varpi} d_n^\tau \le S^\tau, \quad \forall n \in \Xi, \forall \tau \in \Lambda, \tag{8}$$

where the variables are summarized in Table 1 and functions $g(\cdot)$ and $U(\cdot)$ are denoted in (1) and (3), respectively.

2.2. Preliminary Knowledge. The optimal power supply S_*^τ, power consumption d_*^τ, and electricity price ρ_*^τ in period τ can be obtained by solving the optimization problems (7) and (8). Ideally, the users' real power consumption is consistent with the optimal power supply. However, the real situation is that there is a particular discrepancy between real consumption d^τ and optimal supply S_*^τ, and even the discrepancy fluctuates widely in some periods. The real power consumption does not have the stability and dependability of the optimal power supply. The power discrepancy in period τ is described as [10, 11]

$$\varsigma^\tau = d^\tau - S_*^\tau. \tag{9}$$

To keep the real power consumption dependable and steady, we want to adjust d^τ to S_*^τ by price incentive. Users may reduce the power consumption in peak time when the price increases and increase it in valley time when decreased. Next, we need to incorporate the optimal problems (7) and (8) into the exponentially weighted moving average (EWMA) process to minimize the standard error.

3. Problem Formulation and Solutions

3.1. Problem Formulation. Undependability implies that there is no fixed mean value globally, so we need to study the local average and the deviations. We use an EWMA to represent the local average.

Definition 1(see [10]). $\varsigma^t, t = \tau, \tau-1, \ldots,$ is the beginning power discrepancy, $\varsigma_a^t, t = \tau, \tau-1, \ldots,$ is the adjusted one,

$$\widetilde{\varsigma}^{\tau+1} = \lambda\left(\varsigma_a^\tau + \nu\varsigma_a^{\tau-1} + \nu^2\varsigma_a^{\tau-2} + \cdots\right) = \lambda\varsigma_a^\tau + \nu\widetilde{\varsigma}^\tau, \quad 0 < \nu < 1, \tag{10}$$

is called the power discrepancy EWMA in next period $\tau + 1$+1, where $\lambda = 1 - \nu$ is the parameter.

Definition 2 (see [11]). $\rho^t, t = \tau, \tau-1, \ldots,$ is the beginning real-time price, $\rho_a^\tau, t = \tau, \tau-1, \ldots,$ is the adjusted price of ρ^τ,

$$\widetilde{\rho}^{\tau+1} = \lambda\left(\rho_a^\tau + \nu\rho_a^{\tau-1} + \nu^2\rho_a^{\tau-2} + \cdots\right) = \lambda\rho_a^\tau + \nu\widetilde{\rho}^\tau, \quad 0 < \nu < 1, \tag{11}$$

is called the real-time price EWMA in next period $\tau + 1$.

Definition 3 (see [11]). $\rho_r^\tau, t = \tau, \tau-1, \ldots,$ is the readjusted real-time price of ρ^τ,

$$\widetilde{\rho}_a^{\tau+1} = \lambda\rho_r^\tau + \nu\widetilde{\rho}^\tau, \quad 0 < \nu < 1, \tag{12}$$

is called the adjusted price EWMA in next period $\tau + 1$.

Next, we will discuss a data-driven repeated-feedback adjustment strategy and reduce deviations from the objective in power discrepancy utilizing process monitoring and adjustment. If

$$\left|\widetilde{\varsigma}^{\tau+1} - \mu\right| \ge L \tag{13}$$

holds at period $\tau + 1$, the price will be adjusted, where μ is the objective, standard load discrepancy of the optimal problem and L is the boundary.

As we know, if the real power consumption equals the optimal power supply, it will be best. So, the standard power discrepancy in our model is $\mu = 0$. Let $L_1 > 0$ be the upper boundary and $L_2 < 0$ be the lower boundary; we reformulate (13) as

$$\begin{aligned} &\widetilde{\varsigma}^{\tau+1} \ge L_1 \\ &\text{or } \widetilde{\varsigma}^{\tau+1} \le L_2. \end{aligned} \tag{14}$$

Via (14), the automatic monitoring process is developed. In period $\tau + 1$, if $\widetilde{\varsigma}^{\tau+1} \ge L_1$, the prices will be gone up, the power consumption in current period will shift to other periods, thereby reducing the power consumption, and $\widetilde{\varsigma}^{\tau+1}$ is adjusted to objective $\varepsilon_1 \in [0, L_1)$. If $\widetilde{\varsigma}^{\tau+1} \le L_2$, to increase the power consumption in the current period, the prices will be diminished, and then, $\tilde{\varsigma}^{\tau+1}$ is modified to the objective $\varepsilon_2 \in (L_2, 0]$.

3.2. Problem Solutions

Definition 4. Set an inverse proportional function (after this referred to as "IPF") as the demand function. Thus, power discrepancy EWMA $\tilde{\varsigma}^{\tau+1}$ is inverse proportional to price EWMA $\tilde{\rho}^{\tau+1}$ in the form of $\tilde{\varsigma}^{\tau+1} = (a/\tilde{\rho}^{\tau+1})$, where $a > 0$ is a constant.

Theorem 1. *Suppose an IPF with a constant $a\,(a \geq 0)$ is the demand function. Then, if $\tilde{\varsigma}^{\tau+1} \geq L_1 > 0$, we will adjust $\tilde{\varsigma}^{\tau+1}$ to $\varepsilon_1 \in [0, L_1)$, and the change of price is*

$$\theta^{\tau+1} = \frac{a}{\lambda}\left(\frac{1}{L_1} - \frac{1}{\tilde{\varsigma}^{\tau+1}}\right). \tag{15}$$

If $\tilde{\varsigma}^{\tau+1} \leq L_2 < 0$, we will adjust $\tilde{\varsigma}^{\tau+1}$ to $\varepsilon_2 \in (L_2, 0]$, and the change of price is

$$\theta^{\tau+1} = \frac{a}{\lambda}\left(\frac{1}{L_2} - \frac{1}{\tilde{\varsigma}^{\tau+1}}\right). \tag{16}$$

Proof. By condition, in period $\tau + 1$, if $\tilde{\varsigma}^{\tau+1} \geq L_1 > 0$, we will adjust $\tilde{\varsigma}^{\tau+1}$ to $\varepsilon_1 \in [0, L_1)$. At this point, the price EWMA changes from $\tilde{\rho}^{\tau+1}$ to $\tilde{\rho}_a^{\tau+1}$.

According to Definition 4, $\tilde{\varsigma}^{\tau+1} = (a/\tilde{\rho}^{\tau+1})$ and $\varepsilon_1 = (a/\tilde{\rho}_a^{\tau+1})$,

$$\tilde{\rho}^{\tau+1} = \frac{a}{\tilde{\varsigma}^{\tau+1}}, \tag{17}$$

$$\tilde{\rho}_a^{\tau+1} = \frac{a}{\varepsilon_1}, \tag{18}$$

$$\tilde{\rho}_a^{\tau+1} - \tilde{\rho}^{\tau+1} = a\left(\frac{1}{\varepsilon_1} - \frac{1}{\tilde{\varsigma}^{\tau+1}}\right), \tag{19}$$

$$\lambda\rho_r^{\tau} + \nu\tilde{\rho}^{\tau} - \left(\lambda\rho_a^{\tau} + \nu\tilde{\rho}^{\tau}\right) = a\left(\frac{1}{\varepsilon_1} - \frac{1}{\tilde{\varsigma}^{\tau+1}}\right). \tag{20}$$

Denote $\theta^{\tau+1}\colon = \rho_r^{\tau} - \rho_a^{\tau}$ as the change of price, and (20) can be transformed into the following:

$$\begin{aligned} \lambda\rho_r^{\tau} - \lambda\rho_a^{\tau} &= a\left(\frac{1}{\varepsilon_1} - \frac{1}{\tilde{\varsigma}^{\tau+1}}\right), \\ \lambda\theta^{\tau+1} &= a\left(\frac{1}{\varepsilon_1} - \frac{1}{\tilde{\varsigma}^{\tau+1}}\right), \\ \theta^{\tau+1} &= \frac{a}{\lambda}\left(\frac{1}{L_1} - \frac{1}{\tilde{\varsigma}^{\tau+1}}\right). \end{aligned} \tag{21}$$

Similarly, if $\tilde{\varsigma}^{\tau+1} \leq L_2 < 0$, (16) holds. □

3.3. Algorithm. From Theorem 1, if (14) holds, we will adjust the users' real power consumption with price variations to reach an equilibrium state.

Lemma1. *Suppose that the adjusted power consumption is inversely proportional to the change of price. Therefore, the revised users' real power consumption is*

$$d_a^{\tau+1} = d^{\tau+1} - \frac{a}{\theta^{\tau+1}}. \tag{22}$$

Proof. If $\theta^{\tau+1} > 0$, the users' real power consumption will decrease, and if $\theta^{\tau+1} < 0$, it increases. Therefore,

$$\begin{aligned} d_a^{\tau+1} - d^{\tau+1} &= -\frac{a}{\theta^{\tau+1}}, \\ d_a^{\tau+1} &= d^{\tau+1} - \frac{a}{\theta^{\tau+1}}. \end{aligned} \tag{23}$$

Proof is completed. □

Lemma 2. *Set $\varsigma_a^{\tau+1}$ as the adjusted power discrepancy between the users' real power consumption $d^{\tau+1}$ and the optimal power supply $S_*^{\tau+1}$; therefore,*

$$\varsigma_a^{\tau+1} = \varsigma^{\tau+1} - \frac{a}{\theta^{\tau+1}}. \tag{24}$$

Proof. By condition,

$$\varsigma_a^{\tau} = d_a^{\tau} - S_*^{\tau}. \tag{25}$$

According to Lemma 1 and (25), the adjusted power discrepancy is

$$\begin{aligned} \varsigma_a^{\tau+1} &= d_a^{\tau+1} - S_*^{\tau+1} \\ &= d^{\tau+1} - \frac{a}{\theta^{\tau+1}} - S_*^{\tau+1} \\ &= d^{\tau+1} - S_*^{\tau+1} - \frac{a}{\theta^{\tau+1}} \\ &= \varsigma^{\tau+1} - \frac{a}{\theta^{\tau+1}}. \end{aligned} \tag{26}$$

Proof is completed. □

According to the data-driven repeated-feedback adjustment strategy, in the period $\tau, \tau = 1, \ldots, \mathscr{H} - 1$, the algorithm for monitoring and adjustment is as follows.

4. Numerical Tests

In this section, we conduct simulations to demonstrate the effectiveness of the proposed data-driven IPF-based repeated-feedback adjustment strategy through realistic data from [21]. Our simulated smart grid comprises a power supplier and 1000 users ($\varpi = 1000$). Divide the period of two days into 48 hours ($\mathscr{H} = 48$). The parameters α, β, γ in (1)

Table 2: Data used in the simulation.

Data used in Algorithm 1	The period in [21]
The real original price $\{\rho_*^\tau\}$	Price series from Sep 23, 2017, to Sep 24, 2017
The real power consumption $\{d^\tau\}$	The power load data of 2 days from Sep 23, 2017, to Sep 24, 2017
The optimal power supply $\{S_*^\tau\}$	Power load data at the same hour a week ago from Sep 16, 2017, to Sep 17, 2017

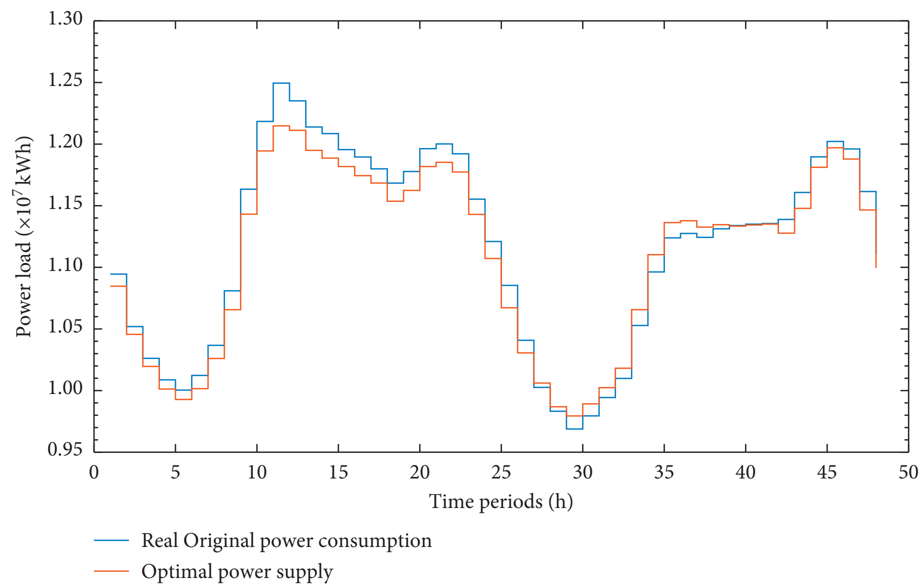

Figure 1: Power load before adjustment (blue lines indicate real original power consumption and red lines denote optimal power supply).

Step I: obtain $\{d^\tau\}$ from smart meters. Solve $\{\rho_*^\tau\}$ and $\{S_*^\tau\}$ according to (7) and (8). Compute $\{\varsigma^\tau\}$ according to (9). Input $t = 1$, let $\varsigma_a^1 = \varsigma^1$, $\rho_a^1 = \rho_*^1$, $\tilde{\varsigma}^1 = 0$, $\delta^1 = \varsigma_a^1 - \tilde{\varsigma}^1 = \varsigma_a^1$, and $\theta^1 = 0$. Input parameters $\lambda, a, L_1, L_2, \varepsilon_1, \varepsilon_2$.
Step II: compute $\tilde{\varsigma}^{\tau+1}$ according to (10). If (14) is not satisfied, $\theta^{\tau+1} = 0$, go to Step III. Else, go to Step IV.
Step III: compute $d_a^{\tau+1}$ and $\varsigma_a^{\tau+1}$ from (22) and (24), respectively. Compute $\rho_a^{\tau+1} = \rho^{\tau+1} + \theta^{\tau+1}$ and $\delta^{\tau+1} = \varsigma_a^{\tau+1} - \tilde{\varsigma}^{\tau+1}$. Iterate τ with $\tau+1$ and go to Step II.
Step IV: compute $\theta^{\tau+1}$ according to Theorem 1; then, return to Step III.

Algorithm 1: Data-driven IPF-based repeated-feedback adjustment strategy.

are 0.01, 0, and 0. Each user's utility function is defined as (3), where the preference parameter ϑ is selected randomly from the interval [1,4].

4.1. Results' Analysis. The profiles of power consumption load, power supply, and price data are obtained from Singapore [21]. The data used in the simulation are listed in Table 2. Figure 1 shows the electric energy loads before adjustment.

From Figure 1, we can see that the power supplier's optimal power supply runs stably, but the discrepancy between the users' real power consumption and optimal power supply is relatively large. For the sake of shortening the gap, the power supplier should take action to encourage users to adjust the real power consumption. Our purpose is to reduce power consumption in peak hours and increase it in low hours, so as to achieve the energy-saving effect by the data-driven IPF-based repeated-feedback adjustment strategy, which can lead to steady real power consumption.

Set $\overline{p}_1 = 75$ and list the parameters in Algorithm 1 in Table 3. The process of repeated-feedback adjustment from the performance of Algorithm 1 in 48 periods is illustrated in Figure 2. Figure 2 shows that the total adjustments times are 12. The standard error of residuals σ_δ is

$$\sigma_\delta = \sqrt{\frac{\sum_{\tau=1}^{\mathscr{H}} \delta_t^2}{\mathscr{H} - 1}} = \sqrt{\frac{\sum_{\tau=1}^{48} \delta_t^2}{47}} = 89.66. \qquad (27)$$

Figure 2 shows that, after applying the algorithm, all points are within the $3\sigma_\delta$ boundary, so there is no anomaly, and we can get steady power consumption.

We can learn from Figure 3 that the electricity price is changed slightly to balance the power discrepancies. The most remarkable change of price is 1.929 F0B4 10^{-3} \$/kWh. Figure 3 also shows that compared with the original users'

Table 3: Simulation results.

Index	$a = 200$, $\lambda = 0.8$, $L_1 = -L_2 = 120$, and $\varepsilon_1 = -\varepsilon_2 = 80$		
	Original pricing	Adjusted pricing	Fixed pricing
Adjustments' times	/	12	/
σ_δ	/	89.66	/
Whole social welfare ($\times 10^8$)	6.32	8.68	3.34
Power supplier's profit ($\times 10^7$)	3.99	4.17	3.69

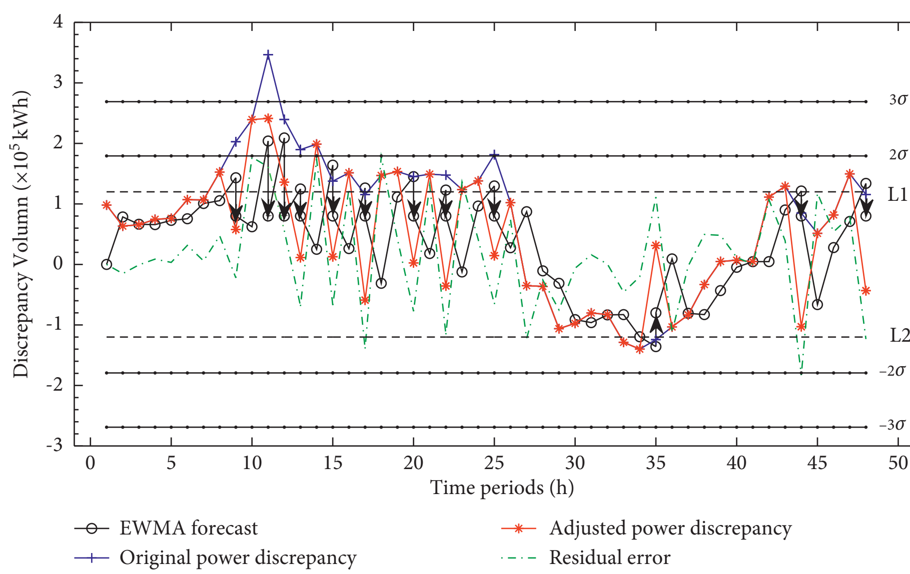

Figure 2: Adjustment effects (black arrows mark the adjustment process, black solid lines with circle markers denote EWMA forecast, blue solid lines with plus sign markers indicate original power discrepancy, red solid lines with asterisks depict adjusted power discrepancy, and green dash-dot lines denote residual error).

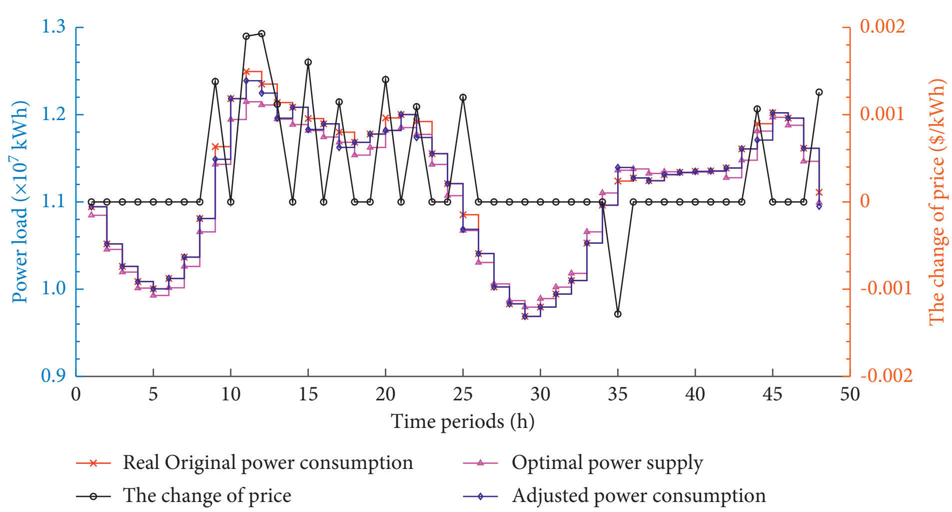

Figure 3: Power load after adjustment (red solid lines with asterisks denote real original power consumption, magenta solid lines with triangle markers indicate optimal power supply, and blue solid lines with point markers depict adjusted power consumption) and the change of price (black solid lines with circle markers denote the change of price).

power consumption, the adjusted users' power consumption is closer to the optimal power supply, achieving the expected effect.

Table 3 and Figure 4 illustrate the whole social welfare computed according to (5) and the profits computed according to (2). We can learn from them that the whole social welfare in the proposed repeated-feedback adjustment strategy is significantly higher than the original one because the users' real adjusted power consumption is much closer to the optimal power supply. The profit is slightly higher than the original one because the power consumption is more stable.

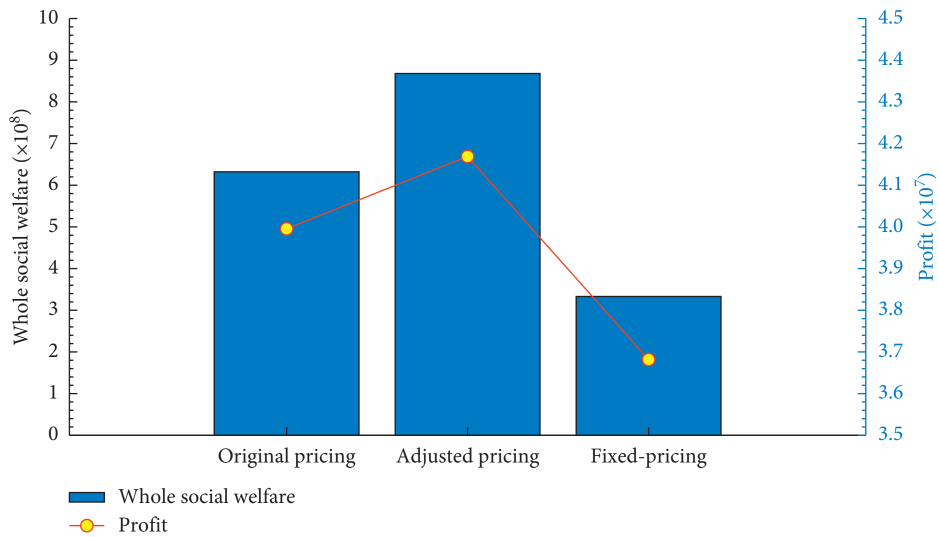

FIGURE 4: Economic benefits of both sides (histogram depicts whole social welfare and red solid lines with point markers denote profit).

TABLE 4: Comparison results under two adjustments.

Index	$a = 100$, $\lambda = 0.6$, $\lambda_2 = 0.8$, $L_1 = -L_2 = 110$, $\varepsilon_1 = -\varepsilon_2 = 75$, and $\chi_1 = \chi_2 = 0$	
	IPF adjustment	LF adjustment
Adjustments' times	11	12
σ_δ	69.43	89.92
Whole social welfare ($\times 10^8$)	8.68	7.09
Power supplier's profit ($\times 10^7$)	4.25	4.14

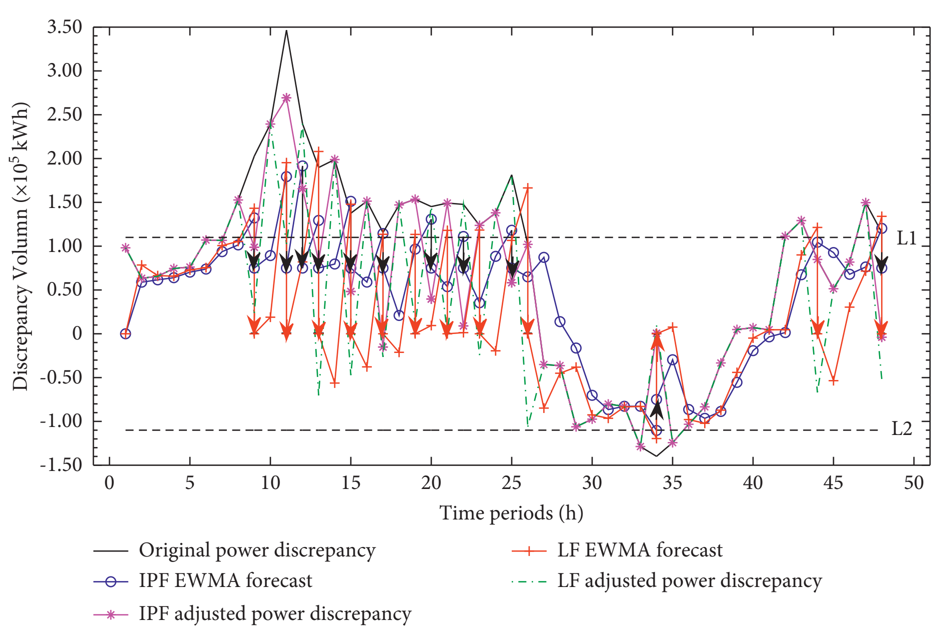

FIGURE 5: Comparison of IPF adjustments (black arrows mark the IPF adjustment process, red arrows mark the LF adjustment process, black solid lines denote original power discrepancy, blue solid lines with circle markers depict IPF EWMA forecast, and magenta solid lines with asterisks indicate IPF adjusted power discrepancy) and LF adjustments (red solid lines with plus sign markers denote LF EWMA forecast and green dash-dot lines indicate LF adjusted power discrepancy).

By running Algorithm 1, we not only can obtain the optimal adjustment strategy and steady power consumption but also can improve the economic benefits of both sides.

4.2. Comparison of Adjustment Effect. To verify the proposed IPF-based repeated-feedback adjustment strategy is more reasonable to obtain steady and dependable power

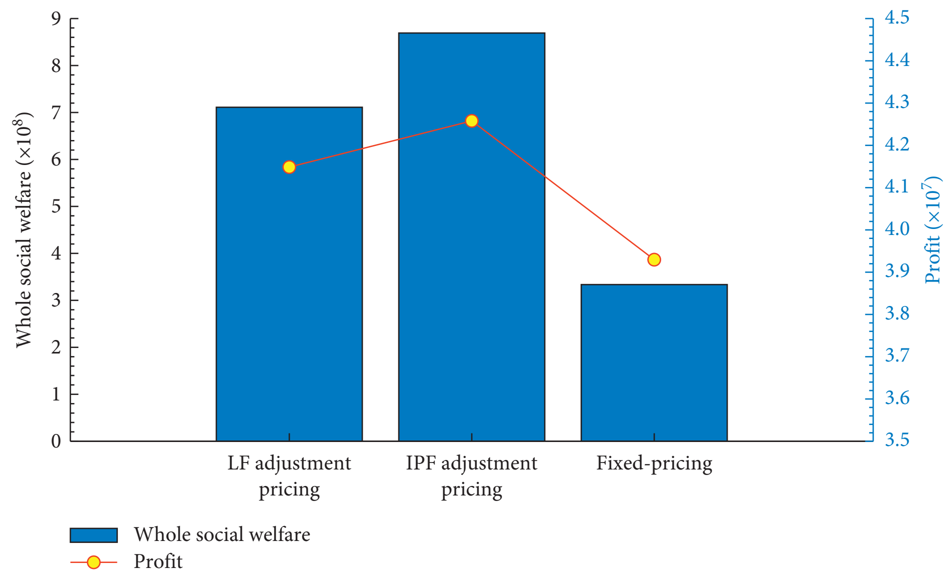

Figure 6: Comparison of economic benefits (histogram denotes whole social welfare and red solid lines with point markers indicate profit).

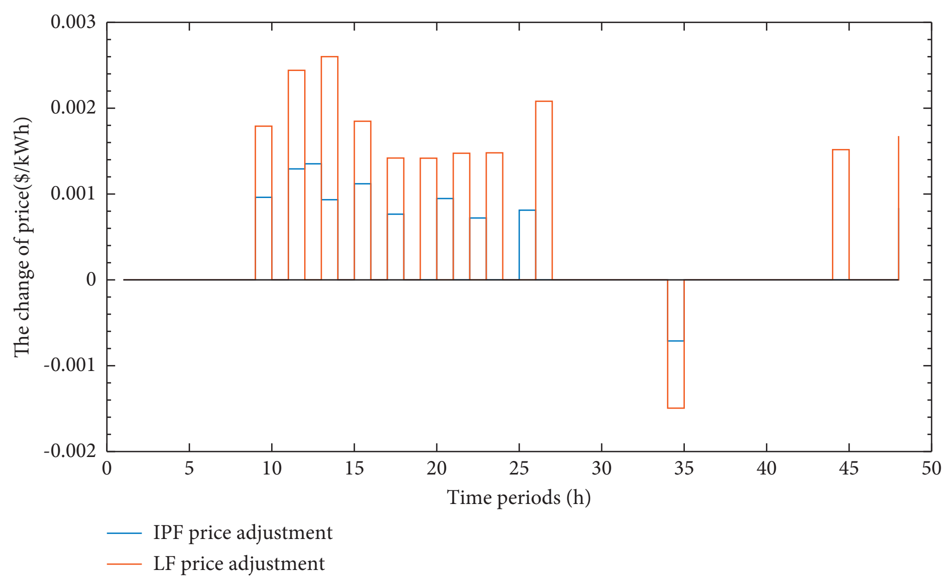

Figure 7: Comparison of price changes (blue solid lines denote IPF price adjustment and red solid lines depict LF price adjustment).

consumption, we compare it with the linear function (after this referred to as "LF")-based strategy model, such as [10], which adjusts the power consumption with the LF. The detailed method is provided in Appendix.

The parameters are listed in Table 4, and the comparison is illustrated in Table 4 and Figures 5–7.

It is shown in Table 4 and Figure 5 that the adjustments times and σ_δ under IPF adjustment strategy are less than that under LF scenario, and the IPF adjusted power discrepancy is steadier than that of the LF scenario.

Table 4 and Figure 6 show that the economic benefits of both sides under the IPF adjustment pricing are more than that under the LF adjustment pricing.

It can be observed in Figure 7 that the change of price under the IPF adjustment pricing is less than in the LF scenario.

The test results mean that it is more reasonable to consider the proposed data-driven IPF-based repeated-feedback adjustment strategy than the LF scenario.

5. Conclusion

A data-driven inverse proportional function-based repeated-feedback adjustment strategy that the power supplier may adopt to monitor the consumption power discrepancy between the real power consumption and the optimal power supply is proposed. The power supplier can get the optimal power supply by the optimal problem in the smart grid. Only when the trend of the power discrepancy is identified as an anomaly by exponentially weighted moving average, we will adjust the real-time price. That is to say, the data-driven inverse proportional function-based repeated-feedback adjustment strategy is conducted only when the power discrepancy deviates far from the standard power discrepancy exceeding either the upper or lower boundary. Appling the data-driven inverse proportional function-based repeated-feedback adjustment strategy, we are able to get the least adjustments times and the steady and dependable power consumption close to the optimal power supply and more whole social welfare and profit. The proposed strategy can be applied to enrich the power grid monitoring and adjustment theory. At the same time, in practical application, it can help power suppliers formulate reasonable electricity price and manage the consumption power.

Appendix

Linear Function (LF)-Based Adjustment Strategy

Theorem A.1. *If* $\widetilde{\varsigma}^{\tau+1} \geq L_1 > 0$ *and* $\widetilde{\varsigma}^{\tau+1}$ *is adjusted to* $\chi_1 \in [0, L_1)$, *the effect* $\theta^{\tau+1}$ *of price adjustment is [10]*

$$\theta^{\tau+1} = \frac{\left(\widetilde{\varsigma}^{\tau+1} - \chi_1\right)}{(\lambda_2 a)}. \tag{A.1}$$

If $\widetilde{\varsigma}^{\tau+1} \leq L_2 < 0$ and $\widetilde{\varsigma}^{\tau+1}$ is adjusted to $\chi_2 \in (L_2, 0]$, the effect $\theta^{\tau+1}$ of price adjustment is [10]

$$\theta^{\tau+1} = \frac{\left(\widetilde{\varsigma}^{\tau+1} - \chi_2\right)}{(\lambda_2 a)}, \tag{A.2}$$

where λ_2 is defined in (10).

Thus, when $\widetilde{\varsigma}^{\tau+1}$ exceeds the boundary L_1 or L_2, the users' real adjusted consumption load $d_a^{\tau+1}$ and the power discrepancy $\varsigma_a^{\tau+1}$ in period τ +1will change as follows [10]:

$$d_a^{\tau+1} = d^{\tau+1} - a\theta^{\tau+1}. \tag{A.3}$$

Data Availability

The data used to support the findings of this study are included in the references within the article.

Conflicts of Interest

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

Acknowledgments

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Research Article

Optimal Administrative Response to Selfish Behaviors in Urban Public Management: The Role of Zero-Determinant Strategies

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City management involves complex interactions between the manager (administrator), who supervises urban appearance and environmental sanitation, and the managed (speculator), who works in urban areas and is subject to management ordinances. This article provides an iterated game framework for analyzing the extent to which zero-determinant strategies can be used to optimize the intensity decision of supervisory action against municipal code violations, thus enhancing administrative efficiency. To account for characteristics of the public affairs context, it is assumed that each player in our model chooses from a finite set of discrete and random courses of game strategy. As our model constitutes a major extension to the seminal Press and Dyson (2012) model, we resort to the theory of stochastic process to prove the existence of multiple zero-determinant strategies when players can adopt many strategies in the iterated game. Various numerical examples are presented to validate such strategies' optimality. Our finding is that, given the probability of adopting a particular strategy, an urban administrator can unilaterally (i) set the speculators' expected payoff to a level equaling to the opportunity cost of abiding by the law and (ii) let their own expected surplus payoff exceed the speculators. Finally, important policy implications can be derived based on these analyses and conclusions.

1. Introduction

With the aiming of reducing the negative externality of individual behavior, urban public management involves using administrative inspection and supervision approaches to improve different aspects of urban public life including the environmental quality, city appearance, public health, and smoothness of traffic flow. The ideal practices for the management of urban areas can be accomplished through good cooperation between speculators exhibiting spontaneous law-abiding behaviors and the administrator performing monitoring duties without coercive enforcement. However, one always observes in the real world all kinds of selfish individual behaviors, which collectively can be coined the term "defection." Such defection behaviors caused various public management problems in Chinese cities such as the public safety concern caused by violations of traffic rules, the food safety issue when operating restaurants without sanitation or hygiene license, and the problem that unregistered vendors and street sellers may adversely affect the positive image of the city. Mitigating the conflict of ideal vs. reality in city administration has become a challenging task for urban public management officers. In the real world, selfish behaviors frequently occur on a large scale, which increases the costs of supervision and reduces the efficiency of public management. How to solve such a problem by devising an implementation path of city management regulations and, more importantly, how to determine the optimal strength of regulatory enforcement remain to be unanswered questions.

Many studies have attempted to address these questions from the perspective of the classic Nash equilibrium [1] and evolutionary game theory [2]. The research in applications of game theory concludes that defection will eventually happen in games like our urban administration setup and that selfish behavior exhibited by the majority of the population will disadvantage selfish speculators themselves as much as it will hurt those managers they are acting against. In practice, policy implementers often reduce the motivation to act selfishly by elevating supervision and intensifying punishment, which leads to significantly higher implementation costs and the occurrence of extreme events such as excessive enforcement or violent resistance. For example, city traffic managers often adopt the method of strengthening law enforcement, hoping to reduce traffic violations by punishing violators harsher and more frequent. But this method is not sustainable due to the high costs of maintaining strong enforcement. Once the strength of enforcement weakens, what often happens is that the illegal behaviors of drivers will return to the previous intensity. All city management efforts are expended in vain. Therefore, the broad questions raised at the end of the previous paragraph can be refined into a more purposeful yet crucial research direction. At what level should government officials set the supervision intensity so that urban public management can achieve a win-win situation, in which the altruistic behavior can be chosen voluntarily by the managed speculators? Due to the existence of payoff dynamics and many alternatives in the choice set, this refined question cannot be answered using merely the traditional game theory.

Therefore, we have constructed a new game theory model in which the players are the administrator and the speculator, and these two types of players can choose multiple different strategies according to varying supervision intensities for each round of the game. In this model, the player's choice of one strategy can be regarded as a Markov process, and there exists a state transferring probability matrix that determines the long-term payoffs of players in this iterated process. We use a random matrix to verify that the administrator can execute a linear mapping between the expected payoffs earned by both the administrator and the speculator through implementing a multistrategy zero-determinant strategy [3] (ZD strategy hereafter) in our model. We find that in the multistrategy iterated urban public management game, ZD strategies are still feasible. However, in contrast to the setting of a two-strategy game [3] or a multiplayer iterated game [4], the administrator player has multiple ZD strategies which are related to the number of strategies that can be chosen by the administrator in each round of the game. Equipped by these ZD strategies, the administrative body can unilaterally pin down the speculator's expected total payoff at a given level of the opportunity cost of law-abiding behavior. Under certain realistic conditions, our model suggests the government shift from increasing supervision intensity to providing public services that can reduce defection behaviors. Besides setting the opponents' total payoffs, administrators can enforce an extortionate linear relation between their own scores and the opponents' scores and can unilaterally ensure that their surplus turns out to be a discrete multiple of the surplus enjoyed by their opponents. Further, if the opposing speculators are rational individuals, the extortion strategy can promote spontaneous cooperative behavior undoubtedly.

Identifying ZD strategies for a multistrategy game matters for extending our understanding of the evolution of cooperation and provides a new perspective for achieving efficient urban public management. The study of a multistrategy game incorporating ZD strategies and the application of such a game to city administration are all research gaps that have yet been explored. The public environment of urban areas is a typical example of public goods. Rational individuals often exhibit defection behavior driven by short-term interests, and as a result, the city's public environment becomes subject to the tragedy of the commons. However, either theoretical quantitative solution from existing microeconomic models or qualitative solution suggested by public management professionals seems to be unrealistic given the complicated choice set of game participants with unbalanced powers. Our proposed model is more in line with the practice because the administrator can adjust supervision strength according to the outcome ZD strategy, hence improving regulatory efficiency in the administrator's viewpoint and promoting potential violators to cooperate voluntarily. All in all, this paper enriches the literature on both ZD strategy game theory and urban public management theory as well as the relevant interdiscipline studies.

As a simple but complete model, we design the urban public management game to describe the decision of administrators about the optimal intensity of supervision, which depends on both the long-term game characteristics and the speculator's willingness to contribute so that the obvious tragedy of the commons can be avoided. Game theory has been proven to be critical for understanding, predicting, and intervening in many important public administration issues, ranging from smart grid pricing [5–7] to environmental pollution [8, 9] and fishery management [10]. Among several possible candidates, we believe that the iterated game serves as the most appropriate tool to provide insights into the abovementioned city administration issues. This is due to the extendibility of the iterated game as it can encompass all useful incentive mechanisms including reputation cooperation [11], kin selection cooperation [12], reciprocity cooperation [13], and reward and punishment [14–16]. Whether these mechanisms can elicit cooperative behavior is decided jointly by both sides of the game. However, without ZD strategy, the administrator cannot unilaterally determine the opponent's payoffs and lacks control over the implementation of these mechanisms. We, therefore, study the iterated urban public management game and apply a novel policy implementation mechanism based on the ZD strategy which empowers us with a strong ability to control the payoffs of speculators and improve their cooperation.

2. Literature Review

A clean and tidy urban environment is crucial for sustainable economic growth and better living conditions. The municipal government's regulations promulgated and decisions on how to enforce them would directly determine the efficiency of urban public management in securing the desired environment and attaining other indirect economic and social goals. Schwartz [17] reveals the importance of government capacity in enforcing a policy after investigating the cases for ten Chinese provinces. Hamm and Schrink [18] point out that the key factor of effective policy implementation is that the enforcement agency should possess sufficient management skills when exercising discretionary power. Kostka [19] believes that the dislocation of public sector functions and accountability has led to serious problems in terms of urban environmental governance. In sum, the regulatory ability, supervisory skills, and competence in duty assignments of municipal agencies represent different facets of government administration. These studies hence can provide solutions to our inefficiency problem of urban public management from merely the standpoint of administrators and via only the means of enhancing government administrative capability.

The incentives of government officials are also a key driver of successfully implementing urban environmental administration policies. Liu et al. [20] document that the structure of motivations designed for local government officials has become an institutional hurdle for environmental policy implementation and enforcement. For example, in China, government officials are more assessed by their performance regarding economic development. Therefore, much attention has been paid to GDP goals, whereas other policy objectives, such as urban public administration in this paper and environmental protection commonly seen in other studies, might be temporarily ignored in the short run. As the high-level government has the power to select politicians, local officials often choose to implement those policies that would please the upper government [21]. This also leads to conflicts between government officials and the general public [22]. In addition, the problem requires a much broader view concerning methodology since multiple actors are reacting strategically in policy implementation. On the one hand, it is difficult to enforce laws and regulations relying on only government bodies. The participation of the policy target group plays a large part here too. On the other hand, the complex policy environment and the shortcomings of the traditional bureaucratic structure make it hard for the government to fulfill tasks with limited resources. Therefore, this perspective, which is known as the policy network perspective, emphasizes the importance of modeling interactions between different actors [23]. The relevant empirical research shows that the participation of the residents of a city exerts a positive impact on urban public environmental policy implementation [24–26]. This strand of studies again highlights policy executors as the leading actor to solve public management problems. But it acknowledges that the policy-based network among the upper government, local officials, and the civil society is more conducive to the implementation of city management policy.

Next, the strength of policy implementation is also a key choice variable in solving the conflict between the administrator and the speculator to reduce the negative externality of defection behaviors. Prior research has pointed out that it is necessary to adopt campaign-style enforcement as an alternative governance mechanism to prevent policy implementation failure [27–29]. However, the campaign-style enforcement of public management policy cannot fundamentally solve the problem of public management under resource constraints. Another way of thinking is to treat the relationship between the city manager and speculators under management as a typical interactive decision game [30–32]. Under the analytical framework of game theory, government officials try their best to implement policies that they anticipate to result in a better public environment. However, selfish individuals constantly speculate to seek policy loopholes for satisfying their private interests, leading to serious negative externalities. The public administrator cannot unilaterally control opponents' payoffs by using traditional game strategies, nor induce speculators to adopt spontaneous cooperative behaviors. Suppressing selfish behaviors in such a collaborative relationship is crucial to turn the current situation around. Fortunately, Press and Dyson [3] introduced a new class of game strategies, i.e., the ZD strategies, for the two-player and two-strategy iterated prisoner's dilemma. Using this new strategy class, a player can unilaterally pin down his or her opponents' expected payoff or extort the opponent player by enforcing a linear relationship between his or her and the opponents' payoffs in the iterated prisoner's dilemma game. Follow-up studies on the ZD strategy [33–36] have reshaped our understanding of the traditional game and expanded the theoretical foundation of applying the game theory to various management fields. To put it in another way, the ZD strategies gives policy implementer a strong control ability, which can, in turn, guarantee the opponents to behave cooperatively. The ZD strategies can be naturally extended to provide solutions to multiplayer iterated games in the context of public goods games. The extant literature tells us that ZD strategies are still effective with many players: a single player is able to unilaterally determine the expected total payoffs for all other players in the multiplayer iterated game setting.

In this paper, we have put the idea of ZD strategy in the evolutionary game into practice in the field of urban public management. Our purpose is to optimize the supervision intensity decision made by the administrator during the process of city management policy implementation. Compared with traditional game theory applications in solving public management problems and in exploiting ZD strategy advantages, we make a distinction between our research and existing works in the following respects. First, we study the urban public administration issues by endogenizing the choice of policy implementation strength by the public environment administrator. Second, we emphasize that the public environment administrator can unilaterally determine the payoffs of speculators and hence bring about spontaneous cooperative behaviors. This capability improves the efficiency of public management. Third, we advance the application-oriented research of ZD strategies [3] to a more generalized stage. In specific, we have taken a step further by extending the two-strategy game to a multi-strategy setting, which can be a big addition to deepen our understanding of cooperation evolution. Finally, we attempt to answer the pivotal but open question in urban public management: can government officials control the behavior of speculators and promote cooperation behavior through effective supervision mechanisms based on the ZD strategies instead of increasing the intensity of supervision and punishment?

3. The Model

3.1. Basic Setup and Payoff Matrix. A typical evolutionary game includes three main elements: the players, the game strategy set, and the payoff function. The players of our urban public management game are the speculator X and the administrator Y. The term "speculator" refers to individuals who engage in irregular or illegal activities to serve their self-interests, such as traffic offenders, unlicensed street vendors or peddlers, and enterprises polluting the natural environment. Let the "administrator" be a member of the government's corresponding administrative department, such as traffic police, a city management officer, and an environmental protection inspector.

The game strategy set includes alternative actions that can be taken by the players in each round of the game. For example, the players' strategy set comprises the cooperation and defection action in the famous prisoner's dilemma game. In our model, the speculator has two alternative actions, which are breaking the regulation $s_X(0)$ and obeying the regulation $s_X(1)$. We thus denote the strategy set of the speculator by $S_X = (s_X(0), s_X(1))$. Turning to the other side, the administrator can take different actions according to different levels of supervision intensity, which constitutes an important decision variable in our model. The supervision intensity $K \in [0, k]$ is a discrete random variable and the strictness of the supervision increases with the value of K. As the administrator can adopt different action strategies with changes in K, the strategy set of the administration is denoted by

$$S_Y = (s_Y(0), s_Y(1), s_Y(2), \ldots, s_Y(k)), \tag{1}$$

where $s_Y(0)$ and $s_Y(k)$ represent nonsupervision and complete supervision, respectively. In the urban public management game, a player will choose a strategy from the set, and the strategy pair (x, y) chosen by both players X and Y is a combination of strategies at each round of the game. When a certain action strategy combination is exogenously given, the result of the game can be expressed as the players' payoff function $u_X(x, y)$ and $u_Y(x, y)$.

The payoff function in city management is related to efficiency gains for the administrator; whereas it is about cost cuts for the speculator. The supervision intensity K will affect both the implementation cost and the expected return of the administrator. Suppose that the total cost of implementation is $k \times c$ at the supervision intensity of k. The reputation gains from efficient public management and the expected fines collected by punishing illegal behavior of speculators are $r_1(k)$ and $r_2(k)$, respectively. We further assume that the cost to speculators comprises two parts: the punishment cost $r_2(k)$ and the opportunity cost a. The opportunity cost equals the sum of gains abandoned when the speculator chooses to conform to laws and regulations. For example, a street peddler who chooses to observe the law will have to forgo illegal income from unlicensed operations and go through complex bureaucratic procedures to establish a real business and pay due taxes. The expected gains from the illegal behavior of speculators are R. According to the cost-benefit analysis conducted above, the payoff matrix of both players under different strategy combinations is given in Table 1.

3.2. Zero-Determinant Strategies in Multistrategy Games. Consider a k-strategy iterated public management game led by the administrator, in which certain intermediate stage games between the speculator and the administrator are infinitely iterated. The existing literature points out that for any strategy of the longer-memory player Y, the shorter-memory player X's score is exactly the same when the same game (same in the sense that the allowed moves and the payoff matrix are all identified) is indefinitely iterated. That is, a long-memory player has no advantage over short-memory players. Therefore, in our urban public management game, we can assume that a player's strategy in the current round of the game depends only on the outcome produced by the previous round. For each round of the game, the two players under concern may choose their respective game strategy from their respective strategy sets. Thus, the possible outcomes obtained by the speculator X with the strategy combination in each round of the game are

$$\begin{pmatrix} s_X(0)s_Y(0) & s_X(0)s_Y(1) & s_X(0)s_Y(2) & \ldots & s_X(0)s_Y(k) \\ s_X(1)s_Y(0) & s_X(1)s_Y(1) & s_X(1)s_Y(2) & \ldots & s_X(1)s_Y(k) \end{pmatrix}. \tag{2}$$

These elements can be denoted as $s_X(i)s_Y(j)$, $i \in \{0, 1\}$, $j \in \{0, 1, 2, 3, \ldots, k\}$, where k is a finite discrete random variable. For the speculator X, a mixed strategy p_{ij}^n $(0 \le p_{ij}^n \le 1,\ n \in \{0, 1\})$ is a vector that consists of conditional probabilities for each strategy $s_X(i)$. These probabilities are given, with respect to each of the possible game outcomes, as follows:

$$p_{ij}^n = \left(p_{00}^0, p_{00}^1, p_{01}^0, p_{01}^1, \ldots, p_{0k}^0, p_{0k}^1, p_{10}^0, p_{10}^1, p_{11}^0, p_{11}^1, \ldots, p_{1k}^0, p_{1k}^1\right), \tag{3}$$

where p_{ij}^n represents the probability of strategy $s_X(n)$ in the current round conditioning on the previous round's results. The superscript and subscript of p_{ij}^n represent the strategy combination of the previous game outcomes and the current game strategy of the speculator X, respectively. Take p_{00}^1 for example; it represents the probability that one simultaneously observes $s_X(1)$ being the present round game strategy and $(s_X(0), s_Y(0))$ being the previous game outcome.

Similarly, the possible outcomes obtained by the administrator Y in each round of the game can be given by

$$\begin{bmatrix} s_Y(0)s_X(0) & s_Y(0)s_X(1) \\ s_Y(1)s_X(0) & s_Y(1)s_X(1) \\ s_Y(2)s_X(0) & s_Y(2)s_X(1) \\ \ldots & \ldots \\ s_Y(k)s_X(0) & s_Y(k)s_X(1) \end{bmatrix}. \tag{4}$$

Table 1: The payoff matrix.

	$S_Y(0)$	$S_Y(1)$	$S_Y(2)$	...	$S_Y(k)$
$S_X(0)$	$a, r_1(0)$	$a, r_1(1) - c$	$a, r_1(2) - 2c$	...	$a, r_1(k) - kc$
$S_X(1)$	$R - r_2(0), r_2(0) + r_1(0)$	$R - r_2(1), r_2(1) + r_1(1) - c$	$R - r_2(2), r_2(2) + r_1(2) - 2c$	...	$R - r_2(k), r_2(k) + r_1(k) - kc$

An element in the above outcome matrix can be abstracted as $s_Y(j)s_X(i)$, $i \in \{0,1\}$, $j \in \{0,1,2,3,\ldots,k\}$. For the administrator Y, the conditional probabilities q_{ji}^m $(0 \le q_{ji}^m \le 1,\ m \in \{0,1,2,3,\ldots,k\})$ for the strategy $s_Y(j)$ with respect to each of these possible outcomes can be written as

$$q_{ji}^m = \left(q_{00}^0, q_{00}^1, \ldots, q_{00}^k, q_{01}^0, q_{01}^1, \ldots, q_{01}^k, \ldots, q_{10}^0, q_{10}^1, \ldots, q_{10}^k, \ldots, q_{k0}^0, q_{k0}^1, \ldots, q_{k0}^k, q_{k1}^0, q_{k1}^1, \ldots, q_{k1}^k\right), \tag{5}$$

where q_{ji}^m represents the probability of strategy $s_Y(m)$ in the current round conditional on the output of the previous round game. That is, the probability of having a supervision intensity of m is q_{ji}^m in the current round, conditional on the outcome of the previous game round.

Since this study considers a memory-one iterated game, the public management game can be characterized by a Markov chain. Suppose that $P(p,q)$ is used to represent the state transition probability matrix of this Markov process.

$$P(p,q) = \begin{bmatrix} p_{00}^0 q_{00}^0 & p_{00}^0 q_{00}^1 & \cdots & p_{00}^0 q_{00}^k & p_{00}^1 q_{00}^0 & p_{00}^1 q_{00}^1 & \cdots & p_{00}^1 q_{00}^k \\ p_{10}^0 q_{01}^0 & p_{10}^0 q_{01}^1 & \cdots & p_{10}^0 q_{01}^k & p_{10}^1 q_{01}^0 & p_{10}^1 q_{01}^1 & \cdots & p_{10}^1 q_{01}^k \\ p_{01}^0 q_{10}^0 & p_{01}^0 q_{10}^1 & \cdots & p_{01}^0 q_{10}^k & p_{01}^1 q_{10}^0 & p_{01}^1 q_{10}^1 & \cdots & p_{01}^1 q_{10}^k \\ p_{11}^0 q_{11}^0 & p_{11}^0 q_{11}^1 & \cdots & p_{11}^0 q_{11}^k & p_{11}^1 q_{11}^0 & p_{11}^1 q_{11}^1 & \cdots & p_{11}^1 q_{11}^k \\ p_{02}^0 q_{20}^0 & p_{02}^0 q_{20}^1 & \cdots & p_{02}^0 q_{20}^k & p_{02}^1 q_{20}^0 & p_{02}^1 q_{20}^1 & \cdots & p_{02}^1 q_{20}^k \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ p_{0k}^0 q_{k0}^0 & p_{0k}^0 q_{k0}^1 & \cdots & p_{0k}^0 q_{k0}^k & p_{0k}^1 q_{k0}^0 & p_{0k}^1 q_{k0}^1 & \cdots & p_{0k}^1 q_{k0}^k \\ p_{1k}^0 q_{k1}^0 & p_{1k}^0 q_{k1}^1 & \cdots & p_{1k}^0 q_{k1}^k & p_{1k}^1 q_{k1}^0 & p_{1k}^1 q_{k1}^1 & \cdots & p_{1k}^1 q_{k1}^k \end{bmatrix}. \tag{6}$$

In the above matrix $P(p,q)$, consider a previous round outcome $(s_X(0), s_Y(0))$. The conditional probabilities that the speculator X and the administrator Y select $s_X(0)$ and $s_Y(0)$ in the current game round are p_{00}^0 and q_{00}^0, respectively. Therefore, the probability of transitioning from the previous state $(s_X(0), s_Y(0))$ to the current state $(s_X(0), s_Y(0))$ is $p_{00}^0 q_{00}^0$. We denote by $\overline{P} = P - I$ such that

$$\overline{P}(p,q) = \begin{bmatrix} p_{00}^0 q_{00}^0 - 1 & p_{00}^0 q_{00}^1 & \cdots & p_{00}^0 q_{00}^k & p_{00}^1 q_{00}^0 & p_{00}^1 q_{00}^1 & \cdots & p_{00}^1 q_{00}^k \\ p_{10}^0 q_{01}^0 & p_{10}^0 q_{01}^1 - 1 & \cdots & p_{10}^0 q_{01}^k & p_{10}^1 q_{01}^0 & p_{10}^1 q_{01}^1 & \cdots & p_{10}^1 q_{01}^k \\ p_{01}^0 q_{10}^0 & p_{01}^0 q_{10}^1 & \cdots & p_{01}^0 q_{10}^k & p_{01}^1 q_{10}^0 & p_{01}^1 q_{10}^1 & \cdots & p_{01}^1 q_{10}^k \\ p_{11}^0 q_{11}^0 & p_{11}^0 q_{11}^1 & \cdots & p_{11}^0 q_{11}^k & p_{11}^1 q_{11}^0 & p_{11}^1 q_{11}^1 & \cdots & p_{11}^1 q_{11}^k \\ p_{02}^0 q_{20}^0 & p_{02}^0 q_{20}^1 & \cdots & p_{02}^0 q_{20}^k & p_{02}^1 q_{20}^0 & p_{02}^1 q_{20}^1 & \cdots & p_{02}^1 q_{20}^k \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ p_{0k}^0 q_{k0}^0 & p_{0k}^0 q_{k0}^1 & \cdots & p_{0k}^0 q_{k0}^k & p_{0k}^1 q_{k0}^0 & p_{0k}^1 q_{k0}^1 & \cdots & p_{0k}^1 q_{k0}^k \\ p_{1k}^0 q_{k1}^0 & p_{1k}^0 q_{k1}^1 & \cdots & p_{1k}^0 q_{k1}^k & p_{1k}^1 q_{k1}^0 & p_{1k}^1 q_{k1}^1 & \cdots & p_{1k}^1 q_{k1}^k - 1 \end{bmatrix}. \tag{7}$$

We further assume that the vector $v = (v_1, v_2, \ldots, v_{2(k+1)})$ is the stationary vector of the state transition matrix P. According to the properties of a random matrix, we obtain

$$v^T P = v^T \text{ or } v^T \overline{P} = 0. \tag{8}$$

The property of the determinant Cramer's rule, when applied to the matrix $\overline{P}$, can result in

$$\operatorname{Adj}(\overline{P})\overline{P} = \det(\overline{P})I, \tag{9}$$

where $\operatorname{Adj}(\overline{P})$ is the adjugate matrix of $\overline{P}$. As can be seen from the $P(p,q)$ matrix, we know that $p_{ij}^0 + p_{ij}^1 = 1$, $q_{ji}^0 + q_{ji}^1 + \cdots + q_{ji}^k = 1$, and the $P(p,q)$ matrix has the unit eigenvalue. Matrix $\overline{P}$ is singular, thus having a zero determinant. It satisfies the following condition:

$$\det(\overline{P}) = \det(\overline{P} - I) = 0. \tag{10}$$

Combining equations (8)–(10), we know that

$$\operatorname{Adj}(\overline{P})\overline{P} = \det(\overline{P})I = v^T \overline{P} = 0. \tag{11}$$

Equation (11) implies that every row of $\overline{P}$ is proportional to the vector v. Suppose that the last row of $\operatorname{Adj}(\overline{P})$ is $(A_{1(2k+2)}, A_{2(2k+2)}, A_{3(2k+2)}, \ldots, A_{(2k+2)(2k+2)})$, which is the algebraic cofactor of the last column of $\det(\overline{\mathrm{P}})$. From equation (11), there exists a constant $\phi \geq 0$ that satisfies

$$\begin{aligned} &\phi A_{1(2k+2)} = v_1, \\ &\phi A_{2(2k+2)} = v_2, \\ &\phi A_{3(2k+2)} = v_3, \ldots, \phi A_{(2k+2)(2k+2)} = v_{2k+2}. \end{aligned} \tag{12}$$

For an arbitrary vector $f = (f_1, f_2, \ldots, f_{2k+2})$, the inner product of $v \cdot f$ satisfies

$$\begin{aligned} v \cdot f = v_1 \cdot f_1 + v_2 \cdot f_2 + \cdots + v_{2k+2} \cdot f_{2k+2} = \phi A_{1(2k+2)} \\ \cdot f_1 + \phi A_{2(2k+2)} \cdot f_2 + \cdots + \phi A_{(2k+2)(2k+2)} \cdot f_{2k+2}. \end{aligned} \tag{13}$$

The Laplace transformation applied to $\det(\overline{P})$ generates

$$\begin{aligned} \det(\overline{P}(p,q)) = a_{1(2k+2)} \cdot A_{1(2k+2)} + a_{2(2k+2)} \\ \cdot A_{2(2k+2)} + \cdots + a_{(2k+2)(2k+2)} \cdot A_{(2k+2)(2k+2)}, \end{aligned} \tag{14}$$

where $a_{(2k+2)(2k+2)}$ is the last column of $\det(\overline{\mathrm{P}})$. If we change the last column of $\det(\overline{\mathrm{P}})$ to f, then we can further combine equations (13) and (14) to arrive at

$$\det(\overline{P}(p,q,f)) = D(p,q,f) = f_1 \cdot A_{1(2k+2)} + f_2 \cdot A_{2(2k+2)} + \cdots + f_{(2k+2)(2k+2)} \cdot A_{(2k+2)(2k+2)}, \tag{15}$$

$$v \cdot f = D(p,q,f) = \begin{bmatrix} p_{00}^0 q_{00}^0 - 1 & p_{00}^0 q_{00}^1 & \cdots & p_{00}^0 q_{00}^k & p_{00}^1 q_{00}^0 & p_{00}^1 q_{00}^1 & \cdots & f_1 \\ p_{10}^0 q_{01}^0 & p_{10}^0 q_{01}^1 - 1 & \cdots & p_{10}^0 q_{01}^k & p_{10}^1 q_{01}^0 & p_{10}^1 q_{01}^1 & \cdots & f_2 \\ p_{01}^0 q_{10}^0 & p_{01}^0 q_{10}^1 & \cdots & p_{01}^0 q_{10}^k & p_{01}^1 q_{10}^0 & p_{01}^1 q_{10}^1 & \cdots & f_3 \\ p_{11}^0 q_{11}^0 & p_{11}^0 q_{11}^1 & \cdots & p_{11}^0 q_{11}^k & p_{11}^1 q_{11}^0 & p_{11}^1 q_{11}^1 & \cdots & f_4 \\ p_{02}^0 q_{20}^0 & p_{02}^0 q_{20}^1 & \cdots & p_{02}^0 q_{20}^k & p_{02}^1 q_{20}^0 & p_{02}^1 q_{20}^1 & \cdots & f_5 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ p_{0k}^0 q_{k0}^0 & p_{0k}^0 q_{k0}^1 & \cdots & p_{0k}^0 q_{k0}^k & p_{0k}^1 q_{k0}^0 & p_{0k}^1 q_{k0}^1 & \cdots & f_{2k} \\ p_{1k}^0 q_{k1}^0 & p_{1k}^0 q_{k1}^1 & \cdots & p_{1k}^0 q_{k1}^k & p_{1k}^1 q_{k1}^0 & p_{1k}^1 q_{k1}^1 & \cdots & f_{2k-1} \end{bmatrix}. \tag{16}$$

In the urban public management game, the inner products $v \cdot u_X$ and $v \cdot u_Y$ yield the speculator X's and the administrator Y's expected payoffs, respectively, in the stationary state. Given equation (16), the inner products $v \cdot u_X$ and $v \cdot u_Y$ are equal to the determinants of the matrix that is obtained by replacing the last column of $\overline{P}$ by u_X and u_Y, respectively. In the stationary state, their respective normalization payoffs are then

$$\begin{aligned} U_X &= \frac{v \cdot u_X}{v \cdot 1} = \frac{D(p,q,u_X)}{D(p,q,1)}, \\ U_Y &= \frac{v \cdot u_Y}{v \cdot 1} = \frac{D(p,q,u_Y)}{D(p,q,1)}, \end{aligned} \tag{17}$$

where 1 is the vector with all components equating to unity. The payoff matrix of Table 1 indicates that

$$\begin{aligned} &u_X = (a, a, a, \ldots, R - r_2(0), R - r_2(1), \ldots, R - r_2(k)), \\ &u_Y = (r_1(0), r_1(1) - c, \ldots, r_1(k) - ck, r_2(0) \\ &\quad + r_1(1), \ldots, r_2(k) + r_1(k) - ck). \end{aligned} \tag{18}$$

According to the properties of matrix determinants, the determinants are unchanged if we add the second column to the k column of $D(p,q,u_Y)$ to the first column, or add the $k+n\,(2 \leq n \leq k-1)$ column to the n column. After performing a determinant-column addition operation on $D(p,q,u_Y)$, the administrator Y's expected payoffs can summarized as

$$v \cdot u_Y = D(p, q, u_Y) = \begin{bmatrix} p_{00}^0 - 1 & q_{00}^1 & q_{00}^2 & \cdots & p_{00}^0 q_{00}^k & p_{00}^1 q_{00}^0 & p_{00}^1 q_{00}^1 & \cdots & r_1(0) \\ p_{10}^0 - 1 & q_{01}^1 - 1 & q_{01}^2 & \cdots & p_{10}^0 q_{01}^k & p_{10}^1 q_{01}^0 & p_{10}^1 q_{01}^1 & \cdots & r_1(1) - c \\ p_{01}^0 - 1 & q_{10}^1 & q_{10}^2 - 1 & \cdots & p_{01}^0 q_{10}^k & p_{01}^1 q_{10}^0 & p_{01}^1 q_{10}^1 & \cdots & \vdots \\ p_{11}^0 & q_{11}^1 & q_{11}^2 & \cdots & p_{11}^0 q_{11}^k & p_{11}^1 q_{11}^0 & p_{11}^1 q_{11}^1 & \cdots & \vdots \\ p_{02}^0 & q_{20}^1 & q_{20}^2 & \cdots & p_{02}^0 q_{20}^k & p_{02}^1 q_{20}^0 & p_{02}^1 q_{20}^1 & \cdots & \vdots \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ p_{0k}^0 & q_{k0}^1 - 1 & q_{k0}^2 & \cdots & p_{0k}^0 q_{k0}^k & p_{0k}^1 q_{k0}^0 & p_{0k}^1 q_{k0}^1 & \cdots & \vdots \\ p_{1k}^0 & p_{k1}^2 & p_{k1}^2 & \cdots & p_{1k}^0 q_{k1}^k & p_{1k}^1 q_{k1}^0 & p_{1k}^1 q_{k1}^1 & \cdots & \vdots \end{bmatrix}. \quad (19)$$

It is noteworthy that equation (19) is a determinant whose first column $\hat{p} = (p_{00}^0 - 1, p_{10}^0 - 1, p_{01}^0 - 1, \ldots, p_{1k}^0)^T$ is solely determined by the speculator X. In contrast, any column $\hat{q}$, taken from the second column to the $k-1$ column, is under full control of the administrator Y. The administrator Y can unilaterally enforce a linear relationship between the two players' expected payoffs such that

$$\alpha U_X + \beta U_Y + \gamma = \frac{D(\hat{p}, \hat{q}, \alpha u_X + \beta u_Y + \gamma)}{D(\hat{p}, \hat{q}, 1)}, \quad (20)$$

where α, β, and γ are all constants. If the city administrator sets the probability of the supervision intensity $\hat{q}$ properly and lets it meet the following condition,

$$\hat{q} = \alpha u_X + \beta u_Y + \gamma, \quad (21)$$

then the determinant $D(\hat{p}, \hat{q}, \alpha u_X + \beta u_Y + \gamma)$ will vanish, and a linear relationship between the two players' expected payoffs can be established such that

$$\alpha U_X + \beta U_Y + \gamma = 0. \quad (22)$$

The mixed strategy $\hat{q}$ resulting in the linear equation (22) is called the multistrategy ZD strategy of a public management game. However, in contrast to the two-strategy game, the administrator Y can set any column from the second to $(k-1)$ of determinant $D(p, q, u_Y)$ equal to $\hat{q}$. Therefore, our model has multiple $(k-2)$ ZD strategies which are related to the number of strategies that can be chosen by the administrator Y at each interactive round of the game.

3.3. The Result of the Zero-Determinant Strategies. In the iterated game, the administrator Y chooses the supervision intensity k from the strategy set S_Y under the game played with the speculator X. Player Y can make a supervision decision based on enforcing the ZD strategies to improve the urban environment management efficiency. Now, we use the probability of supervision intensity $k = 1$ in the long-term iterated game as an example to analyze the results of the ZD strategies. This means that the administrator Y sets the second column of determinant $D(p, q, u_Y)$ equal to $\hat{q}$, that is, $\hat{q} = (q_{00}^1, q_{01}^1 - 1, \ldots q_{k1}^1)$.

We define $\beta = 0$ and $\hat{q} = \alpha u_X + \gamma$ in equation (20). So, Y needs only to play a mixed strategy satisfying the following condition:

$$\hat{q} = [\alpha(a, a, a, \ldots, a, R - r_2(0), R - r_2(1), \ldots, R - r_2(k)) + \gamma \cdot 1]^T, \quad (23)$$

which is a system of equations with $2k$ unknowns. In this situation, the linear relationship between the two players' expected payoffs becomes subject to

$$\alpha U_X + \gamma = D(p, \alpha u_X + \gamma, \alpha u_X + \gamma) = 0, \quad U_X = -\frac{\gamma}{\alpha}. \quad (24)$$

Equation (24) implies that the administrator X unilaterally pins down the speculator X's expected payoffs at the level of $-(\gamma/\alpha)$. The speculators can get extra expected payoffs from speculation behavior, but the administrator can set the value $-(\gamma/\alpha)$ to reduce the expected payoffs and speculation behavior.

Let the equation $\gamma = -(\alpha + \beta)\pi$ hold. Then, equation (22) satisfies

$$\alpha U_X + \beta U_Y - (\alpha + \beta)\pi = 0, \quad (U_Y - \pi) = -\frac{\alpha}{\beta}(U_X - \pi), \quad (U_Y - \pi) = \lambda(U_X - \pi), \quad (25)$$

where $\pi \le R$ and $\lambda = -(\alpha/\beta) > 1$ are constants. The administrator Y can guarantee his own surplus expected payoffs over the speculator X's λ-fold if Y plays a mixed strategy satisfying $\hat{q} = \theta[(u_Y - \pi) - \lambda(u_X - \pi)]$. This is a substrategy, called the λ-extortion, of ZD strategies. Given u_X and u_Y, $\hat{q}$ satisfies the definition as follows:

$$\hat{q} = \theta[((r_1(0), \ldots, r_1(k) - ck, \ldots, r_2(k) + r_1(k) - ck) - \pi) - \lambda((a, \ldots, a, R - r_2(0), \ldots, R - r_2(k)) - \pi)]^T, \quad (26)$$

where a sufficiently small $\theta \geq 0$ is a free parameter to ensure the probability stay within the range of $0 \leq q_{ji}^1 \leq 1$. Equation (25) shows that, irrespective of how speculators evade regulation, the administrator can obtain a higher expected payoff by setting the probability of the mixed strategy $s_Y(1)$ to the holding of equation (26).

4. Numerical Examples

The results of the ZD strategies analyzed in the previous section show that the administrator can, in theory, enforce the ZD strategy to unilaterally define a linear relationship between two players' long-term payoffs. In order to illustrate how the administrator enforces the ZD strategy and provide supportive evidence for the theoretical predictions of the model, we specifically suppose that the administrator Y has three strategies available with $k = 3$ and use numerical examples to fix the specific forms of the function $r_1(k)$ and $r_2(k)$. By doing this, we can get analytical results of the equations (23)–(26). Let the functions $r_1(k)$ and $r_2(k)$ in the payoff matrix take the following form:

$$r_1(k) = \ln(m + k), \tag{27}$$

$$r_2(k) = nk, \tag{28}$$

where the parameters m and n are constants, representing scale parameters in the particular function specifications.

Looking at the second column of equation (19), together with equation (27) and equation (28), we know that the equation system (23) should meet the following list of conditions:

$$\begin{cases} q_{00}^1 = \alpha a + \gamma, \\ q_{01}^1 - 1 = \alpha a + \gamma, \\ q_{10}^1 = \alpha a + \gamma, \\ q_{11}^1 = \alpha R + \gamma, \\ q_{20}^1 - 1 = \alpha(R - n) + \gamma, \\ q_{21}^1 = \alpha(R - 2n) + \gamma. \end{cases} \tag{29}$$

Once the probability q_{11}^1 is identified, the analytical solution to equation (30) can be written as

$$\begin{cases} q_{00}^1 = 0, \\ q_{01}^1 = 1, \\ q_{10}^1 = 0, \\ q_{20}^1 = \dfrac{q_{11}^1}{R - a}(R - n - a) + 1, \\ q_{21}^1 = \dfrac{q_{11}^1}{R - a}(R - 2n - a), \end{cases} \tag{30}$$

in which the parameters R, n, and a are constant terms. Equation (30) hence supports the theoretical results of the ZD strategies in the mixed strategy game. This result shows that the administrator can decide the supervision intensity k according to the probability specified by equation (30) and can unilaterally pin down the speculator's expected payoffs. For example, a probability $q_{01}^1 = 1$ means that the supervision intensity $s_Y(1)$ must be selected by the administrator for the current game round, conditional on the previous game outcome $(s_Y(0), s_X(1))$, which is similar to the tit-for-tat (TFT) strategy [12]. In this situation, the speculator X's expected payoffs are fixed at

$$U_X = \frac{\nu \cdot u_X}{\nu \cdot 1} = -\frac{\gamma}{\alpha} = a. \tag{31}$$

Equation (31) shows that the administrator can unilaterally determine the expected payoffs of the speculators as the opportunity cost of legal behavior a. However, the result is independent of the supervision intensity k and the specific functional forms of $r_1(k)$ and $r_2(k)$. In real life, speculation behavior is often reduced during a campaign of high-intensity enforcement. However, once extraordinary measures are relaxed, the speculation behavior will probably return to its previous high level. This means that the administrator's supervision mode, which is characterized by an increase in supervision and punishment, not only increases the cost of management but also fails to reduce speculation in a fundamental sense.

The administrator should enforce the ZD strategy and reduce the speculator's opportunity cost a of legal behaviors. Therefore, the speculator X's expected payoffs will decrease, and speculators will change their behavior from speculation to cooperation. The public administrator must change the management model from stronger supervision to improving the public management environment and incorporating better service. For example, public administrators should plan urban parking spaces reasonably and reduce parking costs for illegal parking behavior performed by drivers. The administrator should strengthen the government's planning to legalize the activities of peddlers and scientifically plan the number, location, and business hours for peddlers to avoid adversely affecting the daily life of other urban residents. These similar measures, which represent upgrades to administrators' services, improve the public environment and can effectively reduce the opportunity cost a of law-abiding behavior. The numerical example of our model explains again that the ZD strategy and a change in the administrator's management model can promote the emergence of cooperative behavior and efficiency of public management decision-making.

Regarding to the second column of equation (19) and the constraints in equations (27)–(29), the administrator enforces the strategy $\hat{q} = \theta[(u_Y - \pi) - \lambda(u_X - \pi)]$ that satisfies

$$\begin{cases} q_{00}^1 = \theta[(\ln(m) - \pi) - \lambda(a - \pi)], \\ q_{01}^1 - 1 = \theta[(\ln(m+1) - c - \pi) - \lambda(a - \pi)], \\ q_{10}^1 = \theta[(\ln(m+2) - 2c - \pi) - \lambda(a - \pi)], \\ q_{11}^1 = \theta[(\ln(m) - \pi) - \lambda(R - \pi)], \\ q_{20}^1 - 1 = \theta[(n - c + \ln(m+1) - \pi) - \lambda(R - n - \pi)], \\ q_{21}^1 = \theta[(2n - 2c + \ln(m+2) - \pi) - \lambda(R - 2n - \pi)], \end{cases} \tag{32}$$

where the parameters a, R, π, n, and m all take constant values. As long as θ is small enough, it is guaranteed that $0 \leq q_{ji}^1 \leq 1$.

Under the extortion of the ZD strategy $\widehat{q} = \theta[(u_Y - \pi) - \lambda(u_X - \pi)]$, the administrator Y's expected payoffs depend on X's strategy probability, and the speculator X's expected payoffs are maximized when X is fully cooperative, with $\widehat{p} = (p_{00}^0, p_{01}^0, p_{10}^0, p_{11}^0, p_{20}^0, p_{21}^0) = (1, 1, 1, 1, 1, 1)$. Equation (25) shows that the rational fully cooperative behavior of the speculator X will maximize both the players' expected payoffs simultaneously. The result shows that the extortion of strategy will force speculators to choose the strategy of full cooperation (law-abiding behaviors), which is the ideal outcome of the public management game for the administrator. If the probability supervision intensity decision satisfies equation (32), the expected payoffs of both players are, respectively,

$$U_X = R - 2n, \tag{33}$$

$$U_Y = \pi - \lambda(\pi - R + 2n). \tag{34}$$

Equations (33) and (34) together reveal that the surplus expected payoff $U_Y - \pi$ is a λ-fold version of $U_X - \pi$ when the speculator X is fully rational and behaves in a completely cooperative way.

Irrespective of how the speculator chooses the probability of cooperation and defection, the administrator can determine that his surplus payoffs will exceed those of the speculator. However, the size of the surplus payoff $U_Y - \pi$ of the administrator depends on the strategy of the speculator. Therefore, the administrator should guide speculators to adopt full cooperation that maximizes the expected payoffs of both players and improve the decision-making efficiency through the emergence of cooperative behavior. For example, business regulators should reduce the fees and the complexity of approval procedures, and the number of businesses operating without a license will decline. The urban public manager should lower the threshold of access and subsidize the early stage of legal operation for the peddler.

5. Conclusion

The ZD strategies for two-strategy games have changed our understanding of game theory, the ZD approach allows a player to unilaterally determine the expected payoffs of the opponent and have stronger control ability than traditional strategies, such as the TFT, generous TFT (GTFT), and win-stay-lose-shift (WSLS) strategies. There are many interaction phenomena involving regulation and speculation in politics, economics, society, and life. Group decision-making exists widely in society [37, 38]. Selfish defection behavior will lead to the tragedy of the commons and reduce the welfare of the whole society. Therefore, improving cooperative behavior is of great significance in solving social difficulties.

The supervision intensity decision is an important problem in policy implementation in public management. For more general application and research of ZD strategies, we have taken a step beyond a two-strategy game to a multistrategy game, with the iterated urban public management game as the scenario. We prove the existence of ZD strategies for multistrategy games by constructing a direct extension of Press and Dyson's method [3]. Moreover, the conditions of the multistrategy, as well as those of the extortion strategy, are carefully discussed. The results confirm that multiple ZD strategies are different from the two-player games, and the quantity is related to the number of strategies for the player in each round of the game. The administrator can unilaterally control the expected payoffs of speculators and promote the emergence of cooperative behaviors, by enforcing the ZD strategies to determine the level of supervision intensity in policy implementation.

Data Availability

This is a theoretical article with no data available.

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

Evaluation of Vegetable Circulation Efficiency and Analysis of Influencing Factors in Henan Province

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In order to explore the deep-seated reasons affecting the development of vegetable circulation in Henan Province, combined with the panel data of Henan Province from 2014 to 2019, this paper first makes a static analysis on the vegetable circulation efficiency in Henan Province by using DEA method. Second, the Malmquist method is used to establish the total factor productivity evaluation model of vegetable circulation in Henan Province, and the dynamic analysis is carried out. The analysis results show that the main problem in the development of vegetable circulation in Henan Province is the low level of management and technology. Then, GM(1, N) model is established to further analyze the specific factors affecting the vegetable circulation efficiency in Henan Province. Finally, some reasonable suggestions are put forward for the development of vegetable circulation in Henan Province.

1. Introduction

Vegetable circulation plays a very important role in commodity circulation, which is not only related to the vital interests of farmers but also related to the development of China's agricultural economy. Vegetable circulation is the link between production and sales, also an important guarantee to realize the value of vegetables and increase farmers' income. In economics, efficiency usually refers to the ratio of output to input in economic activities. Vegetable circulation efficiency refers to the ratio of output to input in the process of vegetable circulation, which reflects the effectiveness of resource allocation. In recent years, the scale of vegetable production in Henan Province has expanded year by year. In order to ensure the increase of farmers' production and income, it is urgent to improve the efficiency of vegetable circulation and promote the high-quality development of vegetable circulation. Therefore, the research on vegetable circulation efficiency has important practical significance.

The research of vegetable circulation efficiency not only enriches the theoretical system of vegetable circulation research and expands the space and vision of vegetable circulation research but also reduces the cost and loss of vegetable circulation, which is conducive to improving the income level of farmers. Scholars have studied the current situation and problems of vegetable circulation from different perspectives. Zhang [1] believes that the main problems existing in the circulation of vegetable market in China are the lag of infrastructure construction of vegetable market, the imperfection of vegetable market system and market mechanism, and the low degree of organization of vegetable circulation subject. Yuan and Xin [2] believe that government departments should formulate relevant flexible policies, stabilize vegetable production and sales prices, monitor the demand change information of residents in real time, and guide farmers to plant differently. Wang and Chen [3] believe that the main problems in China's vegetable circulation are low degree of organization, many circulation links, and low degree of standardization. Wu and Mu [4] used the spatial dynamic panel model to analyze the spatial-temporal correlation and influencing factors of regional circulation of vegetables. Kuang et al. [5] believe that cultivating and strengthening the main body of production and dredging the links of production and marketing are powerful means to promote the quality and efficiency of vegetable industry. Shang and Huang [6] found that the traditional vegetable circulation mode occupies the main position, and the wholesale market occupies the core position in the vegetable circulation. Shen et al. [7] proposed strengthening the release of information early warning, guiding farmers to grow rationally, innovating and improving the circulation mode, and promoting the docking of vegetable production and marketing. Shen and Mu [8] found that Beijing vegetable market operation has obvious seasonality.

On the analysis and evaluation of vegetable circulation efficiency, scholars have studied it from various angles and achieved fruitful results. Zhou and Lu [9] analyzed the efficiency of different circulation channels of fresh vegetables in Nanjing. Su [10] thought that the circulation efficiency of agricultural products mainly depends on the wholesale link and proposed that the construction of agricultural products wholesale market should be strengthened. He and Wu [11] proposed measures to solve the problem of vegetable circulation efficiency in Wuhan from the perspective of economical circulation mode and administrative management. Guo [12] used data envelopment model to analyze and evaluate the channel efficiency with large supermarket chains as retail terminals. Jiang et al. [13] used analytic hierarchy process to calculate the weight of influencing factors in vegetable circulation and specifically analyzed the main influencing factors in the evaluation results. Jiang [14] constructed the circulation efficiency model of vegetables in Beijing suburbs and analyzed the decisive factors affecting the circulation efficiency. Zhang [15] conducted an empirical analysis on the circulation efficiency of vegetables and analyzed the deep-seated factors affecting the circulation efficiency of vegetables in China. Kim and An [16] used DEA method to study the technical efficiency of rice and vegetable farms. Shrestha et al. [17] used DEA method to evaluate the economic benefits of vegetable farms in Nepal. Shan [18] used data envelopment analysis method to analyze the circulation efficiency of real estate vegetables in Harbin from two aspects of input and output and put forward the optimization path of circulation efficiency of real estate vegetables from four aspects of circulation subject, circulation channel, circulation object, and circulation guarantee measures. Peng and Nan [19] used DEA-Malmquist method to analyze the differences of vegetable circulation efficiency between eastern China and Western China. Zheng [20] measured the circulation efficiency of fresh vegetables from the perspective of industrial chain and put forward the promotion strategy. Li and Mu [21] used the DEA Tobit two-stage model to analyze the vegetable circulation efficiency of farmers in different channels under the wholesale market dominant mode and found that the age of the head of household, the number of years engaged in vegetable production, the distance between the agricultural product market and home, and whether to join the cooperative are the main factors affecting the vegetable circulation efficiency of farmers. Akamin et al. [22] used the stochastic frontier analysis method to estimate the technical efficiency of vegetable farmers and tested its influencing factors. Anik and Salam [23] estimated the driving factors and technical efficiency of okra and eggplant production. Ye [24] used DEA model to evaluate the efficiency of main circulation modes of leafy vegetables in Nanchang suburbs. Bournaris et al. [25] used DEA method to evaluate the production efficiency of greenhouse vegetables. Nedumaran et al. [26] constructed the fresh fruit and vegetable supply chain model and improved the efficiency of the fresh vegetable supply chain.

From the existing research results, domestic scholars mainly focus on theoretical research on the current situation and problems of vegetable circulation. On the analysis and evaluation of vegetable circulation efficiency, foreign scholars mainly focus on the efficiency research in the field of vegetable production, while domestic researches mostly focus on the efficiency research of leading vegetable wholesale market or core vegetable circulation enterprises and take the efficiency of leading vegetable wholesale market or core vegetable circulation enterprises as the evaluation standard of vegetable circulation efficiency in specific areas. It has the disadvantage of generalizing. Due to the lack of a perfect statistical index system in China's vegetable circulation industry, the relevant evaluation indexes have the characteristics of small samples, and even some evaluation indexes still have the problem of lack of data. Using traditional methods such as econometric regression to analyze and evaluate the efficiency of vegetable circulation may produce large deviation. In addition, the vegetable circulation system is a complex system, so it is difficult to find a suitable function model to analyze the circulation efficiency. The Malmquist index analysis method of data envelopment analysis (DEA) has the advantages of no need to set the function form in advance and being not affected by the number of samples and variable dimensions. It can effectively avoid the deviation of the preset model, realize the dynamic cross period measurement of efficiency, decompose the Malmquist index, and find the reasons for the change of the index. DEA-Malmquist method has become the mainstream method of efficiency evaluation. This paper uses DEA-Malmquist method to analyze and evaluate the efficiency of vegetable circulation in Henan Province from both static and dynamic perspectives.

On the research of influencing factors of vegetable circulation efficiency, the existing research results have reference significance for this paper, but little or no consideration has been given to the grey characteristics of influencing factors of vegetable circulation, such as partial information known, partial information unknown, and poor information. GM(1, N) model is one of the grey models considering the influence of many factors, and it has been widely used and innovated. Ma and Liu [27] constructed a discrete GM(1, N) model to analyze the basic law of oil production decline and the related influencing factors; Jiang et al. [28] put forward an improved GM(1, N) model to forecast China's foreign direct investment; Xiong et al. [29] proposed AWGM(1, N) model to predict housing demand; Yang and Li [30] used GM(1, N) model to predict the grain yield in

China. This paper selects the grey GM(1, N) model to analyze the influencing factors of vegetable circulation efficiency in Henan Province, explores the deep-seated reasons of influencing vegetable circulation efficiency, and puts forward suggestions for improvement, so as to promote the high-quality development of vegetable circulation industry in Henan Province.

2. Research Methods

At present, the analysis and evaluation methods of commodity circulation efficiency mainly include comprehensive evaluation method, frontier analysis method, and data envelopment analysis (DEA). The comprehensive evaluation method is subjective and has some human errors. The frontier analysis method is suitable for the efficiency evaluation of single output and needs large data samples, while the DEA method is suitable for the efficiency evaluation of multiple inputs and multiple outputs. Therefore, DEA method has become the mainstream way of efficiency evaluation.

2.1. DEA-BCC Model. CCR model and BCC model are widely used in DEA. Among them, the CCR model assumes that the return to scale of the decision-making unit is fixed, while the BCC model assumes that the return to scale of the decision-making unit is variable. Because there are many subjects to study and it is impossible to achieve the optimal production scale at the same time, and BCC model has the advantage of evaluating the relative technical effectiveness between different decision-making units, this paper uses BCC model for efficiency analysis and evaluation. Assuming that there are n decision-making units, the BCC model can be expressed as

$$\min \theta = V_D,\quad \text{s.t.} \begin{cases} \sum_{i=1}^{n} \lambda_i x_i + S^- = \theta x_t \\ \sum_{i=1}^{n} \lambda_i y_i - S^+ = y_t \\ \sum_{i=1}^{n} \lambda_i = 1,\ i = 1, 2, \ldots, n \\ \lambda_i \geq 0,\ S^-,\ S^+ \geq 0 \end{cases}. \tag{1}$$

In the above equation, θ is the comprehensive efficiency value of the r-th decision-making unit, which can be decomposed into technical efficiency and scale efficiency; S^- and S^+ are input slack variables and output slack variables, respectively; λ_i is the weight of the i-th decision-making unit. When $V_D = 1$ and $S^- = 0$ and $S^+ = 0$, then the r-th decision-making unit is DEA efficient. When $V_D \neq 1$, it means that the r-th decision-making unit is DEA invalid.

2.2. Malmquist Index Model. In 1953, Malmquist, a Swedish economist and statistician, first proposed the Malmquist index model when he studied the consumption problem. After combining with DEA theory, Malmquist index model has been widely used in the field of efficiency evaluation. Malmquist index focuses on observing the relative changes of multiperiod indexes, which is helpful to analyze the dynamic changes of efficiency. The basis of Malmquist index is distance function, which is the reciprocal of the comprehensive efficiency of BCC model. Malmquist index measures the dynamic change of TFP from t period to $t+1$ period.

Suppose that the distance function $D^t(x_r^{t+1}, y_r^{t+1})$ of Malmquist index is obtained by DEA model; then the Malmquist index from t period to $t+1$ period of the r-th decision-making unit can be expressed as

$$\begin{aligned} \mathrm{TFP} &= \left[\frac{D^t\left(x_r^{t+1}, y_r^{t+1}\right)}{D^{t+1}\left(x_r^{t+1}, y_r^{t+1}\right)} \times \frac{D^t\left(x_r^t, y_r^t\right)}{D^{t+1}\left(x_r^t, y_r^t\right)}\right]^{1/2} \times \frac{D^{t+1}\left(x_r^{t+1}, y_r^{t+1}\right)}{D^t\left(x_r^t, y_r^t\right)} \\ &= \mathrm{TC} \times \mathrm{EC} = \mathrm{TC} \times \mathrm{PE} \times \mathrm{SE}. \end{aligned} \tag{2}$$

Malmquist index is the change degree of total factor productivity (TFP). When $\mathrm{TFP} > 1$, TFP shows an upward trend; $\mathrm{TFP} = 1$ indicates that TFP will not change with time. When $\mathrm{TFP} < 1$, TFP shows a downward trend. TFP can be decomposed into technical change (TC) and efficiency change (EC), and EC can be further decomposed into pure technical efficiency (PE) and scale efficiency (SE).

TC reflects the innovation level of technological innovation and management methods. When $\mathrm{TC} > 1$, it indicates technological progress; otherwise, technology will regress. EC measures whether there is a waste of input factors and whether the resource allocation is optimal. When $\mathrm{EC} > 1$, the technical efficiency is improved; otherwise, the technical efficiency is reduced. SE reflects whether the decision-making unit is in the optimal scale. When $\mathrm{SE} > 1$, it indicates that the evaluation object should expand the scale; otherwise, it should reduce the scale. PE reflects the effective utilization degree of the technology and management of the evaluation object. When $\mathrm{PE} > 1$, it indicates that the pure technical efficiency is improved; otherwise, the pure technical efficiency is decreased.

2.3. GM(1, N) Model. Although DEA-Malmquist method realizes the measurement and analysis of efficiency, it does not get the specific influencing factors of efficiency, so it is necessary to analyze the specific influencing factors of efficiency. GM(1, N) model is a differential equation prediction model with first-order N variables, which reflects the influence of $N-1$ influencing factor variables on the first derivative of one system behavior variable. The characteristic sequence of system behavior can be expressed as

$$X_1^{(0)} = \left(x_1^{(0)}(1), \ldots, x_1^{(0)}(i), \ldots, x_1^{(0)}(n)\right). \tag{3}$$

Influencing factor sequence X_i' $(i = 1, 2, \ldots, m)$ can be expressed as

$$\begin{aligned} X_2^{(0)} &= \left(x_2^{(0)}(1), \ldots, x_2^{(0)}(i), \ldots, x_2^{(0)}(n)\right), \\ X_3^{(0)} &= \left(x_3^{(0)}(1), \ldots, x_3^{(0)}(i), \ldots, x_3^{(0)}(n)\right), \\ &\vdots \\ X_N^{(0)} &= \left(x_N^{(0)}(1), \ldots, x_N^{(0)}(i), \ldots, x_N^{(0)}(n)\right). \end{aligned} \tag{4}$$

Let $X_j(1)$ be the 1-AGO sequence of $X_j(0)$ $(j = 1, 2, \ldots, N)$ and let $Z^{(1)}$ be the nearest neighbor mean generating sequence of $X_1{}^{(1)}$; then

$$x_1^{(0)}(k) + a(z)_1^{(1)}(k) = \sum_{j=2}^{N} b_j x_j^{(1)}(k), \quad k = 1, 2, \ldots, n, \tag{5}$$

is called GM(1, N) model.

When the amplitude of change of $X_j{}^{(1)}$ $(j = 1, 2, \ldots, N)$ is very small, the approximate time response of GM(1, N) is as follows:

$$\widehat{x}_1(k+1) = \frac{1}{\alpha}\sum_{j=2}^{N} b_i(x)_i^{(1)}(k+1) + \left[(x)_1^{(1)}(0) - \frac{1}{a}\sum_{j=2}^{N} b_i(x)_i^{(1)}(k+1)\right]e^{-ak}, k = 1, 2, \ldots, n, \tag{6}$$

where $x_1{}^{(1)}(0)$ is taken as $x_1{}^{(0)}(1)$.

The predicted values of system behavior variables are as follows:

$$\widehat{x}_1^{(0)}(k+1) = \widehat{x}_1^{(1)}(k+1) - \widehat{x}_1^{(1)}(k). \tag{7}$$

3. Empirical Analysis

Based on the relevant research results at home and abroad, considering the validity and availability of sample data and the requirements of DEA model, this paper analyzes and evaluates the vegetable circulation efficiency of Henan Province from 2014 to 2019. The sample data comes from Henan statistical yearbook, and the relevant data from 2014 to 2019 are selected for research. The number of employees in transportation, warehousing, wholesale, and retail industries has a missing value, which is supplemented by the average value of the years before and after the missing value.

3.1. Evaluation Index of Vegetable Circulation Efficiency in Henan Province. Input indicators are measured from two aspects: labor input X_1 (expressed by the total number of employees in transportation, as well as storage and wholesale and retail industries related to vegetable circulation) and capital input X_2 (expressed by the total fixed investment in transportation, as well as storage and wholesale and retail industries related to vegetable circulation). The output index is measured by the total amount of vegetable circulation Y, which is expressed by the total amount of vegetable consumption of urban residents. The evaluation index system of vegetable circulation efficiency is shown in Table 1.

Table 1: Evaluation index system of vegetable circulation efficiency in Henan Province.

Criterion layer	Index layer
Input index	Labor input Capital input
Output index	Total circulation of vegetables

3.2. Factors Influencing Vegetable Circulation Efficiency in Henan Province. In order to further investigate the specific influencing factors of vegetable circulation efficiency in Henan Province, according to the relevant theories of commodity circulation and referring to the relevant research results at home and abroad, the vegetable circulation efficiency is selected as the explained variable, and then the transportation infrastructure construction (expressed by highway mileage), labor quality (expressed by the number of college graduates), and the quality of labor force (expressed by the number of college graduates) are selected. Industrial structure (expressed by the proportion of the tertiary industry in GDP), consumption capacity (expressed by the total food consumption expenditure of urban residents), informatization level (expressed by the total telecommunications business), and government support (expressed by the general public budget expenditure of transportation) are used as explanatory variables to establish a grey GM(1, N) model and analyze the influencing factors. The influencing factors of vegetable circulation efficiency are shown in Table 2.

3.3. Static Analysis of DEA Model. Comprehensive efficiency is a comprehensive measure and evaluation of the resource allocation ability and utilization efficiency of decision-making units. Pure technical efficiency is the production efficiency influenced by management level and technical level, while scale efficiency is the production efficiency influenced by production scale. Deap 2.1 software is used to analyze the vegetable circulation efficiency of Henan Province in 2014 and 2019, and the comprehensive efficiency value, pure technical efficiency value, and scale efficiency value of vegetable circulation efficiency are obtained. The results are shown in Table 3.

(1) From the comprehensive efficiency index, the vegetable circulation efficiency of Henan province did not reach DEA efficiency in 2014 and 2019, and the comprehensive efficiency values were 0.789 and 0.772, respectively. From the regional point of view, there are some differences in the circulation

Table 2: Influencing factors of vegetable circulation efficiency in Henan Province.

Influence factors	Description
Transportation infrastructure construction	Expressed by highway mileage
Quality of labor force	Expressed by the number of college graduates
Industrial structure	Expressed by the proportion of the tertiary industry in GDP
Consumption power	Expressed by the total food consumption expenditure of urban residents
Informatization level	Expressed by the total amount of telecommunication services
Government support	Expressed by the general public budget expenditure of transportation

Table 3: Vegetable circulation efficiency of Henan Province in 2014 and 2019.

Prefecture	2014				2019			
	Synthetic efficiency	Technical efficiency	Scale efficiency	Returns to scale	Synthetic efficiency	Technical efficiency	Scale efficiency	Returns to scale
Zhengzhou	0.708	1	0.708	drs	0.782	1	0.782	drs
Kaifeng	0.660	0.702	0.940	drs	0.932	1	0.932	irs
Luoyang	1	1	1	—	0.755	0.812	0.929	drs
Pingdingshan	0.928	0.992	0.936	drs	1	1	1	—
Anyang	0.820	0.903	0.908	drs	1	1	1	—
Hebi	1	1	1	—	0.913	1	0.913	irs
Xinxiang	0.901	1	0.901	drs	0.891	0.891	0.999	irs
Jiaozuo	0.566	0.587	0.964	drs	0.703	0.721	0.975	irs
Puyang	0.862	0.902	0.956	drs	0.574	0.591	0.971	irs
Xuchang	0.529	0.578	0.916	drs	0.774	0.785	0.985	irs
Luohe	0.908	0.942	0.964	irs	0.624	0.647	0.965	irs
Sanmenxia	0.549	0.641	0.857	irs	0.855	0.888	0.963	irs
Nanyang	0.952	1	0.952	drs	0.850	0.999	0.851	drs
Shangqiu	0.598	0.606	0.986	drs	0.443	0.461	0.960	irs
Xinyang	0.745	0.774	0.962	drs	0.628	0.631	0.995	drs
Zhoukou	0.726	0.733	0.989	drs	0.825	0.963	0.857	drs
Zhumadian	1	1	1	—	0.536	0.543	0.987	irs
Jiyuan	0.754	1	0.754	irs	0.805	1	0.805	irs
Evaluation value	0.789	0.853	0.927		0.772	0.830	0.937	

efficiency of different regions. Except for Luoyang, Hebi, Xinxiang, Puyang, Luohe, Nanyang, Shangqiu, Xinyang, and Zhumadian, the comprehensive efficiency of other regions is increasing. Pingdingshan and Anyang would reach the production frontier in 2019, which shows that the optimal allocation of resource input in these areas has been realized, the structure is reasonable, and the input-output has reached the optimal effect. Shangqiu, Zhumadian, and Puyang are in the last three places, and the comprehensive efficiency values are 0.443, 0.536, and 0.574, respectively. The main reason is that the technical efficiency is too low. Therefore, these areas should pay attention to improving the management level and technical level.

(2) From the technical efficiency index, the technical efficiencies of vegetable circulation in Henan Province in 2014 and 2017 were 0.853 and 0.937, respectively, which did not reach the production frontier, indicating that the management level and technical level are the main reasons restricting the improvement of vegetable circulation efficiency in Henan Province. In 2014 and 2017, Zhengzhou, Hebi, and Jiyuan are the regions with effective technical efficiency, which indicates that these cities are more advanced in management and technology, and resources have been fully utilized. The scale efficiency value is the main reason for the low comprehensive efficiency of these cities. These areas should adjust the investment scale to improve the scale efficiency index.

(3) From the scale efficiency index, the scale efficiencies of vegetable circulation in Henan Province in 2014 and 2017 were 0.927 and 0.937, respectively. The scale efficiencies of Zhengzhou, Nanyang, Zhoukou, and Jiyuan are at a low level, among which Zhengzhou, Nanyang, and Zhoukou are areas with increasing returns to scale. We should appropriately increase the input of labor, capital, and other factors and reasonably allocate the proportion to ensure the full use of resources. Jiyuan belongs to the area of diminishing returns to scale, so the direction of capital use should be adjusted.

3.4. Dynamic Analysis of Malmquist Index. Malmquist index can dynamically reflect the change trend of the overall efficiency of vegetable circulation in Henan Province.

Table 4: Malmquist index of vegetable circulation in Henan Province from 2014 to 2019.

Year	Technical efficiency	Technical progress	Pure technical efficiency	Scale efficiency	Total factor productivity
2014-2015	1.048	0.834	1.035	1.012	0.874
2015-2016	0.940	1.113	0.947	0.993	1.046
2016-2017	1.036	0.871	1.060	0.978	0.902
2017-2018	0.987	0.944	0.967	1.021	0.932
2018-2019	0.970	1.112	0.961	1.009	1.079
Mean value	0.995	0.968	0.993	1.002	0.963

Table 5: Malmquist index of vegetable circulation in Henan Province.

Prefecture	Technical efficiency	Technical progress	Pure technical efficiency	Scale efficiency	Total factor productivity
Zhengzhou	1.020	0.948	1.000	1.020	0.967
Kaifeng	1.071	1.044	1.073	0.998	1.118
Luoyang	0.945	0.944	0.959	0.985	0.893
Pingdingshan	1.015	0.962	1.002	1.013	0.976
Anyang	1.041	1.027	1.021	1.020	1.068
Hebi	0.982	0.963	1.000	0.982	0.945
Xinxiang	0.998	0.956	0.977	1.021	0.954
Jiaozuo	1.044	0.931	1.042	1.002	0.973
Puyang	0.922	0.944	0.919	1.003	0.871
Xuchang	1.079	0.933	1.063	1.015	1.006
Luohe	0.928	0.934	0.928	1.000	0.867
Sanmenxia	1.093	0.937	1.067	1.024	1.024
Nanyang	0.978	0.968	1.000	0.978	0.946
Shangqiu	0.942	1.029	0.947	0.995	0.969
Xinyang	0.966	0.981	0.960	1.007	0.948
Zhoukou	1.026	1.023	1.056	0.972	1.049
Zhumadian	0.883	0.992	0.885	0.997	0.875
Jiyuan	1.013	0.915	1.000	1.013	0.928
Mean value	0.995	0.968	0.993	1.002	0.963

Therefore, this paper uses DEAP 2.1 software to analyze and decompose the Malmquist index of 18 cities in Henan Province from 2014 to 2019. The specific results are shown in Tables 4 and 5.

(1) Analysis of the overall efficiency changes. It can be seen from Table 4 that there are fluctuations in the efficiency indexes of Henan Province. The total factor productivity index from 2014 to 2015 is 0.874, and the total factor productivity index from 2018 to 2019 is 1.079, indicating that the vegetable circulation efficiency of Henan Province is on the rise year by year. From the decomposition results of Malmquist index, the technical efficiency index and technical progress index from 2014 to 2015 are 1.048 and 0.834, respectively, and the technical efficiency index and technical progress index from 2018 to 2019 are 0.970 and 1.112, respectively, indicating that the technical efficiency index is in a downward trend, while the technical progress index is in an upward trend. It is shown that the main reason for the increase of vegetable circulation efficiency in Henan Province is the contribution of technological progress. The averages of pure technical efficiency index and scale efficiency index of vegetable circulation in Henan Province from 2014 to 2019 are 0.993 and 1.002, respectively, indicating that the main reason for the decline of technical efficiency in Henan Province lies in the decline of pure technical efficiency year by year. Henan Province needs to improve the management level and optimize the allocation of resources to promote the improvement of vegetable circulation efficiency in Henan Province.

(2) Analysis of efficiency change in different regions. It can be seen from Table 5 that, during 2014–2019, except for Kaifeng, Anyang, Xuchang, Sanmenxia, and Zhoukou, the total factor productivity index of vegetable circulation in the other 13 cities is less than 1, indicating that the vegetable circulation efficiency in most areas of Henan Province presents a downward trend. The decline of vegetable circulation efficiency in Zhengzhou, Pingdingshan, Shangqiu, Luoyang, Hebi, Xinxiang, Jiaozuo, Puyang, Luohe, Nanyang, Xinyang, Zhumadian, and Jiyuan is due to the joint effect of technological progress and technical efficiency.

3.5. Analysis of Influencing Factors of GM(1, N) Model. This paper measures the efficiency of vegetable circulation in Henan Province by Malmquist index analysis method and decomposes the total factor productivity (TFP) index. The main problem of vegetable circulation in Henan Province is that the management level and technical level are weak, but we do not know the specific influencing factors of vegetable circulation efficiency in Henan Province and their influence degree and direction. It is necessary to further analyze the influencing factors of vegetable circulation efficiency. Combined with the basic principle of GM(1, N) model, the grey system theory modeling software 7.0 is used to obtain the analysis model of influencing factors of vegetable circulation efficiency in Henan Province:

$$(x)_1^{(0)}(k) + 0.8568(z)_1^{(1)}(k) = -0.0828(x)_2^{(1)}(k) + 0.0198(x)_3^{(1)}(k) + 3.9755(x)_4^{(1)}(k) - 0.0003(x)_5^{(1)}(k) - 0.0001(x)_6^{(1)}(k) + 0.0035(x)_7^{(1)}(k). \tag{8}$$

The analysis model of influencing factors of vegetable circulation efficiency in Henan Province shows that the coefficients of transportation infrastructure construction, consumption capacity, and informatization level are all negative, which indicates that these factors play a reverse role in hindering the improvement of vegetable circulation efficiency. The coefficients of labor quality, industrial structure, and government support are all positive, indicating that these factors play a positive role in promoting the circulation efficiency of vegetables. The main reasons are as follows: Henan is a large agricultural province with low urbanization rate, slow rural economic development, weak transportation infrastructure, and unsmooth transportation of agricultural products, which to a certain extent restricts the improvement of vegetable circulation efficiency in Henan Province, and the function coefficient reaches 0.0828. The consumption ability of urban residents in Henan Province is relatively weak. For example, in the first half of 2019, the per capita consumption expenditure of 31 provinces in China ranked 25th with 7840 yuan. The consumption level of urban residents is low, which also affects the development of vegetable circulation industry in Henan Province to a certain extent, but the effect is relatively weak, and the effect coefficient is only 0.0003. Informatization is the driving force for the development of modern circulation industry, and the level of informatization also affects the improvement of vegetable circulation efficiency to a certain extent. For a long time, the development level of informatization in Henan Province is relatively backward, which hinders the improvement of vegetable circulation efficiency in Henan Province, but the effect is very weak, and the effect coefficient is only 0.0001.

4. Conclusion and Suggestion

4.1. Conclusion. From 2014 to 2019, the vegetable circulation productivity of Henan Province was on the rise. During 2014-2015 and 2016-2017, the pure technical efficiency of vegetable circulation in Henan Province was relatively high, and the average value of pure technical efficiency during 2014–2019 was 0.993, which indicates that there are some innovations in vegetable circulation technology in Henan Province. The vegetable circulation in Henan Province has a higher scale efficiency value during 2014-2015 and 2017–2019, and the average scale efficiency during 2014–2019 was 1.002, which indicates that Henan Province has a good effect in industrial structure optimization and management level improvement. The technical efficiency of Henan Province during 2014-2015 and 2016-2017 was greater than 1, and the average technical efficiency during 2014–2019 was 0.995, which indicates that the vegetable circulation in Henan Province has high regulation and innovation ability. During 2015-2016 and 2018-2019, the vegetable circulation industry in Henan Province has a high technological progress index, which indicates that Henan Province has a high technological innovation ability.

From 2014 to 2019, the vegetable circulation productivity index in most areas of Henan Province was less than 1, which indicates that the vegetable circulation efficiency presents a downward trend, and the vegetable circulation efficiency in 10 areas presents a downward trend, which is the result of the synchronous decline of the technical progress index and the technical efficiency index. However, the pure technical efficiency index and scale efficiency index of 11 regions were greater than 1, which indicates that these regions have good effects in the optimization of industrial structure, the improvement of management level, and the innovation of circulation technology.

4.2. Suggestion. In terms of capital investment, Zhengzhou, Luoyang, Nanyang, Xinyang, and Zhoukou are in the stage of increasing returns to scale. Increasing the investment of capital elements appropriately in order to improve the efficiency of vegetable circulation is suggested. Excessive capital input may lead to waste of resources. Kaifeng, Hebi, Xinxiang, Jiaozuo, Puyang, Xuchang, Luohe, Sanmenxia, Shangqiu, Zhumadian, and Jiyuan are in the stage of diminishing returns to scale. It is suggested that capital input should be reduced to improve the efficiency of vegetable circulation.

Transportation Infrastructure Construction. The construction of transportation infrastructure plays an important role in promoting vegetable transportation. A perfect transportation network can speed up the circulation of vegetables and increase the circulation of vegetables. Henan Province should increase the investment and construction of vegetable circulation infrastructure, improve the transportation system, build efficient and convenient transportation infrastructure network, reduce the circulation cost, and improve the vegetable circulation speed.

Consumption Ability. The consumption ability of residents is the basic power to improve the efficiency of vegetable circulation. The increase of disposable income of urban residents can increase their purchasing power, promote the scale of vegetable circulation, and improve the efficiency of vegetable circulation. Henan Province should formulate relevant policies to improve the wage level of enterprise employees and establish a normal wage growth mechanism. At the same time, the government should strengthen macro control, restrain the fluctuation of vegetable prices, stabilize the consumption expectations of urban residents, and relieve the worries of consumption.

The Level of Informatization. Informatization is the driving force and symbol of the development of modern circulation industry. The speed of information dissemination determines the circulation speed and quality of vegetables. To improve the circulation speed of vegetables in Henan Province, we need to speed up the construction of vegetable information service and improve the vegetable information service network. Henan Province should promote the opening and sharing of vegetable circulation information, build a public information platform for vegetable circulation, promote the effective connection between various links of vegetable circulation in Henan Province through platform services, promote the optimal allocation of resources, and improve the efficiency of vegetable circulation.

Labor Quality. High-quality vegetable circulation human capital can improve the quality and level of vegetable circulation service, reduce the cost of circulation management, and promote the improvement of circulation efficiency. Henan Province should pay attention to the introduction of vegetable circulation management personnel and technical personnel and, at the same time, strengthen the training of employees to improve their vocational skills.

Industrial Structure. Industrial structure is the proportion of output value of vegetable circulation related industries in GDP, which reflects the development of vegetable circulation industry in the region. Most of the vegetable circulation related industries belong to the tertiary industry, such as the developed wholesale and retail of agricultural products, which will create a good external environment for the development of vegetable circulation industry. Henan Province should vigorously develop the tertiary industry, promote the optimization of industrial structure, prosper the market economy, and promote the development of vegetable circulation industry.

The Degree of Government Support. The degree of government support for vegetable circulation is an important guarantee to improve the efficiency of vegetable circulation. Henan Province should pay attention to the planning of vegetable circulation industry, promote the rational distribution of vegetable wholesale market, and improve the financial and tax policies related to vegetable circulation, such as giving preferential policies in land use, tax, and loans.

Data Availability

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

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

Bingjun Li was responsible for proposing the overall idea and framework of the manuscript. Xueqiang Guo was responsible for data processing and writing of the first draft of the manuscript.

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Research Article

Can the Implied Information of Options Predict the Liquidity of Stock Market? A Data-Driven Research Based on SSE 50ETF Options

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Liquidity reflects the quality of the market. When the market is short of liquidity, it often causes investors' trading difficulties and stock price volatility, expanding the investment risk. As a risk management tool, options attract more informed investors to trade because of their flexible design. To explore whether the implied information based on the formation of option price can predict the liquidity of stock market, we take SSE 50ETF options from February 9, 2015, to December 31, 2020, as the research sample. Based on the idea of data-driven approach, we extract the implied information contained in option price, including implied volatility, implied volatility spread, and variance risk premium. Through the regression analysis method, we examine the ability to predict the liquidity of the stock market. The results show that implied volatility spread has the strongest ability to predict the liquidity of the stock market, and it is more significant within 270 days. Implied volatility contains the information about the short-term (120 days) liquidity of the stock market in the future. It shows that implied volatility and implied volatility spread are good indicators to predict stock market liquidity. In contrast, variance risk premium cannot predict the liquidity of stock market. The research conclusion verifies the role of option-implied information in predicting the stock market's liquidity. By extracting the information of options price, investors and financial regulators can scientifically participate in the financial market under data guidance.

1. Introduction

Liquidity, volatility, and profitability are the essential attributes of the financial market, in which liquidity is in the leading position and is the blood and soul of the market [1, 2]. When the market is short of liquidity, investors often face the problems of transaction difficulty, long transaction completion time, and high transaction cost, which reduces the operational efficiency of the securities market and is not conducive to the healthy and stable development of the market.

Although many scholars at home and abroad have studied liquidity, there is no unified concept for the definition and measurement of liquidity. Harris [3] defined the concept of market liquidity from four dimensions based on the microstructure theory. He believed that liquidity includes four dimensions in the stock market: market width, market depth, market resiliency, and immediacy. Market width represents the deviation degree of transaction price from effective market price; market depth refers to the maximum number of stocks that can be traded without affecting the current market price; market resiliency refers to the speed at which the price returns to the average level after the completion of a large number of stock transactions; immediacy measures whether investors can complete the transaction in time. In addition, some scholars began to explore which factors will affect stock liquidity.

Some common factors affect the liquidity level of all stocks in the market, making the liquidity of different stocks have a significant correlation. That is, the liquidity tendency of individual stocks improves or worsens at the same time. This phenomenon is called Commonality in Liquidity [4]. Commonality in Liquidity indicates that the liquidity of individual stocks is partly determined by the liquidity of the whole market. Therefore, relative to the liquidity of individual stocks, the stock market's liquidity has become one of the hot topics of scholars at home and abroad.

The liquidity of the stock market is very fragile. When the stock market falls, the liquidity will continue to decrease [5, 6]. When the market is in crisis, the liquidity will rapidly decrease or even "evaporate" in a short time, which further leads to the rapid decline of the market and the sharp rise of transaction costs [7]. Looking at the history of world finance, we can find that the fragility of liquidity is often manifested in the form of drastic changes. For example, one of the critical characteristics of the stock market disaster in the United States in 1987 is that the whole market liquidity evaporates rapidly in a very short time. The Asian financial crisis in 1997 was also caused by the rapid decrease of liquidity. The global financial crisis in 2008 was caused by the financial market panic caused by the U.S. subprime mortgage crisis, which led to the liquidity crisis and spread rapidly in the world through the spillover effect between financial markets. As a representative of emerging markets, in recent years, in China's stock market in April 2010, June 2013, and June 2015, stock prices have plummeted. From June 8 to August 26, 2015, Shanghai Composite Index dropped from 5131.88 points to 2927.29 points, down 42.96%, and Shenzhen Composite Index dropped from 2994.85 points to 1695.76 points, down 43.38%. During this period, more than 1000 listed companies chose to suspend trading for hedging, and the stock market's liquidity almost dried up. This stock disaster is mainly reflected in the trading and systemic liquidity crisis. Therefore, investors are deeply aware that the stock market's liquidity is important for regular trading and healthy operation of the market. Information asymmetry and uncertainty usually tend to increase risks [8]. Suppose that we can predict the future liquidity of the stock market according to the relevant indicators and make timely trading adjustments. In that case, it is of great significance to prevent the huge losses caused by liquidity risk.

As a risk management tool, options attract investors with more information to trade. Unlike the spot market, option price contains the expected information of the market and investors for the future market. Therefore, compared with historical information, the implied information extracted from option price is often forward-looking and is a better prediction index [9]. Then, scholars began to explore whether these indicators can predict the stock market-related information. Nowadays, there are only two kinds of stock options in Chinese stock market. The SSE 50ETF options were launched on February 9, 2015, and the CSI 300ETF options were listed on December 23, 2019. Considering the launch time of CSI 300ETF options, the development and price information in the market is not mature enough. By contrast, the SSE 50ETF options have begun to take shape after the development in recent years, including business type, functional positioning, and regulatory system, which can provide high research values for us.

The data-driven approach is to use data as a means of production of extracted features through scientific methods and apply them to problems to be solved. Data-driven methods have certain applicability and advantages in the research of management. Chen and Wang [10] constructed a credit default estimation model under the condition of changing information asymmetry, which is applicable to the risk characteristics of micro and small enterprises. Ji et al. [11] used three different modeling methods for constructing the two-stage mean-risk stochastic minimum cost consensus models to assess the impact of risk on results. Considering the advantages of data-driven approach in solving related problems, we decided to apply this idea to the stock and option markets.

At present, most of the researches focus on the prediction of stock return and volatility, but the prediction of liquidity is rare, and the prediction index is relatively single. The markets focus on the more mature European and American markets, and the research on the Chinese market is relatively more minor. According to the above shortcomings, this paper considers the following. Firstly, based on the data of SSE 50ETF options, we calculate the implied volatility (IV), the implied volatility spread (IVS), and the variance risk premiums (VRP), respectively; analyze whether they can predict the liquidity of Chinese A-share market; and verify the daily data. Whether there is a difference between the weekly data and the monthly data is also considered. Relevant studies show that IV, IVS, and VRP are more significant than other indicators in predicting the return and volatility of the financial market and contain more information about the future of the financial market [12–17]. We have reasons to believe that these three indicators still have advantages in predicting liquidity. Secondly, considering the late start of China's option market, the data is divided into the initial stage and the development stage to verify whether the data has time-varying characteristics. Finally, by changing the calculation method of the index, we examine whether the research conclusion is robust.

The rest of the article is arranged as follows: Section 2 presents the relevant literature. Section 3 describes the related variables and sets the model. Section 4 gives the descriptive statistics and empirical analysis of the sample data to explore whether the implied information of options can predict the future liquidity of the stock market. The final section ends this paper with concluding remarks.

2. Literature Review

When the stock liquidity in the financial market is insufficient, the investors' willingness to hold the asset is low, and the asset's value will be undervalued. In other words, the liquidity level of financial assets will significantly affect its expected return. Therefore, the research on the liquidity of financial assets has always been the focus of academic circles. In recent years, scholars have mainly studied the stock market in the three following aspects.

2.1. Liquidity and Its Measurement. There is no unified definition of liquidity. Scholars have studied liquidity measurement from different perspectives. Demsetz [18], Black [19], and Kyle [20] proposed that bid-ask spread is an important index to measure market liquidity based on price method. The smaller bid-ask spread is, the smaller the transaction cost is, which means better market liquidity. Since the price method ignores the quantity factor, Grossman [21] used the transaction amount within a certain period as the index to measure the market liquidity. Since then, scholars began to combine the first two types of research and put forward the index based on the combination of price and trading volume. Martin [22] constructed the relevant index, which is composed of the square of the difference between the closing price of the day and the closing price of the previous day divided by the trading volume of the day. The larger the index, the lower the market liquidity. The illiquidity index proposed by Amihud [5] uses the ratio between the absolute value of stock return and transaction amount to measure and analyze. So far, different scholars have put forward different liquidity measurement indicators based on the research, which cover multiple dimensions of liquidity information and have specific use-value in practical application.

2.2. Factors Affecting Liquidity. The existing papers mainly analyze the influencing factors of stock market liquidity from the micro and macro levels. According to the market microstructure, scholars analyze the influence of micro factors on stock market liquidity from different perspectives.

Ignacio et al. [23] found a positive correlation between corporate information disclosure and stock liquidity, and press conferences increase informed trading and uninformed trading. Jyoti [24] studied the relationship between stock market liquidity and investor sentiment. The irrational composite sentiment index (ASI) is constructed to measure the sentiment of institutional investors. The empirical results show that when the market sentiment is bullish, the stock market has high liquidity. Abdulrahman and Atsuyuki [25] studied the impact of emerging market stock liquidity and future investment. There is a positive correlation between future investment and stock liquidity.

Scholars who focus on the relationship between macroeconomic factors and stock market have also made a lot of achievements. Bai and Qin [26] found that market liberalization will increase the liquidity risk of emerging stock market. Cao and Kling [27] showed that the impact of policy on market liquidity has short-term timeliness, while the effects of the macroeconomic environment on financial market are minor. Basistha and Kurov [28] proved that the impact of monetary policy on the stock market changes with economic cycle change, and the impact of monetary policy on the stock market is greater during the economic recession.

2.3. The Prediction of Stock Market Attribute by the Implied Information of Options. Compared with the spot market, options market has a particular information advantage, which is mainly because, compared with the spot market, the benefits of high leverage and low transaction cost of the options market make many informed traders choose to trade in the options market first. New predictors can be used as an important branch of prediction development [29]. Scholars find that the implied information of options market may also have the spot market return and volatility information. Bali and Hovakimian [12] and Bollerslev et al. [13] found that the variance risk premium of options market includes the return information of future stock market. Chen et al. [14] found that the deviations from put-call parity can predict future volatility. After controlling the variables such as implied volatility, information shock, and short selling limit, the result of volatility prediction is still significant. Based on the option data of three major energy markets, Cao et al. [15] found that variance risk premium is better than other indicators in forecasting volatility. Marcel and Chardin [16] used regression analysis method to analyze individual stock and found that the implied volatility spread of individual stock options can predict the long-term equity premium of the underlying stock. Henrique and Marcelo [17] analyzed the relationship between liquidity and implied volatility, which shows that the increase of implied volatility will improve the illiquidity of the market. The research results of these scholars show that the implied information of options has a particular ability to predict the return and volatility of the future stock market, which confirms that the information of options is forward-looking relative to the spot market and is a better prediction index.

3. Research Design and Data Description

The complete data-driven links usually cover data acquisition, data modeling, data analysis, and data feedback. In the research and design link, the section introduces the idea of data-driven approach. Firstly, we collect the trading data published in the securities market and filter and clean them according to the requirements to get the final sample of the study. Secondly, based on the variance swap principle and Black-Scholes option pricing formula, the prediction indexes are extracted from the price information. Meanwhile, we construct the multiple linear regression model to verify the prediction effect of indicators on stock market liquidity. Finally, according to the empirical results of the model, we analyze the theoretical logic and practical significance behind them and send the analysis results to investors to make more reasonable investment.

3.1. Variable Selection

3.1.1. Implied Information of Options

(1) Implied Volatility (IV). Based on the volatility index of Shanghai Stock Exchange and variance swap principle [30], the most recent contract with a maturity of more than 7 days is called the near month contract, and next near contract is called the next month contract. The calculation formula of volatility in recent months is as follows:

$$\sigma_1^2 = \frac{2}{T}\sum_i \frac{\Delta K_i}{K_i^2} e^{rT} P(K_i) - \frac{1}{T}\left(\frac{F}{K_0} - 1\right)^2, \tag{1}$$

where σ_1^2 is near month volatility; T is the expiration time of the contract; r is the risk-free interest rate; K_i is the strike price of the option; F is the forward price, and $F = K + e^{rT}(C - P)$; C and P represent the price of call and put options, respectively; K is the minimum price difference between call and put option; ΔK_i is the execution price interval corresponding to the execution price i, which is $K_{i+1} - K_{i-1}/2$; K_0 is the first option strike price below the forward price F. The calculation method of next month volatility σ_2^2 is consistent with that of near month volatility.

Implied volatility is calculated using the following formula:

$$\begin{aligned} \mathrm{IV} &= \left[T_1\sigma_1^2\left(\frac{NT_2 - N_{30}}{NT_2 - NT_1}\right) + T_2\sigma_2^2\left(\frac{N_{30} - NT_1}{NT_2 - NT_1}\right)\right] \times \frac{N_{365}}{N_{30}}, \\ T_1 &= \frac{NT_1}{N_{365}}, \\ T_2 &= \frac{NT_2}{N_{365}}, \end{aligned} \tag{2}$$

where NT_1 and NT_2 are the numbers of minutes remaining after the expiration of the near month option and the next near month option, respectively; Nn is the number of minutes in n days.

(2) Implied Volatility Spread (IVS). According to the principle of parity, implied volatility of call options should be equal to that of put options. However, in the real market, due to the existence of transaction costs, margin system, short selling mechanism, and informed trading, there are differences in the implied volatility of call and put options, which indicates that option pricing is unreasonable and there are arbitrage opportunities. Therefore, according to Cremers and Weinbaum [31], the calculation formula of implied volatility spread is as follows:

$$\mathrm{IVS}_t = \mathrm{IV}_t^{\mathrm{call}} - IV_t^{\mathrm{put}} = \sum_{j=1}^{N_t} w_j\left(\mathrm{IV}_{j,t}^{\mathrm{calls}} - \mathrm{IV}_{j,t}^{\mathrm{puts}}\right), \tag{3}$$

where N_t means that there are n pairs of options on day t, and the call and put options with the same maturity and exercise price are an option pair; W_j is the weight of the open position of the pair of options j on day t in the total open position on day t; $\mathrm{IV}_{j,t}^{\mathrm{calls}}$ and $\mathrm{IV}_{j,t}^{\mathrm{puts}}$, respectively, represent the implied volatility of the call and put options in the pair of options j on day t.

(3) Variance Risk Premium (VRP). Empirical research shows that the implied variance of options is higher than the realized variance, reflecting the demand of investors to hedge volatility risk with options. Bollerslev et al. [32] defined variance risk premium as the difference between implied variance and realized variance, which can help investors better manage their portfolios and hedge risks. The calculation formula is as follows:

$$\begin{aligned} \mathrm{VRP}_t &= \mathrm{IV}_t - \mathrm{RV}_t, \\ \mathrm{RV}_t &= \sum_{i=1}^{n}\left[\ln\left(\frac{P_{t,i}}{P_{t,i-1}}\right)\right]^2, \end{aligned} \tag{4}$$

where IV_t and RV_t are the implied variance and realized variance on day t, respectively; $P_{t,\,i}$ represents observation i of the underlying asset price on day t.

3.1.2. Liquidity Index. At present, there is no consensus on the method of liquidity measurement in academic circles. Henrique and Marcelo [17] have summarized more than ten liquidity indicators. Among them, the illiquidity index proposed by Amihud [5] has been adopted as the measurement standard by many scholars at home and abroad. Wan et al. [33] evaluated the liquidity index and found that Amihud index performs better under price shocks. Based on the above research findings, we use the illiquidity index proposed by Amihud as the proxy variable of stock liquidity, and the smaller the Amihud value is, the better the stock liquidity is. The calculation method is as follows:

$$\mathrm{Amihud}_{i,d} = \frac{1}{D}\sum_{d=1}^{D}\frac{\left|R_{i,d}\right|}{\mathrm{VOLD}_{i,d}}. \tag{5}$$

The liquidity of the stock market is calculated as follows:

$$\mathrm{Amihud}_{M,d} = \frac{1}{N}\sum_{t=1}^{N}\mathrm{Amihud}_{i,d}, \tag{6}$$

where $R_{i,d}$ and $\mathrm{VOLD}_{i,d}$, respectively, represent the absolute value of the return rate and the transaction amount of stock i on day d; D represents the transaction days; N is the number of stocks normally traded on day d in the market. When selecting samples, the stocks with less than 200 trading days in the previous year are excluded, and the stocks with annual liquidity of the previous year accounting for the first 1% and the last 1% of all stocks in the A-share market are excluded; the shares of ST, ST*, and PT companies are excluded.

3.1.3. Control Variables

(1) Risk-Free Interest Rate (R_F). Risk-free interest rate is usually regarded as the basic interest rate of the market, which affects the expectation of investors for the return of financial assets. It affects the price and liquidity of assets in the market. We use Shanghai Interbank Offered Rate (SHIBOR) as the risk-free interest rate.

(2) Shanghai Stock Index Return (SIR). Generally, the index return often represents the overall situation of the market. When the market return is optimistic, it will attract investors to pour funds into the market and promote the liquidity of the financial market. Therefore, the Shanghai stock index return is taken as the control variable, and its calculation formula is as follows:

$$\mathrm{SIR}_t = \frac{P_t - P_{t-1}}{P_{t-1}}, \tag{7}$$

where P_t and P_{t-1} represent the closing prices of Shanghai stock index on days t and $t-1$, respectively.

(3) CSI Aggregate Bond Index Return (CIR). Stocks and bonds are regarded as important financial assets in the securities market, and they will interact with each other. Griffin et al. [34] found a two-way risk spillover effect between the stock market and the corporate bond market. Marcello [35] thought that there is a negative correlation between the returns of stocks and bonds. The change of CSI aggregate bond index reflects the change of bond market price. Therefore, considering the impact of the bond market on the liquidity of the stock market, CSI aggregate bond index yield is included in the control variable. The calculation formula is as follows:

$$\mathrm{CIR}_t = \frac{\mathrm{IP}_t - \mathrm{IP}_{t-1}}{\mathrm{IP}_{t-1}}, \tag{8}$$

where IP_t and IP_{t-1} represent the closing prices of the CSI aggregate bond index on days t and $t-1$, respectively.

(4) RMB Exchange Rate (ER). Long et al. [36] pointed out that the RMB exchange rate has a negative impact on Chinese stock prices. Huang et al. [37] analyzed the impact of exchange rate fluctuations on the stock market, and there are differences in the degree, direction, and duration of the impact of exchange rate fluctuations on the stock market in different countries. Relevant studies have shown that the change of RMB exchange rate directly impacts the operation of China's A-share market. In the case of RMB appreciation, investors will have more confidence in China's market and promote the liquidity of the stock market. Therefore, under the indirect pricing method, the amount of RMB convertible into US $1 is used as the index of RMB exchange rate, which is included in the control variable. The smaller the value, the greater the external value of RMB.

3.2. Model Setting. In order to test the prediction effect of option implied information on stock market liquidity, we use the research of Henrique and Marcelo [17] for reference:

$$\begin{aligned}
\text{liquidity}_{t+d} &= \alpha + \beta \mathrm{IV}_t + \gamma_1 R_{F,t} + \gamma_2 \mathrm{SIR}_t + \gamma_3 \mathrm{ER}_t + \gamma_4 \mathrm{CIR}_t + \varepsilon_t,\\
\text{liquidity}_{t+d} &= \alpha + \beta \mathrm{IVS}_t + \gamma_1 R_{F,t} + \gamma_2 \mathrm{SIR}_t + \gamma_3 \mathrm{ER}_t + \gamma_4 \mathrm{CIR}_t + \varepsilon_t,\\
\text{liquidity}_{t+d} &= \alpha + \beta \mathrm{VRP}_t + \gamma_1 R_{F,t} + \gamma_2 \mathrm{SIR}_t + \gamma_3 \mathrm{ER}_t + \gamma_4 \mathrm{CIR}_t + \varepsilon_t,
\end{aligned} \tag{9}$$

where liquidity_{t+d} indicates the liquidity of the stock market on day $t+d$; IV_t, IVS_t, and VRP_t represent implied volatility, implied volatility spread, and variance risk premium of day t, respectively.

4. Empirical Results and Analysis

Based on the launch time of SSE 50ETF options, we select the stock and options data from February 9, 2015, to December 31, 2020, as the research sample, with a total of 1437 trading days. The data comes from CSMAR Database and RESSET Database.

4.1. Descriptive Statistical Analysis. Table 1 reports the descriptive statistics of related variables, and Figures 1–3 show the original data chart of IV, IVS, and VRP, respectively. The implied volatility fluctuated wildly in the second half of 2015, which was mainly due to the liquidity crisis in the stock market in 2015, which led to the stock disaster and the price fluctuation, and then the implied volatility tended to be stable. During the stock market crash in the second half of 2015 and the epidemic period in the first half of 2020, VRP showed a significant negative situation. During the crisis, the government often adopted the rescue measures, which is equivalent to giving the market a free put option. Therefore, in the options market, investors expect the future volatility to be rebalanced, and IV will be less than the higher RV, resulting in VRP less than 0. The mean value of IVS is −0.023. Most of the values are negative, which indicates that the implied volatility of put options is greater than that of call options in the SSE 50ETF options market, reflecting that investors hold more pessimistic sentiment in the selected data range. Consistent with IV and VRP, IVS fluctuated significantly in the two crisis periods and remained relatively stable in the rest of the time.

4.2. Correlation Analysis. To avoid multicollinearity among explanatory variables, Pearson correlation coefficients among variables are reported in Table 2, which are all below 0.8. The last line of Table 2 gives the coefficient of variance expansion (VIF) of explanatory variables, which are less than 10, indicating that there is no multicollinearity problem among explanatory variables. Therefore, the multiple linear regression model we construct can be used for subsequent empirical analysis.

4.3. Regression Analysis

4.3.1. Forecasting Power of IV on Stock Market Liquidity. Table 3 reports the prediction of implied volatility for the liquidity of the stock market in the short term. From the regression results, we can find that, in the short term, implied volatility has significant prediction ability for the liquidity of the stock market, and the coefficients are significant at the significance level of 1%. The coefficient of IV is positive, which indicates that, with the increase of implied volatility, the greater the illiquidity index, the lower the liquidity of stock market. This may be due to the changes of the underlying assets measured by volatility. The greater the volatility is, the more unstable the asset price is, which leads to less financial assets available for trading and greater market friction. On the other hand, high volatility also reflects that investors are in a negative state on the overall sentiment of the market. Investors tend to reduce their trading frequency, and the market is not active, resulting in a low level of liquidity in the market.

The risk-free interest rate also has a particular prediction effect on the liquidity of the stock market, which is significant in the time interval of more than 30 days, and the coefficient is positive, indicating that the higher the risk-free interest rate is, the lower the overall liquidity of the market

Table 1: Descriptive statistics of variables.

	No. of obs.	Mean	Median	Max	Min	Std. dev.	Skewness	Kurtosis
IV	1437	0.231	0.211	0.828	0.081	0.103	1.623	7.202
IVS	1437	−0.023	−0.002	0.370	−0.985	0.099	−3.200	25.450
VRP	1437	0.029	0.040	0.258	−0.609	0.088	−2.268	13.402
R_F	1437	0.009	0.008	0.014	0.004	0.002	0.390	2.532
SIR	1437	0.000	0.001	0.058	−0.085	0.015	−1.012	9.529
ER	1437	6.682	6.713	7.132	6.108	0.276	−0.471	2.298
CIR	1437	0.018	0.020	0.728	−0.729	0.079	0.258	18.004

Figure 1: IV original data chart of SSE 50ETF options.

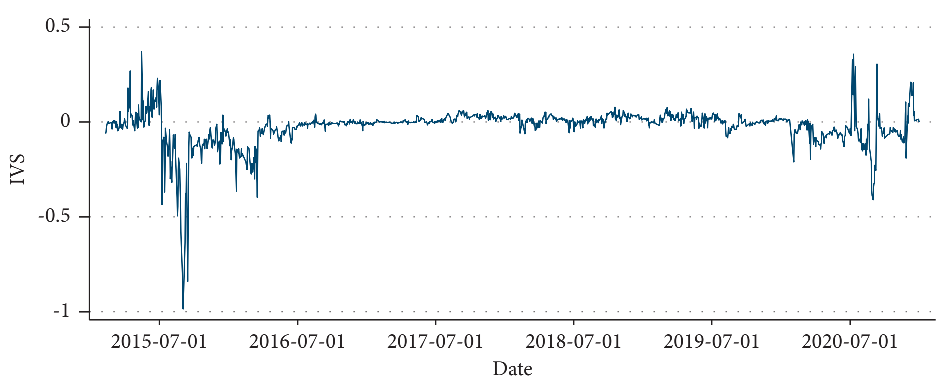

Figure 2: IVS original data chart of SSE 50ETF options.

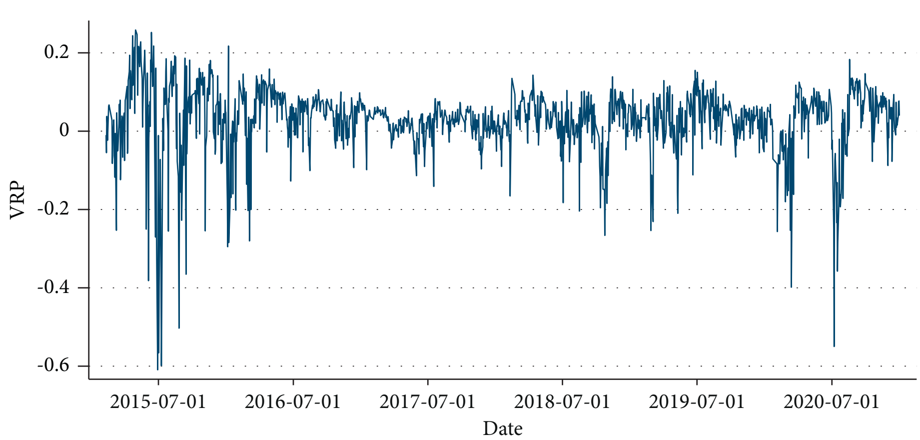

Figure 3: VRP original data chart of SSE 50ETF options.

Table 2: Correlation analysis of variables.

	Amihud	IV	IVS	VRP	R_F	SIR	ER	CIR
Amihud	1.000							
IV	0.311***	1.000						
IVS	−0.067**	−0.350***	1.000					
VRP	−0.080***	−0.164***	0.015	1.000				
R_F	−0.069***	−0.192***	0.197***	−0.021	1.000			
SIR	−0.222***	−0.088***	0.020	0.062**	0.008	1.000		
ER	−0.085***	−0.517***	0.109***	−0.071***	−0.466***	0.004	1.000	
CIR	0.237***	0.126***	−0.063**	0.036	0.020	−0.104***	−0.098***	1.000
VIF		2.45	1.16	1.14	2.05	1.02	2.75	1.03

Note. ***, **, and * indicate significance at 1%, 5%, and 10% significance levels, respectively, the same as the following table.

Table 3: Short-term forecasting power of IV on stock market liquidity.

	1 d	5 d	10 d	30 d	60 d	90 d	120 d
IV	0.133*** (9.00)	0.107*** (8.75)	0.118*** (7.88)	0.097*** (6.47)	0.069*** (4.60)	0.047*** (2.85)	0.038*** (3.03)
R_F	0.841 (1.30)	0.552 (0.84)	0.944 (1.44)	2.031*** (3.07)	4.137*** (6.30)	5.014*** (6.78)	4.173*** (7.66)
SIR	0.002 (0.03)	−0.053 (−0.71)	0.122 (1.62)	0.129* (1.71)	0.161* (2.15)	−0.018 (−0.22)	0.023 (0.38)
ER	0.017*** (2.72)	0.010 (1.61)	0.010* (1.64)	0.005 (0.73)	0.002 (0.25)	0.004 (0.60)	0.014*** (2.77)
CIR	0.050*** (3.65)	0.034*** (2.49)	0.023* (1.68)	0.002 (0.18)	0.005 (0.36)	−0.004 (−0.25)	0.013 (1.13)
Adjusted R^2 (%)	8.49	6.60	6.27	4.68	5.89	4.99	4.66

will be. On the one hand, the return of most assets in the market is based on the risk-free return rate. The rise of risk-free rate leads to the rise of investors' expected rate of return on assets, and the increase of asset price leads to the decrease of asset trading volume, which reduces the liquidity of the market. On the other hand, with the increase of risk-free interest rate, investors turn part of their investment funds to the bank deposit or bond market, weakening the liquidity of the stock market. Table 3 also reflects the regression results of the other three control variables. We also find that, compared with the risk-free rate, the prediction ability of Shanghai stock index return, CSI aggregate bond index return, and RMB exchange rate liquidity is not significant. Both SIR and CIR have positive and negative regression results. The regression coefficients of exchange rate (ER) are all positive, but they are only significant in 1 d, 10 d, and 120 d. This may be because the appreciation of RMB will make some investors invest in foreign financial markets, resulting in a certain degree of decline in the liquidity of China's market. However, due to the rapid development of China's financial market in recent years, the standardized regulatory system ensures the stability and security of the market. Therefore, the proportion of investors turning to foreign markets is relatively small, and the impact on liquidity is not significant enough.

Table 4 reports the medium- and long-term forecasting ability of implied volatility on stock market liquidity. Compared with the short-term range in three months, the forecasting ability is significantly reduced. It is significant at the level of 10% in 210 d. The coefficient is negative in 240 d to 360 d, which indicates that investors recognize and reflect the information contained in implied volatility in the medium and long term. In the medium and long term, the risk-free interest rate still maintains a significant forecast level. In addition, the forecast effect of exchange rate increases significantly, and the medium- and long-term regression coefficient is significantly positive, which indicates that the exchange rate contains the information of future medium- and long-term stock market liquidity.

The information in Tables 3 and 4 shows that the short-term (within 120 days) prediction ability of implied volatility on stock market liquidity is better, and the medium- and long-term prediction effect is not significant. Hence, the short-term implied volatility is a better prediction index.

4.3.2. Forecasting Power of IVS on Stock Market Liquidity. Table 5 shows the prediction of implied volatility spread (IVS) for stock market liquidity. For the short-term time interval within three months, IVS has strong prediction ability, and the coefficients except 90 d are significant at 1% significance level. In the medium and long term, 270 d can be regarded as a watershed. Within 270 d, the prediction ability is still strong, while the prediction ability from 270 d to 360 d is poor, and the coefficients are not significant. According to the regression results in the table, we find the implied volatility spread contains the short-term and medium-term liquidity information of the future stock market, and the coefficient is positive, indicating that the market liquidity is negatively correlated with the implied volatility spread. This may be because when IVS is greater than 0, investors are generally optimistic about the market, so they will choose to hold stocks to bring higher returns from the rise of stock prices. The number of stocks used for trading in the market will decrease, so the liquidity of stock in the market will decline.

4.3.3. Forecasting Power of VRP on Stock Market Liquidity. Table 6 shows the ability of variance risk premium (VRP) to predict liquidity. The coefficient of VRP is significantly negative in 10 d and significantly positive in 30 d at the 5%

Table 4: Medium- and long-term forecasting power of IV on stock market liquidity.

	150 d	180 d	210 d	240 d	270 d	300 d	330 d	360 d
IV	0.015 (1.18)	0.007 (0.54)	0.023* (1.84)	−0.020* (−1.64)	−0.010 (−0.78)	−0.005 (−0.40)	−0.018 (−1.45)	−0.033** (−2.52)
R_F	3.878*** (7.11)	4.279*** (7.84)	5.937*** (11.04)	4.961*** (9.05)	5.565*** (9.92)	5.316*** (9.38)	4.999*** (8.81)	3.367*** (5.80)
SIR	0.022 (0.36)	0.033 (0.53)	0.009 (0.15)	−0.063 (−1.05)	−0.054 (−0.89)	−0.017 (−0.27)	−0.017 (−0.27)	−0.135 (−2.12)
ER	0.015*** (2.98)	0.021*** (3.99)	0.036*** (6.98)	0.030*** (5.85)	0.039*** (7.50)	0.043*** (8.21)	0.044*** (8.32)	0.039*** (7.25)
CIR	−0.003 (−0.25)	0.008 (0.67)	0.008 (0.73)	0.009 (0.82)	−0.010 (−0.87)	−0.012 (−1.03)	0.012 (0.95)	0.006 (0.50)
Adjusted R^2 (%)	4.28	5.92	10.92	12.78	15.40	15.70	17.47	15.00

Table 5: Forecasting power of IVS on stock market liquidity.

	Panel A: short-term forecasting power of IVS on stock market liquidity							
	1 d	5 d	10 d	30 d	60 d	90 d	120 d	
IVS	0.032*** (2.76)	0.037*** (3.18)	0.048*** (4.19)	0.062*** (5.43)	0.051*** (4.45)	0.026** (2.00)	0.023** (2.43)	
R_F	−2.941*** (−5.19)	−2.825*** (−4.97)	−2.686*** (−4.73)	−1.283** (−2.26)	1.707*** (3.05)	3.476*** (5.49)	2.856*** (6.20)	
SIR	−0.071 (−0.94)	−0.117 (−1.55)	0.055 (0.72)	0.072 (0.95)	0.121 (1.61)	−0.048 (−0.59)	0.000 (0.01)	
ER	−0.025*** (−5.33)	−0.262*** (−5.69)	−0.028 (−6.10)	−0.029 (−6.33)	−0.023 (−5.02)	−0.013 (−2.65)	0.001 (0.24)	
CIR	0.061*** (4.35)	0.044** (3.16)	0.034** (2.43)	0.013 (0.91)	0.012 (0.91)	0.002 (0.09)	0017 (1.51)	
Adjusted R^2 (%)	3.82	3.46	3.39	3.88	5.80	4.66	4.43	
	Panel B: medium- and long-term forecasting power of IVS on stock market liquidity							
	150 d	180 d	210 d	240 d	270 d	300 d	330 d	360 d
IVS	0.048*** (5.04)	0.047*** (4.78)	0.025** (2.53)	0.034 (1.63)	0.025*** (2.60)	0.009 (0.89)	−0.003 (−0.29)	0.008 (0.78)
R_F	2.809*** (6.15)	3.460*** (7.57)	5.007*** (10.89)	5.616*** (12.39)	5.475*** (11.45)	5.318*** (10.94)	5.498*** (11.31)	4.074*** (8.18)
SIR	0.008 (0.14)	0.023 (0.37)	−0.009 (−0.14)	−0.030 (−0.49)	−0.051 (−0.85)	−0.014 (−0.23)	−0.005 (−0.09)	−0.118* (−1.85)
ER	0.006* (1.74)	0.014*** (3.78)	0.027*** (7.23)	0.036*** (10.33)	0.039*** (10.78)	0.044*** (11.91)	0.051*** (13.48)	0.049*** (12.44)
CIR	0.002 (0.15)	0.012 (1.11)	0.012 (1.06)	−0.006 (−0.52)	−0.009 (−0.82)	−0.013 (−1.04)	0.010 (0.82)	0.003 (0.21)
Adjusted R^2 (%)	5.94	7.49	11.11	12.79	15.81	15.75	17.47	14.74

significance level. This may be, because when the variance risk premium rises, investors' aversion to risk rises, and they choose to trade in the market to reduce their holdings. After a period of time, they usually reduce trading to wait for better opportunities. After 30 days, there was no significant predictive ability. Generally speaking, VRP contains less information about future stock market liquidity and has no significant ability to predict market liquidity.

Comparing the regression results of IV, IVS, and VRP, we confirm that both implied volatility and implied volatility spread can predict the liquidity level of short-term stock market, and both are good predictors. For the medium-term time interval, IVS is better than IV, which indicates that implied volatility spread contains information about market liquidity for a longer time, which implied volatility does not have. For the time interval of more than 270 days, both of them did not show good prediction ability. In contrast, variance risk premium has no significant ability to predict stock market liquidity.

4.3.4. Forecasting Power of Weekly and Monthly Data on Stock Market Liquidity. Referring to the research of Han and Li [38], there are differences in the information contained in the data of different time dimensions. Therefore, this section examines the ability of weekly and monthly IV, IVS, and VRP to predict the liquidity of the stock market.

Table 6: Forecasting power of VRP on stock market liquidity.

	Panel A: short-term forecasting power of VRP on stock market liquidity							
	1 d	5 d	10 d	30 d	60 d	90 d	120 d	
VRP	−0.051*** (−4.08)	−0.042*** (−3.35)	−0.038*** (−2.99)	0.025** (1.98)	−0.001 (−0.03)	0.010 (0.91)	−0.004 (−0.43)	
R_F	−2.640*** (−4.86)	−2.432*** (−4.45)	−2.120*** (−3.87)	−0.354 (−0.64)	2.404*** (4.43)	2.879*** (5.78)	3.177*** (7.25)	
SIR	−0.048 (−0.64)	−0.097 (−1.28)	0.074 (0.97)	0.067 (0.88)	0.125* (1.66)	0.024 (0.35)	0.006 (0.09)	
ER	−0.023*** (−5.19)	−0.024*** (−5.38)	−0.025*** (−5.52)	−0.023*** (−5.00)	−0.018*** (−4.08)	−0.008* (−1.86)	0.003 (0.82)	
CIR	0.061*** (4.39)	0.044*** (3.14)	0.033** (2.34)	0.008 (0.59)	0.010 (0.70)	−0.010 (−0.75)	0.016 (1.40)	
Adjusted R^2 (%)	4.42	3.54	2.81	2.17	4.49	3.78	4.05	
	Panel B: medium- and long-term forecasting power of VRP on stock market liquidity							
	150 d	180 d	210 d	240 d	270 d	300 d	330 d	360 d
VRP	−0.012 (−1.17)	−0.009 (−0.86)	−0.004 −0.37)	−0.001 (−0.10)	0.004 (0.37)	0.011 (1.01)	0.008 (0.76)	0.007 (0.58)
R_F	3.457*** (7.92)	4.082*** (9.33)	5.315*** (12.28)	5.335*** (12.28)	5.790*** (12.79)	5.491*** (11.83)	5.504*** (11.80)	4.240*** (8.87)
SIR	0.019 (0.31)	0.033 (0.54)	−0.001 (−0.02)	−0.050 (−0.83)	−0.050 (−0.83)	−0.020 −0.33)	−0.013 (−0.21)	−0.120* (−1.89)
ER	0.011*** (2.96)	0.019*** (5.15)	0.029*** (8.29)	0.036*** (10.34)	0.042*** (12.11)	0.045*** (12.80)	0.049*** (13.85)	0.048*** (12.97)
CIR	−0.001 (−0.11)	0.009 (0.76)	0.010 (0.90)	−0.004 (−0.31)	−0.011 (−0.95)	−0.014 (−1.11)	0.009 (0.72)	0.002 (0.13)
Adjusted R^2 (%)	4.28	5.95	10.67	12.43	15.36	15.74	17.20	14.34

Table 7: Forecasting power of weekly and monthly IV, IVS, and VRP on market liquidity.

	4 weeks	8 weeks	12 weeks	16 weeks		1 months	2 months	3 months	4 months
IV_W	0.111*** (7.30)	0.087*** (5.55)	0.072** (4.48)	0.035** (2.22)	IV_m	0.180*** (5.70)	0.138*** (3.98)	0.108*** (2.99)	0.063** (2.11)
IVS_W	0.033* (1.87)	0.059*** (3.36)	0.057*** (3.21)	0.027 (1.57)	IVS_m	0.051 (1.06)	0.069 (1.44)	0.061 (1.28)	0.033 (0.86)
VRP_W	0.058** (2.34)	0.020 (0.82)	−0.003 (−0.30)	0.006 (0.25)	VRP_m	0.085 (1.10)	−0.011 (−0.14)	−0.010 (−0.13)	0.010 (0.16)

Note. IV_W, $IVS_{W,}$ and VRP_W are weekly IV, IVS, and VRP; IV_m, IVS_m, and VRP_m are monthly IV, IVS, and VRP, respectively.

Table 7 reports the forecasting ability of weekly and monthly IV, IVS, and VRP. The weekly and monthly data of implied volatility still maintain a relatively stable forecasting effect, indicating that the low-frequency implied volatility still contains the liquidity information of the stock market in the next four months. The forecasting effect of implied volatility spread has declined, and the forecasting ability of weekly data in liquidity is still significant. At the same time, the coefficient of IVS_m is positive, but it is not significant. This may be because the value of IVS is positive and negative and, with lower frequency of data, the related information may be offset, which reduces the forecasting ability of IVS. Therefore, the higher the frequency of data, the better the prediction effect for the implied volatility spread. In contrast, the weekly and monthly variance risk premium is still unable to predict the liquidity in the stock market.

4.4. Robustness Test. In order to test the reliability of the above empirical results, the three following kinds of robustness tests are carried out to examine the reliability of IVS on the liquidity prediction ability of the stock market.

4.4.1. Phased Regression Analysis. As can be seen from Figure 2, in the early stage of the introduction of SSE 50ETF options, the parity relationship of put and call options deviated seriously, and IVS was obviously different from 0. Therefore, this section attempts to explore whether IVS had different liquidity forecasts in different periods. In order to find the liquidity information contained in IVS, the sample period is divided into two parts: the early stage of development (February 9, 2015, to December 31, 2017) and the development period (January 1, 2018, to December 31, 2020).

Table 8: Robustness test: forecasting power of IVS on stock market liquidity at different stage.

	Panel A: forecasting power at the early stage of development						
	1 d	5 d	10 d	30 d	60 d	90 d	120 d
IVS	0.000 (0.01)	0.009 (0.65)	0.020 (1.50)	0.041*** (3.16)	0.022* (1.77)	−0.020* (−1.90)	−0.004 (−0.55)
R_F	−1.384* (−1.80)	−1.150 (−1.49)	−0.849 (−1.10)	1.890** (2.50)	6.467*** (8.91)	6.265*** (10.17)	5.186*** (13.24)
SIR	0.127 (1.38)	−0.082 (−0.90)	0.120 (1.32)	0.154* (1.71)	0.169** (1.96)	−0.091 (−1.25)	−0.014 (−0.30)
ER	−0.055*** (−8.98)	−0.056*** (−9.22)	0.060*** (−9.82)	−0.070*** (−11.74)	−0.068*** (−11.90)	−0.038*** (−7.89)	−0.017*** (−5.77)
CIR	0.018 (0.92)	0.019 (0.99)	−0.008 (−0.40)	−0.027 (−1.43)	−0.024 (−1.32)	−0.02 (−1.20)	−0.013 (−1.39)
Adjusted R^2 (%)	11.87	11.73	12.29	17.28	23.92	17.67	22.61
	Panel B: forecasting power in the development period						
	1 d	5 d	10 d	30 d	60 d	90 d	120 d
IVS	0.060** (2.42)	0.051** (2.05)	0.058** (2.30)	0.034 (1.38)	0.026 (1.09)	0.000 (−0.01)	−0.011 (−0.45)
R_F	3.225** (2.21)	3.350** (2.27)	3.132** (2.12)	4.651*** (3.18)	3.063** (2.13)	2.743* (1.95)	1.356 (0.89)
SIR	−0.449*** (−3.50)	−0.224 (−1.73)	−0.083 (−0.64)	−0.161 (−1.25)	−0.046 (−0.36)	−0.008 (−0.06)	0.004 (−0.87)
ER	0.022* (1.72)	0.018 (1.33)	0.014 (1.02)	0.021 (1.58)	−0.014 (−1.08)	−0.033*** (−2.66)	−0.042*** (−3.34)
CIR	0.043** (2.09)	0.019 (0.93)	0.024 (1.13)	−0.005 (−0.22)	0.003 (0.15)	−0.040 (−1.99)	0.004 (0.21)
Adjusted R^2 (%)	4.73	2.33	2.23	2.69	5.74	10.13	9.18

Table 9: Robustness test: forecasting power of volume weighted IVS on stock market liquidity.

	1 d	5 d	10 d	30 d	60 d	90 d	120 d	150 d
IVS	0.014 (1.34)	0.021** (1.99)	0.033*** (3.08)	0.040*** (3.78)	0.035*** (3.39)	0.008 (0.85)	0.020** (2.06)	0.045*** (4.57)
	180 d	210 d	240 d	270 d	300 d	330 d	360 d	
IVS	0.044*** (4.08)	0.037*** (3.18)	0.035*** (2.96)	0.032*** (2.69)	−0.006 (−0.45)	−0.002 (−0.19)	0.009 (0.71)	

Table 10: Robustness test: based on turnover IVS to predict the liquidity of stock market.

	1 d	5 d	10 d	30 d	60 d	90 d	120 d	150 d
IVS	−0.728*** (−3.02)	−0.642*** (−2.65)	−0.489** (−2.00)	−0.627** (−2.50)	−0.744*** (−2.85)	−0.171 (−0.69)	−0.634*** (-2.79)	−0.481** (−2.3)
	180 d	210 d	240 d	270 d	300 d	330 d	360 d	
IVS	−0.476** (−2.38)	−0.577*** (−3.08)	−0.435** (−2.44)	−0.049 (−0.27)	−0.355* (−1.89)	0.601*** (3.24)	−0.043 (−0.23)	

Table 8 shows the forecasting effect of IVS of SSE 50ETF options in different development periods. In the early stage of development, the market pricing efficiency is low, and IVS contains less market information, so the early prediction ability is low, and the prediction effect for the stock market liquidity within the next 30 days is not significant. For the development period, the forecast effect is better than that in the initial stage, which shows that, with the continuous development of SSE 50ETF options, the market pricing efficiency gradually improves, and the forecast effect tends to be stable.

4.4.2. Adjust the Calculation Method of IVS. Nikolaos and Thanos [39] pointed out that the trading volume of options likely reflects market information flows and investors' expectations about specific types of movements of the underlying market index. Therefore, in this section, IVS is calculated based on the trading volume of options on the same day to examine the robustness of the conclusion:

$$\mathrm{IVS}_t = \mathrm{IV}_t^{\mathrm{call}} - \mathrm{IV}_t^{\mathrm{put}} = \sum_{j=1}^{N_t} w_j\left(\mathrm{IV}_j^{\mathrm{calls}} - \mathrm{IV}_{j,t}^{\mathrm{puts}}\right), \tag{10}$$

where W_j is the weight of the trading volume of the pair of options j on day t in the total trading volume of that day, and the rest is the same as formula (3).

Table 9 reports the IVS regression results based on the weighted calculation of trading volume. We confirm that the prediction of implied volatility spread on the liquidity of stock market is still significant. Compared with the IVS based on the weighted calculation of open position, only the coefficients of 1 d and 90 d are not significant. The other time intervals within 270 d are significant, indicating that the prediction power of IVS on liquidity is reliable and robust.

4.4.3. Change the Liquidity Index of Stock Market. Referring to the researches of Abdulrahman and Atsuyuki [25] and Karen et al. [40], we use turnover rate to measure the liquidity of stock market, which refers to the ratio of share turnover calculated by the sum of share volumes of stock i on day d.

$$\begin{aligned}\mathrm{Turn}_{i,d} &= \frac{\text{share volume}_{i,d}}{\text{share out}_{i,d}} \times 100,\\ \mathrm{Turn}_{m,d} &= \frac{1}{N}\sum_{t=1}^{N}\mathrm{Turn}_{i,d},\end{aligned} \tag{11}$$

where N is the number of stocks normally traded in the A-share market, excluding the stocks of ST, ST*, and PT companies.

Through turnover rate to measure liquidity, the regression results are shown in Table 10. We find that the results are robust. IVS still contains information about the liquidity of the stock market in the future. It has a significant ability to predict liquidity in the short-term and medium-term markets. The coefficient is negative, indicating that there is a negative correlation between the two.

5. Conclusions and Discussion

By analyzing the implied information of SSE 50ETF options, including implied volatility, implied volatility spread, and variance risk premium, this paper investigates its ability to predict stock market liquidity. Implied volatility contains the information of short-term (120 days) liquidity of stock market. It shows that IV and IVS are good indicators to predict the liquidity of the stock market. In contrast, variance risk premium (VRP) cannot significantly predict the liquidity of the stock market. At the same time, the influence of different frequency index data on the prediction effect is also considered. The regression results show that the prediction effect of weekly data and monthly data is lower than that of daily data, indicating that the daily data has the strongest prediction ability. In addition, in order to examine the reliability of the relevant conclusions, the robustness test of the prediction ability of implied volatility spread is still valid.

The options market plays a role in sharing and transferring risks, representing investors' views on the future of the market, including information about the stock market's future. Liquidity is a vital attribute reflecting the quality of the market, and liquidity risk is increasingly concerned by market participants. The implied information of options has a significant ability to predict the liquidity of the stock market. Therefore, investors should pay full attention to the implied information of options, learn the knowledge of options theory, and actively use the implied information to trade at the right time to achieve the purpose of reducing risk.

Data Availability

The data were taken from the CSMAR and RESSET databases.

Conflicts of Interest

The authors declare no conflicts of interest.

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Research Article

A Joint Optimization Model of Production Scheduling and Maintenance Based on Data Driven for a Parallel-Series Production Line

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The maintenance of a production line is becoming more important with the development of demanding higher operational efficiency and safety in industrial system. However, a production line often operates under dynamically operational and environmental conditions and the production scheduling is also a very important factor for the maintenance of a production line. First, this paper proposes an integrated data-driven model that coordinates maintenance planning decisions with production scheduling decisions to solve the problem of scheduling and maintenance planning for a parallel-series production line. The degradation information is considered, and the total cost is to be minimized in the proposed model. Also, the total cost is related with production process and maintenance considering reliability of equipment. Then, in order to better describe the relationship between production and maintenance, the accumulative processing time of equipment is used as the input of its failure function. Also, an ability factor is developed to control its reduced level by adopting preventive maintenance. Finally, a case study is used to demonstrate the implementation and potential applications of the proposed model. The long-term wear test experiments are conducted at a research laboratory facility of Shanghai Pangyuan Machinery Co., Ltd. The result proves that the proposed method is feasible and efficient to solve the joint decision-making problem for a parallel-series production line with multivariety and small batch production. The proposed model in this paper is suitable for semiconductor manufacturing.

1. Introduction

Production scheduling and maintenance planning are among the most common and significant problems faced by the manufacturing industries [1–5]. Production scheduling problems generally involve the assignment of jobs or operations to machines, while maintenance actions are carried out to retain a system or to restore it to an acceptable operating condition. Despite the trade-offs between the two activities, they are typically planned and executed independently in real manufacturing settings even if manufacturing productivity can be improved by optimizing both production scheduling and maintenance planning decisions simultaneously.

In a real production line, one machine may fail due to its degradation and usage. The consequent repair and replacement will make machines unavailable, which disorders production scheduling. Hence, how to schedule maintenance planning to keep machines in good operating condition and with high reliability and further make production scheduling based on maintenance has become a vital issue for the achievement of manufacturing [6–10].

For a parallel-series production line, the problem of single machine availability captures a growing interest in a variety of areas [11–14]. Pan et al. [15] proposed a scheduling model for single machine system incorporating production scheduling and machine maintenance, so as to maximize the machine's availability. A heuristic algorithm was proposed to optimize the integrated model of production scheduling and PM [16]. Subsequently, a method for joint production scheduling problem by considering multiresources and preventive maintenance was proposed [17] and its validity was proved. This model has been used for a repairable system [18], and an improved genetic algorithm was used to solve the joint problem for a single machine, and joint decision-making policy could obtain better result than independent policy [19]. Other areas of application of this problem, including production and assembly lines, communication and radar systems, signal processing, and surveillance, are discussed by Mirabedini et al. [20, 21].

Most maintenance scheduling (MS) problems appearing in the literature involve a rather simple maintenance plan, and the joint optimization of a multiple equipment system can be more complex. Berrichi et al. [22] developed the problem of a parallel system and used an ant colony algorithm to solve it. Also, Moradi et al. [23] researched a flexible job-shop problem and integrated production scheduling and fixed interval preventive maintenance. A dynamic preventive maintenance for a multicomponent system was integrated into a production scheduling [24]. An improved genetic algorithm based on mixed coding was used to solve this integrated model [25]. They formulated a Markov decision process model to determine the maintenance plan and develop sufficient conditions guaranteeing its monotonicity in both machine condition and demand [26, 27]. A multiobjective approach for parallel machines was proposed to allow decision-makers to find compromise solution between production scheduling and maintenance planning: minimizing both maximum completion time and total maintenance cost [28, 29]. Chang [30] presented a service-oriented dynamic multilevel predictive maintenance grouping strategy. Yan et al. [31] presented a joint optimization method for both buffer stocks control and preventive maintenance inspection interval. Celen and Djurdjanovic [32] proposed a decision-making method based on a partially observable Markov decision process to deal with interactions between maintenance and production operations in flexible manufacturing systems (FMSs). For a parallel-series production line with multivariety and small batch production, Wu et al. [33] considered joint production and maintenance scheduling of a multiproduct batch chemical manufacturing plant by an industrial case study. Li [34] optimized the setup time of the product to achieve the purpose of improving the time efficiency for the multi-product production system in the factories worldwide. Xia et al. [35] developed a fleet maintenance cost saving (FMCS) policy to optimize condition-based opportunistic maintenance and reduce the total maintenance cost efficiently.

In this paper, we develop an integrated data-driven model incorporating production scheduling and maintenance planning for a parallel-series production line with multivariety and small batch production. The existing literature often ignores the influence of machine degradation on production scheduling, and only few researchers studied processing time model based on machine's usage. However, machine's usage cannot describe its real health condition. Thus, the motivations and contributions of the paper include that processing time model can be improved, an integrated mathematical model considering scheduling and maintenance is proposed, and a parallel-series production line with multivariety and small batch production is considered. In this paper, first, the degradation information of the machine based on Weibull distribution is integrated into the proposed model. The joint objective function considers production cost, preventive maintenance cost, minor repair cost for unexpected failures, and replacement cost. Second, in order to better describe the relationship between production and maintenance, the accumulative processing time of equipment is used as the input of its failure function, and the failure rate is the direct factor affecting maintenance planning. The planning output will directly influence the accumulative processing time of equipment and then affect the failure function of equipment. Moreover, the actual maximum available processing time of each cycle equals the maximum available processing time minus the maintenance time. Then, in order to better describe the maintenance effect, the accumulative processing time of equipment is described as an index to reflect the maintenance effect. The maintenance effect can partly reduce the accumulative processing time. Moreover, an ability factor is developed to control its reduced level by adopting preventive maintenance and the replacement can reduce the accumulative processing time to 0. Finally, a case study demonstrates the potential applications of the proposed model. The optimal maintenance planning and assignment of each job can be obtained. By comparing these solutions with the results obtained from conducting the preventive maintenance planning and job scheduling problems independently, the result indicates that the proposed method is feasible and efficient to solve the joint decision-making problem for a parallel-series production line with multivariety and small batch production.

This paper is organized as follows. Section 2 describes the parameters of the proposed models. Section 3 focuses on the development of the data-driven production scheduling approach for the parallel-series production line. Section 4 focuses on the development of the data-driven maintenance planning approach for the parallel-series production line. Section 5 presents the joint optimization data-driven model of production scheduling and maintenance planning for the parallel-series production line with multivariety and small batch production. A numerical example is introduced in Section 6, and some results are discussed. Section 7 draws some conclusions from this work.

2. Notation

In this paper, the parameters are described as follows:

N: the number of production cycles during the planning period

K: types of products

M: the number of equipment in the production line

$U_{\max}$: maximum available processing time of one production cycle

sc_k: setup cost of product k, $k = 1, 2, \ldots, K$

pc_k: production cost of product k per unit, $k = 1, 2, \ldots, K$

h_k: inventory cost of product k per unit, $k = 1, 2, \ldots, K$

a_k: processing time of product k, $k = 1, 2, \ldots, K$

s_{ki}: inventory of k at the end of i-th cycle, $k = 1, 2, \ldots, K$ and $i = 1, 2, \ldots, N$

d_{ki}: demand for k in i-th cycle, $k = 1, 2, \ldots, K$ and $i = 1, 2, \ldots, N$

c_m: repair preparation cost for one time

A_j: preventive maintenance cost of equipment j for one time, $j = 1, 2, \ldots, M$

R_j: replacement cost of equipment j for one time, $j = 1, 2, \ldots, M$

F_j: minor repair cost of equipment j for one time, $j = 1, 2, \ldots, M$

$E(B_{ij})$: expectation of the number of failures of equipment j occurred in i-th cycle, $i = 1, 2, \ldots, N$ and $j = 1, 2, \ldots, M$

z_{ij}: accumulative processing time of equipment j from initial using time to the end of i-th cycle, $i = 1, 2, \ldots, N$ and $j = 1, 2, \ldots, M$

$\lambda_{j0}(t)$: failure rate function of equipment j under the maximum production ability, $j = 1, 2, \ldots, M$

t_p: preventive maintenance time

t_r: replacement time of equipment, $t_r > t_p$

b_j: ability factor of preventive maintenance and it reflects the ability reduced accumulative processing time of equipment j by preventive maintenance, $j = 1, 2, \ldots, M$

$\lambda_{ij}(t)$: failure rate function of equipment j in i-th cycle and it is related with accumulative processing time of equipment j and maximum available processing time, $i = 1, 2, \ldots, N$ and $j = 1, 2, \ldots, M$

Variable:

x_{ki}: planning output of product k in i-th cycle, $k = 1, 2, \ldots, K$ and $i = 1, 2, \ldots, N$

st_{ki}: binary variable ($st_{ki} = 1$ if k is produced in i-th cycle; otherwise, $st_{ki} = 0$), $k = 1, 2, \ldots, K$ and $i = 1, 2, \ldots, N$

m_{ij}: binary variable, performed preventive maintenance action for equipment j at the beginning of i-th cycle, $i = 1, 2, \ldots, N$ and $j = 1, 2, \ldots, M$

r_{ij}: binary variable, performed replacement action for equipment j at the beginning of i-th cycle, $i = 1, 2, \ldots, N$ and $j = 1, 2, \ldots, M$

C_1: total production cost

C_2: total maintenance cost

C_3: total cost

3. Production Scheduling Model

For a parallel-series production line, which produces K products, a planning period consisting of N production cycles is considered. Assume that the demand of each product is d_{ki} $(k = 1, 2, \ldots, K;\ i = 1, 2, \ldots, N)$ at the beginning of each production cycle; d_{ki} can be obtained by orders or marketing prediction. The production line will generate a production preparation cost for each production cycle. The enterprises complete all demands after the production line is started. However, inventories can be accumulated by producing large quantities of products at one time, which can lead a larger inventory cost and generate a greater harm to the production line. Thus, the optimal production quantity x_{ki} $(k = 1, 2, \ldots, K;\ i = 1, 2, \ldots, N)$ at the beginning of each production cycle can be obtained by using the production scheduling model with constraints of production capacity. It can satisfy the demand of each product at the beginning of each cycle, balance the production preparation cost and the inventory cost, and also minimize the total production cost including the production preparation cost, production cost, and inventory cost.

The data-driven production scheduling optimization model for a parallel-series production line with multivariety and small batch production is as follows:

$$\text{Min} \quad C_1 = \sum_{k=1}^{K} \sum_{i=1}^{N} \left(sc_k \times st_{ki} + pc_k \times x_{ki} + h_k \times s_{ki} \right), \tag{1}$$

s.t.

$$\sum_{k=1}^{K} a_k \times x_{ki} \le U_{\max}, \quad i = 1, 2, \ldots, N, \tag{2}$$

$$s_{k(i+1)} = s_{ki} + x_{k(i+1)} - d_{k(i+1)}, \quad k = 1, 2, \ldots, K,\ i = 1, 2, \ldots, N, \tag{3}$$

$$st_{ki} = \begin{cases} 1, & \text{if } x_{ki} > 0, \\ 0, & \text{if } x_{ki} = 0, \end{cases} \quad k = 1, 2, \ldots, K, i = 1, 2, \ldots, N, \tag{4}$$

$$0 \le x_{ki} \le \sum_{l=i}^{N} d_{kl}, \quad k = 1, 2, \ldots, K,\ i = 1, 2, \ldots, N, \tag{5}$$

$$s_{k1} = x_{k1} - d_{k1}, \quad k = 1, 2, \ldots, K, \tag{6}$$

$$s_{ki} \ge 0, = 1, 2, \ldots, K, i = 1, 2, \ldots, N. \tag{7}$$

Equation (1) denotes the objective function of production scheduling model, which is to minimize the total production cost, including production preparation cost, production cost, and inventory cost, during a planning period. Equation (2) is the production capacity constraint, and it denotes that the production time of each production cycle must be no more than its available maximum processing time $U_{\max}$. Equation (3) describes the inventory and reflects the relationship between demand and inventory. The inventory of product k at the end of $(i+1)$-th cycle equals the summation of its inventory at the end of i-th cycle plus the planning output $x_{k(i+1)}$ at $(i+1)$-th cycle minus demand $d_{k(i+1)}$ at $(i+1)$-th cycle. Equation (4) denotes the production preparation cost of product k at i-th cycle. Also, if product k is produced at i-th cycle, then st_{ki} equals 1, otherwise, 0. Equation (5) is the production capacity constraint of product k at i-th cycle. Also, the planning output of the current cycle cannot exceed the accumulated demand of the current cycle and the following cycles due to the assumption that inventory after finishing the planning period is 0. Equation (6) denotes the inventory of product k at the end of the first cycle (assuming that the inventory of product k at the beginning of first cycle is 0). Equation (7) is the nonnegative constraint of inventory.

4. Maintenance Planning Model

Equipment can wear out with the increase of production time, and failures can interrupt the production. Thus, maintenance activities need to be performed in order to achieve continuous production. In the current paper, the maintenance activities include nonrepair, preventive maintenance, and replacement. The preventive maintenance can decrease the accumulative processing time of equipment, and the replacement can reset the accumulative processing time of equipment. Moreover, because of some random failures during practical production, minor repair can be performed in order to carry out production and avoid shortage, which makes equipment restore to production status as soon as possible. Thus, minor repair time can be neglected and it cannot influence the accumulative processing time of equipment. The objective of the maintenance planning model is to minimize the total maintenance cost, including maintenance preparation cost, preventive maintenance cost, replacement cost, and minor repair cost. The aim of the model is to choose the optimal maintenance activities for equipment at the beginning of each cycle.

In this section, the data-driven maintenance planning optimization model of the production line with multivariety and small batch production can be obtained as follows:

$$\text{Min} \quad C_2 = \sum_{i=1}^{N} c_m \times \left(1 - \prod_{j=1}^{M}\left(1 - m_{ij}\right)\left(1 - r_{ij}\right)\right) + \sum_{i=1}^{N}\sum_{j=1}^{M}\left(A_j \times m_{ij} + R_j \times r_{ij} + F_j \times E\left(B_{ij}\right)\right), \tag{8}$$

s.t.

$$m_{ij} + r_{ij} \le 1, \quad i = 1, 2, \ldots, N, j = 1, 2, \ldots, M, \tag{9}$$

$$m_{ij}, r_{ij} \in \{0, 1\}, \quad i = 1, 2, \ldots, N, j = 1, 2, \ldots, M. \tag{10}$$

Equation (8) denotes the objective function of maintenance planning model, which is to minimize the total maintenance cost, including maintenance preparation cost, preventive maintenance cost, replacement cost, and minor repair cost, during a planning period. The expected number of random failures at i-th cycle is

$$E\left(B_{ij}\right) = \int_{z_{(i-1)j}\times\left[\left(1-m_{ij}\right)\left(1-r_{ij}\right)+b_j\times m_{ij}\right]}^{z_{ij}} \lambda_{j0}(t)\mathrm{d}t, \tag{11}$$

where z_{ij} denotes the accumulative processing time of equipment j from the beginning to the end of i-th cycle. Equation (9) is the maintenance constraint of equipment and denotes that only one maintenance activity is performed at the beginning of each cycle. If $m_{ij} = 0$ and $r_{ij} = 0$, there will be nonrepair at the beginning of i-th cycle for equipment j. If $m_{ij} = 1$ and $r_{ij} = 0$, preventive maintenance will be performed at the beginning of i-th cycle for equipment j. If $m_{ij} = 0$ and $r_{ij} = 1$, replacement will be performed at the beginning of i-th cycle for equipment j. Equation (10) is the binary variables constraint of maintenance.

The maintenance effect is to decrease the accumulative processing time of equipment. If the accumulative processing time of equipment j at the end of $(i-1)$-th cycle is $z_{(i-1)j}$ and the preventive maintenance is performed for equipment j during the i-th cycle, the accumulative processing time of equipment j becomes $b_j \times z_{(i-1)j}$. If the replacement is performed for equipment j, the accumulative processing time of equipment j will be reset. Thus, at the end of i-th cycle, there are three descriptions for z_{ij}, including nonrepair, preventive maintenance, and replacement.

$$z_{ij} = \begin{cases} z_{(i-1)j} + U_{\max} - t_p \times m_{ij} - t_r \times r_{ij}, & m_{ij} = 0, r_{ij} = 0, \\ b_j \times z_{(i-1)j} + U_{\max} - t_p \times m_{ij} - t_r \times r_{ij}, & m_{ij} = 1, r_{ij} = 0, \\ U_{\max} - t_p \times m_{ij} - t_r \times r_{ij}, & m_{ij} = 0, r_{ij} = 1. \end{cases} \tag{12}$$

Based on equation (12), z_{ij} can be obtained as follows:

$$z_{ij} = U_{\max} - \max\left\{\left[1-\prod_{j=1}^{M}\left(1-m_{ij}\right)\right]\times t_p, \left[1-\prod_{j=1}^{M}\left(1-r_{ij}\right)\right]\times t_r\right\} + z_{(i-1)j}\times\left[\left(1-m_{ij}\right)\left(1-r_{ij}\right)+b_j\times m_{ij}\right], \tag{13}$$

where $z_{1j} = U_{\max} - t_p \times m_{1j} - t_r \times r_{1j}$.

5. Joint Optimization Model of Production and Maintenance

A production line possesses the production requirements defined in Section 3 and the failure, replacement, and preventive maintenance characteristics described in Section 4. Therefore, the data-driven joint optimization model is introduced to address this problem due to its excellent performance in fusing multiple features in the process of ranking. Furthermore, assume that products are not pre-empted for preventive maintenance and products interrupted by failure can be resumed after maintenance without any additional time. Both production scheduling and maintenance planning are to minimize the total production/maintenance cost. Thus, it is superior to solve the production scheduling and maintenance planning problems for the production line simultaneously than independently. For obtaining an optimal production planning, decision on whether to perform maintenance activities or not must be made. The integrated problem is more complicated because the production line includes parallel and series equipment simultaneously. Equipment may or may not fail during each production cycle, and maintenance decisions will divide all equipment into three groups at the same time, including nonrepair group, replacement group, and preventive maintenance group, and it can decrease the maintenance cost and increase productivity.

The assumptions for the joint optimization problem are as follows:

(1) In the parallel-series production line, the type of parallel equipment is the same.

(2) The production preparation time at the beginning of each cycle is used to maintain equipment. The time of replacement is longer than preventive maintenance time; thus, the replacement time is described as the maintenance time if the replacement is performed.

(3) The planning output of parallel equipment is equal.

For a production line with multivariety and small batch production, the integrated optimization model of production scheduling and maintenance planning is as follows:

$$\begin{aligned}\text{Min}\quad C_3 = {} & \sum_{k=1}^{K}\sum_{i=1}^{K}\left(sc_k\times st_{ki} + pc_k\times x_{ki} + h_k\times s_{ki}\right)\\ & + \sum_{i=1}^{N} c_m\times\left(1-\prod_{j=1}^{M}\left(1-m_{ij}\right)\left(1-r_{ij}\right)\right) + \sum_{i=1}^{N}\sum_{j=1}^{M}\left(A_j\times m_{ij} + R_j\times r_{ij} + F_j\times E\left(B_{ij}\right)\right),\end{aligned} \tag{14}$$

s.t.

$$\sum_{k=1}^{K} a_k\times x_{ki} \le U_{\max} - \max\left\{\left[1-\prod_{j=1}^{M}\left(1-m_{ij}\right)\right]t_p, \left[1-\prod_{j=1}^{M}\left(1-r_{ij}\right)\right]t_r\right\}, \tag{15}$$

$$s_{k(i+1)} = s_{ki} + x_{k(i+1)} - d_{k(i+1)},\quad k = 1,2,\ldots,K, i = 1,2,\ldots,N, \tag{16}$$

$$st_{ki} = \begin{cases}1, & \text{if } x_{ki} > 0,\\ 0, & \text{if } x_{ki} = 0,\end{cases}\quad k = 1,2,\ldots,K, i = 1,2,\ldots,N, \tag{17}$$

$$m_{ij} + r_{ij} \le 1,\quad i = 1,2,\ldots,N, j = 1,2,\ldots,M, \tag{18}$$

$$0 \le x_{ki} \le \sum_{i=1}^{N} d_{kl},\quad k = 1,2,\ldots,K, i = 1,2,\ldots,N, \tag{19}$$

$$s_{k1} = x_{k1} - d_{k1},\quad k = 1,2,\ldots,K, \tag{20}$$

$$s_{ki} \ge 0,\quad k = 1,2,\ldots,K, i = 1,2,\ldots,N, \tag{21}$$

$$m_{ij}, r_{ij} \in \{0,1\},\quad i = 1,2,\ldots,N, j = 1,2,\ldots,M. \tag{22}$$

Equation (14) denotes the objective function of the integrated optimization model, which is to minimize the total production cost, including production preparation cost, production cost and inventory cost, and the total maintenance cost, including maintenance preparation cost, preventive maintenance cost, replacement cost, and minor repair cost, during a planning period. Equation (15) is the production capacity constraint and denotes that the maximum available processing time equals the maximum available processing time $U_{\max}$ minus the maintenance activities time. Equation (16) describes the inventory, and it reflects the relationship among demand, inventory, and output. Also, the inventory of product k at the end of $(i+1)$-th cycle equals the summation of its inventory at the end of i-th cycle and the planning output $x_{k(i+1)}$ minus demand $d_{k(i+1)}$ during $(i+1)$-th cycle. Equation (17) denotes the production preparation cost of product k at i-th cycle. Also, if product k is produced at i-th cycle, st_{ki} equals 1, otherwise 0. Equation (18) is the maintenance constraint, and it denotes that only one maintenance activity is performed at the beginning of each cycle. Equation (19) is the output constraint of product k at i-th cycle. Also, the planning output of the current cycle cannot exceed the accumulated demand of the current cycle and the following cycles because the output depends on demand. Equation (20) denotes the initial value of the inventory. Equation (21) is the nonnegative constraint of inventory. Equation (22) is the binary variable constraint of maintenance.

$E(B_{ij}) = \int_0^{U_{\max}} \lambda_{j0}(t)\mathrm{d}t$ describes the expectation of random failures of equipment j in i-th cycle. The accumulative processing time of equipment reflects the influence of production on maintenance. Thus, the failure rate function of equipment j in i-th cycle can be expressed as follows:

$$\lambda_{ij}(t) = g_j(x_i) \times \lambda_{j0}(t) = \frac{z_{ij}(x_i)}{U_{\max}} \times \lambda_{j0}(t), \tag{23}$$

where $z_{ij}(x_i)$ denotes the accumulative processing time of all products completed by equipment j from initial production to the end of i-th cycle and $\lambda_{j0}(t)$ is the failure rate function of equipment j under the maximum production capacity.

For a production line, the production is completed by using multiequipment. Also, the production output of each equipment in the production line is equal, so the output of product k completed on each equipment is x_{ki}/n, where n denotes the number of equipment. The accumulative processing time of equipment in the parallel process can be described as follows:

$$z_{ij} = \begin{cases} z_{(i-1)j} + \sum_{k=1}^{K} a_k \times \dfrac{x_{ki}}{2}, & m_i = 0, r_i = 0, \\ b \times z_{(i-1)j} + \sum_{k=1}^{K} a_k \times \dfrac{x_{ki}}{2}, & m_i = 1, r_i = 0, \\ \sum_{k=1}^{K} a_k \times \dfrac{x_{ki}}{2}, & m_i = 0, r_i = 1. \end{cases} \tag{24}$$

Equation (24) denotes the accumulative processing time of equipment j at the end of i-th cycle after performing nonrepair, preventive maintenance, and replacement at the beginning of i-th cycle, respectively. The three parts of equation (24) can be combined as follows:

$$z_{ij} = \left[\left(1 - m_{ij}\right)\left(1 - r_{ij}\right) + b_j \times m_{ij}\right] \times z_{(i-1)j} + \sum_{k=1}^{K} a_k \times \frac{x_{ki}}{2}, \tag{25}$$

where $z_{1j} = \sum_{k=1}^{K} a_k \times x_{k1}/2$.

For the series equipment in the production line, the production output of each equipment may not be equal. Thus, its accumulative processing time can be obtained as follows:

$$z_{ij} = \left[\left(1 - m_{ij}\right)\left(1 - r_{ij}\right) + b_j \times m_{ij}\right] \times z_{(i-1)j} + \sum_{k=1}^{K} a_k \times x_{ki}. \tag{26}$$

6. Case Study

6.1. Experimental Description. In this numerical example, the long-term wear test experiments were conducted at a research laboratory facility (Shanghai Pangyuan Machinery Co., Ltd.). In the test experiments, one pump was worn by running it using oil containing dust. The degradation stages in this hydraulic pump wear test case study correspond to different stages of flow loss in the pump. As the flow rate of a pump clearly indicates pump's health state, the degradation stages corresponding to different degrees of flow loss in a pump were defined as the health states of the pump in the test.

The hydraulic pump needs to produce 2 types of products ($K = 2$), the work of the hydraulic pump (system) needs 5 equipment to cooperate with each other ($M = 5$), and the planning period consists of 8 production cycles ($N = 8$). Thus, maintenance optimization is performed to the 5 equipment of the hydraulic pump. The health of the hydraulic pump will be worn gradually with the increase of time in the process of operations. In order to maintain its normal work and avoid high cost and risk, the pump needs to perform maintenance activities. Moreover, the replacement can be performed with the increase of production cost and maintenance cost. The total cost of both production and maintenance is described as the optimization objective to make the maintenance scheduling strategy. Figure 1 shows the schematic diagram of the relationship among 5 equipment. Equipment 1 is denoted as M_1. Also, all of the models are coded in Visual C# and ran on a personal computer with a 2.10 GHzn2 CPU and 4.0 GB RAM. Moreover, the parameters used for the data-driven method are detailed in Tables 1–3.

6.2. Data Preparation

6.2.1. Production Cost. For two types of products, the production time per unit is 0.06 and 0.01 ($a_1 = 0.06$ and $a_2 = 0.01$), respectively. The related costs and demand of each production cycle are given in Tables 1 and 2, respectively.

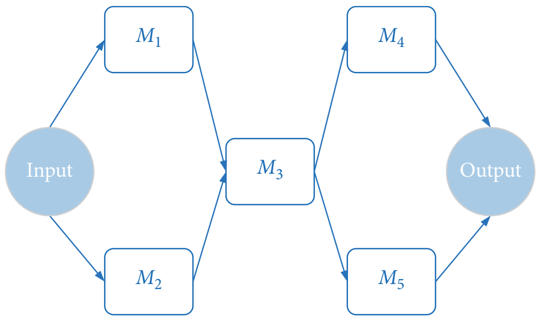

Figure 1: The relationship among five machines.

6.2.2. Maintenance Cost. In the process of maintenance optimization, Weibull distribution is used to describe the failure rate and obtain degradation information of the production line. $\lambda_j(t) = (\beta_j/\eta_j) \times (t/\eta_j)^{\beta_j - 1}$. Its scale and shape parameters corresponding to different equipment are different. The Weibull parameter values can be calculated based on pump's failure data information from the literature [36] and maximum likelihood estimation [37] (see Table 3). Moreover, the preventive maintenance cost, replacement cost, minor repair cost, and ability factor of preventive maintenance for each machine are also given in Table 3.

6.2.3. Other Parameters. The other parameters are as follows:

$$\begin{aligned} c_m &= 10, \\ t_p &= 0.9, \\ t_r &= 2.7, \\ U_{\max} &= 30. \end{aligned} \tag{27}$$

Thus, equation (14) is used to combine the data as the input for the proposed data-driven method.

6.3. Result Analysis. In the case study, Visual C# is used to solve the joint optimization problem between production scheduling and maintenance. The minimal total cost for 8 production cycles of a parallel-series production line can be obtained ($C_{\min} = 11206.73$). The optimal maintenance planning can be shown in Table 4.

It can be seen in Table 4 that equipments 1 and 2 will perform preventive maintenance at the beginning of cycles 2 and 5, respectively. Equipment 4 and 5 will perform preventive maintenance in cycles 3 and 5, respectively. Because of the lower replacement cost, the optimal maintenance planning of equipment 3 will perform replacement at the beginning of cycle 5. Thus, the optimal maintenance planning for each machine of the parallel-series production line is different due to maintenance cost and degradation of equipment. For industries, health status, failure, and maintenance status of equipment need to be carefully recorded to provide data for production scheduling and maintenance.

In Table 5, the optimal production scheduling is given. Because of the conflict between production preparation cost and inventory cost, the mutual influence between production scheduling and maintenance planning, the optimal planning output of each production cycle is not the actual demand. If these types of data are obtainable in the practical application, they can also be introduced into the feature of scheduling and maintenance in the proposed data-driven method.

6.4. Maintenance Scheduling Strategy Comparison. In order to analyze the performance of the integrated model, it can be compared with the production scheduling model and maintenance planning model by considering the influence of maximum available processing time $U_{\max}$ and the number of production cycles N. The total cost of the three models can be computed based on the different $U_{\max}$ and N, respectively. Moreover, the difference *diff* is described as the summation of the optimal production cost and the optimal maintenance cost minus the optimal total cost of the integrated model based on different $U_{\max}$, and it can be found in Table 6.

Table 6 shows that the integrated model has a better performance for saving cost based on different maximum available processing time $U_{\max}$ and the *diff* is proportional to $U_{\max}$. Similarly, the integrated model can better decrease the total cost with the increase of the production capacity.

Table 7 shows the *diff* that the summation of the optimal production cost and the optimal maintenance cost minus the optimal total cost of the integrated model based on different production cycles N. Also, the integrated model has a better performance for saving cost than the cost summation of production scheduling model and maintenance planning model. The *diff* is most when the number of production cycle for one planning period is 5, and it decreases gradually with the increase of the number of production cycles. It indicates that the production cycle for one planning period needs to be limited in industries based on joint optimization results. In this case, the optimal production cycle for one planning period is 5. The integrated model cannot obtain the best performance.

In order to directly describe the superiority of $U_{\max}$ and N to the integrated model, Figure 2 is used to analyze the change of *diff*. In Figure 2, the curve reflects the change of *diff* with the increase of $U_{\max}$ from the bottom to top. The *diff* is proportional to $U_{\max}$ for the certain N. The *diff* increases and then decreases with the change of the number of N. Moreover, there is always one N^* so that the integrated model can obtain best performance.

Nowadays, periodic maintenance, defined as significant activities carried out regularly to maintain condition or operational status of a parallel-series production line, is a common maintenance strategy. The periodic maintenance includes periodic inspections, periodic repairs, and preventive maintenance. In this paper, periodic maintenance aims to obtain the optimal maintenance strategies in one life cycle of a parallel-series production line [11]. The integrated model can be compared with the periodic maintenance model integrated production by considering the influence of maximum available processing time $U_{\max}$ and the number of production cycles N. The total cost of the two models can be computed based on the different $U_{\max}$ and N.

Table 1: The related costs of products.

Product	sc_k	pc_k	h_k
$K=1$	90	3	0.1
$K=2$	120	4	0.2

Table 2: The demand of products.

i	1	2	3	4	5	6	7	8
d_{2i}	206	198	184	217	183	105	140	237
d_{2i}	116	130	160	135	123	168	160	115

Table 3: The related maintenance parameters.

j	1	2	3	4	5
η_j	50	50	58	60	60
β_j	2	2	2	2	2
A_j	15	15	20	25	25
R_j	1000	1000	100	2000	2000
F_j	60	60	70	65	65
b_j	0.5	0.5	0.7	0.6	0.6

Table 4: The optimal maintenance planning.

i	1	2	3	4	5	6	7	8
m_{i1}, r_{i1}	0	$m_{12}=1$	0	0	$m_{15}=1$	0	0	0
m_{i2}, r_{i2}	0	$m_{22}=1$	0	0	$m_{25}=1$	0	0	0
m_{i3}, r_{i3}	0	0	0	0	$r_{35}=1$	0	0	0
m_{i4}, r_{i4}	0	0	0	0	$m_{45}=1$	0	0	0
m_{i5}, r_{i5}	0	0	$m_{53}=1$	0	$m_{55}=1$	0	0	0

Table 5: The optimal production scheduling.

i	1	2	3	4	5	6	7	8
x_{2i}	206	198	184	400	0	105	140	237
x_{2i}	116	290	0	135	123	168	160	115

Table 6: The difference value between the independent model and integrated model ($N=4$).

U_{max}	Production scheduling model and maintenance planning model			The total cost of the integrated model	*diff*
	The total maintenance cost (C_2)	The total production cost (C_1)	C_1+C_2		
30	700.69	5091.50	5792.19	5398.97	393.22
35	863.00	5091.50	5954.50	5356.03	598.47
40	1045.57	5091.50	6137.07	5316.08	820.47
45	1252.97	5091.50	6344.47	5291.03	1053.44
50	1475.00	5091.50	6566.50	5272.59	1293.91
55	1719.61	5091.70	6801.31	5257.50	1543.81
60	1937.96	5091.70	7019.66	5244.92	1774.74

Table 8 shows that the integrated model has a better performance for saving cost based on different maximum available processing time U_{max}, and the *diff* is proportional to U_{max}. Similarly, the integrated model can better decrease the total cost with the increase of the production capacity.

Table 9 shows the *diff* that the optimal maintenance cost of periodic maintenance model integrated production minus the optimal total cost of the integrated model based on different production cycles N. Also, the integrated model has a better performance for saving cost.

Table 7: The difference value between the independent model and integrated model (U_{max} = 30).

N	Production scheduling model and maintenance planning model			The total cost of the integrated model	*diff*
	The total maintenance cost (C_2)	The total production cost (C_1)	$C_1 + C_2$		
1	94.43	1292.00	1386.43	1313.28	73.15
2	335.58	2451.80	2787.38	2535.84	251.54
3	533.81	3796.40	4330.21	3946.07	384.14
4	700.69	5091.50	5792.19	5398.97	393.22
5	847.72	6268.90	7116.62	6635.97	480.65
6	981.81	7350.80	8332.61	8238.29	94.32
7	1105.14	8511.20	9616.34	9598.67	17.67
8	1220.43	9813.90	11034.33	11026.73	7.6

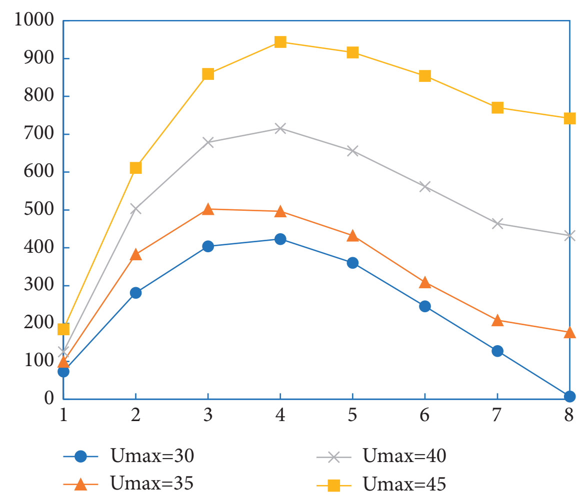

Figure 2: The influence of U_{max} and N on *diff*.

Table 8: The difference value between the periodic maintenance model integrated and integrated model ($N = 4$).

U_{max}	Periodic maintenance model integrated production	The total cost of the integrated model	*diff*
30	5673.23	5398.97	274.26
35	5779.15	5356.03	423.12
40	5836.78	5316.08	520.7
45	6091.56	5291.03	800.53
50	6266.71	5272.59	994.12
55	6535.81	5257.5	1278.31
60	6709.6	5244.92	1464.68

Table 9: The difference value between the periodic maintenance model integrated and integrated model ($U_{max} = 30$).

N	Periodic maintenance model integrated production	The total cost of the integrated model	*diff*
1	1367.34	1313.28	54.06
2	2616.89	2535.84	81.05
3	4120.97	3946.07	174.9
4	5563.61	5398.97	164.64
5	6998.15	6635.97	362.18
6	8301.66	8238.29	63.37
7	9615.04	9598.67	16.37
8	11031.16	11026.73	4.43

7. Conclusions

Both production scheduling and maintenance planning play important roles in the manufacturing industries. In order to optimize the overall performance of the manufacturing system, it is necessary for enterprises to integrate production scheduling and maintenance planning together.

This paper emphasizes the need of an integrated model for a parallel-series production line with multivariety and small batch production. The objective is to minimize the total cost, including production cost and maintenance cost. Also, the total cost is related with production process and maintenance considering reliability of equipment, including preventive maintenance, minor repair for the unexpected failures, and replacement. Moreover, the importance of different equipment is considered in the proposed model. Finally, we investigate the value of integrating production scheduling with maintenance planning by conducting an extensive experimental study to form the input of the data-driven method for multivariety and small batch scheduling problems. From the experiment results, it can be found that the proposed method is superior to the independent production scheduling model and maintenance planning model in terms of both feasibility and efficiency for a parallel-series production line with multivariety and small batch production.

The long-term wear test experiments are conducted at a research laboratory facility of Shanghai Pangyuan Machinery Co., Ltd. Industrial implementation and demonstration of the newly proposed methods in a real factory environment is still maintained, and the primary effect can be obtained. The proposed model in this paper is suitable for semiconductor manufacturing. Also, the limitations of this paper cannot integrate diagnosis information based on online data.

Furthermore, a number of interesting directions for further research can be followed based on the ideas proposed in this study. For instance, the newly proposed strategy can be extended to address predictive maintenance problems with a high degree of flexibility by considering prognostics and diagnostics information.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The author declares that there are no conflicts of interest.

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Research Article

Data-Driven Consumption Load Monitoring and Adjustment Strategy in Smart Grid

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The enhancement of the intelligent construction of the power grid and widespread popularity of smart meters enable large amounts of electrical energy consumption data to be collected and analyzed. Based on the data, the energy provider gives a guiding price in the future periods to users. It encourages users to be more economical and smarter in the process of using electricity. By applying the social welfare model to equate demand and supply in every time interval, we gain the optimal prices and generation capacity. Nevertheless, the truth is that there is a great gap between the consumers' booked electrical energy consumption and the optimal generation capacity, causing the power system overload and even outage. This article puts forward a novel automatic process control strategy in order to monitor the gap between the consumers' booked electrical energy consumption and optimal generation capacity by using statistical method to predict the future one. When the predicted value exceeds the boundary, the energy provider adopts the changeable electricity price to stimulate consumers to adjust their electrical energy demands so that it can have smoothly actual electrical energy consumption. Our adjustment method is data-driven exponential function-based adjustment. Case study results show that the strategy can obtain small adjustment times, stable actual consumption load, and controllable prediction errors. Different from the linear monitoring and adjustment strategy, our approach obtains almost the same adjustment frequency, less standard deviation of residuals, and higher total social welfare and energy provider profit.

1. Introduction

With the development of urbanization, human beings' material living quality has improved dramatically. However, some issues such as the environmental pollution also have emerged. In order to decrease the environmental pollution and avoid overconsumption of resources, words like peak carbon dioxide emissions and carbon neutrality have been hotly discussed. Mentioning energy consumption, human beings turn to some clean sustainable energy resources including hydropower and solar energy rather than restricting traditional coal fossil energy.

The limitation of traditional power grid's rigid construction, namely, the lack of flexibility for grid connection with new energy and the delays in the transmission of information due to the backward communication network and so on, may cause problems, for example, the supply-demand imbalance. Due to the defects of the previous generation of grid and the emergence of mobile communication technology, smart grid was put forward by IBM (in America) in 2006, "next generation power grid" [1]. Not only America and EU countries but also China has picked up some cities as pilot ones for SG (smart grid) [2]. Compared with traditional grid, SG has the following advantages: timely reliable two-way communication among data on the network, the supply-demand balance on account of information interaction, simple and convenient storage of the distribution energy for security of the microgrid connection benefiting from the development of high capacity battery technology, and highly efficient calculating ability generated from the creative model and smart algorithm.

Smart meter develops rapidly with the gradually mature communication technology, which integrates the metering and data interaction functions of traditional one. So, users and energy providers can exchange data. Meanwhile, it also can analyze, forecast, and manage the consumption load.

Equipped with advanced sensor technology and reliable terminal equipment, real-time pricing (RTP) is booming. Different from traditional pricing structures, reasonable RTP can keep supply and demand in balance and keep the consumers' and suppliers' comfort maximized, because it has the flexible and intelligent characteristics.

The ultimate purpose of RTP research by domestic and foreign experts is to achieve maximized total social welfare [3, 4]. For this aim, a distributed dynamic pricing algorithm was developed to obtain peak-shaving and valley-filling [4]. Lately, this sort of RTP models has been advanced vigorously in terms of model improvement and stronger algorithm convergence. Chiu et al. [5] researched on an energy transaction billing system by using a dynamic pricing mechanism. Zhu et al. [6] got a better rate of convergence and a better operation effect by solving the model with ADMM algorithm.

RTP highlights the stable and reliable theoretical pricing policy and optimal generation capacity, but it is out of line with reality. The original intention is to guide users to make rational use of electric energy through changing electricity prices and balance the smart grid. Nevertheless, the truth is that the majority of consumers are unwilling to adjust their electricity demand with the ever-changing electricity price every hour. That causes the practical electrical energy consumption to lose control again and leads to the loss of the smart grid stability and reliability. Even in extreme cases, the fact that the energy provider offers the booked consumption to the users may cause blackouts at peak time. To solve the blackout, the electricity companies and power plants have to face the increasing energy cost, which is far more than the revenues. That is the least thing that the energy provider wants to have. In order to prevent this, we should work out a solution based on the operation of RTP model. It can not only make the power system have a limited changing price through the automatic monitoring but also have a smooth and steady practical electrical energy consumption. In other words, the users' practical electrical energy consumption is close to the optimal generation capacity from the RTP model. In the existing literature, there are many studies on how to manage the electrical energy consumption in smart grid. However, they rarely consider how to reduce the adjustment frequency of electricity price [7, 8].

The automatic process control (APC) strategy can make up for this shortcoming. It can offer effective process monitoring and adjustment. Box [9] applied APC method to product control. We will make an adjustment when the process is beyond the boundary set before. In this way, the adjustment frequency will decrease and the production quality will often be controlled in a certain range. The APC strategy is widely used in product, manufacture, and service fields. Hernández et al. [10] put forward a control tool to monitor variables. Yuan et al. [11] studied an APC chart to identify exceptions. To monitor the gap between the booked and optimal electrical energy consumptions, He et al. [12] researched a line function-based APC strategy. However, the APC strategy has not been widely used in SG [13–15].

A new data-driven exponential function-based APC strategy is proposed in this paper. We use exponentially weighted moving average (EWMA) to monitor electrical energy consumption. After obtaining the dynamic pricing from energy providers, the users can book one day or more of electricity in advance through the smart meters. At that time, the energy providers can monitor users' booked consumption load and calculate the difference between the optimal generation capacity and it. Since then, it is the turn to use data-driven APC scheme to manage electrical energy consumption by changing the dynamic pricing. There is a long research history of the EWMA for scholars from home and abroad. Yang et al. [16] designed a Phase Two EWMA control model to monitor alterable dimension mean vector. In statistical applications, EWMA is often used to predict trends [17–19]. He et al. [20] studied an EWMA prediction model to monitor the process of electrical energy consumption. In this paper, EWMA is applied to predict the next interval gap between the optimal electrical energy generation capacity and the booked electrical energy consumption. When it exceeds the preset boundary, rising or reducing the price in some time interval is supposed to be adopted to stimulate the demand response. In this way, it can get a few adjustments and avoid the side effects on the users caused by the frequent price adjustments. The stable consumption load is finally achieved.

The research features and highlights of this article are listed as follows:

(1) This study comes up with an original data-driven exponential function-based automatic process control strategy to manage the gap between the consumers' booked electrical energy consumption and the optimal generation capacity

(2) A small adjustment number is obtained by the data-driven exponential function adjustment method, which can achieve a practical electrical energy consumption approaching the optimal generation capacity after adjustment

(3) This strategy can make up for the defects of the RTP algorithm and achieve effective peak carbon dioxide emissions effects

The remaining part of this article is arranged as follows: data-driven APC strategy is offered in Section 2. In Section 3, the algorithm is proposed. Case studies and result analysis are included in Section 4. The conclusions are drawn in Section 5.

2. Data-Driven APC (Automatic Process Control) Strategy

The structure of the SG system discussed in this article is as follows: a power plant, an energy provider, and a few users. The users have installed smart meters. The power plant transmits the power to an energy provider. The energy provider collects the power consumption data from users through smart meters. The energy providers apply the social welfare maximization model to calculate price of next time interval and transmit it to users. After receiving the price as p dollars/kWh, users reserve consumption load from the energy provider (one day or even one week). Set the number of consumers as N, and assume that the time period of electrical energy operation is divided into T intervals. Suppose that set $\aleph = \{1, 2, \ldots, N\}$ represents consumers and set $\Gamma = \{1, 2, \ldots, T\}$ represents time intervals. The energy provider obtains each user i's $(i \in \aleph)$ valley and peak electrical energy consumption data in interval $t \in \Gamma$ according to the past data provided by the smart meter, namely, m_i^t and M_i^t. Denote x_i^t as user i's electrical energy consumption in interval t, and its range can be assumed as $m_i^t \le x_i^t \le M_i^t$. The detailed social welfare model is available in Appendix.

After we solve the optimization problem (C.1)–(C.3) (see Appendix), optimal price p_t^* and theoretical optimal generation capacity G_t^* in interval t can be gained. The electricity supplier obtains a smooth and steady electrical energy consumption based on G_t^*. But this is just an optimal situation. Most often, consumers' booked electrical energy consumption observed from smart meters is considerably different from optimal generation capacity G_t^*. Guiding the consumers to use electrical energy appropriately is the most effective way to prevent this kind of phenomenon.

Taking users' demand response mechanism to price into account, we calculate the gap between optimal generation capacity with the social welfare model and the booked consumption loads. Later, when it exceeds the boundary, we use the data-driven APC scheme to change the gap. The energy provider changes prices to make users adjust their actual consumption loads. In the end, the actual electrical energy consumption is near the optimal generation capacity. Moreover, we can obtain higher social welfare and the energy provider can get more profit with data-driven APC strategy than before. We first introduce the definition of the EWMA estimation [12, 20].

2.1. EWMA Estimation. We suppose that the users book the electrical energy consumption of the next interval, and the reservation retains an important reference value for accurate adjustment.

In order to accurately obtain the extent of gap between booked electrical energy consumption x_t of users in time interval t and optimal generation capacity G_t^*, we set gap d_t as

$$d_t = x_t - G_t^*, \tag{1}$$

and we predict the next gap value d_{t+1} by the EWMA model from last adjusted gap value. The details of the calculation are as follows.

Set the initial gap value as d_τ, $\tau = t, t-1, \ldots$, and set the adjusted one as d'_τ, $\tau = t, t-1, \ldots$. The EWMA $\overline{d}_{t+1}$ of gap value d_{t+1} in time interval $t+1$ is in the following formula:

$$\overline{d}_{t+1} = \theta \overline{d}_t + \mu d'_t, \tag{2}$$

in which $\theta = 1 - \mu$ is the discount factor.

Similarly, EWMA $\overline{p}_{t+1}$ of price p_{t+1} in interval $t+1$ is

$$\overline{p}_{t+1} = \theta \overline{p}_t + \mu p'_t, \tag{3}$$

in which p'_t is changed price in interval t.

In the process of adjustment, the changed EWMA value $\overline{p}'_{t+1}$ in interval $t+1$ is

$$\overline{p}'_{t+1} = \theta \overline{p}_t + \mu p''_t, \tag{4}$$

where p''_t is readjusted price in interval t.

2.2. Data-Driven APC Electrical Energy Monitoring. In this section, we discuss how to develop a data-driven APC electrical energy monitoring strategy in order to minimize the difference from the goal electrical energy gap E. We will change the price when the EWMA value is beyond the boundary as

$$\begin{aligned} &\overline{d}_{t+1} \ge B_1 \\ &\text{or } \overline{d}_{t+1} \le B_2, \quad B_1 \ge 0, B_2 \le 0, \end{aligned} \tag{5}$$

where B_1 is prestipulated upper limit and $B_2$is prestipulated lower limit. In the process of monitoring, when $\overline{d}_{t+1}$ conforms to (5), the EWMA value $\overline{d}_{t+1}$ is out of the limits. The action of adjusting it to get nearer to the goal value will be taken. It is obvious in test results that, to achieve a stable subsequent adjustment, it is worthy of discussion to find a way to set parameters $E_1 \ge 0$ and $E_2 \le 0$ of the target process properly.

When monitoring users' booked consumption load, we obtain a series $\{\overline{d}_t\}_{t=1}^T$ of EWMA estimation. If $\overline{d}_{t+1}$ satisfies (5), the users' booking electrical energy consumption has been beyond the steady limit. For preventing the consumers' blind electricity utilization, the energy provider applies the users' price demand response. It guides the users to use power properly, which achieves smooth and steady electrical energy consumption.

2.3. Data-Driven APC Adjustment. If the automatically calculated estimated value $\overline{d}_{t+1}$ exceeds the upper boundary B_1, it means the booked electrical energy consumption is beyond expectation. Meanwhile, the real-time price will be increased to induce consumers to reasonably reduce the booked electrical energy consumption. By the same token, if $\overline{d}_{t+1}$ is lower than the lower boundary B_2, it means scheduled electrical energy consumption is lower than expectation and the remaining power is sufficient. It is necessary to reduce the real-time price to encourage consumers to add more booked electrical energy consumption at that moment. Energy provider can even encourage users to store electricity in their own batteries to get through the period of rising prices. Through the above adjustments, users can be guided to reasonable electrical energy consumption. Therefore, a smooth and steady supply of electricity can be ensured from the energy supplier.

The strategy needs to be discussed in terms of the quantitative relation between price changes and the gap between users' booked electrical energy consumption and optimal generation capacity. The relationship can be tested by relevant data. In order to explain the adjustment strategy, we provide the following theorem.

Theorem 1. *Set the demand function as an exponential function. The gap EWMA estimation* $\overline{d}_{t+1}$ *is exponential to electricity price EWMA value* $\overline{p}_{t+1}$*, and the form is* $\overline{d}_{t+1} = k_1 e^{k_2 \overline{p}_{t+1}}$ *or* $\overline{d}_{t+1} = -k_1 e^{-k_2 \overline{p}_{t+1}}$*;* $k_1 > 0$ *and* $k_2 < 0$ *are constants. When the load gap satisfies* $\overline{d}_{t+1} \geq B_1 > 0$*,* $\overline{d}_{t+1}$ *is adjusted to* $E_1 \in [0, B_1)$*, and then the price variation is*

$$\delta_{t+1} = \frac{1}{\mu k_2}\left(\ln E_1 - \ln \overline{d}_{t+1}\right). \tag{6}$$

When $\overline{d}_{t+1} \leq B_2 < 0$, $\overline{d}_{t+1}$ is adjusted to $E_2 \in (B_2, 0]$, and then the price variation is

$$\delta_{t+1} = \frac{1}{-\mu k_2}\left(\ln\left|E_2\right| - \ln\left|\overline{d}_{t+1}\right|\right). \tag{7}$$

Proof. In interval $t+1$, when $\overline{d}_{t+1} \geq B_1 > 0$, $\overline{d}_{t+1}$ has to adjust to $E_1 \in [0, B_1)$. Meanwhile, the EWMA price is shifted from $\overline{p}_{t+1}$ to $\overline{p}_{t+1}'$. Under the assumed condition, we have

$$\begin{aligned} \overline{d}_{t+1} &= k_1 e^{k_2 \overline{p}_{t+1}}, \\ E_1 &= k_1 e^{k_2 \overline{p}_{t+1}'}, \end{aligned} \tag{8}$$

which can be written as

$$\begin{aligned} \ln \overline{d}_{t+1} &= \ln k_1 + k_2 \overline{p}_{t+1}, \\ \ln E_1 &= \ln k_1 + k_2 \overline{p}_{t+1}', \\ \ln E_1 - \ln \overline{d}_{t+1} &= k_2\left(\overline{p}_{t+1}' - \overline{p}_{t+1}\right). \end{aligned} \tag{9}$$

According to (3), (4), (8), and (9), we have

$$\begin{aligned} \ln E_1 &- \ln \overline{d}_{t+1} \\ &= k_2 \mu\left(p_t'' - p_t'\right). \end{aligned} \tag{10}$$

Setting $\delta_{t+1}\colon = p_t'' - p_t'$ as change in price, we have

$$\delta_{t+1} = \frac{1}{\mu k_2}\left(\ln E_1 - \ln \overline{d}_{t+1}\right). \tag{11}$$

Similarly, when $\overline{d}_{t+1} \leq B_2 < 0$, we adjust $\overline{d}_{t+1}$ to $E_2 \in (B_2, 0]$; under the assumed condition, we have

$$\begin{aligned} \overline{d}_{t+1} &= -k_1 e^{-k_2 \overline{p}_{t+1}}, \\ E_2 &= -k_1 e^{-k_2 \overline{p}_{t+1}'}, \end{aligned} \tag{12}$$

so we obtain

$$\begin{aligned} \ln\left|\overline{d}_{t+1}\right| &= \ln\left|-k_1\right| - k_2 \overline{p}_{t+1}, \\ \ln\left|E_2\right| &= \ln\left|-k_1\right| - k_2 \overline{p}_{t+1}', \\ \ln\left|E_2\right| - \ln\left|\overline{d}_{t+1}\right| &= -k_2\left(\overline{p}_{t+1}' - \overline{p}_{t+1}\right) = -\mu k_2 \delta_{t+1}. \end{aligned} \tag{13}$$

Hence, from above, formula (7) is established. □

3. Algorithm

According to Theorem 1, the adjusted electrical energy consumption in interval $t+1$ is

$$x_{t+1}' = \begin{cases} x_{t+1} - k_1 e^{k_2 \delta_{t+1}}, & \delta_{t+1} > 0, \\ x_{t+1}, & \delta_{t+1} = 0, \\ x_{t+1} + k_1 e^{k_2 \delta_{t+1}}, & \delta_{t+1} < 0. \end{cases} \tag{14}$$

Then we have

$$\begin{aligned} d_{t+1}' &= d_{t+1} + x_{t+1}' - x_{t+1} \\ &= \begin{cases} d_{t+1} - k_1 e^{k_2 \delta_{t+1}}, & \delta_{t+1} > 0, \\ d_{t+1}, & \delta_{t+1} = 0, \\ d_{t+1} + k_1 e^{k_2 \delta_{t+1}}, & \delta_{t+1} < 0. \end{cases} \end{aligned} \tag{15}$$

We get optimal solution $\{p_t^*\}_{t=1}^T$ and $\{G_t^*\}_{t=1}^T$ by applying Lagrange dual method to solve the social welfare maximization problem (C.1)–(C.3) (see Appendix). Smart meters feed users' booked electrical energy consumption series $\{x_t\}_{t=1}^T$ back to the energy supplier. According to (1), we calculate the series $\{d_t\}_{t=1}^T$ of gap between booked electrical energy consumption x_t of users in interval t and optimal generation capacity G_t^*. Let the initial adjusted consumption load gap $d_1' = d_1$, $p_1' = p_1^*$, and $\overline{d}_1 = 0$, so that the initial predicted error is $e_1 = d_1' - \overline{d}_1 = d_1'$. Set the initial price adjustment as $\delta_1 = 0$. Suppose that the parameters $k_1 > 0$ and $k_2 < 0$, $0 \leq E_1 < B_1$, $B_2 < E_2 \leq 0$, and $\mu \in [0, 1], \omega \in [1, 4]$. In interval $t \in \Gamma$, applying data-driven APC strategy, the monitoring and adjustment algorithm is summarized as Algorithm 1.

4. Case Analysis

The operation effect of data-driven exponential function-based APC monitoring and adjustment strategy is analyzed through Singapore's power market data [21] in this part.

4.1. Power Load. We select RTP data from Mar 5, 2017, to Mar 6, 2017, and electrical energy consumption data from Mar 3, 2017, to Mar 6, 2017, for simulation. In Algorithm 1, we set the RTP data as the initial booked sequences $\{p_t^*\}_{t=1}^T$. In equation (1), we set the electrical energy consumption data from Mar 5, 2017, to Mar 6, 2017, as booked electrical energy consumption $\{x_t\}_{t=1}^T$. Past electrical energy data at the corresponding time from Mar 3, 2017, to Mar 4, 2017, is regarded as optimal generation capacity $\{L_t^*\}_{t=1}^T$ in equation (1). The original power loads are shown in Figure 1.

As illustrated in Figure 1, the users' booked consumption power load runs far away from the optimal generation capacity. In order to encourage users to reasonably consume power, the data-driven APC strategy needs to be adopted. This means that the adjustment of electricity prices is set by suppliers. Then it will guide consumers to adjust real electrical energy consumption.

4.2. Numerical Analysis for APC Adjustment. Let $\overline{p}_1 = 75$, and see Section 3 for the other initial arguments. Set the parameters in Algorithm 1 as follows: $k_1 = 20, k_2 = -1$, $\mu = 0.3$, $B_1 = 800, B_2 = -800$, $E_1 = B_1/2$, and $E_2 = B_2/2$. Assume that the arguments a, b, c in equation (B.3) are

Step 1: calculate $\overline{d}_{t+1}$ according to (2). If (5) holds, turn to Step 4. Otherwise, $\delta_{t+1} = 0$, turn to Step 2.
Step 2: calculate x'_{t+1} according to (14), d'_{t+1} according to (15), $e_{t+1} = d'_{t+1} - \overline{d}_{t+1}$.
Step 3: repeat Step 1.
Step 4: when $\overline{d}_{t+1} \geq B_1 > 0$, let $\delta_{t+1} = (1/\mu k_2)(\ln E_1 - \ln \overline{d}_{t+1})$, when $\overline{d}_{t+1} \leq B_2 < 0$, let $\delta_{t+1} = (1/-\mu k_2)(\ln|E_2| - \ln|\overline{d}_{t+1}|)$, then turn to Step 2.

Algorithm 1: Data-driven APC algorithm.

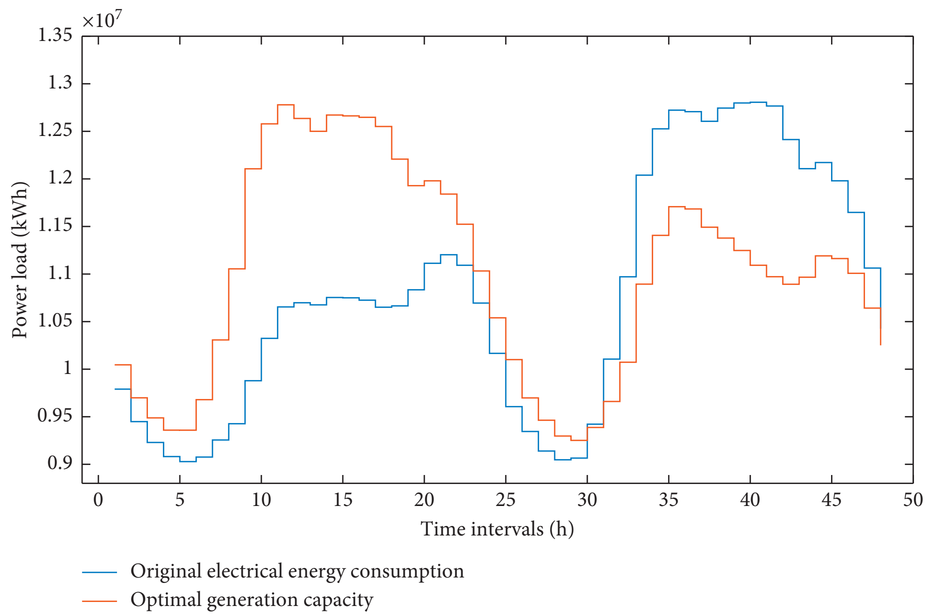

Figure 1: Comparison between optimal generation capacity and booked electrical energy consumption.

0.01, 0, 0. Figures 2–5 show the APC strategy simulation results.

Figure 2 depicts that electrical energy gap series are steadier than the ones without adjustment after 11 adjustments. By experience, the average adjustment interval is $47/11 = 4.3$, and the standard deviation of residuals is $\sigma = \sqrt{(\sum_{t=1}^{T} e_t^2/(T-1))} = \sqrt{(\sum_{t=1}^{48} e_t^2/47)} = 734$. No points outside the range 3σ indicate that there is no sign of the abnormality.

As can be seen in Figure 3, adjusted electricity consumption is nearer optimal generation capacity than the one without adjustment, and expected effects can be achieved. Figure 4 shows that the electricity price has changed 11 times. The biggest change in price is -3.376×10^{-3} units. During these periods, we encourage the consumers to buy and use more electrical energy consumption. We apply equation (C.1) to calculate the total social welfare to get 6.34×10^8, and we apply equation (B.4) to calculate the profit to get 3.82×10^7. As can be seen from Figure 5 by running our strategy, we can obtain higher social welfare and profits than those without adjustment.

Besides improving energy provider's profit and total social welfare, the data-driven APC adjustment strategy helps to balance power supply and prevent SG outages.

4.3. Comparison between Two Different Demand Function Adjustments. Reference [12] points out that there is a linear relationship between the EWMA predicted value $\overline{d}_{t+1}$ of consumption load gap and the EWMA predicted value $\overline{p}_{t+1}$ of price. This paper proposes that $\overline{d}_{t+1}$ and $\overline{p}_{t+1}$ are presented as an exponential function. The arguments are $k_1 = 120$, $k_2 = -1$, $k = 500$, $\mu = 0.5$, $B_1 = 1000$, $B_2 = -1000$, $E_1 = B_1/2$, and $E_2 = B_2/2$. The comparison of the electrical energy consumption results adjusted by these two methods is shown in Table 1 and Figures 6–8.

From Table 1 and Figure 6, we can learn that the adjustment frequency of the exponential adjustment is slightly higher than that of the linear one, but the standard deviation of the exponential adjustment is smaller than that of the linear adjustment.

Table 1 and Figure 7 illustrate that total social welfare and energy provider's profit of the exponential demand function are higher than those of the linear one. Figure 8 presents that price

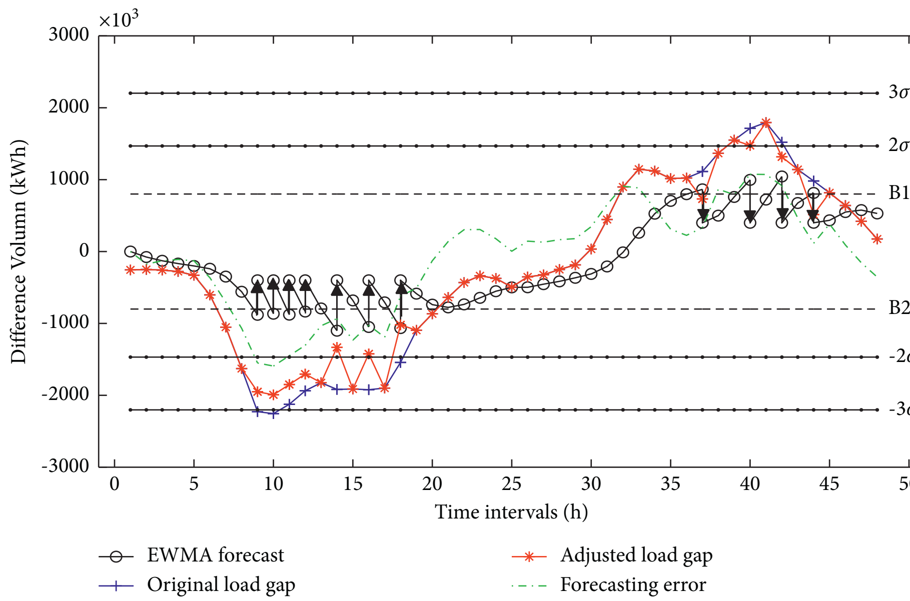

Figure 2: APC strategy process.

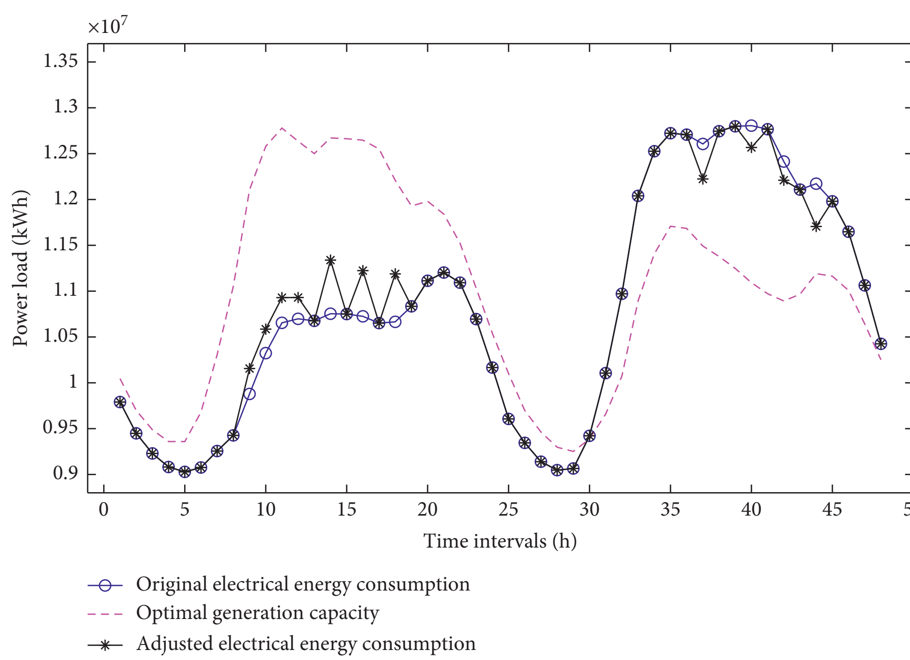

Figure 3: Electrical energies comparison.

adjustment effects of exponential demand function are better than those of the linear one. In particular, even the adjustment frequency with the exponential adjustment is slightly more than that in the linear one, and the standard deviation of residuals, total social welfare, and energy provider's profit with exponential demand function are better than those of the linear function adjustment.

From the observation results, we can conclude that, in general, the effect of exponential function adjustment is better than that of linear function adjustment.

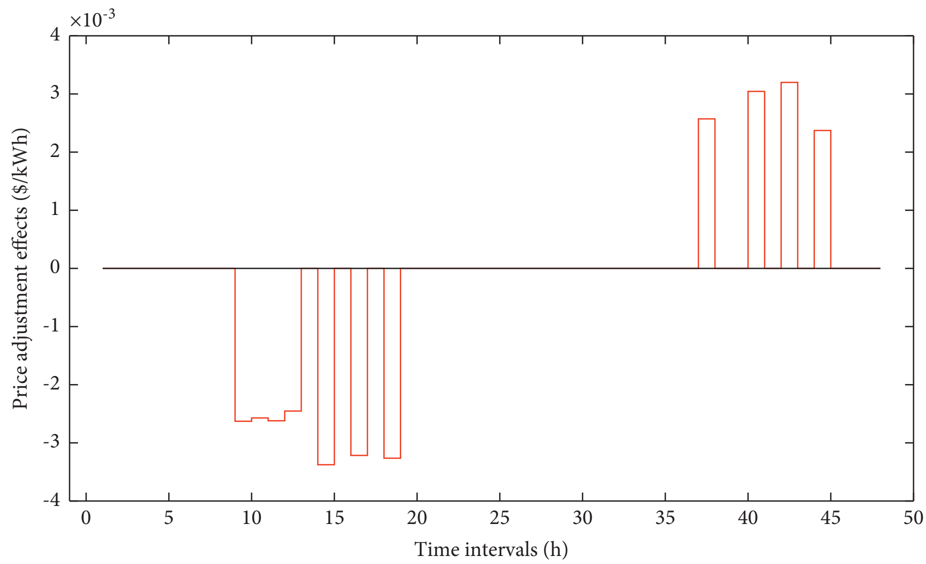

FIGURE 4: Price adjustment effects.

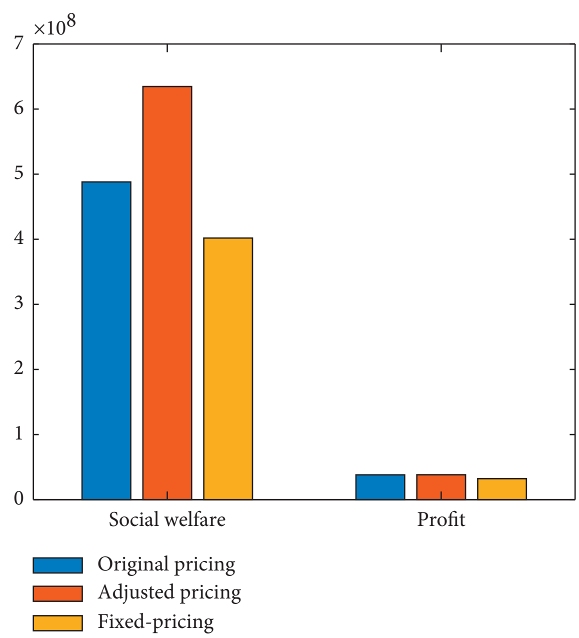

FIGURE 5: Comparison of total social welfare and energy provider's profit, with original and adjusted pricing strategies.

Table 1: Comparison results.

	Exponential adjustment	Linear adjustment
Adjustment frequency	10	9
Standard deviation	585	625
Social welfare	6.35×10^8	5.24×10^8
Profit	3.82×10^7	3.76×10^7

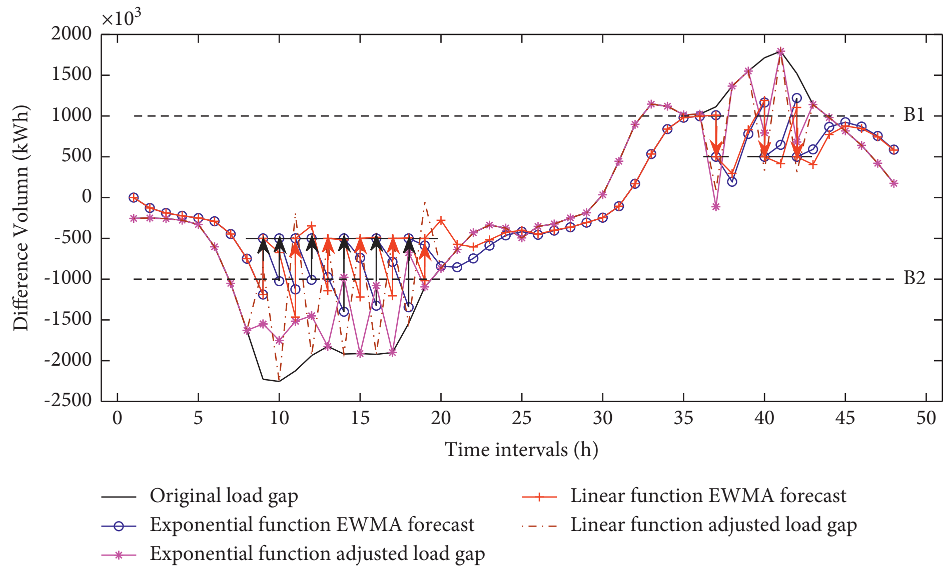

Figure 6: Comparison of adjustments in different APC strategies.

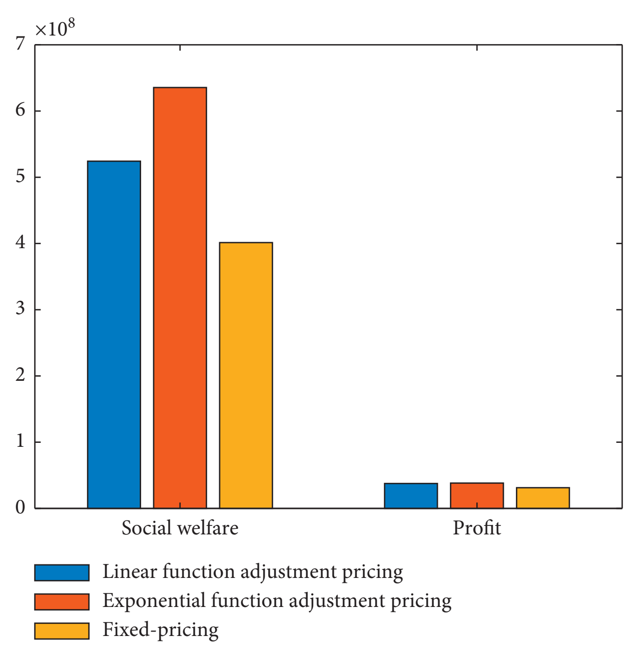

Figure 7: Comparison of total social welfare and energy provider's profit, with linear and exponential adjustment pricing strategies.

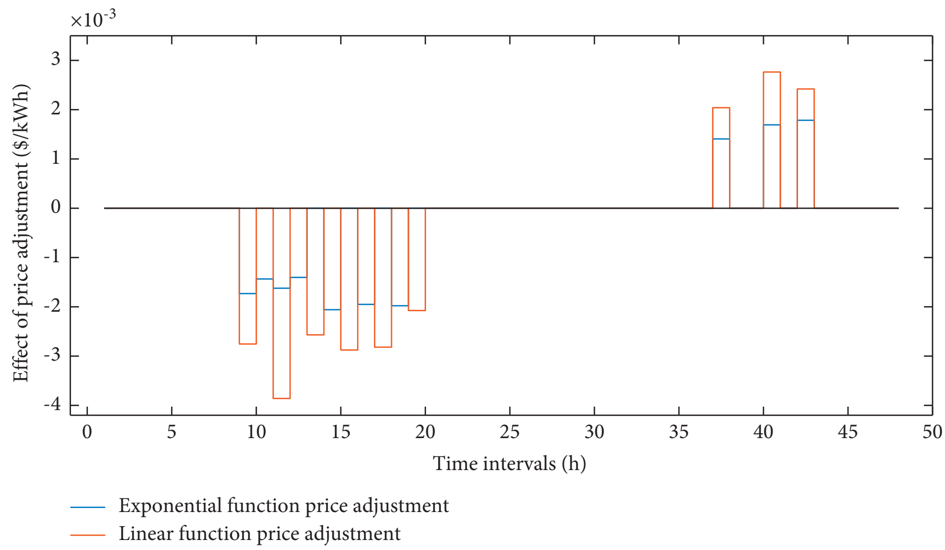

Figure 8: Comparison of price adjustment effects in different adjustment strategies.

5. Conclusions

In our smart grid system, users can book a day or more of electrical energy consumption according to dynamic pricing provided by the energy provider. This energy provider monitors the real-time booked consumption loads and obtains the stable consumption load through the price demand response mechanism. The automatic process control strategy put forward in the article is as follows. Manage power consumption process. That is to say, the energy supplier monitors the gap between the optimal generation capacity given by the social welfare maximization problem and consumers' booked electrical energy consumption. Then predict next time interval electrical energy consumption gap with statistical average model. It is only when predicted average number is beyond the presupposed boundary that price rises and cuts are used to change the price and to stimulate demand response. In this way, the adjustment frequency is not too great, and the users will change their initial consumption plan (i.e., reservation consumption) during the actual power consumption process. So the electrical energy consumption can become stable and the grid can run reliably and safely. The case analysis show that the network system of the energy provider automatically monitors and adjusts the price so as to get a small adjustment frequency, a stable actual electrical energy consumption, and a controllable residual standard deviation. After comparison, the exponential function adjustment method proposed in this paper is also shown to be more suitable than the linear one.

Appendix

The Social Welfare Model

A. Users' Utility Function. Based on microeconomics, a utility function $U(x,\omega)$ can be chosen to show the users' satisfactory degree after power consumption. x means the consumption load, and ω gives consumers' electrical energy consumption wills, changing with intervals and consumers. Consider no electricity demand and no utility. We choose logarithmic functions as [20]

$$U\left(x_i^t,\omega\right)=\begin{cases}\omega\ \ln\left(x_i^t+1\right), & \text{if } x_i^t\geq 0,\\ 0, & \text{if } x_i^t<0.\end{cases} \tag{A.1}$$

px denotes the consumers' cost, and the benefit function of each user is

$$W\left(x_i^t,\omega_i^t\right)=U\left(x_i^t,\omega_i^t\right)-p_t x_i^t, \tag{A.2}$$

where $W(x_i^t,\omega_i^t)$ is the welfare function of consumer i in interval t. It is assumed that the goal of every consumer is getting the optimal benefit value; that is, the maximum utility function and the minimum power consumption cost are generated.

B. The Energy Provider Profit Function. G_t denotes the energy provider's generation capacity in interval t. $G_t^{\max}$ and $G_t^{\min}$ denote peak and valley generation capacities, respectively. When consumers book electrical energy consumption several days ago, and the energy provider supplies power according to the booked electrical energy consumption, the energy system in this article will not have a blackout due to insufficient power supply. We assume $G_t^{\max}$ equals the amounts of maximum electrical energy demands of all users, and $G_t^{\min}$ equals those of minimum ones. $G_t^{\max}$ and $G_t^{\min}$ are expressed as follows [4]:

$$G_t^{\max}=\sum_{i=1}^{N}M_i^t, \tag{B.1}$$

$$G_t^{\min}=\sum_{i=1}^{N}m_i^t. \tag{B.2}$$

The power generation cost $C(G_t)$ in time interval t of the energy provider is [4]

$$C(G_t) = aG_t^2 + bG_t + c, \tag{B.3}$$

where $a > 0, b, c \geq 0$ are presupposed arguments. $p_t G_t$ is the energy provider's sales amount. Then the energy provider's profit in interval t is [4]

$$P(G_t) = p_t G_t - C(G_t). \tag{B.4}$$

C. The Social Welfare Maximization Problem. We discuss the optimization problem for the SG system in this article. The following formula shows the maximum total social welfare [4]:

$$\max_{x_i^t, G_t} \sum_{i=1}^{N} U(x_i^t, \omega_i^t) - C(G_t). \tag{C.1}$$

The constraint condition (C.2) displays that the consumption loads are less than the supply ones:

$$\text{s.t.} \sum_{i=1}^{N} x_i^t \leq G_t, \quad i \in \aleph, t \in \Gamma, \tag{C.2}$$

$$\begin{aligned} m_i^t &\leq x_i^t \leq M_i^t, \\ G_t^{\min} &\leq G_t \leq G_t^{\max}. \end{aligned} \tag{C.3}$$

Namely, under such a real-time electricity price mode, power failure caused by insufficient power supply can never happen. Because the objective function displayed in (C.1) is concave and the constraint condition (C.2) is linear, the model (C.1)–(C.3) is a convex programming problem. Therefore, not a few algorithms can solve the consumption load and generation capacity. For example, interior point algorithm can solve the problem. However, these algorithms cannot solve the exact RTP, a key point in controlling and managing the electrical energy consumption in the article. So the dual method is applied to solve problem (C.1)–(C.3).

Data Availability

The data used to support the findings of this study are included in the references within the article.

Conflicts of Interest

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

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Research Article

Prediction of Vegetable Supply in Henan Province Based on PSO-GM (1, *N*) Model

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GM (1, *N*) model is one of the grey prediction models considering the influence of many factors. This paper improves GM (1, *N*) model and constructs PSO-GM (1, *N*) model. Firstly, Lasso method is used to select the influencing factors, then the priority of influencing factors and the value of parameter *N* in GM (1, *N*) model are determined, and finally PSO method is used to optimize GM (1, *N*) model. Taking the vegetable supply in Henan Province as the research object, this paper makes an empirical test by using PSO-GM (1, *N*) model. The results show that the key factors affecting the vegetable supply in Henan Province are the number of rural employees, highway mileage, and application of pesticide. The vegetable supply in Henan Province will continue to show a steady growth trend in the next three years.

1. Introduction

Vegetables are essential agricultural products in the daily life of urban and rural residents. Effectively ensuring the supply of vegetables has become a great event related to people's livelihood. Vegetable supply is affected by many factors such as natural climate, production capacity, and transportation. Effectively identifying the key factors affecting vegetable supply and accurately predicting the future vegetable supply are of great practical significance for stabilizing vegetable market supply and stabilizing vegetable price fluctuation.

Scholars have studied the influencing factors analysis and prediction model construction of vegetable supply from different angles. Wu and Mu [1] found that the urban population has the greatest impact on the circulation of vegetables; Hu et al. [2] analyzed the impact of agricultural informatization on vegetable yield; Yu [3] found that the main factors affecting vegetable production are planting area, vegetable consumption, and agricultural financial expenditure; Yang and Sun [4] found that the main factors affecting vegetable yield are economic development, technical investment, and land; Li and Mu [5] analyzed the impact of financial capital on Farmers' willingness to continue planting vegetables; Yin [6] constructed a wavelet neural network prediction model and predicted tomato yield; Qiao ad Liu [7] analyzed the impact of the aging of vegetable farmers on vegetable yield. Jin et al. [8] analyzed the role of logistics service providers in detail. From the existing research results, scholars mainly focus on the field of vegetable production, which cannot completely reflect the whole process of vegetable supply. Scholars rarely or even did not consider the grey characteristics of some known information, some unknown information, and poor information of the influencing factors of vegetable supply. In addition, when constructing the prediction model, the multicollinearity and overfitting between the influencing factors are not considered deeply. When considering the influence of multiple factors, Lasso (least absolute shrinkage and selection operator) method can eliminate those unimportant factors from many influencing factors, select a few important factors that have a significant impact on the system, and effectively eliminate the problems of multicollinearity and overfitting. GM (1, *N*) model is one of the grey prediction models considering the influence of many factors. In view of the large error of the grey prediction model in practical application, this paper proposes an improved PSO-GM (1, N) model, which provides a new way to study the prediction of vegetable supply.

2. PSO-GM (1, N) Model

For a multifactor prediction problem, let $X_0 = (x_0(1), x_0(2), \ldots, x_0(n))$ be the system characteristic data sequence, and $X_i = (x_i(1), x_i(2), \ldots, x_i(n))$ be the influencing factor sequence. In order to eliminate the multicollinearity problem of relevant influencing factors, PSO-GM (1, N) first screens the relevant influencing factors by Lasso method, then determines the priority of influencing factors and the value of parameter N in GM (1, N) model, that is, the second selection of relevant influencing factors, and finally optimizes GM (1, N) model by PSO method.

2.1. Lasso Method. Lasso is a regularized compression estimation method proposed by statistician Robert Tibshirani in 1996. Regularization is a strategic method that can constrain the characteristics of the model and prevent overfitting. Based on the loss function of the least squares (ordinary least square (OLS)), Lasso uses the sum of the absolute values of the regression coefficients as a penalty function to compress the regression coefficients. When the sum of the absolute values of the regression coefficients is small enough, some regression coefficients can be compressed to zero, and then the variables with zero coefficients can be eliminated, so as to achieve the effect of variable selection [9]. Assumed linear regression model $X_0 = \beta X + \varepsilon$, where X_0 is the system behavior characteristic vector, X is the influence factor variable matrix, and β is the coefficient vector, then the coefficient estimation of Lasso method is as follows:

$$\widehat{\beta} = \arg\min\left\{ \|Y - X\beta\|^2 + \lambda \sum_{j=1}^{p} \left|\beta_j\right| \right\}. \tag{1}$$

Here, $X_0 = (x_0(1), x_0(2), \ldots, x_0(n))$.

$$X = \begin{bmatrix} x_1(1) & x_2(1) & \ldots & x_s(1) \\ x_1(2) & x_2(2) & \ldots & x_s(2) \\ \vdots & \vdots & \ddots & \vdots \\ x_1(n) & x_2(n) & \ldots & x_s(n) \end{bmatrix}, \tag{2}$$

where $\|Y - X\beta\|^2$ is the loss function, $\lambda \sum_{j=1}^{p} |\beta_j|$ is the regularization function, and λ is the adjustment parameter, also known as regularization parameter; it is mainly used to balance loss function and regularization function. When λ $(\lambda \geq 0)$ is increasing gradually from 0, the regularization function can set the estimated values of some coefficients to zero, so as to eliminate the corresponding variables and achieve the purpose of variable selection. The value of λ is determined by cross validation, that is, one part of the influencing factor sample data is selected as the training set and the other part is selected as the validation set, and different models are generated under the same training set. When the error of the verification set in these models is the smallest, at this time, λ is selected. Using Lasso method, if m main influencing factors are selected from s influencing factors, i.e., the influencing factor set is screened for the first time, it can be recorded as $X_i'(i = 1, 2, \ldots, m)$.

2.2. Priority of Influencing Factors. Based on the set of influencing factors selected for the first time, Deng's grey relational analysis model is used to determine the priority of each influencing factor. Due to the different dimensionless processing methods of the original data, it has different effects on the grey correlation order of the influencing factors. Here, this paper uses six processing methods, i.e., ① initial value, ② average value, ③ minimization, ④ maximization, ⑤ centralization, and ⑥ difference.

Because the correlation order is reflected in the difference of the influence factors on the system behavior, and the more obvious the difference is, the better the reasonable correlation order is selected based on the following principles. Suppose six dimensionless processing methods are used to get the correlation degree of influencing factors as $r_k^i (i = 1, 2, \ldots, m, k = 1, 2, \ldots, 6)$. On the premise of small amount of calculation, two principles are proposed to judge the reasonable correlation order [10]:

$$\Delta_k = \max\left\{r_i^k\right\} - \min\left\{r_i^k\right\}, \quad (k = 1, 2, \ldots, n), \text{ as large as possible,} \tag{3}$$

$$\sigma_k = \frac{1}{n}\sqrt{\left(r_i^k - \frac{1}{n}\sum_{i=1}^{n} r_i^k\right)^2}, \text{ as large as possible.} \tag{4}$$

For the influencing factor sequence $X_i'(i = 1, 2, \ldots, m)$, according to the above principles, the reasonable correlation order of influencing factors can be determined. For convenience of expression, it is recorded here as follows:

$$X_1' > X_2' > \cdots > X_i' \cdots > X_m', \quad (i = 1, 2, \ldots, m). \tag{5}$$

2.3. GM (1, N) Model and Its N Value Determination Method

2.3.1. GM (1, N) Model. GM (1, N) model is a first-order differential equation prediction model with N variables, which reflects the influence of N–1 influencing factor variables on the first derivative of one system behavior variable. In order to be consistent with the traditional GM (1, N) model representation method, the corresponding system behavior characteristic sequence and the influencing factor sequence selected and determined for the first time are reexpressed as follows:

$$X_1^{(0)} = \left(x_1^{(0)}(1), \ldots, x_1^{(0)}(i), \ldots, x_1^{(0)}(n)\right). \tag{6}$$

Influencing factor sequence $X_i'(i = 1, 2, \ldots, m)$ can be expressed as

$$\begin{aligned} X_2^{(0)} &= \left(x_2^{(0)}(1), \ldots, x_2^{(0)}(i), \ldots, x_2^{(0)}(n)\right), \\ X_3^{(0)} &= \left(x_3^{(0)}(1), \ldots, x_3^{(0)}(i), \ldots, x_3^{(0)}(n)\right), \\ &\vdots \\ X_N^{(0)} &= \left(x_N^{(0)}(1), \ldots, x_N^{(0)}(i), \ldots, x_N^{(0)}(n)\right). \end{aligned} \tag{7}$$

Let $X_j^{(1)}$ be the 1-AGO sequence of $X_j^{(0)}$, $(j = 1, 2, \ldots, N)$, and $Z^{(1)}$ be the nearest neighbor mean generating sequence of $X_1^{(1)}$, then

$$x_1^{(0)}(k) + a z_1^{(1)}(k) = \sum_{j=2}^{N} b_j x_j^{(1)}(k), \quad k = 1, 2, \ldots, n. \tag{8}$$

is called GM (1, N).

When the amplitude of change of $X_j^{(1)}$, $(j = 1, 2, \ldots, N)$, is very small, the approximate time response of GM (1, N) is as follows:

$$\hat{x}_1(k+1) = \frac{1}{\alpha}\sum_{j=2}^{N} b_i x_i^{(1)}(k+1) + \left[x_1^{(1)}(0) - \frac{1}{a}\sum_{j=2}^{N} b_i x_i^{(1)}(k+1)\right]e^{-ak}, \quad k = 1, 2, \ldots, n, \tag{9}$$

where $x_1^{(1)}(0)$ is taken as $x_1^{(0)}(1)$.

The predicted values of system behavior variables are as follows:

$$\hat{x}_1^{(0)}(k+1) = \hat{x}_1^{(1)}(k+1) - \hat{x}_1^{(1)}(k). \tag{10}$$

2.3.2. Determination of N Value in GM (1, N) Model. At present, GM (1, N) model has been widely used and innovated. Ma and Liu [11] proposed discrete GM (1, N) model and analyzed the basic law of oil production decline and the influence of related factors; Fan [12] proposed an improved GM (1, N) soybean price forecasting model; Xie et al. [13] proposed the GICM model, screened the key indicators of complex products, and improved the prediction accuracy of GM (1, N) model; Ren [14] used GM (1, N) method to model anaerobic digestion system and predict methane production; Zeng et al. [15] proposed a new multivariable grey prediction GM (1, N) model; Xiong et al. [16] improved GM (1, N) model and proposed AWGM (1, N) model to predict housing demand; Yang and Liu [17] used GM (1, N) model to predict China's grain output; Cheng et al. [18] established grey GM (1, 3) model to simulate and predict the main influencing factors of clean energy consumption; Zhang [19] analyzed the influencing factors of ginger planting area from the aspects of economy, input, and output and established a grey prediction model.

From the existing research results, no scholar has studied the value of parameter N in GM (1, N) model. This paper proposes a method to determine the value of the parameter N in GM (1, N) model: according to the correlation order of the influencing factors of system behavior, the influencing factor variables are selected in order to establish the model.

In order to test the accuracy of the prediction results of the model, the last three samples are selected from the n sample of the system as the comparison value of the prediction results of the model, and the model is established by using n–3 sample data. Through the test of the prediction effect, the optimal N value is determined. The specific steps are as follows:

In Step 1, based on the reexpression of influencing factor sequence in relation (5) and 2.3.1, select $X_2^{(0)}$, establish GM (1, 2) model, and predict the three periods of n–2, n–1, and n. Through comparing with the actual value and calculating the average relative error, the result is recorded as ε_2.

In Step 2, according to the above method and the correlation order of influencing factors determined in relation (5), the GM (1, 3) model, GM (1, 4) model,. . .,GM (1, N) model are established, respectively, and the average relative errors are calculated, which are recorded as $\varepsilon_3, \varepsilon_4, \ldots, \varepsilon_N$.

In Step 3, when $\varepsilon_i (i = 2, 3, \ldots, N)$ is the minimum, the prediction accuracy of the model is the highest. In this case, the value of i is the optimal solution, that is, the GM (1, i) model is the optimal prediction model.

This process can be called the second selection influencing factor set.

2.3.3. PSO-GM (1, N) Prediction Model. Particle swarm optimization (PSO) initializes a group of random particles and then finds the optimal value through multiple iterations.

In each iteration, each particle updates its speed and position through the individual extreme $p$best and global extreme $g$best. The calculation formula is as follows:

$$v_{k+1} = wv_k + c_1 r_1 (p\text{best}_k - x_k) + c_2 r_2 (g\text{best}_k - x_k),$$
$$x_{k+1} = x_k + v_{k+1}, \tag{11}$$

where v_k is the current velocity of the particle, x_k is the current position of the particle, $p\text{best}_k$ is the position of the optimal value currently found by the particle, and $g\text{best}_k$ is the position of the optimal value currently found by the whole population. w is the inertia weight, c_1, c_2 is the acceleration coefficient, usually $c_1 = c_2 = 2$. r_1, r_2 is a random number between (0, 1). Through continuous updating, particles finally reach the position of the global optimal value.

According to the basic principle of GM (1, N) model, let $u = (a, b_1, b_2, \ldots, b_{n-1})^T$; the calculation formula is $u = (B^T B)^{-1} BY$, where

$$B = \begin{bmatrix} -z_1^{(1)}(2) & x_2^{(1)}(2) & \ldots & x_n^{(1)}(2) \\ -z_1^{(1)}(3) & x_2^{(1)}(3) & \ldots & x_n^{(1)}(3) \\ \vdots & \vdots & \ddots & \vdots \\ -z_1^{(1)}(n) & x_2^{(1)}(n) & \ldots & x_n^{(1)}(n) \end{bmatrix},$$
$$Y = \begin{bmatrix} x_1^{(0)}(2) \\ x_1^{(0)}(3) \\ \vdots \\ x_1^{(0)}(n) \end{bmatrix}. \tag{12}$$

It can be seen that the representation of GM (1, N) model depends on matrix B. The estimated value of the parameter u is obtained according to the above method, but it is not necessarily optimal. In this paper, PSO-GM (1, N) model is proposed: add other parameters to matrix B, and then use particle swarm optimization algorithm to obtain the optimal parameter u. Matrix B with parameters is reexpressed as follows:

$$B = \begin{bmatrix} -k_1 * z_1^{(1)}(2) & k_2 * x_2^{(1)}(2) & \ldots & k_N * x_N^{(1)}(2) \\ -k_1 * z_1^{(1)}(3) & k_2 * x_2^{(1)}(3) & \ldots & k_N * x_N^{(1)}(3) \\ \vdots & \vdots & \ddots & \vdots \\ -k_1 * z_1^{(1)}(n) & k_2 * x_2^{(1)}(n) & \ldots & k_N * x_N^{(1)}(n) \end{bmatrix}. \tag{13}$$

Then, the parameter $(\hat{a}, \hat{b}_1, \hat{b}_2, \ldots, \hat{b}_{n-1})^T$ is reestimated according to formula $u = (B^T B)^{-1} BY$, the parameter in $(\hat{a}, \hat{b}_1, \hat{b}_2, \ldots, \hat{b}_{n-1})^T$ is a function of $k_i\,(i = 1, 2, \ldots, N)$, and GM (1, N) is also a function of $k_i\,(i = 1, 2, \ldots, N)$.

According to the optimal prediction model GM (1, N) determined in 2.3.2, the relative errors of the model in three periods of $n-2$, $n-1$, and n are calculated, respectively: $\varepsilon(n-2)$, $\varepsilon(n-1)$, and $\varepsilon(n)$. The minimum average relative error in these three periods is taken as the objective function of particle swarm optimization algorithm, which is specifically expressed as follows:

$$\min \text{avg} = \frac{1}{3} (\varepsilon(n-2) + \varepsilon(n-1) + \varepsilon(n)). \tag{14}$$

3. Prediction of Vegetable Supply in Henan Province

3.1. Data Sources and Influencing Factors. Due to the lack of a perfect statistical index system for agricultural products logistics, this paper selects the product of the number of urban residents and the per capita fresh vegetable purchase of urban residents in Henan Province from 2007 to 2019 as the vegetable supply (X_0) and uses the predicted value of vegetable supply (X_0) to reflect the development and change of vegetable supply in Henan Province in the future. According to the existing research results and the principles of comprehensiveness, representativeness, and operability of index selection, 9 influencing factors are selected: vegetable planting area (X_1) (thousand hectares), the application amount of pesticide (X_2) (10 thousand tons), the usage of plastic film (X_3) (10 thousand tons), plastic film coverage area (X_4) (thousand hectares), the number of rural employees (X_5) (10 thousand people), the investment in transportation, storage, and postal industry (X_6) (100 million RMB), highway mileage (X_7) (10 thousand km), the tonnage of road truck (X_8) (10 thousand tons), and the number of employees in highway transportation industry (X_9) (people). The data in this paper are all from the statistical yearbook of Henan Province.

3.2. Data Processing and Result Analysis

3.2.1. Determination of the First Influencing Factor Set. Based on the influence factor set selected in 3.1, this paper takes the sample data of influence factors from 2007 to 2016 as the training set and uses Lasso method to determine the influence factors with the help of MATLAB software. The minimum error value can be obtained by iterating the program for 8 times. The factors corresponding to the nonzero term in the regression coefficient are the selection results of Lasso method. The specific results are shown in Table 1.

3.2.2. Priority of Influencing Factors Selected for the First Time. According to the influence factor set selected for the first time, the method established in 2.2 is used for processing, and the specific calculation results are shown in Table 2. According to the judgment criteria (3) and criteria (4), the ideal correlation order of influencing factors is obtained after the initial value processing method:

$$X_4' > X_6' > X_1' > X_3' > X_2' > X_5' > X_7'. \tag{15}$$

3.2.3. Determination of N Value in GM (1, N) Model. For expression (13), the method determined in 2.3.2 is used for processing, and the results are shown in Table 3. Because ε_4 (4.93%) is the minimum value of $\varepsilon_i\,(i = 2, 3, \ldots, N)$, so $N = 4$, that is, the influencing factors of the second selection

Table 1: Set of influencing factors for the first selection.

Factors influencing the first choice	Unit
Application amount of pesticide X_1'	10 thousand tons
Usage of plastic film X_2'	10 thousand tons
Plastic film coverage area X_3'	1 thousand hectares
Number of rural employees X_4'	10 thousand people
Investment in transportation, storage, and postal industry X_5'	100 million RMB
Highway mileage X_6'	10 thousand km
Tonnage of road truck X_7'	10 thousand tons

Table 2: Correlation order of various processing methods and its judging criteria.

Processing method	Correlation order of influencing factors	Δ_k	σ_k
① Initial value	$X_4' > X_6' > X_1' > X_3' > X_2' > X_5' > X_7'$	0.4192	0.0677
② Average value	$X_4' > X_6' > X_1' > X_3' > X_2' > X_7' > X_5'$	0.3573	0.0612
③ Minimization	$X_6' > X_4' > X_3' > X_1' > X_2' > X_7' > X_5'$	0.3367	0.0529
④ Maximization	$X_1' > X_3' > X_6' > X_4' > X_2' > X_5' > X_6'$	0.3885	0.0660
⑤ Centralization	$X_5' > X_6' > X_4' > X_7' > X_2' > X_1' > X_3'$	0.0534	0.0077
⑥ Difference	$X_6' > X_3' > X_6' > X_2' > X_7' > X_1' > X_5'$	0.0801	0.0100

Table 3: Variable selection results of GM (1, *N*) model.

Model	Average relative error of prediction	Error value (%)
GM (1, 2)	ε_2	14.74
GM (1, 3)	ε_3	22.75
GM (1, 4)	ε_4	4.93
GM (1, 5)	ε_5	8.30
GM (1, 6)	ε_6	9.65
GM (1, 7)	ε_7	8.67
GM (1, 8)	ε_8	8.06

are the number of rural employees, highway mileage, and application amount of pesticide.

3.2.4. Prediction Results of PSO-GM (1, N) Model and Analysis of Influencing Factors. The PSO-GM (1, *N*) model established in 2.3.3 is used to predict the vegetable supply in Henan Province from 2017 to 2019, in which the number of particles is 100, the inertia weight is 1, the acceleration coefficient is 2, and the number of iterations is 1000. After many experiments and based on the sample data from 2010 to 2016, the average relative error of vegetable supply in Henan Province from 2017 to 2019 is the smallest, reaching 2.38%.

In order to compare the rationality of the prediction results, PSO-GM (1, 4) model, GM (1, 4) model, GM (1, 1) model, and multiple linear regression method are used to predict the vegetable supply in Henan Province. The actual value of vegetable supply in Henan Province from 2017 to 2019 is taken as the standard. The results are shown in Table 4. It can be seen from Table 4 that the average relative error from high to low is PSO-GM (1, 4) model, GM (1, 4) model, GM (1, 1) model, and multiple linear regression. It can be concluded that compared with the traditional GM (1, *N*) model, PSO-GM (1, *N*) model greatly improves the prediction accuracy and is much higher than other prediction models. It has strong rationality and can effectively predict the future vegetable supply.

According to the result of 3.2.3, PSO-GM (1, 4) model is used to forecast the vegetable supply in Henan Province in the next three years. The results are shown in Table 5. The data of influencing factors in the next three years are obtained by GM (1, 1) model, and the results are shown in Table 6.

It can be concluded from Table 5 that the vegetable supply in Henan Province will still show a steady growth trend in the next three years, and it is expected to reach 6.35 million tons in 2023. The key factors affecting the vegetable supply in Henan Province are the number of rural employees, highway mileage, and pesticide application. Among them, the number of rural employees and road mileage has a positive impact on vegetable supply, while the application amount of pesticides has a negative impact on vegetable supply.

Vegetable production is a labor-intensive industry; the number of labor has a direct impact on vegetable production. With the development of social economy, agricultural machinery has greatly improved labor productivity, but in vegetable production, due to the limitations of vegetable types and terrain, agricultural machinery is difficult to get effective application and still needs a lot of labor for manual operation. Therefore, the impact of rural employment on vegetable supply is positive.

Table 4: Prediction results of PSO-GM (1, 4)/GM (1, 4)/GM (1, 1)/multiple linear regression.

Year	Actual value	PSO-GM (1, 4)	GM (1, 4)	GM (1, 1)	Multiple linear regression
2017	504.11	518.49	546.50	543.01	535.48
2018	538.41	536.02	571.50	587.93	480.18
2019	570.21	548.23	568.90	636.57	490.72
Average relative error (%)		2.38	4.93	9.52	10.32

Table 5: Forecast value of vegetable supply in Henan Province.

Vegetable supply	Year		
	2021	2022	2023
Estimate	578.27	592.07	635.71

Table 6: Prediction of influencing factors of vegetable supply.

Influence factors	Year		
	2021	2022	2023
Number of rural employees	4083	3915	4440
Highway mileage	27.17	27.28	27.38
Application amount of pesticide	9.51	8.97	8.45

The modes of freight transportation include road transportation, railway transportation, waterway transportation, and air transportation. Due to the characteristics of short distance transportation of vegetables, highway transportation is widely used in vegetable transportation. Transportation infrastructure construction plays an important role in promoting vegetable transportation. Perfect traffic network can speed up the circulation of vegetables and expand the scale of vegetable market. Highway mileage is an important indicator of regional traffic infrastructure. Therefore, the impact of highway mileage on vegetable supply is positive.

The excessive pesticide residue in vegetables is an important task in the supervision of vegetable quality and safety. In the process of vegetable production, due to the frequent occurrence of diseases and insect pests, farmers have overdose in vegetable production in order to ensure vegetable yield. Due to the strict control of government departments, the supply of vegetable market has decreased significantly. In order to stabilize the normal supply of vegetable market, it is urgent to reduce the use of pesticides. Therefore, the effect of pesticide application on vegetable supply is negative.

4. Conclusions

Vegetable supply is affected by multiple factors, and the relationship between influencing factors is complex. In this paper, when using PSO-GM (1, N) model to predict vegetable supply in Henan Province, firstly, Lasso method is used to select many factors affecting vegetable supply for the first time, which eliminates the problems of multicollinearity and overfitting between factors. Then, based on the grey correlation analysis, the priority of the influencing factors is sorted, the determination method of parameter N in GM (1, N) is proposed, and the influencing factors are selected for the second time. Finally, the PSO method is used to optimize the GM (1, N) model, which greatly improves the prediction accuracy. Based on PSO-GM (1, N) model, the vegetable supply in Henan Province in the next three years is predicted. The results show that the vegetable supply in Henan Province continues to show an increasing trend. The key factors affecting vegetable supply in Henan Province are the number of rural employees, highway mileage, and application of pesticide. The PSO-GM (1, N) model proposed in this paper provides a new method for multifactor grey prediction. However, this study does not consider the impact of adjacent provinces on vegetable supply in Henan Province, especially spatial autocorrelation. Next, the temporal and spatial evolution law of vegetable supply in Henan Province will be explored from the two dimensions of time and space.

Data Availability

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

Conflicts of Interest

The authors have no conflicts of interest.

Authors' Contributions

Bingjun Li was responsible for proposing the overall idea and framework of the manuscript. Xueqiang Guo was responsible for data processing and writing of the first draft of the manuscript.

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