Discrete Dynamics in Nature and Society

Public Health, Safety, and Sustainable Resilient Cities

Lead Guest Editor: Wei Zhang
Guest Editors: Guangdong Wu and Chunming (Victor) Shi

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Research Article

Participant and Strategy Selection of Health QR Code Product Experience Design during the COVID-19 Pandemic in China: The Information Security Perspective

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Health QR code is an Internet product designed and developed by China to combat the COVID-19 pandemic. In order to build a public health and epidemic prevention barrier, the Chinese government's health QR code product is a useful attempt to deal with epidemic prevention and control and social governance in the way of "Internet plus big data". In the process of health QR code product design and development, we conduct a security analysis of information data and employ project management, product design, development and testing, online, and operational product experience design methods. User requirements and product definitions for the health QR code include management, design, development, and testing. The main participants of health QR code product experience design are divided into product manager, design and development team, and users. The relationships among the product manager, the design and development team, and users are established using the evolutionary game method. It is found that the cost of information security has an important influence on the choice of the user policy. Product managers, driven by benefits and values, may ignore the importance of information security when choosing the strategy for health QR code products, which will affect users' enthusiasm to use them to some extent and limit their use scenarios and application scope. Therefore, in order to achieve healthy user interaction and sustainable experience design of health QR code products, it is necessary to strengthen data security protection and reduce the cost of information interaction and sharing. Furthermore, on the basis of enhancing user viscosity and improving the usability of health QR code products, our research results show the further need for demand mining and version upgrading of health QR code products.

1. Introduction

As an Internet product, the health QR code was designed and developed by China during the fight against the new crown epidemic. China has divided the risk level of new crown disease into three criteria by region. The three criteria are low-risk area, medium-risk area, and high-risk area. Health QR code is based on personal declaration information, travel data, contact personnel information, medical treatment data, identification, data comparison, rules, and other means, to achieve personal epidemic risk level identification and visual display of the "e-health certificate" QR code. Health QR code is everyone's "electronic health certificate" and records the health QR code holder's epidemic risk level information; epidemic risk level is usually presented in red, yellow, and green. Green code users can travel, yellow code users have restricted travel, and red code users prohibited travel. This is shown in Figure 1.

Under the background that information security is being paid more attention, in the process of product experience design of health QR code product, the definition of group attribute information and interaction behavior data is clearer for product managers and design teams. In the process of product experience design, the work of product experience design should be carried out carefully under the premise of better protection of personal privacy information. In the process of user research, it is necessary to do qualitative research on user requirements and quantitative

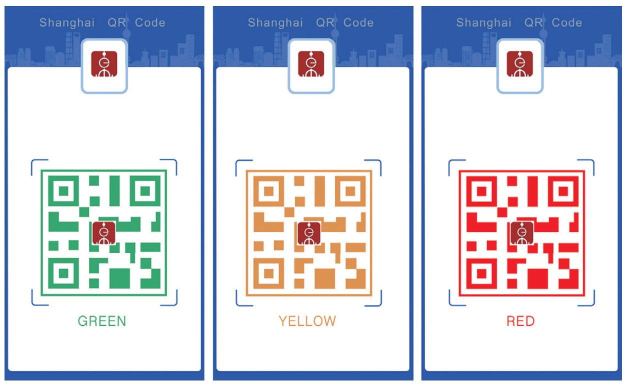

Figure 1: User interface for Shanghai health QR code product.

statistics on the priority of requirements. In the process of experience design of information products, it is necessary to utilize data legally and to mine the value of group attribute information and interactive behavior data [1]. With the constant variation of COVID-19, the health QR code information product collects the user's travel information, carries out information exchange in different scenarios, and realizes information exchange and dissemination with health QR code.

2. Literature Review

2.1. Information Product. Commercial competition of information products in the field of the Internet usually has three main driving forces: business model, technology, and user experience. At a time when there is little difference between the two factors, user experience is the fiercest battleground [2]. The three dimensions of business model, technology, and user are integrated into the process of product design. The role groups represented are product manager, design and development team, and user. Product managers predict the market, competing products, and self-development based on market requirement document (MRD) and product requirement document (PRD), aiming at version iteration and function upgrade of information products, the market, and product requirement documents to the design and development team for product research and development work. Then, MRD and PRD confirm the outline of the information product to serve the target users. Target users are evaluated and give feedback through the use of information products. The product manager develops a new version of the market and product requirement documents based on the use of the target audience, in order to pave the way for the next version of information product design and development, thus forming a closed loop.

Internet information product experience design refers to the research, design, and development of user experience around the information product (APP). The product design process is mainly considered from three aspects: commerce, information technology and users [3]. The role groups represented by the three aspects are product manager, design and development team, and target users. The product manager combs and summarizes the market requirement document (MRD) and product requirement document (PRD). The product manager carries out version iterations for information products and forecasts the future development of the market, competitive products, and their own products. Based on the market and product requirement document, the design and development team carries out product function development, promotes the iterative launch of information products, meets the needs of target users, and expands the target user group. After using the information products, the target user group will evaluate and give feedback. By investigating the use intention of the target user group, the product manager forms an iterative version of the market and product requirements document, which lays a foundation for the design and development of the new version of information products. Through the interaction of the three groups, the iterative upgrading of information products is formed. Information product design and development is an iterative process.

2.2. User Experience. Experience design has a lot to do with user experience. ISO 9241-210 : 2019 defines user experience as "people's cognitive impressions and responses to the products, systems, or services they use or expect to use". User's perceptions and responses result from the use and anticipated use of a system, product, or service [4]. Experience design is the participation of consumers in the design, in the design of the service as a "stage", the product as a "prop", and the environment as a "set". Designing for the users' experience involves considering, where appropriate, organizational impacts, user documentation, online help, support and maintenance, training, long-term use, and product packaging [5].

2.3. Product Experience Design. The related research of product experience design began in Europe and developed in America. It can be divided into four stages:

(1) The Industrial Revolution gave birth to human-computer interaction: the study of Ergonomics, which originated in the World War II era as the study of the control interface of military equipment, was designed to evolve from "useful" to "efficient", by American industrial designer Henry Dreves [6].

(2) Human-centered interaction design: with the development of Ergonomics, the focus of attention had shifted from machine to human, and "interaction design" has been emphasized. In 1995, Alan Cooper, a software engineer, began to systematically expound the design principles of human-computer interaction [7]. Then, the "user experience design" and "user-centered design" concept proposed by Harvard University Donald Norman (Don Norman) formed the user experience design trend of the future [8]. Then, in 1999, Elizabeth Sandl of Ohio State University came up with a "design for experience" [9]. California Institute of the Arts Sedov first linked experience to design in a 2001 monograph, thinking about experience in a design context [10].

(3) "Emotional Design" of information industry: Norman delved into how to incorporate emotional

effects into product design from three dimensions: instinct, behavior, and reflection (2003); in "systems and services", the author discussed" design for experience" to realize the further development from user experience to experience design (2011) [11].

(4) Experience Design in the age of smart media. Richard put forward the concepts of design management and design business [12]. In the industrial community, with the introduction of the iPhone in 2007, the launch of Google's Android operating system in 2009, and the launch of the iPad in 2010, bringing the evolution of experience design to the Fast Lane of the Mobile Smart Internet, the iOS operating system design specification, released in 2010, is a design guide for experience design.

2.4. Agile Development and Design Sprint. In software development, agile (sometimes written agile development) [13] practices involve discovering requirements and developing solutions through the collaborative effort of self-organizing and cross-functional teams and their customers and users [14]. It advocates adaptive planning, evolutionary development, early delivery, and continual improvement, and it encourages flexible responses to change.

Agile development takes the evolution of user's requirements as the core and adopts an iterative and step-by-step method to develop software. In agile development, software projects are split into subprojects early in their construction, and the results of each subproject are tested and characterized by visibility, integration, and usability. In other words, a large project is broken up into small, interconnected projects that can run independently and this is done separately, all the while keeping the software usable.

The design sprint is a time-constrained, five-phase process that uses design thinking with the aim of reducing the risk when bringing a new product, service, or feature to the market [15]. The process aims to help teams clearly define goals, validating assumptions and deciding on a product road map before starting development [16]. It seeks to address strategic issues using interdisciplinary, rapid prototyping, and usability testing. This design process is similar to Sprints in an agile development cycle [17].

Design Sprint is a combination of design thinking and agile development of two design methods, through team building, targeting, incubating ideas, incubating prototypes, and rapid verification of the design process; it is a short-term and rapid development method for a known problem that needs to be solved [18].

2.5. Evolutionary Game Theory. Game Theory originated from the book *Theory Games and Economic Behavior* written by John von Neumann and Oskar Morgenstern in 1944, which laid the Theoretical and Methodological Foundation of Game Theory. In 1965, Reinhard Selten introduced the concept of Nash Equilibrium into the analysis of dynamic problems and put forward the famous concept of "subgame-perfect equilibrium". John Harsanyi then introduced incomplete information into Game Theory and proposed the concepts of the incomplete game and Bayes equilibrium, as well as the methods to deal with the incomplete information game. In the 1990s, Friedman explored Evolutionary Game Theory and research methods in the field of economics [19]. A three-way evolutionary game model is built around product managers, design and development teams, and users, focusing on the impact of business model value performance and usability evaluation of the target user group on the experience design process of information products; as a key group of information product development, the design and development team is, in essence, the transfer process of knowledge related to information products, most of which are tacit knowledge with exclusive characteristics; it is often seen as a personal asset and a guarantee of job security in an organization [20]. Therefore, in the process of experience design of information product requirements, the product manager may not have enough time or high quality for the design and development team according to the requirements of the market and the target user group; this possibility has led to the emergence of a game among three participants in the experience design process of information products. And this game is also a repeated process because information product requirement development cannot be completed at one time; it usually needs to be repeated many times [21]. Evolutionary game is introduced to study the interaction mechanism and participation strategy selection of main stakeholders in Internet information product design based on bounded rationality [22].

3. The Evolutionary Game Model

3.1. Model Description. During an epidemic of COVID-19, the health QR code is an Internet information product of public health and antiepidemic service. Health QR code product's original intention comes from the user's demand. It can quickly adjust and reflect the product design level, implement product iteration update, in order to better retain users, improve the user experience, and then form a closed loop of user growth. In the era of big data, user data analysis is an important prerequisite for mining user needs, and the collection and mining of user personal data will accelerate the risk of personal information leakage. Based on this, this paper constructs an evolutionary game model of stakeholders in the iterative design process of health QR code products, considering the influence of user information security; the relationship between the players is shown in Figure 2.

As shown in Figure 2, the health QR code product iteration involves three main stakeholders: product manager, design and development team, and user. By analyzing the user data, the product manager forms the MRD and PRD and forecasts the market, competition, and self-development of the information product based on MRD and PRD. Subsequently, the product manager will market product requirement documents to the design and developmental team, by which the corresponding research and development work, finally, is delivered as an online service to users. The product manager forms a new version of the market and product requirement document through the user's feedback to the information product, which paves the way for the

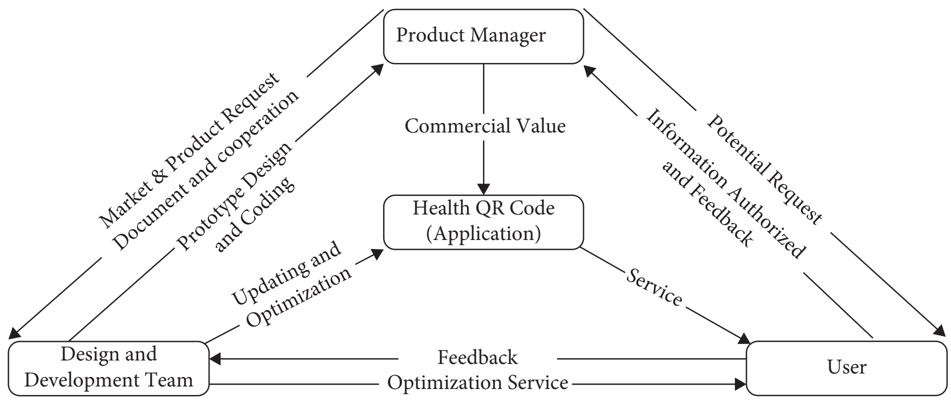

Figure 2: Tripartite game diagram.

design and development of the next version of the information product, thus forming a closed loop. Product managers and design and development teams work together through product iterations to provide users with an increasing sense of experience, to enhance user stickiness, to meet the needs of users while achieving the common goal of fighting the epidemic. As the final service object of the product, the feedback of user experience plays an important role in the iterative updating of information products.

In the era of big data, data has become an important resource. From a business perspective, the collection and utilization of user's personal data can help product managers to discover new user needs and provide better service for users, but it will also increase the risk of user data leakage; once the user's private information is divulged, it will have a seriously bad influence on the user and the information product, so this paper considers the influence of the user's data security on the product experience design. As mentioned above, the product manager acts as a bridge between the client's side and the product of health QR code design side in experience design and development of the health QR code product. The product manager will discover the user requirements of the design and development team, to achieve functional development and service upgrades. However, in the process of forming MRD and PRD, product managers may generate different oriented MRD and PRD based on two different starting points: benefit and experience. At the same time, with the development of technology, information product development has gradually changed from the traditional function-oriented and technology-oriented to user experience-oriented. As a result, product managers and design teams have two different approaches toward information product development, one based on performance and the other based on experience. One of the contributions of this paper is to explore the interactive mechanism of the stakeholders in the design process of health QR code as an information product, analyze how to promote product managers and design and development teams to transform into user experience-oriented development philosophy, provide better service for users, and extend the life cycle of health QR code information products.

3.2. Model Assumptions. Based on the description in Section 3.1 and the tripartite game diagram, the following hypotheses are proposed.

Hypothesis 1. This study assumes that stakeholders in the process of experience design of the health QR code are product managers, design and development teams, and user groups [23]. Experienced design and development of the health QR code is not quickly achieved, in which stakeholders need to learn, try mistakes, imitate the behavior of others, constantly adjust and modify personal behavior strategy, and then achieve a stable equilibrium [24].

Hypothesis 2. Product managers and design and development teams assume different strategies based on two different starting points: efficiency and experience. Therefore, the strategic space for setting the product manager group is {experience-oriented, benefit-oriented}, The proportion of choosing a benefit-oriented strategy is x $(0 \leq x \leq 1)$, the design and development team's strategy space is {experience design, agile development and design sprint}, and the percentage that chooses an experience design strategy is y $(0 \leq y \leq 1)$. Users can choose to license their private data to information products for better service, or they can choose not to license their private data to apps for data security reasons. Therefore, the policy space for the user community is set to {Authorized information sharing, not authorized information sharing}, where the percentage of authorization policies selected is z $(0 \leq z \leq 1)$. The health QR code products studied in this paper are products that already have a certain scale of users, so the experience design and development process is mainly embodied in product version iteration, optimization, and new function development, etc., where the user has authorized the product to collect its basic information. Therefore, the article sets authorized information sharing as a higher level of information sharing and may involve some personal privacy information. It should be noted that in reality, the function of product manager includes but is not limited to the function described in this paper. In addition, this paper also assumes that the experience/benefit-oriented needs of the product manager have an important embodiment of the user-centered/product-centered work philosophy of the product manager.

Hypothesis 3. If the user is authorized to share personal information in the process of using the product, the user can get the best user experience after the experience-oriented design upgrade; the benefit is R_{u1}; when the product manager and the design and development team do not choose the same strategy, that is, only one side chooses the user experience-oriented strategy, which is the focus of the study, the payoffs are all R_{u2}. After the product's performance-oriented and agile development upgrade, user revenue was R_{u3}. According to the degree of product experience design, the user benefits after product upgrade under the authorized information sharing strategy $R_{u1} > R_{u2} > R_{u3}$. At the same time, the collection and mining of user's personal data will accelerate the risk of personal information leakage [24]. As a result, authorized sharing of user information can result in additional potential losses C_u such as privacy breaches. If users are not authorized to share information in the process of use, because the product manager cannot accurately explore their needs, so different types of product upgrades to its revenue are less than the same situation authorized to share information users' revenue, that is $R_{u1} > R'_{u1}$, $R_{u2} > R'_{u2}$, and $R_{u3} > R'_{u3}$. In addition, the effect of the degree of product experience design on user revenue is also valid under the unauthorized information sharing policy; that is to say, $R'_{u1} > R'_{u2} > R'_{u3}$ is valid.

Hypothesis 4. When the user chooses the authorized information sharing strategy in the process of using the product, the product manager can precisely discover more user requirements and improve user stickiness. Therefore, this paper assumes that user-authorized information sharing strategy will increase the revenue of product managers with different demand-oriented strategies; that is, there is a revenue coefficient of $\beta\,(\beta > 1)$; when the user shares the authorized information, the revenue of the product manager's choice of experience-oriented demand is βR_{m1}, the revenue of the benefit-oriented demand is $\beta R'_{m1}$, and R_{m1} and $R_{m1}'$are the revenue of the product manager under the above two strategies when the user does not authorize information sharing. Product managers also face the potential loss (reputation, etc.) L_m of user privacy due to the higher level of information sharing and the adverse impact of information disclosure. It should be noted that regardless of whether the user chooses to authorize information sharing, the cost for product managers to propose experience-oriented requirements is C_{m1}, and the cost for benefit-oriented requirements is C_{m1}'. The introduction of experience-oriented requirements improves the user experience, as does the cost to the product manager, so there are $C_{m1} > C_{m1}'$. At the same time, when the product manager proposes the experience-oriented requirement, if the design and development team focus on the experience design, the two sides will bring the additional synergy benefit ΔR_{m1}. When a product manager brings forward a benefit-oriented requirement, an experience design by the design and development team will bring additional revenue to the product manager $\Delta R'_{m1}$. Furthermore, regardless of the strategy chosen by the product manager, coordination costs arise when design development teams conflict with the product manager's design philosophy C_{m2}.

Hypothesis 5. When users authorize information sharing, the design and development team can obtain more additional information and user feedback, more specifically meet the needs put forward by the product manager, solve the user pain points, and reduce the design and development cost. Therefore, this paper assumes that user authorized information sharing can effectively reduce the difficulty of development and design, that is, there is a cost coefficient δ $(0 < \delta < 1)$, so that the design and development cost can be reduced when user authorized information sharing. At this time, the costs paid by team experience design and agile development (including the additional costs paid for properly storing user information) are δC_{d1} and $\delta C'_{d1}$ respectively, where C_{d1} and C'_{d1} are the cost of experience design and agile development strategy selected by the design and development team when the user does not authorize information sharing. No matter whether the user authorizes information sharing or not, the benefit obtained by the design team from experience design is R_{d1}, and the benefit obtained from agile development is R'_{d1}, which is obviously $R_{d1}>R'_{d1}> C'_{d1}> C'_{d1}$. When users authorize information sharing, no matter what strategy the design and development team chooses, the design and development team will face potential losses L_d (reputation, etc.) caused by user privacy data disclosure. As stated in Hypothesis 4, if both the design and development team and the product manager carry out user experience-oriented product design, additional synergy benefits will be generated, which is ΔR_{m1} , but when their design concepts conflict, the performance loss to the design and development team will be C_{d2}.

Thus, relevant symbols and meaning descriptions of the Internet product experience design strategy selection model are shown in Table 1.

As mentioned earlier, the user can choose whether to authorize information, and the product manager can choose experience-oriented or benefit-oriented information product design and development strategies. The design and development team can adopt the product experience design method or agile development and design sprint method to obtain different income orientations under different strategies. The tripartite game tree formed by the three parties is shown in Figure 3.

4. The Analysis of Multiagent Evolutionary Game Model

4.1. Establishment of Multiagent Evolutionary Game Model. Based on the game diagram of product manager, design and development team, and users and the above basic assumptions, the payment matrix of user's choice of authorized information sharing strategy and unauthorized information sharing strategy for health QR code product experience design is obtained, as shown in Tables 2 and 3.

Based on the above payment matrix, the expected returns U_{m1} for the experience-oriented strategy, U_{m2} for the benefit-oriented strategy, and U_m for the group of product managers are

Table 1: The symbols and meaning description.

Symbols	Meaning description
x	The probability that the product manager selects the experience-oriented strategy; then $1-x$ is the probability of selecting the benefit-oriented strategy $(0 \le x \le 1)$
y	The probability that the design and development team carries out experience design; then $1-y$ is the probability of agile development and design sprint $(0 \le y \le 1)$
z	If the user selects the probability of authorizing information sharing, then $1-z$ is the probability of not authorizing information sharing $(0 \le z \le 1)$
R_{u1}	Experience-oriented in the case of authorized information sharing & the benefits of users after the upgrade of experience design
R_{u2}	In the case of authorized information sharing, only one party chooses to be user-experience-oriented. The benefits of users after product upgrading
R_{u3}	Benefit orientation of products in the case of authorized information sharing & benefits of users after agile development and upgrading
C_u	Authorized information sharing will bring potential extra losses to users, such as privacy disclosure
R'_{u1}	Experience-oriented in the case of unauthorized information sharing & the benefits of users after the upgrade of experience design
R'_{u2}	In the case of unauthorized information sharing, only one party chooses to be user-experience-oriented. The benefits of users after product upgrading
R'_{u3}	Benefit orientation of products without authorized information sharing & benefits of users after agile development and upgrading
β	Revenue promotion coefficient of authorized information sharing for product managers $(\beta > 1)$
R_{m1}	Revenue generated when product managers choose experience-oriented needs without authorizing information sharing
R_{m1}'	Revenue generated when the product manager selects benefit-oriented demand without authorizing information sharing
L_m	Potential loss (reputation, etc.) to the product manager due to the risk of user privacy data disclosure under authorized information sharing
C_{m1}	The product manager chooses to propose the cost of experience-oriented demand
C'_{m1}	The product manager chooses to propose the cost of benefit-oriented demand
ΔR_{m1}	The product manager puts forward experience-oriented requirements and the design and development team carries out experience design, which brings synergy benefits to both parties
$\Delta R'_{m1}$	The product manager puts forward benefit-oriented requirements, and the design and development team carries out experience design, which brings additional benefits to the product manager
C_{m2}	Coordination cost of product manager when the design and development team conflicts with the design concept of product manager
δ	Cost reduction factor of authorized information sharing for design and development team $(0 < \delta < 1)$
C_{d1}	Cost of experience design strategy selected by design and development team without authorization of information sharing
C'_{d1}	Cost of design and development team choosing agile development and design sprint strategy without authorized information sharing
R_{d1}	Benefits of experience design by design and development team
R'_{d1}	Benefits of agile development and design sprint by design and development team
L_d	Potential loss to the design and development team due to the risk of user privacy data disclosure in the case of authorized information sharing
C_{d2}	The performance loss caused by the conflict with the design concept of the product manager to the design and development team

$$\begin{aligned} U_{m1} &= yz\left(\beta R_{m1} - C_{m1} + \Delta R_{m1} - L_m\right) + y(1-z)\left(R_{m1} - C_{m1} + \Delta R_{m1}\right) \\ &\quad + (1-y)z\left(\beta R_{m1} - C_{m1} - C_{m2} - L_m\right) + (1-y)(1-z)\left(R_{m1} - C_{m1} - C_{m2}\right) \\ &= R_{m1} - C_{m1} - C_{m2} + y\left(\Delta R_{m1} + C_{m2}\right) + z\left[(\beta-1)R_{m1} - L_m\right], \end{aligned} \tag{1}$$

$$\begin{aligned} U_{m2} &= yz\left(\beta R'_{m1} - C'_{m1} + \Delta R'_{m1} - C_{m2} - L_m\right) + y(1-z)\left(R'_{m1} - C'_{m1} + \Delta R'_{m1} - C_{m2}\right) \\ &\quad + (1-y)z\left(\beta R'_{m1} - C'_{m1} - L_m\right) + (1-y)(1-z)\left(R'_{m1} - C'_{m1}\right) \\ &= R_{m1}' - C'_{m1} + y\left(\Delta R'_{m1} - C_{m2}\right) + z\left[(\beta-1)R'_{m1} - L_m\right], \end{aligned} \tag{2}$$

$$U_m = xU_{m1} + (1-x)U_{m2}. \tag{3}$$

The design team's expected payoff for choosing an experience design strategy U_{d1}, the design team's expected payoff for choosing agile development and design sprint strategy U_{d2}, and the design team's expected payoff U_d are

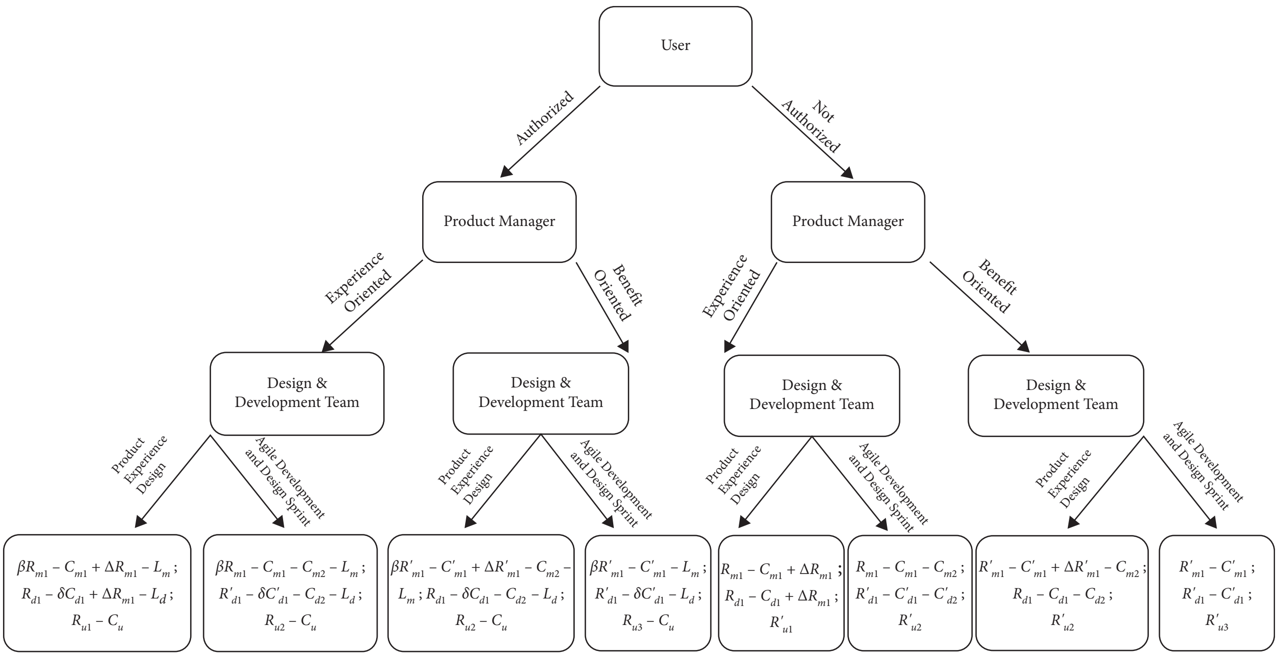

Figure 3: The tripartite game tree.

Table 2: Payment matrix under user-selected authorization information sharing policy (z).

Product manager	Design and development team	
	Product experience design (y)	Agile development and design sprint ($1-y$)
Experience orientation (x)	$(\beta R_{m1} - C_{m1} + \Delta R_{m1} - L_m; R_{d1} - \delta C_{d1} + \Delta R_{m1} - L_d; R_{u1} - C_u)$	$(\beta R_{m1} - C_{m1} - C_{m2} - L_m; R'_{d1} - \delta C'_{d1} - C_{d2} - L_d; R_{u2} - C_u)$
Benefit orientation ($1-x$)	$(\beta R'_{m1} - C'_{m1} + \Delta R'_{m1} - C_{m2} - L_m; R_{d1} - \delta C_{d1} - C_{d2} - L_d; R_{u2} - C_u)$	$(\beta R'_{m1} - C'_{m1} - L_m; R'_{d1} - \delta C'_{d1} - L_d; R_{u3} - C_u)$

Table 3: Payment matrix under user-selected unauthorized information sharing policy ($1-z$).

Product manager	Design and development team	
	Product experience design (y)	Agile development and design sprint ($1-y$)
Experience orientation (x)	$(R_{m1} - C_{m1} + \Delta R_{m1}; R_{d1} - C_{d1} + \Delta R_{m1}; R'_{u1})$	$(R_{m1} - C_{m1} - C_{m2}; R'_{d1} - C'_{d1} - C_{d2}; R'_{u2})$
Benefit orientation ($1-x$)	$(R'_{m1} - C'_{m1} + \Delta R'_{m1} - C_{m2}; R_{d1} - C_{d1} - C_{d2}; R'_{u2})$	$(R_{m1}' - C_{m1}'; R_{d1}' - C_{d1}'; R'_{u3})$

$$\begin{aligned} U_{d1} &= xz\left(R_{d1} - \delta C_{d1} + \Delta R_{m1} - L_d\right) + x(1-z)\left(R_{d1} - C_{d1} + \Delta R_{m1}\right) \\ &\quad + (1-x)z\left(R_{d1} - \delta C_{d1} - C_{d2} - L_d\right) + (1-x)(1-z)\left(R_{d1} - C_{d1} - C_{d2}\right) \\ &= R_{d1} - C_{d1} - C_{d2} + x\left(\Delta R_{m1} + C_{d2}\right) + z\left[(1-\delta)C_{d1} - L_d\right], \end{aligned} \tag{4}$$

$$\begin{aligned} U_{d2} &= xz\left(R'_{d1} - \delta C'_{d1} - C_{d2} - L_d\right) + x(1-z)\left(R'_{d1} - C'_{d1} - C_{d2}\right) \\ &\quad + (1-x)z\left(R'_{d1} - \delta C'_{d1} - L_d\right) + (1-x)(1-z)\left(R'_{d1} - C'_{d1}\right) \\ &= R'_{d1} - C'_{d1} - xC_{d2} + z\left[(1-\delta)C'_{d1} - L_d\right], \end{aligned} \tag{5}$$

$$U_d = yU_{d1} + (1-y)U_{d2}. \tag{6}$$

The expected revenue of users choosing authorized information sharing strategy U_{u1}, the expected revenue of users choosing nonauthorized information sharing strategy U_{u2}, and the expected revenue of users group U_u are

$$\begin{aligned} U_{u1} &= xy\left(R_{u1}-C_u\right)+x(1-y)\left(R_{u2}-C_u\right)+(1-x)y\left(R_{u2}-C_u\right) \\ &\quad +(1-x)(1-y)\left(R_{u3}-C_u\right) \\ &= R_{u3}-C_u+x\left(R_{u2}-R_{u3}+yR_{u1}-yR_{u2}\right)+(1-x)y\left(R_{u2}-R_{u3}\right), \end{aligned} \tag{7}$$

$$\begin{aligned} U_{u2} &= xyR'_{u1}+x(1-y)R'_{u2}+(1-x)yR'_{u2}+(1-x)(1-y)R'_{u3} \\ &= R'_{u3}+x\left(R'_{u2}-R'_{u3}+yR'_{u1}-yR'_{u2}\right)+(1-x)y\left(R'_{u2}-R'_{u3}\right), \end{aligned} \tag{8}$$

$$U_u = zU_{u1}+(1-z)U_{u2}. \tag{9}$$

According to the copy dynamic equation method of the evolutionary game, the copy dynamic equation of the demand-oriented strategy choice of the product manager is obtained by the combination of (1) and (2):

$$F_m(x)=\frac{\mathrm{d}x}{\mathrm{d}t}=x(1-x)\left[R_{m1}-C_{m1}-C_{m2}-R'_{m1}+C'_{m1}+y\left(\Delta R_{m1}-\Delta R'_{m1}+2C_{m2}\right)+z(\beta-1)\left(R_{m1}-R'_{m1}\right)\right]. \tag{10}$$

By the same token, the replication dynamic equations for the Design Development Strategy Selection and the user information authorization strategy selection are as follows:

$$F_d(y)=\frac{\mathrm{d}y}{\mathrm{d}t}=y(1-y)\left[R_{d1}-C_{d1}-C_{d2}-R'_{d1}+C'_{d1}+x\left(\Delta R_{m1}+2C_{d2}\right)+z(1-\delta)\left(C_{d1}-C'_{d1}\right)\right], \tag{11}$$

$$\begin{aligned} F_u(z)=\frac{\mathrm{d}z}{\mathrm{d}t} &= z(1-z)\left[R_{u3}-C_u-R'_{u3}+x\left(R_{u2}-R_{u3}-R'_{u2}+R'_{u3}\right)\right. \\ &\quad \left.+xy\left(R_{u1}-R_{u2}-R'_{u1}+R'_{u2}\right)+(1-x)y\left(R_{u2}-R_{u3}-R'_{u2}+R'_{u3}\right)\right]. \end{aligned} \tag{12}$$

4.2. Stability Analysis of Evolutionary Game. In order to explore the stability strategy of system evolution and the corresponding conditions, (4), (8), and (12) are used simultaneously to obtain the dynamic system composed of product manager, design and development team, and users as follows:

$$\begin{cases} F_m(x)=x(1-x)\left[R_{m1}-C_{m1}-C_{m2}-R'_{m1}+C'_{m1}+y\left(\Delta R_{m1}-\Delta R'_{m1}+2C_{m2}\right)+z(\beta-1)\left(R_{m1}-R'_{m1}\right)\right], \\ F_d(y)=y(1-y)\left[R_{d1}-C_{d1}-C_{d2}-R'_{d1}+C'_{d1}+x\left(\Delta R_{m1}+2C_{d2}\right)+z(1-\delta)\left(C_{d1}-C'_{d1}\right)\right], \\ F_u(z)=z(1-z)\left[R_{u3}-C_u-R'_{u3}+x\left(R_{u2}-R_{u3}-R'_{u2}+R'_{u3}\right)+xy\left(R_{u1}-R_{u2}-R'_{u1}+R'_{u2}\right)+(1-x)y\left(R_{u2}-R_{u3}-R'_{u2}+R'_{u3}\right)\right]. \end{cases} \tag{13}$$

Based on (13), we can obtain eight pure strategy local equilibria$E_1(0,0,0)$, $E_2(1,0,0)$, $E_3(0,1,0)$, $E_4(0,0,1)$, $E_5(1,1,0)$, $E_6(1,0,1)$, $E_7(0,1,1)$, and $E_8(1,1,1)$ and one mixed strategy local stability point $E_9(x^*,y^*,z^*)$ where

$$\begin{cases} x^* = \dfrac{R'_{d1} - C'_{d1} - R_{d1} + C_{d1} + C_{d2} - z^*(1-\delta)(C_{d1} - C'_{d1})}{\Delta R_{m1} + 2C_{d2}}, \\ y^* = \dfrac{R'_{u3} - R_{u3} + C_u - x^*(R_{u2} - R_{u3} - R'_{u2} + R'_{u3})}{x^* R_{u1} - x^* R'_{u1} + (1-2x^*)R_{u2} - (1-x^*)R_{u3} - (1-2x^*)R'_{u2} + (1-x^*)R'_{u3}}, \\ z^* = \dfrac{R'_{m1} - C'_{m1} - R_{m1} + C_{m1} + C_{m2} - y^*(\Delta R_{m1} - \Delta R'_{m1} + 2C_{m2})}{(\beta-1)(R_{m1} - R'_{m1})}. \end{cases} \tag{14}$$

It is important to note that $E_9(x^*, y^*, z^*)$ can only become evolutionarily stable if and only if $0 \le x^*, y^*, z^* \le 1$ occurs.

The study of Wei et al. [25] shows that we only need to analyze the stability of the above 8 pure strategy equilibrium points when we analyze the three-party evolutionary game. Friedman [19] proposed that the local stability of the equilibrium point can be analyzed by the Jacobi Matrix. According to the judgment method of evolutionarily stable strategy, this strategy is evolutionarily stable strategy. Therefore, draw on previous research methods for the following analysis. Based on (13), the Jacobi Matrix of the system is

$$J = \begin{bmatrix} \dfrac{\partial F_m(x)}{\partial x} & \dfrac{\partial F_m(x)}{\partial y} & \dfrac{\partial F_m(x)}{\partial z} \\ \dfrac{\partial F_d(y)}{\partial x} & \dfrac{\partial F_d(y)}{\partial y} & \dfrac{\partial F_d(y)}{\partial z} \\ \dfrac{\partial F_u(z)}{\partial x} & \dfrac{\partial F_u(z)}{\partial y} & \dfrac{\partial F_u(z)}{\partial z} \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \\ J_{31} & J_{32} & J_{33} \end{bmatrix}. \tag{15}$$

Among them,

$$\begin{aligned} J_{11} &= (1-2x)[R_{m1} - C_{m1} - C_{m2} - R'_{m1} + C'_{m1} + y(\Delta R_{m1} - \Delta R'_{m1} + 2C_{m2}) + z(\beta-1)(R_{m1} - R'_{m1})], \\ J_{12} &= x(1-x)(\Delta R_{m1} - \Delta R'_{m1} + 2C_{m2}), \\ J_{13} &= x(1-x)(\beta-1)(R_{m1} - R'_{m1}), \\ J_{21} &= y(1-y)(\Delta R_{m1} + 2C_{d2}), \\ J_{22} &= (1-2y)[R_{d1} - C_{d1} - C_{d2} - R'_{d1} + C'_{d1} + x(\Delta R_{m1} + 2C_{d2}) + z(1-\delta)(C_{d1} - C'_{d1})], \\ J_{23} &= y(1-y)(1-\delta)(C_{d1} - C'_{d1}), \\ J_{31} &= z(1-z)[R_{u2} - R_{u3} - R'_{u2} + R'_{u3} + y(R_{u1} - 2R_{u2} + R_{u3} - R'_{u1} + 2R'_{u2} - R'_{u3})], \\ J_{32} &= z(1-z)[x(R_{u1} - R_{u2} - R'_{u1} + R'_{u2}) + (1-x)(R_{u2} - R_{u3} - R'_{u2} + R'_{u3})], \\ J_{33} &= (1-2z)[R_{u3} - C_u - R'_{u3} + x(R_{u2} - R_{u3} - R'_{u2} + R'_{u3}) + xy(R_{u1} - R_{u2} - R'_{u1} + R'_{u2}) + (1-x)y(R_{u2} - R_{u3} - R'_{u2} + R'_{u3})]. \end{aligned} \tag{16}$$

Based on the research ideas of Fang et al. [26], the evolutionary stability analysis of the above 8 pure strategy equilibrium points was conducted.

(1) The eigenvalue of the Jacobi matrix at $E_1(0,0,0)$ is

$$\begin{cases} \lambda_1^{E_1} = R_{m1} - C_{m1} - C_{m2} - R'_{m1} + C'_{m1}, \\ \lambda_2^{E_1} = R_{d1} - C_{d1} - C_{d2} - R'_{d1} + C'_{d1}, \\ \lambda_3^{E_1} = R_{u3} - C_u - R'_{u3}, \end{cases} \tag{17}$$

when $\lambda_1^{E_1}$, $\lambda_2^{E_1}$, and $\lambda_3^{E_1}$ are all less than 0, $E_1(0,0,0)$ will become the evolutionarily stable strategy. The product manager and the design development team choose the benefit-oriented strategy in the iterative design and development of the health QR code product, and the user is not authorized to share personal information.

(2) The eigenvalue of the Jacobi matrix at the equilibrium point $E_2(1,0,0)$ is

$$\begin{cases} \lambda_1^{E_2} = -(R_{m1} - C_{m1} - C_{m2} - R'_{m1} + C'_{m1}) = -\lambda_1^{E_1}, \\ \lambda_2^{E_2} = R_{d1} - C_{d1} - R'_{d1} + C'_{d1} + \Delta R_{m1} + C_{d2}, \\ \lambda_3^{E_2} = R_{u2} - C_u - R'_{u2}. \end{cases} \tag{18}$$

According to (18), $\lambda_1^{E_2} = -\lambda_1^{E_1}$. Therefore, $E_2(1,0,0)$ and $E_1(0,0,0)$ cannot be evolutionarily stable strategies at the same time. When $R'_{m1} - C'_{m1} < R_{m1} - C_{m1} - C_{m2}$, $R_{d1} - C_{d1} + \Delta R_{m1} < R'_{d1} - C'_{d1} - C_{d2}$, and $R_{u2} - C_u < R'_{u2}$, $E_2(1,0,0)$ will become the evolutionarily stable strategy. This means that even if the user chooses not to authorize information sharing, and the design team chooses agile for technical and cost reasons, when the product manager deducts the coordination cost of the design team's inconsistent development thinking; when the net income of experience-oriented demand is higher than that of benefit-oriented demand, the product managers will still choose the experience-oriented strategy; that is, the design and development demand based on user experience is proposed.

(3) The eigenvalue of the Jacobi matrix at $E_3(0,1,0)$ is

$$\begin{cases} \lambda_1^{E_3} = R_{m1} - C_{m1} + \Delta R_{m1} - R'_{m1} + C'_{m1} - \Delta R'_{m1} + C_{m2}, \\ \lambda_2^{E_3} = -\left(R_{d1} - C_{d1} - C_{d2} - R'_{d1} + C'_{d1}\right) = -\lambda_2^{E_1}, \\ \lambda_3^{E_3} = R_{u2} - C_u - R'_{u2}. \end{cases} \tag{19}$$

Based on (19), both $E_3(0,1,0)$ and $E_1(0,0,0)$ cannot be evolutionarily stable strategies. If $R_{m1} - C_{m1} + \Delta R_{m1} < R'_{m1} - C'_{m1} + \Delta R'_{m1} - C_{m2}$, $R_{d1} - C_{d1} - C_{d2} > R'_{d1} - C'_{d1}$, and $R_{u2} - C_u < R'_{u2}$ meet simultaneously, $E_3(0,1,0)$ is the evolutionarily stable strategy of the system. At this point, the net income of the product manager choosing an experience-oriented strategy is lower than that of the benefit orientation strategy, and the net income of the design and development team choosing experience design strategy is higher than that of agile development and design sprint strategy. For users, even if the design and development team experience the iteration of an information product, the net benefit of choosing an authorized information sharing strategy is lower than that of a not authorized information sharing strategy.

(4) The eigenvalue of Jacobi matrix at equilibrium point $E_4(0,0,1)$ is

$$\begin{cases} \lambda_1^{E_4} = R_{m1} - C_{m1} - C_{m2} - R'_{m1} + C'_{m1} + (\beta - 1)\left(R_{m1} - R'_{m1}\right), \\ \lambda_2^{E_4} = R_{d1} - C_{d1} - C_{d2} - R'_{d1} + C'_{d1} + (1 - \delta)\left(C_{d1} - C'_{d1}\right), \\ \lambda_3^{E_4} = -\left(R_{u3} - C_u - R'_{u3}\right) = -\lambda_3^{E_1}. \end{cases} \tag{20}$$

It can be seen from $\lambda_3^{E_4} = -\lambda_3^{E_1}$ that $E_1(0,0,0)$ and $E_4(0,0,1)$ cannot be evolutionarily stable strategies at the same time. When $\beta R_{m1} - C_{m1} - C_{m2} < \beta R'_{m1} - C'_{m1}$, $R_{d1} - \delta C_{d1} - C_{d2} < R'_{d1} - \delta C'_{d1}$, and $R_{u3} - C_u > R'_{u3}$, $E_4(0,0,1)$ is the evolutionarily stable strategy. After the product is upgraded, because the benefits of the upgraded product for the authorized information users are much greater than those for the unauthorized information sharing or the users' weak awareness of information security, the net profit of authorized information sharing is greater than that of unauthorized information sharing. Therefore, the user will choose the authorization information sharing policy. It can be seen that the lower the cost of users' authorized information sharing (such as additional potential losses such as privacy disclosure), the greater the probability of users choosing authorized information sharing.

(5) The eigenvalue of the Jacobi matrix at $E_5(1,1,0)$ is

$$\begin{cases} \lambda_1^{E_5} = -\left(R_{m1} - C_{m1} + \Delta R_{m1} - R'_{m1} + C'_{m1} - \Delta R'_{m1} + C_{m2}\right) = -\lambda_1^{E_3}, \\ \lambda_2^{E_5} = -\left(R_{d1} - C_{d1} + \Delta R_{m1} - R'_{d1} + C'_{d1} + C_{d2}\right) = -\lambda_2^{E_2}, \\ \lambda_3^{E_5} = R_{u1} - C_u - R'_{u1}. \end{cases} \tag{21}$$

It can be concluded from (21) that $E_5(1,1,0)$, $E_2(1,0,0)$, and $E_3(0,1,0)$ cannot become an evolutionary stability strategy at the same time. In order for $E_5(1,1,0)$ to be ESS, $R_{m1} - C_{m1} + \Delta R_{m1} > R'_{m1} - C'_{m1} + \Delta R'_{m1} - C_{m2}$, $R_{d1} - C_{d1} + \Delta R_{m1} > R'_{d1} - C'_{d1} - C_{d2}$, and $R_{u1} - C_u < R'_{u1}$ must be satisfied simultaneously. At this point, the sum of the net benefits of the product manager's proposed experience-oriented demand and the collaborative benefits of the design and developmental team's experience design is greater than the sum of the net benefits of the product manager's proposed benefit-oriented demand and the design team's developmental and experience design. The sum of the synergistic benefits from the experience design and development of the design and development team is higher than the difference between the net benefits from agile development and design sprint. The performance losses are caused by the failure to develop according to the experience needs of the product manager. The net income of authorized information sharing by users is lower than that of unauthorized information sharing. In this case, users cannot get enough profit from the behavior strategy of authorization information and eventually tend to choose the strategy of nonauthorization information sharing.

(6) The eigenvalue of the Jacobi matrix at $E_6(1,0,1)$ is

$$\begin{cases} \lambda_1^{E_6} = -\left(R_{m1} - C_{m1} - C_{m2} - R'_{m1} + C'_{m1} + (\beta - 1)\left(R_{m1} - R'_{m1}\right)\right) = -\lambda_1^{E_4}, \\ \lambda_2^{E_6} = R_{d1} - C_{d1} - R'_{d1} + C'_{d1} + \Delta R_{m1} + C_{d2} + (1-\delta)\left(C_{d1} - C'_{d1}\right), \\ \lambda_3^{E_6} = -\left(R_{u2} - C_u - R'_{u2}\right) = -\lambda_3^{E_2}. \end{cases} \tag{22}$$

According to $\lambda_1^{E_6} = -\lambda_1^{E_4}$ and $\lambda_3^{E_6} = -\lambda_3^{E_2}$, $E_6(1,0,1)$, $E_2(1,0,0)$, and $E_4(0,0,1)$ cannot be evolutionarily stable strategies at the same time. When $\beta R_{m1} - C_{m1} - C_{m2} > \beta R'_{m1} - C'_{m1}$, $R_{d1} - \delta C_{d1} + \Delta R_{m1} < R'_{d1} - \delta C'_{d1} - C_{d2}$, and $R_{u2} - C_u > R'_{u2}$, $E_6(1,0,1)$is the evolutionary stable strategy. In this case, the product manager and user choose to share experience-oriented requirements and authorization information, respectively, to get more profit, and the design and development team chose agile development and design sprint strategy because of technical constraints and high development cost.

(7) The eigenvalue of Jacobi matrix at equilibrium point $E_7(0,1,1)$ is

$$\begin{cases} \lambda_1^{E_7} = R_{m1} - C_{m1} - R'_{m1} + C'_{m1} + \Delta R_{m1} - \Delta R'_{m1} + C_{m2} + (\beta - 1)\left(R_{m1} - R'_{m1}\right), \\ \lambda_2^{E_7} = -\left(R_{d1} - C_{d1} - C_{d2} - R'_{d1} + C'_{d1} + (1-\delta)\left(C_{d1} - C'_{d1}\right)\right) = -\lambda_2^{E_4}, \\ \lambda_3^{E_7} = -\left(R_{u2} - C_u - R'_{u2}\right) = -\lambda_3^{E_3}. \end{cases} \tag{23}$$

It can be concluded from (23) that $E_7(0,1,1)$, $E_3(0,1,0)$, and $E_4(0,0,1)$ cannot become evolutionary stability strategy at the same time. If $\beta R_{m1} - C_{m1} + \Delta R_{m1} < -\beta R'_{m1} + C'_{m1} - \Delta R'_{m1} + C_{m2}$, $R_{d1} - \delta C_{d1} - C_{d2} > R'_{d1} - \delta C'_{d1}$, and $R_{u2} - C_u > R'_{u2}$ are simultaneously true, $E_7(0,1,1)$ is an evolutionarily stable strategy. In this case, the design and development team and users can make more profits by choosing experience design strategy and authorization information sharing strategy, respectively.

(8) The eigenvalue of the Jacobi matrix at $E_8(1,1,1)$ is

$$\begin{cases} \lambda_1^{E_8} = -\left(R_{m1} - C_{m1} - R'_{m1} + C'_{m1} + \Delta R_{m1} - \Delta R'_{m1} + C_{m2} + (\beta - 1)\left(R_{m1} - R'_{m1}\right)\right) = -\lambda_1^{E_7}, \\ \lambda_2^{E_8} = -\left(R_{d1} - C_{d1} - R'_{d1} + C'_{d1} + \Delta R_{m1} + C_{d2} + (1-\delta)\left(C_{d1} - C'_{d1}\right)\right) = -\lambda_2^{E_6}, \\ \lambda_3^{E_8} = -\left(R_{u1} - C_u - R'_{u1}\right) = -\lambda_3^{E_5}. \end{cases} \tag{24}$$

$\lambda_1^{E_8} = -\lambda_1^{E_7}$, $\lambda_2^{E_8} = -\lambda_2^{E_6}$, and $\lambda_3^{E_8} = -\lambda_3^{E_5}$ indicate that $E_8(1,1,1)$ and $E_5(1,1,0)$, $E_6(1,0,1)$, and $E_7(0,1,1)$ cannot be evolutionarily stable strategies at the same time.

In the context of big data, product managers put forward experience-oriented requirements, design and development teams conduct experience-oriented development, and users' authorized information sharing is an ideal balance in the process of information product update and iterative development and design and also a benign interaction state expected to be realized between users and information product holders in the real world.

In order to achieve this ideal equilibrium state, namely, to ensure that $E_8(1,1,1)$ is the only evolutionarily stable strategy, the following conditions need to be met:

(i) $\lambda_1^{E_8}$, $\lambda_2^{E_8}$, and $\lambda_3^{E_8}$ are all less than 0. Correspondingly, $\beta R_{m1} - C_{m1} + \Delta R_{m1} > \beta R'_{m1} - C'_{m1} + \Delta R'_{m1} - C_{m2}$; in the case of user authorization information sharing, the sum of the net benefits of product manager proposing experience-oriented demand and the collaborative benefits of design and the development team carrying out experience design is greater than the sum of the net benefits of product manager proposing benefit-oriented demand and design team developing experience design. $R_{d1} - \delta C_{d1} + \Delta R_{m1} > R'_{d1} - \delta C'_{d1} - C_{d2}$; the sum of the net benefits of the design and development team's experience design and the synergistic benefits brought by the product manager's experience co-operation work philosophy is higher than the net benefits of agile development and design sprint after deducting the performance loss caused by the conflict between the design team and the product manager's philosophy. $R_{u1} - C_u > R'_{u1}$; the net benefit of user-authorized information sharing after product experience-oriented & experience-oriented upgrading is higher than that of nonauthorized information sharing strategy.

(ii) At least one of the inequalities in $\lambda_1^{E_1} > 0, \lambda_2^{E_1} > 0$, and $\lambda_3^{E_1} > 0$ is true. This means that $R_{m1} - C_{m1} - C_{m2} > R'_{m1} - C'_{m1}$; after deducting the coordination cost caused by the inconsistency between the product manager and the design and development team, the net benefit of the experience-oriented demand proposed by the product manager is higher than the benefit-oriented net benefit. $R_{d1} - C_{d1} - C_{d2} > R'_{d1} - C'_{d1}$; after deducting the performance loss caused by the inconsistency of the design and development team and product manager, the net benefit of experience design of the design and development team is higher than that of agile development and design sprint. $R_{u3} - C_u > R'_{u3}$; the net benefit of user-authorized information sharing is higher than that of non-authorized information sharing strategy after product benefit-oriented and agile development upgrade.

(iii) At least one of the inequalities in $\lambda_1^{E_2} > 0, \lambda_2^{E_2} > 0$, and $\lambda_3^{E_2} > 0$ is true. Correspondingly, $R_{m1} - C_{m1} - C_{m2} < R'_{m1} - C'_{m1}$ implies the opposite of the first inequality in (ii). The sum of the net benefits of the product manager's proposed experience-oriented demand and the collaborative benefits brought by the design and developmental team's experience design is greater than the net benefits of the product manager's proposed benefit-oriented demand after deducting the coordination costs inconsistent with the design and development team's concept. $R_{u2} - C_u > R'_{u2}$; after only one of the designers and developers updates information products based on experience orientation, the net income of authorized information sharing by users is higher than that of unauthorized information sharing.

(iv) At least one of the inequalities in $\lambda_1^{E_3} > 0, \lambda_2^{E_3} > 0$, and $\lambda_3^{E_3} > 0$ is true. This means that $R_{m1} - C_{m1} + \Delta R_{m1} > R'_{m1} - C'_{m1} + \Delta R'_{m1} - C_{m2}$; the sum of the net benefits of the product manager proposing experience-oriented demand and the collaborative benefits of the design and development team carrying out experience design is greater than the sum of the net benefits of the product manager proposing benefit-oriented demand and design team developing experience design. $R_{d1} - C_{d1} - C_{d2} < R'_{d1} - C'_{d1}$ is the opposite of the second inequality in (ii). $R_{u2} - C_u > R'_{u2}$ has the same meaning as the last inequality in (iii).

(v) At least one of the inequalities in $\lambda_1^{E_4} > 0, \lambda_2^{E_4} > 0$, and $\lambda_3^{E_4} > 0$ is true. Correspondingly, $\beta R_{m1} - C_{m1} - C_{m2} > \beta R'_{m1} - C'_{m1}$; in the case of user authorization information sharing, after deducting the coordination cost caused by the inconsistency between the product manager and the design and development team, the net income proposed by the product manager for experience-oriented demand is higher than the net income for benefit-oriented demand. $R_{d1} - \delta C_{d1} - C_{d2} > R'_{d1} - \delta C'_{d1}$. In the case of user authorization information sharing, after deducting the performance loss caused by the inconsistency between the design and development team and the product manager, the net benefit of the design and developmental team from experience design is higher than the net benefit of agile development and design sprint. $R_{u3} - C_u < R'_{u3}$, contrary to the meaning of the last inequality in (ii).

$E_8(1,1,1)$ is the only evolutionarily stable strategy if and only if (I)-(v) are both satisfied.

Through the above analysis, we can find that the user information security cost has an important influence on the choice of user strategy, but when the design and development team and the product manager make the choice of experience design strategy, they are unaffected by potential loss due to user data breach. As a profit-oriented information product, it can be further developed in the commercial promotion mode of health QR code, which should not overemphasize the profit and neglect the full protection of data security. This will aggravate the conflict between the user and the information product holding enterprise and is not conducive to extending the life cycle of the Internet information product. At the same time, the design development team and product manager's choice of experience design strategy is mainly affected by the expected revenue of different strategies. If product managers and design development teams can benefit more from this strategy (such as increasing the number of new users and increasing the stickiness of users) through user-experience-centered information product design iterations, the impact is further amplified by the Revenue Enhancement Factor (β) and cost reduction factor (δ) that result from the sharing of user-authorized information; the greater the probability that the product manager and the design and development team will choose a user-experience-oriented development concept, the better the interaction between the information product owner and the user is. In the process of information product design, service thinking and experience thinking need to be introduced in order to understand its own complexity [27]. To this end, its stakeholders should strengthen the awareness of the crisis, strengthen data security protection, reduce the cost of user information sharing, change the design concept of product experience to improve user stickiness, and provide users with more quality services, to extend the life cycle of health QR code products.

5. Conclusions and Discussions

Internet product experience design, which involves product managers, design and development teams, and users, is an effective iteration of health QR code product renewal. From the point of view of the product manager, it is benefit and function first; from the point of view of the design and development team and from the point of view of users, it is to use the service of information products to meet related needs. We should promote the health QR code information experience design through the tripartite cooperation drive, and under the premise of user information security, accurately excavate and guide user demand and plan the future development trend of information products. In the process of market research, requirement analysis, interaction and visual design and development, market operation, version iteration, and update of health QR code product, the strategy choice of the participants is grasped, to explore the role and value of product manager, design, and development team and users.

Based on the analysis and research of experience design of health QR code products, we can discuss and think about the following problems. First, Internet product experience design is an extension of traditional industrial design, integrating information product demand, user experience, and value efficiency. Secondly, in the industrial era, the focus is on function, quality, and the bulk copy of the goods. In the Internet age, the emphasis is on business and users, faster access to goods, and enhanced experience. In the age of the Internet of things, data and demand are valued, and differentiation demands are met with precision. Finally, the Internet product experience designer needs to master the scene, the mode, and the emotion design. In the user demand data, user behavior parameters, software and hardware integration, information products workflow innovation are needed. Therefore, in industrial design, the design method combines the user and the technology. In Internet experience design, design thinking combines users, business models, and technology. In Internet experience design, data design thinking combines user, business model, and technology.

Data Availability

No data were used to support this study.

Conflicts of Interest

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

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Research Article

The Influence of Prosocial and Antisocial Emotions on the Spread of Weibo Posts: A Study of the COVID-19 Pandemic

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This study investigates the influences of the prosocial and antisocial tendency of Weibo users on post transmission during the COVID-19 pandemic. To overcome the deficiency of existing research on prosocial and antisocial emotions, we employ a web crawler technology to obtain post data from Weibo and identify texts with prosocial or antisocial emotions. We use SnowNLP to construct semantic dictionaries and training models. Our major findings include the following. First, through correlation analysis and negative binomial regression, we find that user posts with high intensity and prosocial emotion can trigger comments or forwarding behaviour. Second, the influence of antisocial emotion on Weibo comments, likes, and retweets are insignificant. Third, the general emotion about prosocial comments in Weibo also shows the emotion trend of prosocial comments. Overall, a major contribution of this paper is our focus on prosocial and antisocial emotions in cyberspace, providing a new perspective on emotion communication.

1. Introduction

Since the outbreak of the new coronavirus in late 2019, more than 200 countries and billions of people worldwide have been severely impacted. As a result, "social distancing" has been implemented in most parts of the world. This leads to more interactions through social media.

As a diversified social media in China, Weibo (microblog) can meet people's demands for obtaining, spreading, and expressing information. During the pandemic, the use of Weibo increased significantly. In 2020, Weibo platform users hit a record in the first quarter. According to its first quarter earnings data, active users were 550 million per month, including 241 million users who used frequently. Social media, such as Weibo, provide freedom and convenience for online discussion but also become an outlet for public catharsis. Eisenberg and Mussen [1] put forward the concept of prosocial and antisocial behaviour, in which prosocial behaviour can be summarized as "voluntary action aimed at helping or benefiting another person or group of people." Antisocial behaviour is a general term for acts that infringe upon the interests of individuals and society and is usually described as destructive behaviour. Online antisocial behaviour has also begun to become widespread and persistent with the widespread use of online social media in recent years. This behaviour was once called cyberbullying in 2000, but it is now also referred to as cyber "sprays." In Weibo discussions on the pandemic, we anticipate encouragement and comfort but cannot ignore hatred and abuse. The spread of pro-(anti-) social emotions not only affects our experience in the Weibo community but also relates to how we get through the crisis. However, few studies have focused on the spread of online pro-(anti-) social emotions. In existing studies, these emotion expressions are often simply classified as negative and positive. However, in fact, a few words in cyberspace can rise to prosocial and antisocial levels. They also have an incalculable impact on our online community experience and real-life experience. For instance, as Weinstein and Ryan [2] proposed, both the giver and the recipient of the network's prosocial emotion can feel more happiness, such as positive optimism, vitality, and self-esteem. While the network's antisocial feelings such as malice and hatred which bring destructive influence are self-evident, cases of depression caused by network violence are enough to show its negative impact. As for explaining the causes of prosocial and antisocial tendencies, the general intuition and consensus are that they are caused by personality and growth in the environment. People with a positive attitude are more willing to show prosocial tendencies, while arrogant people without empathy are more likely to have antisocial personalities. However, anyone may show altruistic behaviour. This is a new perspective adopted in this paper. In addition, we analyze whether prosocial and antisocial emotions in cyberspace stimulate more attention and response, intensify emotions, and infect each other.

Sina Weibo is the largest open social platform in China at present. Under the connection of stranger relationships, the evolution of popular public opinion is often not only limited to the event itself but also the emotion communication and confrontation of the public opinion in discussions. The driving factors behind users' likes, comments, and forwarding of microblog posts are very complex. In the research on the influencing factors of microblog forwarding, they are summarized into two dimensions: one is the characteristics of users, such as users' interests, account years, and social influence and the other is the text characteristics of microblog, such as emotional expression, topic reference, and URL. Wang et al. [4] established an information communication model based on the SIR model to study information communication in Weibo's network. They considered the different influencing factors such as credibility and network weight. This paper mainly focuses on the influence of prosocial and antisocial emotion expressions in Weibo posts on Weibo likes, comments, and retweets and on emotion tendencies in comments. Emotion characteristics have attracted more research attention. For example, Stieglitz and Dang-Xuan [5] investigated whether the emotions in political tweets on Twitter have an impact on their forwarding volume. As early as 1992, Hatfield et al. [6] proposed emotion contagion with the development and popularity of social media or computer-mediated communication, and the study of online emotion communication began to prevail. Many researchers, based on the concept of emotion contagion in [6], carried out research in political, economic, cultural, and social fields. However, the existing studies on emotion communication pay little attention to prosocial and antisocial emotions in social media. Prosocial and antisocial behaviours are not only a topic worthy of attention in offline society but also have important research value in online social networks. They can bring new ideas to the governance of cyberspace and the guidance of public opinion, especially during public health emergencies like the COVID-19 pandemic. It also provides a new angle for understanding the information dissemination path of social media. As the phenomenon of network violence occurs more frequently, the causes and effects of network antisocial tendency need more in-depth research. In addition, previous studies on social media emotion communication used offline experiments or questionnaires to measure the behavioural characteristics of users. To control the experimental errors in these aspects, this study uses a web crawler to collect user data from the real Weibo environment. In particular, it uses natural language processing (SnowNLP) to automatically score emotion tendencies and avoid the subjective effects of artificial coding to ensure the objectivity of the study. This research is not only closely related to the discussion of the epidemic event of COVID-19 but also through this major public crisis to explore the common prosocial phenomenon in cyberspace. Through exploring the role of prosocial emotion in Weibo information transmission and arousing the attention of online users from all walks of life to be aware of this antisocial phenomenon, the creation of a more directed online environment can actively encourage the expression of prosocial emotion. This is a major contribution of this research.

2. Literature Review

2.1. Prosocial and Antisocial Emotions in Cyberspace. Two opposing kinds of behaviour, prosocial and antisocial, first appeared in research topics based on criminal behaviour in the middle and late twentieth century which were concerned by scholars in sociology, psychology, social psychology, and psychiatry. The study of prosocial and antisocial behaviours in cyberspace comes into being with the vigorous development of the network society. In recent years, these concepts have been gradually applied to the research and description of the network society. There are no essential differences between prosocial and antisocial behaviours in cyberspace or social media and real society, but the background, environment, and form of behaviour have changed. These differences make the study of prosocial and antisocial behaviours in the Internet have some theoretical background support, but there is also space for exploration and innovation.

Earlier network prosocial research started in [7]. Researchers explored the relationship between altruism and prosocial behaviour through network games. They applied the generalized reciprocity theory [8], joint construction theory, and strengthening spiral model [9] to the interpretation of network prosocial behaviour. In the network community, they explored the interpersonal relation establishment and maintenance and perceived the mutual benefit win-win criterion. For example, Erreygers et al. [10] believe that when people observe the prosocial behavior of others or are actively treated by others, they will also show their prosocial behavior. This behavior has more communication power in online situations, such as social media websites or post bar forums, than offline behavior, because online behavior has greater potential to reach a wider range of the public. There are different definitions of different research topics about the measurement of network prosocial behaviour. For example, Lapidot-Lefler and Barak [11] studied whether situational factors cause online self-disclosure and prosocial behaviour, assessing the extent of prosociety by analyzing whether experimental participants help others in the chat text, praising chat partners, and creating a positive atmosphere. Wang and Feng [12] analyzed prochild altruistic behaviour in the network, where the online prosocial behaviour is divided into the following categories: technical services, information consultation, online resources, spiritual support, game support, and social assistance. This classification comprehensively summarizes the manifestations of online prosocial behaviour.

Several other terms describe online antisocial behaviour, for example, the word “Troll” mentioned by Bishop [13] is one of the fastest-moving computer-related jargon of the twenty-first century. As an extension of the Internet, Troll describes people who make inflammatory, repugnant, or destructive statements to distract from the topic, disrupt online discussions, or try to provoke others. In addition, there are words such as malice, hatred, discrimination, attack, provocation, and confrontation. Moor defines “malicious” as showing hostility by insulting or using other offensive languages. There is no formal definition of hate speech, but there is a consensus that it targets vulnerable social groups. Jacobs and Potter and Walker [14, 15] put forward this similar point of view. Grigg [16] defines it as intentional injury to individuals or groups of any age, whose acts are offensive, derogatory, and harmful. These descriptions of different meanings are specific emotion manifestations of online antisocial behaviours, which are violence in cyberspace. Usually, these antisocial behaviours have specific objects to attack, such as individuals or groups. They may be one-to-many, one-to-one, or more-to-many.

2.2. Emotion Polarity and Information Dissemination Power. The research on the communication effect has been a very mature branch in the field of communication. In the closed loop of communication, it cannot be separated from the analysis and consideration of the communication effect. As early as the 1930s and 1940s, scholars of social sciences such as communication and psychology studied persuasion techniques and communication effects. Guo [17] summarized in his writings that scholars argued that “touching” objects in the way of “appealing to feelings” was an important reason for the influence of communication effects. This is mainly by creating a certain atmosphere or using strong emotion words to infect the object to seek a specific communication effect. In the Internet age, speech is almost the most important medium of communication in mass communication and interpersonal communication. Also, the feelings carried in the process of communication become one of the key factors that affect information dissemination. The emotion state of the content may affect whether the information will be shared or not [18], and the way it affects changes with different Internet situations.

The social attributes of Weibo and the transmission path of information are mainly commenting, forwarding, and likes. As a social platform with two main functions of understanding real-time information and social interaction, Weibo’s information dissemination itself has a strong social gene, and the influence of emotion in the process of communication is significant, which is reflected in the frequency of comment forwarding. There are many cases about the relationship between emotion factors and network information dissemination at home and abroad. Why is specific online content faster and wider than others in information dissemination? Berger and Milkman [19] gave corresponding responses from a psychological perspective through empirical research, and their findings suggest that content containing highly positive (exclamatory) or negative (angry or anxious) emotions are more communicative. However, Godes and Mayzlin [20] assert that negative information which is more propagative is inaccurate. Goodman [21] believes that similar research is mainly an understanding of what type of news people encounter, rather than what people are spreading. Zhang et al. [22] studied the spread of rumors in social networks from the perspective of the influence of communicators. They think it is of great significance to find out the influential spread of rumors to prevent and control the spread. On this basis, this study considers that identifying the emotions contained in network information is also a reliable way to control the effective and safe dissemination of information. With the development of the Internet and social media, people’s opportunities to share and disseminate information actively increase, so the emotions contained in the content spread in cyberspace have research value. In addition, it will bring new thinking about sharing important information online or developing marketing strategies.

Emotion also plays a very important role in the political communication of social media. Stieglitz and Dang-Xuan [23] analyzed 64,431 political tweets on Twitter in 2012 and found a positive correlation between the vocabulary of one tweet expressing the emotion dimension and the forwarding rate. The forwarding and commenting functions of Twitter, although simple, are also powerful information diffusion mechanisms and have the potential to increase political participation, which may be the idea behind Trump’s Twitter usage. In [24], this information diffusion mechanism was found to be widespread in major social platforms. With behavioural feedback, Joyce and Kraut [25] investigated the emotions triggered by information on social platforms. They found that positive emotions of information strengthen the platform or community awareness of users and encourage their continuous participation, while negative emotions generate feedback through interactions including antisocial tendencies such as hostility and insult. Xu et al. [26] studied the dynamic relationship between online sentiment and stock market performance and found a power-law cross-relationship between financial market and network sentiment in some developed countries and all developing countries. This indicates that sentiment in Internet information can affect investors’ behaviour in financial markets. In addition, studies have also found that emotions (positive or negative) expressed in posts from different social media platforms (such as Weibo and forums) may spread in subsequent corresponding comments or responses.

2.3. Social Media’s Prosocial and Antisocial Emotion Contagion. Prosocial and antisocial behaviours in cyberspace are usually characterized by extreme emotion or specific behaviour, which is confined to the virtual characteristics of network media, especially emotion expression. For example, prosocial behaviour is often manifested in positive encouragement, praise, and information sharing

[27]. In several aspects, antisocial behaviour covers a variety of Internet behavioural chaos and has been widely concerned within academic circles and other domains, such as hatred, provocation, discrimination, and malice. The most widely accepted concept in China is the online jargon “keyboard man,” meaning a shy person. The above behaviours are published and disseminated on social networks in the form of text containing strong emotions, with positive or negative effects. According to [6], there is a broad concept of emotion transmission. More researchers have extended it to the study of emotion communication in cyberspace, such as [28]. The receiver can perceive the publisher’s emotion state through text content and emotion clues.

Specifically, the role of pro- (anti-) social emotion in social media is not only to contribute to the dissemination of information but also an important factor in the spread of pro- (anti-) social behavior. Thirlwall et al. [29] revealed that events that trigger a strong response on Twitter are associated with increased emotion expression. In a later study, Kramer et al. [30] proved the hypothesis empirically. An experiment with people using Facebook found that when positive expression decreased, people produced fewer positive comments and more negative comments, while when negative expression decreased, the opposite situation occurred. This further shows that emotion states can be transmitted to others through an emotion contagion mechanism and make others feel the same emotion unconsciously.

Overall, most of the existing research on the emotion communication of social media is based on positive and negative emotions in a broad sense. However, there are few cases about the spread and influence of prosocial or antisocial emotions in social media. This is a research gap in the current era of social networks. To fill this gap, this study explores the role of prosocial and antisocial behaviours or emotions in the information dissemination of cyberspace.

3. Research Questions and Hypotheses

As an emotion expression, prosocial and antisocial behaviours in social media have even stronger communication power and effect than general emotion communication. Prosocial behaviour is more easily recognized in an online network environment with redundant information. This is because these behaviours express very strong emotions and can easily lead to empathy and more feedback and response. In the face of the COVID-19 crisis, in Weibo, there is no lack of gratitude to medical staff and encouragement to patients. However, there are also a lot of malicious speculations about the source of the virus and discrimination against the people in the epidemic area. Prosocial speech makes people feel better during the epidemic, and antisocial feelings cause harm to society. This study aims to identify prosocial and antisocial behaviours in the Weibo platform during the pandemic and to explore their role in transmission and contribution to Weibo transmission. According to the information dissemination characteristics of Weibo, the influence of a Weibo post can often be judged by its number of comments, forwarding numbers, and likes. On this basis, this study puts forward the following hypotheses.

Hypothesis 1. Weibo posts have pro-(anti-) social feelings, and the stronger the emotion is, the more the comments, retweets, and likes they receive.

Hypothesis 2. Weibo posts have pro-(anti-) social feelings, and the stronger the post emotion is, the overall emotion of the comments is also more pro-(anti-) social feelings.

In Hypothesis 1, considering that the number of Weibo bloggers’ fans and the number of Weibo are also factors affecting the number of comments they receive, the number of fans directly affects the number of comments [31]. The frequency of Weibo releases may lead to more dialogue and discussion [32]. In the analysis of the communication influence of official Weibo, the number of fans and the number of posts represent the amount of Weibo radiation and the activity of Weibo, respectively, in the evaluation index system of the government Weibo communication influence, so in the research model of this paper, it is also considered as an independent variable, but not the focus of this paper.

Hypothesis 2 relates to the process of predicting and analyzing the overall emotion of comments, in addition to taking the pro-(anti-) social emotion intensity of the original Weibo as the main independent variable. The original Weibo word number and whether there are @ symbols are also involved in the model construction. This is because the number of words on Weibo is related to the richness of the content, and the use of the @ symbol tag emphasizes the social element of Weibo. This means interactivity, as Honeycutt and Herring [33] mentioned, which enables Weibo to be used very effectively for dialogue and collaboration. Figure 1 illustrates the research hypotheses and the core variables in this research.

4. Analysis

4.1. Data Collection. In this study, the COVID-19 pandemic was taken as the research context, and the dataset obtained by web crawler was used to study the public opinion of this public health event in Weibo. First of all, this study obtained data samples from January 20 to March 18, 2020. The main reason is that this time interval is the main period from the full outbreak to the basic control of the epidemic situation in China. Secondly, we selected a series of terms that were used more frequently during the epidemic as keywords for data crawling, including “unknown pneumonia,” “epidemic,” “virus,” “new coronavirus,” and “human-to-human transmission.” The choice of these keywords is based on the popular search terms on the Weibo platform, news reports, and the everyday expressions of COVID-19. In addition, after cleaning, reloading, and removing nonpersonal accounts such as media accounts, the remaining data were used as samples of experimental analysis.

It is worth noting that when processing data, we have considered the official website media, government spokespersons, and other related Weibo accounts. This is because the official information is often more neutral, positive, and authoritative, which will interfere with the reliability of the experimental results. Therefore, we first deleted the contents of government microblog accounts on the Sina Weibo

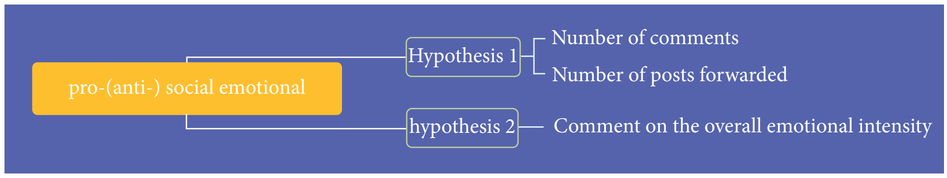

Figure 1: The research hypotheses and the core variables.

platform. The names of the accounts come from official statistics and the verification of Weibo search engines, including the Weibo of central government agencies, courts, procuratorates, public security Weibo, and party and government news release Weibo. These accounts are mainly derived from the statistics and disclosure data of the official website's government affairs Weibo, and they have high dissemination and influence. There is a total of about 70 accounts, and the accounts that need to be excluded from our original data are 34. Secondly, we also collected the Weibo account names of relevant media such as the People's Daily and other central government official media and local official media, including 18 central government media and local government media in various provinces and cities. Regarding the removal of media accounts, we believe that the relevant information released by the official media or ordinary media will interfere with the accuracy of the experimental results. Therefore, in data cleaning, all have been deliberately eliminated. The method of removal is the same as that of government Weibo.

4.2. Text Analysis. The object of text emotion analysis is the short text data from Weibo. The text content is usually concise, and the number of words is not more than 140. These text features are important factors to be considered in the process of research. Especially in the analysis of prosocial and antisocial emotions, the lexical database is directly related to the accuracy of the analysis results.

In the experiment, we use the Python natural language processing package SnowNLP to classify the captured Weibo text data into antisocial-prosocial emotion tendencies. SnowNLP can make up for the lack of prosocial and antisocial semantic recognition through the analysis model needed for text corpus training. During this process, this study used more than 360,000 Sina Weibo text data with emotion tagging as a prosocial and antisocial sentiment analysis corpus. This Weibo dataset is a collection of posts with pronounced emotional characteristics collected from the Weibo platform through multiple crawls. Out of a total of 363,324 Weibo posts, the final usable training set obtained by de-duplication and cleaning is 361,279. Among them, prosocial content contained about 201,170 emotion corpuses such as joy, positive, and optimistic, and antisocial content contained about 160,109 emotion corpuses such as anger, disgust, malice, and insult. After replacing and retraining the corpus set of the original model, the obtained model is used as the main emotion analysis tool in this study. SnowNLP return value represents the polarity of emotion, and the value ranges from negative 0.5 to positive 0.5. Being closer to 0.5 means being more prosocial. Being closer to −0.5 means being more antisocial. Through many trials, adjustments, and tests of the new model, the emotion score is more reasonable than the original model. For example, the statement "I am depressed today" has an emotion score of −0.1485 in the original model and −0.0509 in the retrained model. Therefore, the latter score can describe the emotion state of "I am depressed today" more accurately. The new model is suitable for the analysis of pro-(anti-) social emotion. Table 1 shows 10 examples of pro- and antisocial Weibo posts on the COVID-19 pandemic. The texts under the English translation are the original Chinese expressions.

4.3. Data Analysis. For Hypothesis 1, the dependent variable comment number is discrete data, which is usually more appropriate for Poisson regression model. From the results of descriptive statistics in Table 2, the standard deviation of the number of comments ($N = 6{,}608$) in the model is significantly higher than the average. Therefore, to reduce the influence of heteroscedasticity and extreme value, it is more reasonable to choose negative binomial regression in the regression model of Hypothesis 1.

To ensure that the regression model is meaningful, before the return of variables, several factors affecting the number of comments are analyzed. Based on the characteristics of the dataset, 1,736 Weibo data without noticeable sentiment tendencies are eliminated (within positive and negative 0.1). Then, we separate Weibo posts with positive and negative emotion scores. As a result, the number of prosocial samples is 2,917, and the number of antisocial samples is 1,955. The correlations between pro-(anti-) social emotion and other variables are shown in Tables 3 and 4, respectively.

The results of correlation analysis showed that the prosocial affective tendency of posts had a significant positive correlation with the number of comments and forwarding ($r = 0.073$, $\mathrm{pr} = 0.01$; $r = 0.057$, $\mathrm{pr} = 0.01$). There was no correlation with the number of likes. However, there is no significant correlation between antisocial emotion and post comment number, forwarding number, and likes number. Therefore, we further conduct negative binomial regression on prosocial emotion and post comment numbers and forwarding numbers and analyze the specific degree of influence. The results are shown in Tables 5 and 6. In the negative binomial regression analysis of prosocial emotion, the number of fans and the number of posts on the number of comments and forwarding, it can be seen that when these two variables (the number of fans and the number of microblogs)were added, the tendency of prosocial emotion has a significant positive effect on the number of post comments and

Table 1: Examples of prosocial and antisocial Weibo posts and their emotion scores.

	Weibo posts	Emotion tendency	Emotion score
1	Different lantern festival, thanksgiving care. Looking forward to the epidemic early past, about three or five friends together to spring	Prosocial society	0.3321
2	The army's success in developing the new crown vaccine is so exciting	Prosocial society	0.3885
3	Isolate virus does not isolate love ha ha ha ha ha ha ha	Prosocial society	0.3910
4	I hope everyone is well, which country you are! Really!!! The world is beautiful. Don't waste your life on viruses~	Prosocial society	0.3771
5	This time we go out as little as possible, where more people go less, go out must remember to wear masks, prevent and cure virus infection, the new year hope @ Xiao Jie-crazy and roll happy #2020 new year #	Prosocial society	0.3877
6	We sincerely wish to report that dogs are infected with coronavirus and die immediately	Antisocial	−0.3942
7	What is the most terrible is not a virus, not a disease, not a monster, not a ghost or a man	Antisocial	−0.3800
8	Rumors of some celebrity mothers dying of COVID-19	Antisocial	−0.3862
9	Kill bats? Really illiterate? An indispensable important species in the food chain. You say extinction is extinction?	Antisocial	−0.3982
10	May the virus defeat *m* country at an early date	Antisocial	−0.3905

Table 2: Descriptive statistics.

	Number of samples (N)	(M)	Maximum (X)	Average (E)	Standard deviation
Emotion score	6608	−0.399881	0.399609	0.017155	0.223863
Number of comments	6608	0	496	3.20	16.090
Number of fans	6608	0	22141108.0	121912.168	685984.9662
Number of posts	6608	0	570893	8585.80	26427.423
Forwarding	6608	0	575	2.09	19.343
Number of likes	6608	0	9145	15.38	157.977

Table 3: Correlation analysis between prosocial emotion and the number of comments.

	Emotion score	Number of comments	Forwarding	Number of likes	Number of fans	Number of posts
Emotion score	1					
Number of comments	0.073**	1				
Forwarding	0.057**	0.584**	1			
Number of likes	0.017	0.819**	0.437**	1		
Number of fans	0.030	0.412**	0.317**	0.444**	1	
Number of posts	0.066**	0.047*	0.063**	0.034	0.268**	1

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Table 4: Correlation analysis between antisocial emotion and the number of comments.

	Emotion score	Number of comments	Forwarding	Number of likes	Number of fans	Number of posts
Emotion score	1					
Number of comments	−0.026	1				
Forwarding	−0.037	0.640**	1			
Number of likes	−0.038	0.742**	0.597**	1		
Number of fans	0.025	0.271**	0.233**	0.296**	1	*
Number of posts	0.013	0.030	0.035	0.076**	0.270**	1

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

forwarding ($B = 7.285$; $B = 9.905$). In addition, the number of fans and posts of bloggers has a significant impact on the number of comments and retweets, so it is reasonable to include these two variables in the model, which also shows that the factors affecting Weibo transmission are diverse and complex.

To test Hypothesis 2, this study adopts the method of correlation analysis. In addition, in the variable design process, this study will take whether the control variables in Model 2 have @ labels designed as dummy variables 1 (yes) and 0 (no). By filtering the data in the total sample ($N = 6,608$) and removing Weibo with 0 comments and

Table 5: Negative binomial regression parameter estimates (prosocial posts and number of comments).

Independent variables	B	Standard error	Hypothesis testing		Logistic likelihood	AIC	BIC
			Wald chi-square value	Significance			
Emotion score	7.285	0.3695	388.847	0.000	−3954.988	7917.997	7941.905
Number of fans	0.982	0.0258	1444.154	0.000			
Number of posts	−0.581	0.0408	202.419	0.000			

Table 6: Negative binomial regression parameter estimates (prosocial posts and number of forwarded posts).

Independent variables	B	Standard error	Hypothesis testing		Logistic likelihood	AIC	BIC
			Wald chi-square value	Significant significance			
Emotion score	9.905	0.4214	553.507	0.000	−2886.640	5781.280	5805.174
Number of fans	0.000	0.000	514.103	0.000			
Number of posts	0.000	0.000	22.520	0.000			

Table 7: Analysis of the correlations between Weibo prosocial emotion and the overall emotion value of comments.

	Emotion score	Number of Weibo words	Is there a @ tag	Comments on the overall emotion value
Emotion score	1			
Number of Weibo words	0.233^{**}	1		
Is there a @ tag	0.100	0.215^{**}	1	
Comments on the overall emotion value	0.421^{**}	0.093	0.068	1

$^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

Table 8: Analysis of the correlations between Weibo antisocial emotion and the overall emotion value of comments.

	Emotion score	Number of Weibo words	Is there a @ tag	Comments on the overall emotion value
Emotion score	1			
Number of Weibo words	0.009	1		
Is there a @ tag	0.020	0.215^{**}	1	
Comments on the overall emotion value	0.393^{**}	0.013	0.041	1

$^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

Weibo comment settings, the number of remaining samples is 3,120. The related analysis results are shown in Tables 7 and 8. Data show that both prosocial emotions ($r = 0.421$, $p < 0.01$) and antisocial emotions ($r = 0.393$), $p < 0.01$) were positively correlated with the overall emotion value of the comments. Among them, social and emotion contagion is slightly stronger, and Hypothesis 2 holds.

4.4. Visualization Analysis of Pro-(Anti-) Social Posts. After a statistical analysis of Weibo posts with prosocial or antisocial emotion tendencies, we can test the initial hypothesis that prosocial Weibo posts can promote the transmission and contagion of posts themselves. But how this influence is formed, or what characteristics it has, is also information worth mining. Therefore, this study will mainly show the logic behind this phenomenon through data.

First, in order to observe the path of prosocial posts and antisocial posts in the comment feedback and the differences between them, this study based on pro-(anti-) social Weibo dataset generated the network topology diagram of post comments by Gephi software, as shown in Figure 2. As a whole, the topology shows that both pro- and antisocial posts have a common multidirectional interaction when they trigger comments, retweets, or likes, that is, when users respond to pro- or antisocial posts, they tend to comment, retweet, and like at the same time or respond multiple times to comments, showing more emotion interaction than ordinary posts, which can be observed from nodes of different colours in the topology (different colour nodes represent the frequency of Weibo users in comments, retweets, and likes, where orange represents the frequency of one time, and all other colour nodes represent frequencies of 2 or more). However, from the difference between the two, the orange colour nodes of prosocial posts are less, that is, the users who have comments, likes, and retweets have more secondary or multiple interactions, and the central node radius of prosocial post topology is large. This indicates that the number of comments radiated by posts is more, which is consistent with the related analysis results mentioned in this study.

Figure 2: Topology of Weibo post comments.

5. Conclusions and Limitations

In the post-truth era, emotions instead of reasoning can become the tipping point of news events. Based on this phenomenon, this study attempts to explore the influence of prosocial and antisocial emotions of users in social media on the Weibo blog communication during the COVID-19 pandemic. By grasping user-related topics and analyzing prosocial and antisocial emotions during the pandemic in China, we found that the prosocial blog posts by Weibo users attracted more comments. Although antisocial blog did not have the same effect in the study, we can conclude that antisocial emotion blogs have similar contributions to the transmission of Weibo in a similar way. However, the transmission effect will have different effects depending on different people who post on microblog. Non-news Weibo prosocial emotions can generate more feedback, and negative or antisocial content in news posts can cause viral transmission. Since there is no significant positive correlation between antisocial feelings and the number of comments in the blog post on COVID-19, this study follows the principle of conservative interpretation. Because the COVID-19 pandemic, a major public health crisis, is a major national event, Weibo users are optimistic, and public opinion as a whole is positive. The public shares positive things on social media, encourage each other, and praise the "devotees" and "retrograde people" during the pandemic. This prosocial behaviour and emotion are also spreading and dominating antisocial emotions. With the continuous strengthening of the "prosocial" trend, the "antisocial" voice gradually falls silent.

In this study, the conclusion also shows that the other manifestation of the influence of social media's pro-(anti-) emotion on the transmission of information is formed by the mechanism of emotion transmission. Hansen et al. [34] came to the same conclusion in the study on Twitter. In the event of the COVID-19 outbreak, both prosocial and antisocial responses of Weibo users have contributed to the tide of public opinion. Under microblog containing pro-(anti-) social feelings, the comments are generally more pro-(anti-) social. These conclusions are of great value and significance to the guidance of public opinion and to improve the effectiveness of information dissemination.

Compared with other studies on social media emotion communication, this paper chooses the two concepts of prosocial and antisocial emotions, which are helpful to expand the direction of existing research. In addition, this study adopts the way of network data capture. More realistic network media social situations can avoid other subjective factors of excessive intervention, hence making the conclusions more robust. However, because this study is aimed at the single social event of the COVID-19 pandemic, there are inevitable accidents and differences. Future studies can focus on a wider range of events. The prosocial and antisocial behaviours studied in this paper only lie in the emotion expression behaviour of Weibo texts, which is one of the contents of cyberspace pro-(anti-) social behaviours. However, they cannot represent the general pro-(anti-) social behaviours. Nonetheless, the prosocial and antisocial behaviours in cyberspace are still rich and complex, which are worthy of further research [35].

Data Availability

The data were collected by an Internet web crawler technology and are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Female Directors and Carbon Information Disclosure: Evidence from China

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In recent years, natural disasters and public health events caused by global warming have occurred frequently around the world. It has become a global consensus to actively respond to climate change. Firms are the main source of greenhouse gas emissions. The disclosure of carbon information is one of the most important ways for firms to respond to climate change. The effect of female directors on carbon information disclosure is still unclear. Considering that China is the largest country in greenhouse gas emissions and the social status of females in China is different from western countries, this paper explores the effect of female directors on carbon information disclosure by firms in China. Based on the sample of listed Chinese firms in high carbon industries during the period of 2012–2017, our empirical results show that female directors have a positive association with carbon information disclosure. In addition, we find that the power, educational level, and financial background of female directors have positive impacts on firms' carbon information disclosure. Our findings make a significant contribution to the ongoing debate on the role of female directors and provide new insights and policy implications for firms, regulators, and other stakeholders.

1. Introduction

In recent years, natural disasters and public health events caused by global warming such as floods, hurricanes, heat waves, forest fires, and outbreaks of infectious diseases have occurred frequently. Actively responding to climate change has become a global consensus. Greenhouse gases (GHG) emissions are the main causes of global warming, and firms, especially those in high carbon industries, are the main source of GHG emissions. Carbon information disclosure (CID), as an important way to reflect the behavior of firms in responding to climate change, has attracted increasing attention from researchers and practitioners. China, as the world's second largest economy, has become the largest carbon emitter, with its emissions of CO_2 accounting for 28% of the total amount [1]. To reverse the situation, China made a significant US-China Joint Statement on Climate Change on 12 November 2014. In the statement, China plans to peak its carbon emissions no later than 2030, which leads Chinese firms to a tremendous pressure of energy saving and emission reduction. Therefore, shareholders and other stakeholders intend to monitor and supervise firms' carbon emissions better, which is one of the biggest motivators of the steady growth of firms' CID in China in both quality and quantity in recent years [2].

Previous studies usually use a virtual variable or the index to measure firms' CID behavior. The virtual variable represents whether the firms disclose carbon information or whether they respond to the CDP questionnaire [3, 4]. The index based on the content analysis method or the scores of CDP questionnaires represents the quality of firms' CID [2, 5]. Unlike several countries such as France, Australia, Japan, the United States, and Canada that have implemented mandatory schemes that require disclosure of GHG emissions, China has not formulated mandatory CID requirements yet. The carbon information disclosed by firms in China can be regarded as voluntary [6]. Additionally, Chinese firms have a low rate of response to the CDP survey

[7]. Based on the above, we adopt the content analysis to measure the CID behavior of firms. The research on the influencing factors of CID mainly focuses on the following aspects: (1) the firm characteristic factors, such as firm size [8–11], liability [12], and profitability [5]; (2) the corporate governance factors, such as board effectiveness [12], board independence [13], environmental committee [14–16], and ownership structure [2]; and (3) other factors, such as country [8], industry [2], regulations [17], and culture [18].

Previous studies have shown that the presence of female directors can increase firm's attention to social responsibility and environmental issues [19]. Moreover, it is generally recognized that the gender diversity of the board of directors plays an important role in promoting the environmentally friendly activities of firms [20]. Nevertheless, there are few studies on the effect of female directors on CID, and there are no unanimous conclusions [16, 21]. Agency theory emphasizes that board members require managers to act in accordance with the interests of shareholders to reduce agency costs, and resource dependence theory suggests that board members need to bring resources to the organization. These two theories explain the necessity of female directors participating in corporate governance. Moreover, upper echelons theory considers that characteristics have an impact on human behavior which can help firms select board members. The following four characteristics of women make female directors excellent candidates to improve the level of firms' CID: interpersonal relationship, self-awareness, attitude to law and regulation, and attitude to work. The motivation of this study arises from the fact that so few research works focus on the role of women in CID. Considering that the culture and social status of women in China are different from those of western developed countries, it is necessary to investigate the influence of female directors on CID of firms in China. Our study also analyzes the influences of power, educational level, financial background, and legal background of female directors on firms' CID.

This study makes the following contributions to the existing literature. First, to the best of our knowledge, this study is the first to empirically investigate the impact of female directors' heterogeneous characteristics on firms' CID. Existing research on the determinants of the firm's CID usually regards female directors as homogeneous, which leads to inconsistent conclusions to a certain extent. This study finds that female directors on boards have a significantly positive effect on firms' CID, and the power, educational level, and financial background of female directors have positive impacts on firms' CID.

Second, this study uses text analysis based on annual and social responsibility reports of Chinese firms to analyze CID quality. Existing research has explored the relationship between female director ratio and CID of firms based on CDP data. Considering that CID is voluntary in China and Chinese firms have a low rate of response to the CDP survey [7], annual and social responsibility reports are the main and important accessible source of carbon information for stakeholders of Chinese firms. This study calculates an index using text analysis based on carbon-related information in Chinese firms' annual and social responsibility reports.

Third, focusing on the Chinese context, this study can provide empirical evidence on female directors' role in firms' CID behavior in eastern developing countries. European countries such as Norway, Netherlands, and Italy have mandated quotas for women on board. Even in western countries where there are no mandatory requirements, the proportion of female directors is relatively high [16]. However, in eastern countries such as China, there are no mandated quotas for women on board, and women's social status is relatively low. In ancient Chinese feudal society, women are only "family persons" with very low social society [22]. In modern Chinese society, women's social status has been relatively improved, and there is a loud slogan that "women can hold up half the sky." However, Chinese traditional culture such as Confucianism still has a negative influence on the board gender diversity of firms in China [23]. In the context of China, this study can better investigate the influence of female directors on firms' CID behavior in eastern countries. Furthermore, the findings based on the context of China can add value to the theoretical completeness of previous research on female directors and CID based on western developed countries.

The remainder of this paper is structured as follows: Section 2 reviews the existing relevant literature. Section 3 presents the theoretical analysis and research assumptions. Section 4 describes the selection of samples and data and the research methods used in this paper. Section 5 shows our empirical results and conducts the robustness tests. Section 6 discusses the research conclusions.

2. Literature Review

2.1. The Influencing Factors of Carbon Information Disclosure. Over the decades, global warming has aroused widespread concern all over the world, and the GHG emissions are mainly attributed to firms. In this context, the external pressure on firms to disclose carbon information is increasing, especially for firms in carbon-intensive industries [24], in which the carbon information transparency is enhanced compared to less carbon-intensive industries [25, 26]. Additionally, environmental NGOs, governments, and investors claim that firms should disclose information related to their GHG emissions [27]. Matsumura et al. believe that the cost of not disclosing carbon information is very high, which will have a negative impact on the value of firms [28]. Therefore, most firms tend to voluntarily disclose carbon information to enhance their environmentally friendly image in the eyes of the stakeholders [29]. Some firms are gradually developing sectors and systems for the assessment, accounting, reporting, and management of GHG emissions and their related impacts [30].

The existing research on the influencing factors of CID mainly focuses on three aspects: The first aspect is firm characteristics. Prior studies suggest that the firm with a larger size is more likely to disclose high quality carbon information [8–11]. Ben-Amar and Mcilkenny find a negative association between the firm's liability level and voluntary disclosure [12]. Faisal et al. report a positive association between the profitability of the firm and CID quality [5]. The second aspect is corporate governance. Board effectiveness is an important factor affecting the tendency and quality of CID [12]. Liao et al. argue that the level of CID is higher for firms, of which the board is more independent [13]. Recent empirical evidence shows that the establishment of an environmental committee under the board of directors contributes to the disclosure of carbon information [14–16]. Peng et al. perform an empirical analysis of Chinese firms and show that the more decentralized the ownership is, the more likely the firm is to disclose carbon information [2]. The third aspect includes other factors. There is evidence showing that country, industry, regulations, and culture also affect firms' CID. Freeman and Jaggi find that firms registered in countries that ratified the Kyoto Protocol are more likely to disclose GHG emissions information [8]. Firms in high-emission industries are more likely to disclose more carbon information [2]. Environmental regulations and legal sources are essential to firms' CID behavior [17]. He et al. find that traditional Chinese culture such as Confucianism can also have a positive effect on the quality of firms' CID in China [18].

Existing literature on CID shows that the board of directors plays an important role. Therefore, the effectiveness of boards will still be the core of research on corporate governance [31]. On the basis of principal-agent theory and the theory of resource dependence, the board of directors mainly has the two functions of supervision and suggestion in the firm [32]; that is, the board not only supervises the behavior of management on behalf of shareholders [33], but also relies on its own professional knowledge to provide advice and consulting services for the company [34]. According to the existing literature, several board characteristics that affect the effectiveness of corporate governance and CID include board size and independence, board diversity, and CEO duality. These studies suggest that the board that is larger, independent [13], and diverse [12, 13, 35] can positively influence firms' CID. The diversity of the board of directors plays an important part in improving corporate governance [36], and the impact of gender diversity on corporate governance and CID is receiving increasing attention in recent years.

2.2. The Outcomes of Board Gender Diversity. Previous research has explored the outcomes of board gender diversity. The research mainly covers three aspects. The first aspect is the effect of board gender diversity on firm performance. Existing studies have inconsistent evidence on the effect of female directors on firm performance. Post and Byron find that female directors have a positive association with firms' accounting returns, especially in countries where shareholder protections are strong [37]. The results of other studies also show that board gender diversity could improve firm value or financial performance [38–40]. However, Joecks et al. find that the link between gender diversity and firm performance follows a U-shape [41]. Abdullah et al. find that female directors can create value for some firms and decrease it for others [42]. The absence of a significant relationship between gender diversity and firm financial performance is also supported by empirical evidence [43].

The second aspect is the effect of board gender diversity on corporate social responsibility (CSR). Most studies' results show that board gender diversity has a positive effect on CSR. For example, firms with a higher percentage of women in boardrooms have better CSR disclosure [44, 45], higher CSR ratings [19], and stronger CSR performance [46, 47]. Women on the board of directors could increase the firm's sense of responsibility to society [48], and they care about human rights and contribute to the improvement of corporate governance [49]. However, Manita et al. find that there is no significant relationship between board gender diversity and ESG disclosure [20]. Studies have also shown that CSR is a diverse and complex concept, and female directors are only related to some specific CSR dimensions, such as environmental aspects [50].

The third aspect is the effect of board gender diversity on environmental issues. Environmental concerns are also a nonignorable part of gender diversity research. Studies have shown that female directors can improve environmental corporate social responsibility [51]. Empirical research shows that female directors help reduce firms' environmental violations [52]. As an integral part of corporate environmental social responsibility disclosure, GHG related disclosure has walked onto the stage. There are few studies separately investigating the association between GHG related disclosure and female board representation [16], and the existing studies show inconclusive results. For example, the research result of Kilic and Kuzey shows that there is an insignificant association between board gender diversity and carbon emission disclosure in Turkey [21]. However, Hollindale et al. find that firms with multiple female directors in Australia make higher quality GHG emissions related disclosures [16]. Liao et al. find a significant positive association between gender diversity and GHG information disclosure of firms in the United Kingdom [13]. More precisely, Ben-Amar et al. find that female boardroom participation in Canadian firms is positively related to the voluntary disclosure of carbon information and further find that gender diversity on boards of directors can only have an impact on the disclosure of carbon information when there are more than two women on board [53].

3. Theory and Hypotheses Development

3.1. Female Directors and Carbon Information Disclosure. When studying gender diversity and environmental concerns, there are two questions worth considering. First, why do female directors need to do this? Agency theory provides an internal motivation to explain this problem, caused by the agency conflict between managers and shareholders [54]. Managers usually focus on increasing self-interest, which in turn damages the interests of shareholders [47]. Therefore, it is a reasonable demand for board members to be supervisory and ask managers to behave on behalf of the shareholders' best interests, which is protected by law [12]. Hence, the supervisory function of female directors is one of the effective means to resolve agency conflicts and improve corporate governance efficiency [13, 43, 49, 55, 56]. Resource dependence theory provides an external motivation to answer this question. It advocates that board members need to bring resources to their organizations [57]. These resources can be knowledge, skills and experiences [58], human resources [49], and interpersonal relationships and values [45]. Therefore, female directors can play an advisory role in the firm, providing suggestions and resources that enable the firm to develop steadily.

The second question is, why can female directors do this? Upper echelons theory suggests that top executives' knowledge, experience, values, and personalities have an influence on their process of decision-making [59]. This theory gives a better understanding of what kind of board members should be chosen and can help firms solve environmental problems. Compared to men, there are several aspects that affect female directors' decision-making: (1) interpersonal communication: they are democratic, cooperative, caring (willing to help, getting along well, kind, sympathetic, responding to the needs of others, not self-centered) [53, 60]; (2) self-awareness: they have high moral standards and value quality of life rather than material success (full of social responsibility, caring about the environment, caring about health, having environmental sensitivity) [50, 61, 62]; (3) attitude to law and regulation: they are cautious (risk aversion, abiding by the law) [12, 56, 63, 64]); (4) attitude towards work: they are dedicated and possess high skills (hardworking, industrious) [65, 66]. Thus, female directors have a different cognitive frame to a board on account of different experiences and value orientation, and gender diverse boards may tend to consider, discuss, and integrate information more deeply and carefully than homogeneous groups [37]. Female directors could enhance communication with key stakeholders who care about environmental issues [67]. Female directors' high sensitivity to people and surroundings makes them care more about environmental issues. Since female directors are more likely to be more concerned about loss of reputation and litigation [68], they have a nature of abiding by laws and regulations. Most importantly, they are dedicated to what they are doing. Finally, due to the above characteristics of female directors, they have a propensity to make environment-friendly decisions, which will affect the firm's CID decisions. Their supervisory and advisory functions and the resources they can bring to the organization improve the firm's governance quality and thus affect the firm's CID quality. Therefore, we formulate the following hypothesis.

Hypothesis 1. Female directors are positively associated with firms' carbon information disclosure.

3.2. The Characteristics of Female Directors and Carbon Information Disclosure. Women face complex and various challenges in the process of accessing power [60]. It is feasible that women who can conquer so many obstacles and break through a mass of barriers must obtain outstanding abilities to find their way out in the male-dominated territory [69]. In China, female directors account for only around 11% of seats in recent years [47, 70]. In addition, there are no mandated quotas for women on board in China. Based on the above, we can conclude that, in this male-dominated board structure, when female directors are presidents or CEOs, female directors can be treated as a symbol of competency and power to the board. Van Staveren suggests that more women at the top position can effectively avoid the occurrence of banking crisis [63]. Female directors can also improve the efficiency of risk management in R&D investments [71]. Based on the above analysis, when female directors have power, it is reasonable to presume that they will use this power to make firms pay attention to environmental issues such as CID. Therefore, we formulate the following hypothesis.

Hypothesis 2. The power of female directors is positively associated with firms' carbon information disclosure.

According to Hitt and Tyler, the manager's view of the world, philosophy, values, and even ability of cognizance can be influenced by educational level [72]. Vives and Gadenne et al. propose that having a higher level of education generates a greater level of commitment to CSR activities [73, 74]. Managers with high level education usually care more about environmental issues and may apply their knowledge to put pressure on firms to deal with environmental violation and take action to correct bad behavior [75]. Beji et al. find that the educational level of directors is positively and significantly associated with CSR and environmental performance of firms [49]. As China's carbon emission policy becomes stricter, carbon management and CID will be one of the most important environmental issues for Chinese firms. Based on the above analysis, we argue that female directors with higher educational level will have more environmental consciousness and are more likely to make requests to disclose more carbon information. Therefore, we formulate the following hypothesis.

Hypothesis 3. The educational level of female directors is positively associated with firms' carbon information disclosure.

According to the studies of Hambrick and Mason [59] and O'Fallon and Butterfield [76], it is difficult for people's decision-making not to be influenced by vocational education. Previous research shows that there is a positive relationship between business education and CSR [77]. Panapanaan et al. propose that business studies have a link with ethics, CSR, sustainability, and, consequently, boost ethics in a firm [78]. Most directors with financial background have received business education and they would care more about CSR and sustainability issues than directors with other expertise. Moreover, directors with financial background can better understand the consequences of financial reporting decisions. As an important part of financial reporting, carbon information is concerned by shareholders and CID is related to firms' value [79], capital cost [80], and financial performance [81]. Directors with financial background would make firms disclose more carbon information, and female directors with financial background are expected to have more influence on CID than male directors with financial background. From recent literatures, we can discover that female directors can affect many aspects of the firm's financial status. For example, research shows that female board representation with business expertise and audit committee membership can strongly improve earnings management [82]. Based on the above analysis, we propose that female directors with financial expertise are an important factor for ensuring the quality of corporate governance. It is also sensible that female directors pay more attention to the boundary between corporate performance and environmental protection, and those with financial background can better balance them. Therefore, we formulate the following hypothesis.

Hypothesis 4. The financial background of female directors is positively associated with carbon information disclosure.

In addition to the financial background, what cannot be ignored is that legal awareness can also exert an influence on human's behavior. Most directors and managers with a legal background have received legal degrees. Prior research has demonstrated that individuals with legal degrees exhibit distinctive decision-making patterns compared to those without legal degrees [83]. Barker and Mueller argue that an executive with legal degrees tends to be more conservative in business activities [84]. Previous research finds that managers with legal background tend to spend less on R&D [84] and guide down earnings forecasts due to a greater sensitivity to litigation risk [85]. Considering that they usually prefer risk mitigation, we expect that directors with a legal background will care more about the potential costs of CID. Firms tend to disclose less carbon information because directors with legal background exhibit greater risk aversion. However, female directors will have a positive impact on the firms' CID based on the analysis of Hypothesis 1. We predict that the positive impact of female directors on CID may be offset by their own legal background. Therefore, we formulate the following hypothesis.

Hypothesis 5. The legal background of female directors is not associated with carbon information disclosure.

4. Research Design

4.1. Samples. Firms' CID started relatively late in China compared with firms in developed countries. At present, Chinese government has not issued a mandatory CID policy yet; Chinese firms' CID is voluntary. Firms in high carbon industries are more sensitive to climate change risks than other firms, and they are more likely to report more carbon information to reduce compliance costs at an early stage. Many studies conclude that firms in high carbon industries disclose more carbon information than firms in low carbon industries [2, 12, 53]. The Ministry of Environmental Protection of China has identified 16 industries as heavily polluting industries, namely, thermal power generation, steel, cement, electrolytic aluminium, coal, metallurgy, chemicals, petrochemicals, building material, paper, brewing, pharmaceuticals, fermentation, textile, leather, and mining. The heavily polluting industries mostly overlap with the top 13 GHG emissions industries [2]. We could find that most of the heavily polluting industries are also high carbon industries.

Based on the above, the initial samples of our study include all A-share listed firms in high carbon industries, which include heavily polluting industries and the top 13 GHG emissions industries in China between the years 2012 and 2017. Firms with missing data and marked with ST and *ST are excluded from samples. To better investigate the trends in the CID quality of firms in high carbon industries in China between the years 2012 and 2017, balanced panel data were used in this study. The final samples include 541 A-share listed firms in high carbon industries in China. The distribution of industries for sample firms is shown in Table 1. The carbon information is derived from firms' annual reports, social responsibility reports, and sustainable development reports. The other data are from the CSMAR database and the RESSET database.

4.2. Measures

4.2.1. Carbon Information Disclosure. In this research, we adopt two variables as the dependent variables to measure the firms' CID. One is a dummy variable (CID_DUM) that is equal to 1 if the firm discloses carbon information and 0 otherwise. The other is the quality of the firm's CID (CID_QUALITY), measured by content analysis. Content analysis was adopted in the same way as Peng et al.; it was used in their research for evaluating the quality of CID [2]. Carbon information disclosed by firms is identified by eight items (I_1 to I_8) which strictly refer to CDP's questionnaire. The detailed information of the eight items is shown in Table 2. The specific scoring rules are shown in Table 3.

Each firm is assigned a score of CID quality based on the following equation:

$$\mathrm{Score}\,(\mathrm{CID})_j = \sum_{i=1}^{8} \mathrm{Score}\left(I_j^i\right). \qquad (1)$$

In equation (1), $\mathrm{Score}\,(\mathrm{CID})_j$ is the total score of CID for firm j, representing the quality of CID of firm j, and Score (I_j^i) refers to firm j's score on item i.

4.2.2. Female Directors. The independent variable is female directors. Based on the previous research, the proportion of female directors (FEM_RAT) is utilized in our research [13, 53]. Besides, according to Hollindale et al.'s study, we also adopt a dummy variable (FEM_DUM) that is coded 1 if the firms have at least one female director and 0 otherwise [16]. To further explore the mechanism of the effect of female directors on CID, four variables representing different characteristics of female directors were selected, namely, whether the female directors are presidents or CEOs (POWER) and female directors' educational background (EDUC), financial background (FINAN), and legal background (LEGAL).

4.2.3. Controls. To control for the firm characteristics that may drive the examined relationship, we introduce ten control variables into our regression model.

Table 1: Industry distribution of the sample firms.

Industries	N	Percentage
Production and supply of electric power, heat, gas, and water	66	12.20
Steel, electrolytic aluminium, metallurgy	48	8.87
Cement, building material	45	8.32
Coal, mining	54	9.98
Chemicals, petrochemicals	117	21.63
Papermaking and paper products	14	2.59
Brewing, fermentation	40	7.39
Pharmaceuticals	102	18.85
Textile	22	4.07
Leather, furs, and related products	5	0.92
Agro-food processing	25	4.62
Special equipment, transportation equipment, communications, and related equipment manufacturing	3	0.56
Total	541	100

Table 2: Eight items of CID.

Item	Detailed information
I_1	Targets and results of emission reduction
I_2	Method of measuring carbon emission
I_3	Scope 1 emission data: direct greenhouse gas emissions
I_4	Scope 2 emission data: indirect greenhouse gas emissions of energy
I_5	Scope 3 emission data: other indirect greenhouse gas emissions
I_6	Energy consumption of total operation in the reporting year
I_7	Emissions trading
I_8	Other carbon-related information

The items of CID are adopted from Peng et al. [2].

Table 3: Scoring rules of eight items of CID.

	Score	Scoring rules
I_1 I_2 I_3 I_4 I_5 I_6	0, 1, 2, 3	No information scores 0, general nonquantitative information scores 1, and some quantitative information scores 2. For I_1, detailed quantitative information scores 3 (e.g., the time, quantitative targets, completeness of targets). For I_2, detailed measuring process scores 3 (e.g., the method used, the formula used, and the parameter applied). For I_3, I_4, and I_5, detailed quantitative information scores 3 (e.g., the boundaries used for scope 1, 2, or 3 greenhouse gas inventory and emissions figures in metric tons of CO_2). For I_6, detailed quantitative information scores 3 (e.g., fuel consumption data in tons and per value).
I_7 I_8	0, 1, 2, 3	No information scores 0, general nonmonetary information scores 1, other concrete nonmonetary information scores 2, and monetary information records 3.

The scoring rules of eight items of CID are adopted from Peng et al. [2].

(1) Size. Larger firms are more vulnerable to public attention than smaller ones. Investors have higher information quality requirements for larger firms. Large firms will disclose carbon information to improve their image. Prior research indicates that a larger size of the firm is associated with a better CID quality [8, 13]. Accordingly, we control for firm size, as measured by the natural logarithm of the total assets.

(2) Leverage. Financial leverage is an important indicator that not only reflects the degree of use of firms' external funds, but also reflects the firms' financial risk. Highly leveraged firms are under greater financial pressure and may disclose less high quality carbon information. Previous studies have shown a negative effect of financial leverage on firms' CID [2, 7, 12]. However, some studies have also shown that financial leverage has no significant impact on the disclosure of firms' environmental information [86].

(3) Profitability. Firms with high profitability have sufficient funds to ensure that they could bear the costs associated with CID. On the contrary, the disclosure of carbon information is beneficial to the establishment of a good corporate image and, in turn, attracts more investors. Less profitable firms are limited by the lack of their own resources and are unlikely to take the initiative to disclose relevant information. Some studies have found a positive correlation between profitability and CID quality [5, 12, 87, 88]. Consequently, profitability in our study measured by return on assets (ROA) was controlled. However, some studies have also shown that there is no significant correlation between firm profitability and CID [8, 24].

(4) Ownership Concentration. Previous studies have shown that ownership concentration may have an influence on firms' CID, but the relationship between ownership

concentration and CID quality is unclear. Berthelot and Robert find that firms with widely held ownership voluntarily disclose more climate change information [14]. However, Li et al. found that there is no significant relationship between the proportion of first shareholders and CID [7]. In our study, ownership concentration (OC) was measured by the shareholding ratio of the top 10 shareholders.

(5) Independence of the Board. The independence of the board of directors is an important guarantee for it to perform its supervisory functions. More independent directors can urge firms to better fulfill the obligation of environmental information disclosure. Previous studies have indicated that firms with a larger proportion of independent directors in the board are more likely to make comprehensive financial information disclosure [89] and to disclose carbon information [13]. Therefore, the independence of the board may have a positive impact on CID. The percentage of independent directors on the board (IND) measures the independence of the board in our study.

(6) Duality. The president has decision-making powers and supervision powers, and CEO is the executor of board decisions and is supervised by the board. The presence of the same person holding the position of president and CEO could positively affect corporate social responsibility [19]. Alternatively, the decision-making, oversight, and executive functions being concentrated on a single individual will weaken the supervision power. Prior research has shown that there exists a negative association between duality and CID [7]. We use a dummy variable (DUAL) to measure the duality.

(7) Firm Value. Tobin's q measured by the ratio of market value to asset replacement cost could represent the firm value. Firms with low firm value have a stronger willingness to disclose environmental information to gain the favor of investors and the government. Previous studies indicated that there is a significant negative correlation between firm value and CID [15]. We use Tobin's q (TOBINQ) as the proxy of firm value.

(8) Nature. Previous studies have found that the state-owned nature of firms has a significant positive impact on CID [7]. In China, firms are mainly divided into state-owned enterprises (SOEs) and non-state-owned enterprises, with the former having a strong executive power in responding to national policies. At present, the Chinese government has been advocating a low carbon economy. Therefore, state-owned enterprises are more active than non-state-owned enterprises in energy conservation, emission reduction, and CID. However, some studies found that the influence of the state-owned nature of the firm on CID is not significant [4, 5]. A dummy variable (NATURE) was introduced in our study: 1 for SOEs, 0 for others.

(9) Listing Age. The listing age of a firm has a significant positive influence on a firm's environmental performance [9]. The number of years a firm has been publicly traded is positively associated with the quality of firms' CID [2]. However, there are studies finding that a firm's listing age is not significantly related to the quality of CID [7]. Accordingly, the listing age of the firm (AGE) is introduced in our study as a control variable.

(10) Audit Firm. According to Dunn and Mayhew [90], a more professional accounting firm will provide more professional knowledge and advice to the clients in handling the disclosure related issues [90]. In addition, firms are willing to hire highly specialized audit firms, which is an obvious signal of the firms to disclosure high quality information. Based on the above, we expect that listed firms that hire the big four accounting firms are more likely to disclose carbon information and the quality of CID is higher. A dummy variable (AUDF) was introduced in our study: it equals 1 if a firm hires the big four accounting firms and 0 otherwise. The summary of the variable definitions is shown in Table 4.

4.3. Model. To test the hypotheses of this study, the following multiple regression models were constructed:

$$\text{CID\_DUM} = \alpha + \beta \text{Female}_{i,t} + \gamma \text{Controls}_{i,t} + \varepsilon_{i,t}, \tag{2}$$

$$\text{CID\_QUALITY} = \alpha + \beta \text{Female}_{i,t} + \gamma \text{Controls}_{i,t} + \varepsilon_{i,t}, \tag{3}$$

$$\text{CID\_DUM} = \alpha + \beta_1 \text{Power}_{i,t} + \beta_2 \text{Educ}_{i,t} + \beta_3 \text{Finan}_{i,t} + \beta_4 \text{Legal}_{i,t} + \gamma \text{Controls}_{i,t} + \varepsilon_{i,t}, \tag{4}$$

$$\text{CID\_QUALITY} = \alpha + \beta_1 \text{Power}_{i,t} + \beta_2 \text{Educ}_{i,t} + \beta_3 \text{Finan}_{i,t} + \beta_4 \text{Legal}_{i,t} + \gamma \text{Controls}_{i,t} + \varepsilon_{i,t}, \tag{5}$$

where Female was measured by two alternative variables: the dichotomous indicator variable (FEM_DUM) and the percentage of female directors (FEM_RAT). The hypotheses were tested using multiple regression, with each of the two independent variables regressed on the dependent variable, respectively. In models (2) and (4), CID_DUM is a dichotomous variable, which represents the firm's decision on whether to disclose carbon information. Hence, we

Table 4: Variable definitions.

Variables	Measurement
CID_DUM	A dummy variable that is equal to 1 if the firm makes carbon information disclosure and 0 otherwise
CID_QUALITY	The scores of carbon information disclosure quality determined by content analysis
FEM_DUM	A dummy variable that is equal to 1 if there is at least one female director on board and 0 otherwise
FEM_ RAT	The ratio of the number of female directors to the total number of board members
POWER	A dummy variable that is equal to 1 if there is a female director as president or CEO and 0 otherwise
EDUC	A dummy variable that is equal to 1 if there is at least one female director with a master's degree or above and 0 otherwise
FINAN	A dummy variable that is equal to 1 if there is at least one female director with a financial background and 0 otherwise
LEGAL	A dummy variable that is equal to 1 if there is at least one female director with a legal background and 0 otherwise
SIZE	The natural logarithm of total assets
LEV	The ratio of total debt to total assets
ROA	Return divided by total assets
OC	The percentage of total ordinary shares owned by the top ten shareholders
IND	The percentage of independent directors on the board
DUAL	A dummy variable that equals 1 if the positions of the president and CEO are held by the same person and 0 otherwise
TOBINQ	The ratio of the market value to the replacement cost of the total assets of the firm
NATURE	A dummy variable that is equal to 1 if the nature of the firm is state-owned and 0 otherwise
AGE	The natural logarithm of the listing years of firms
AUDF	A dummy variable that is equal to 1 if the audit firms hired by the firm are the big four accounting firms and 0 otherwise

performed probit model regression to examine the effect of female directors and their characteristics on the firms' CID. In models (3) and (5), CID_QUALITY represents the quality of firms' CID. We utilized ordinary least squares (OLS) analysis to examine the influence of female directors and their different characteristics on the quality of CID. The characteristics of female directors selected for this study include female directors' power, educational background, financial background, and legal background.

5. Results

5.1. Descriptive Statistics and Correlation Analysis. Table 5 provides the distribution of the number and percentage of sample firms that disclosed carbon information and had female directors by year. The number of sample firms disclosing carbon information and having female directors showed an overall growth trend between 2012 and 2017. On average, 49.60% of the sample firms voluntarily disclosed carbon information. In addition, 70.79% of the sample firms have female directors.

Descriptive statistics of the variables are shown in Table 6. The results show that there exists a big gap in the quality of CID among firms. The mean of FEM_RAT is 0.137, revealing that women only account for about 14% of the boards of sample firms, which is a relatively low level. The mean of FEM_DUM is 0.708, which shows that about 71% of the sample firms have women on the board. Around half of the female directors in sample firms have a master's degree or higher degrees, and about 41% of female directors have financial background. The proportion of female directors having power or legal background is relatively low, only 20.4% and 10.9%, respectively. The mean of ROA is 4.78%, and the maximum and minimum values of ROA are 51.66% and −39.92%, respectively, which illustrates that the rate of return on total assets among firms has a great difference. The minimum and maximum of OC are 1.3% and 98.6%, respectively, which means that the ownership concentration of sample firms has an obvious difference. The mean value of DUAL is 0.222, which means that the same person holds the position of president and CEO in 22.2% of the sample firms. The mean of NATURE is 0.473, which indicates that there is no significant difference between the proportion of state-owned enterprises and non-state-owned enterprises in the sample. The mean of AUDF is 0.065, which implies that merely 6.5% of the sample firms employed the big four accounting firms.

Table 7 shows the Pearson correlation and variance inflation factor (VIF) for dependent, independent, and control variables. The correlation coefficients for CID_DUM, FEM_DUM, and FEM_RAT are positive and significant, supporting Hypothesis 1. The correlation coefficients for CID_DUM, EDUC, and FINAN are positive and significant, supporting Hypotheses 3 and 4. The relatively low correlation coefficients between independent and control variables and their VIF suggest that there is no multicollinearity problem in the four models of this study.

5.2. Multiple Regression Results. We tested the relation between female directors and firms' CID decisions utilizing probit regression. The results in columns 1 and 2 of Table 8 (model (2)) show that the coefficients of FEM_DUM and FEM_RAT are positive and significant at the 1% level. These results indicate that firms with female directors are more likely to disclose carbon information, and the increasing of the representation of women on board could promote firms' CID decisions and attention to climate change issues. These results support Hypothesis 1. Our findings are consistent with prior research based on British and Canadian firms which shows that there is a positive association between board gender diversity and firm's response to CDP questionnaire [13, 53]. As for the control variable, firm size and hiring the big four accounting firms have a significant positive effect on firms' CID. Meanwhile, state-owned enterprises are more likely to disclose carbon information to

Table 5: The percentage of firms disclosing carbon information and having female directors.

Year	Total	Firms disclosing carbon information		Firms with female directors	
		N	%	*N*	%
2012	541	256	47.32	367	67.84
2013	541	257	47.50	375	69.32
2014	541	258	47.69	380	70.24
2015	541	267	49.35	387	71.53
2016	541	287	53.05	395	73.01
2017	541	285	52.68	394	72.83
Total	3246	1610	49.60	2298	70.79

Table 6: Descriptive statistics of variables.

Variable	*N*	Mean	SD	Min	Max
CID_DUM	3246	0.496	0.500	0	1
CID_QUALITY	3246	1.380	2.158	0	16
FEM_DUM	3246	0.708	0.455	0	1
FEM_RAT	3246	0.137	0.126	0	0.857
POWER	3246	0.204	0.403	0	1
EDUC	3246	0.464	0.499	0	1
FINAN	3246	0.413	0.492	0	1
LEGAL	3246	0.109	0.312	0	1
SIZE	3246	22.41	1.294	19.08	28.51
LEV	3246	0.414	0.203	0.014	1.059
ROA	3246	4.782	5.820	−39.92	51.66
OC	3246	0.577	0.154	0.013	0.986
IND	3246	0.370	0.053	0.182	0.667
DUAL	3246	0.222	0.416	0	1
TOBINQ	3246	1.993	1.698	0.123	21.02
NATURE	3246	0.473	0.499	0	1
AGE	3246	2.308	0.667	0	3.296
AUDF	3246	0.065	0.247	0	1

the public than non-state-owned enterprises because state-owned enterprises have always been active responders to government policies in China. We also find that both leverage and listing age are significantly negatively related to voluntary disclosure of carbon information.

We also examine the relationship between female directors and CID quality using ordinary least squares (OLS) regression, and the regression results are as shown in columns (3) and (4) of Table 8 (model (3)). The coefficient of FEM_DUM is 0.337, which is significant at the 1% level. This result suggests that firms with women on board are more likely to disclose high quality carbon information compared with firms whose board members are all male. The coefficient of FEM_RAT is 1.565, which is significant at the 1% level, implying that the higher the proportion of female directors in the firm, the higher the quality of the firm's CID. Therefore, Hypothesis 1 is supported. Meanwhile, state-owned enterprises and firms with larger size, lower leverage, more independent boards, separation of president and CEO positions, higher firm value, and the big four accounting firms hired are more likely to disclose higher quality carbon information.

The regression results of models (4) and (5) are shown in columns (1) and (2) of Table 9, respectively. The coefficient of POWER is positive and statistically significant at the 1% level for regressions in model 4 and model 5, meaning that female directors who also hold the position of president or CEO can promote the firms' CID. The finding supports Hypothesis 2. The coefficients for EDUC are positive and significant at the 1% level, which support Hypothesis 3 that highly educated female directors are positively associated with firms' CID compared with female directors with lower levels of education. The regression result shows that female directors' financial background has a positively impact on firms' CID decisions, which supports Hypothesis 4. However, we also find that the effect of female directors' financial background on firms' CID quality is limited. Moreover, female directors' legal background has no significant impact on firms' CID decisions and CID quality. Thus, Hypothesis 5 is supported.

5.3. Robustness Tests

5.3.1. Endogeneity. According to previous research, endogeneity problems could exist for board gender diversity. In our study, the relationship between female directors and firms' CID may be driven by omitted unobserved factors or by reverse causality. Some omitted unobservable firm characteristics, such as firm culture, could be linked to both female directors and firms' CID. The literature generally deals with unobservable variables by using a fixed effect

Table 7: Pearson correlation of variables.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	VIF
(1) CID_DUM	1.000																		—
(2) CID_QUALITY	0.645***	1.000																	—
(3) FEM_DUM	0.060***	0.027	1.000																2.42
(4) FEM_RAT	0.081***	0.003	0.702***	1.000															2.94
(5) POWER	0.008	−0.006	0.324***	0.419***	1.000														1.33
(6) EDUC	0.121***	0.106***	0.595***	0.546***	0.146***	1.000													1.76
(7) FINAN	0.062***	−0.012	0.539***	0.605***	0.174***	0.377***	1.000												1.78
(8) LEGAL	0.032*	0.031*	0.223***	0.226***	−0.028	0.249***	0.004	1.000											1.16
(9) SIZE	0.330***	0.446***	−0.091***	−0.153***	−0.123***	0.012	−0.099***	0.017	1.000										2.38
(10) LEV	0.153***	0.203***	−0.059***	−0.134***	−0.158***	0.005	−0.055***	0.008	0.527***	1.000									1.99
(11) ROA	−0.021	−0.028	0.044**	0.070***	0.083***	0.056***	0.005	−0.005	−0.058***	−0.415***	1.000								1.47
(12) OC	0.096***	0.133***	−0.060***	−0.091***	−0.010	−0.035***	−0.060***	−0.062***	0.289***	−0.030*	0.183***	1.000							1.50
(13) IND	0.030*	0.025	−0.021	0.078***	0.024	−0.003	−0.041***	0.019	−0.012	−0.051***	−0.004	0.034*	1.000						1.05
(14) DUAL	−0.082***	−0.141***	0.019	0.062***	0.089***	−0.037**	0.010	−0.040**	−0.163***	−0.114***	0.034*	−0.068***	0.092***	1.000					1.10
(15) TOBINQ	−0.185***	−0.203***	0.049***	0.089***	0.148***	0.019	0.026	0.014	−0.487***	−0.548***	0.430***	0.026	0.067***	0.123***	1.000				1.86
(16) NATURE	0.156***	0.273***	−0.100***	−0.193***	−0.209***	0.039***	−0.134***	−0.001	0.382***	0.374***	−0.175***	0.034*	−0.043**	−0.247***	−0.308***	1.000			1.54
(17) AGE	0.096***	0.196***	−0.046***	−0.080***	−0.129***	0.101***	−0.054***	0.060***	0.347***	0.364***	−0.111***	−0.293***	−0.024	−0.175***	−0.178***	0.465***	1.000		1.77
(18) AUDF	0.161***	0.272***	−0.056***	−0.059***	−0.050***	0.025	−0.046***	0.000	0.367***	0.079***	0.041**	0.214***	0.042**	−0.075***	−0.123***	0.123***	0.075***	1.000	1.20

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

Table 8: Regression results of Hypothesis 1.

Variables	CID_DUM				CID_QUALITY			
	(1)		(2)		(3)		(4)	
FEM_DUM	0.310***	(5.76)			0.337***	(4.53)		
FEM_RAT			1.624***	(7.99)			1.565***	(5.53)
SIZE	0.380***	(11.18)	0.385***	(11.32)	0.708***	(15.84)	0.712***	(15.95)
LEV	−0.556**	(−3.16)	−0.514***	(−2.91)	−1.041***	(−4.29)	−1.000***	(−4.12)
ROA	−0.003	(−0.55)	−0.004	(−0.72)	−0.018**	(−2.18)	−0.019**	(−2.29)
OC	−0.160	(−0.83)	−0.100	(−0.51)	−0.155	(−0.57)	−0.094	(−0.34)
IND	0.931*	(1.95)	0.644	(1.34)	1.570**	(2.37)	1.300*	(1.96)
DUAL	−0.035	(−0.61)	−0.038	(−0.64)	−0.221***	(−2.67)	−0.225***	(−2.73)
TOBINQ	0.006	(0.25)	0.010	(0.41)	0.098***	(2.98)	0.102***	(3.11)
NATURE	0.202***	(3.33)	0.235***	(3.84)	0.496***	(5.81)	0.526***	(6.15)
AGE	−0.148***	(−2.79)	−0.146***	(−2.74)	0.050	(0.68)	0.051	(0.70)
AUDF	0.402***	(3.40)	0.382***	(3.25)	1.119***	(7.66)	1.107***	(7.59)
Constant	−8.727***	(−11.62)	−8.795***	(−11.72)	−15.056***	(−15.21)	−15.085***	(−15.27)
Year	Yes		Yes		Yes		Yes	
Industry	Yes		Yes		Yes		Yes	
Observations	3,220		3,220		3,246		3,246	
Pseudo-R^2	0.130		0.137					
R-squared					0.269		0.271	

Note: z-statistics are in parentheses in columns (1) and (2). t-statistics are in parentheses in columns (3) and (4). $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

Table 9: The impact of the characteristics of female directors on firms' CID.

Variables	CID_DUM (1)	CID_QUALITY (2)
POWER	0.172*** (2.77)	0.365*** (4.20)
EDUC	0.259*** (4.74)	0.355*** (4.70)
FINAN	0.185*** (3.45)	0.025 (0.34)
LEGAL	−0.010 (−0.13)	−0.053 (−0.48)
SIZE	0.384*** (11.22)	0.702*** (15.73)
LEV	−0.552*** (−3.13)	−1.027*** (−4.25)
ROA	−0.004 (−0.67)	−0.018** (−2.24)
OC	−0.183 (−0.94)	−0.181 (−0.67)
IND	0.979** (2.04)	1.503** (2.27)
DUAL	−0.025 (−0.43)	−0.223*** (−2.71)
TOBINQ	0.007 (0.28)	0.094*** (2.87)
NATURE	0.220*** (3.57)	0.507*** (5.91)
AGE	−0.161*** (−3.01)	0.038 (0.51)
AUDF	0.376*** (3.17)	1.094*** (7.52)
Constant	−8.746*** (−11.59)	−14.767*** (−14.97)
Year	Yes	Yes
Industry	Yes	Yes
Observations	3220	3246
Pseudo-R^2	0.139	
R-squared		0.277

Note: z-statistics are in parentheses in column (1). t-statistics are in parentheses in column (2). $^{***}p < 0.01$ and $^{**}p < 0.05$.

model. The results based on fixed effect model are reported in column (1) of Table 10, which shows that female directors have a positive influence on firms' CID quality.

The endogenous relation may also exist when reverse causality exists between firms' CID and female directors. Firms with high quality CID or caring more about environmental issues may be more likely to employ women as board members. Alternatively, female directors may also self-select into environmentally friendly firms due to their characteristics. In our study, this means that current female boardroom representation may be influenced by firms' past CID quality. Our study controls for the possible reverse causality using the system GMM method. The system GMM model shows the same results in column (2) of Table 10: the effect of female directors on firms' CID quality is significantly positive. Our results are thus robust to controlling for endogeneity.

5.3.2. Alternative Independent Variables. We use two other measurements to estimate female directors, FEM_NUM and INDFEM, respectively. The explanatory variable

Table 10: Regression results of the fixed effect and system GMM models.

Variables	Fixed effect CID_QUALITY (1)	System GMM CID_QUALITY (2)
Lag CID_QUALITY		0.514*** (7.47)
FEM_RAT	1.072*** (3.44)	2.192*** (3.84)
SIZE	0.169* (1.92)	0.371*** (6.06)
LEV	0.158 (0.54)	−0.296 (−1.39)
ROA	0.006 (0.87)	−0.005 (−0.78)
OC	−0.438 (−1.13)	0.027 (0.10)
IND	1.255* (1.90)	−0.135 (−0.23)
DUAL	−0.112 (−1.38)	−0.074 (−1.23)
TOBINQ	0.004 (0.14)	0.050** (2.38)
NATURE	−0.123 (−0.42)	0.288*** (3.32)
AGE	−0.069 (−0.39)	0.035 (0.59)
AUDF	−0.041 (−0.13)	0.596*** (2.89)
Constant	−2.644 (−1.42)	95.671*** (2.69)
Year	Yes	Yes
Industry	No	Yes
Observations	3,246	2,705
R-squared	0.015	
Arellano–Bond AR (1) (z, p value)		−5.66 ($p \leq 0.001$)
Arellano–Bond AR (2) (z, p value)		1.63 ($p = 0.104$)
Sargan test (chi-square, p value)		122.15 ($p \leq 0.001$)
Hansen test (chi-square, p value)		20.59 ($p = 0.151$)

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

Table 11: Regression results of alternative independent variables.

Variables	CID_DUM		CID_QUALITY	
	(1)	(2)	(3)	(4)
FEM_NUM	0.183*** (7.87)		0.193*** (6.03)	
INDFEM		2.544*** (8.39)		1.680*** (3.97)
SIZE	0.376*** (11.05)	0.395*** (11.57)	0.703*** (15.76)	0.716*** (15.97)
LEV	−0.513*** (−2.91)	−0.564*** (−3.19)	−0.995*** (−4.11)	−1.047*** (−4.31)
ROA	−0.004 (−0.69)	−0.005 (−0.86)	−0.019** (−2.28)	−0.019** (−2.29)
OC	−0.095 (−0.49)	−0.133 (−0.68)	−0.084 (−0.31)	−0.143 (−0.53)
IND	0.991** (2.07)	0.456 (0.95)	1.636** (2.47)	1.229* (1.84)
DUAL	−0.037 (−0.62)	−0.024 (−0.40)	−0.224*** (−2.72)	−0.217*** (−2.63)
TOBINQ	0.010 (0.41)	0.013 (0.53)	0.102*** (3.12)	0.101*** (3.08)
NATURE	0.222*** (3.63)	0.198*** (3.24)	0.516*** (6.05)	0.489*** (5.73)
AGE	−0.143*** (−2.70)	−0.156*** (−2.93)	0.054 (0.74)	0.040 (0.54)
AUDF	0.397*** (3.36)	0.397*** (3.38)	1.121*** (7.69)	1.117*** (7.64)
Constant	−8.704*** (−11.6)	−8.855*** (−11.79)	−15.011*** (−15.22)	−15.002*** (−15.15)
Year	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes
Observations	3220	3220	3246	3246
Pseudo-R^2	0.137	0.139		
R-squared			0.273	0.268

Note: z-statistics are in parentheses in columns (1) and (2). t-statistics are in parentheses in columns (3) and (4). $^{***}p < 0.01$, $^{**}p < 0.05$, and $^{*}p < 0.1$.

FEM_NUM is calculated as the number of women board members, and INDFEM is calculated as the percentage of female independent directors scaled by the total number of board members. We rerun models (2) and (3) using FEM_NUM and INDFEM as alternative key independent variables. As reported in Table 11, the coefficients of both FEM_NUM and INDFEM are consistently positive and significant. These results indicate that the finding that there is a positive correlation between female directors and firms' CID is robust and credible.

6. Conclusions

This study examined the potential effect of female directors on firms' CID based on a sample of listed firms in China's high carbon industries in the period between 2012 and 2017. Two alternative variables were used in this paper to measure female directors and firms' CID. We find that female directors have a significant positive impact on firms' CID. Moreover, the result indicates that there is a trend for listed firms in China to appoint women to the board of directors.

To some extent, the increase in board gender diversity proves the effectiveness of corporate governance policies.

On the basis of the above research, we further explore the effect of the characteristics of female directors on firms' CID. We find that the power and educational level of female directors have a significant positive impact on firms' CID decisions and CID quality. The financial background of female directors has a significant positive impact on firms' CID decisions, while the legal background of female directors has no significant impact on firms' CID behavior.

Based on the empirical results, we could propose some practical implications. First, the statistical results show that firms that disclose carbon information account for less than half of the total sample. This provides a reference for the future mandatory CID policy issued by the Chinese government. Second, since female directors can promote firms' CID decisions and CID quality, Chinese firms can improve their level of information disclosure related to climate change through appointing more female directors. To achieve the target of peaking carbon emissions before 2030 and reaching carbon neutrality before 2060, Chinese government might establish a mandatory quota system of female directors to improve the climate change governance of firms in China. Third, this study finds that the power, educational level, and financial background of female directors in China have a positive impact on firms' CID. Therefore, Chinese firms should appoint more female directors with high level education or financial background to promote firms' CID and appoint female directors as CEO under the same conditions to promote firms' CID behavior.

As in all empirical studies, our study has several limitations. First, the CID index used in our research may not cover all the information that can fully reflect the quality of CID. Second, our study considers only the association between female directors and CID. Future research would benefit from exploring the black box of governance and examining the channels through which female directors positively affect CID. Third, our study focuses on a sample of high carbon industries in China. Therefore, our results may not hold for firms in other industries or firms outside China. The role and influences of female directors may vary across countries. However, our findings may be applied to other Asian countries where the social status of females may be relatively lower than that in western countries, which inspires further discussion and testing by scholars.

Data Availability

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

Conflicts of Interest

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

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Research Article

Analysis of Economic Effect and Mechanism of Basic Medical Insurance for Urban Employees in China

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The purpose of social basic medical insurance is to solve the problem that "medical treatment is difficult and expensive." With the implementation of new technologies and new diagnosis and treatment methods, the price of medicine has risen sharply. Under this background, can basic medical insurance still relieve the economic pressure of patients? Based on the tracking data of China Health and Nutrition Survey (CHNS) from 2006 to 2015, by constructing Heckman sample selection model, the paper finds that the basic medical insurance for urban employees (UEBMI) leads to an increase in medical expenses, among which only 0.61% can be attributed to the release of normal medical demand and 114.47% can be attributed to moral hazard; for flexible employees, 249.52% increase can be attributed to adverse selection. Based on this, the paper puts forward two suggestions: first, promoting Hierarchical Treatment Model to control the growth of medical expenses and second, guiding flexible employees to participate in the UEBMI.

1. Introduction

Medical insurance is a risk sharing mechanism between healthy people and unhealthy people or between health and sickness. Its direct function is to ensure people's financial accessibility of medical services when they are sick [1]. China's multilevel medical security system includes social basic medical insurance, supplementary medical insurance, commercial medical insurance, and medical assistance. Among them, the universal coverage of social basic medical insurance is the main health policy promoted in China's medical reform, and it is also a policy that attracts worldwide attention. However, this policy costs so much, and whether such heavy expenditure has played its due role has drawn scholars' debate over years.

Studies by scholars [2–6] have all confirmed that compared with patients who bear medical expenses alone, patients with medical insurance face a lower medical price, and this distorted medical service prices may lead to an increase in utilization of medical services and medical expenses. Common problems in medical market, such as adverse selection mentioned in [7–12] and moral hazard mentioned in [13–16], will also lead to the waste of medical resources, resulting in significantly higher growth rate of medical expenses per capita than income growth. Although there are many research results on this topic, the existing studies still have some limitations: First, they pay more attention to the "burden reduction" effect of medical insurance on vulnerable groups such as the elderly and children and analyze the impact of the new rural cooperative medical insurance on the patients' economic burden, while paying insufficient attention to the employees with only basic medical insurance. Second, there has been no consensus of views when separating adverse selection effect from moral hazard effect. Although many scholars agree that moral hazard and adverse selection, which are prevalent in the medical insurance market, will lead to a substantial increase in medical expenses, the decomposition of their effects is still a "roadblock" in empirical research. At present, scholars mainly use three methods to separate these two effects: (1) distinguishing them through natural experiments or random experiments, but natural experiments are rare and random experiments are costly; (2) according to the time sequence of occurrence, using dynamic data to separate moral hazard from adverse selection; (3) using the characteristics of specific insurance markets and types. Scholars have different views on which method is more reasonable. In this paper, we study the economic effects of UEBMI, while the economic effects are affected by adverse selection and moral hazard. Adverse selection has nothing to do with income in UEBMI; it can occur in both high-income and low-income groups. However, people with fixed jobs are forced to participate in insurance based on enterprises, and there will be no adverse selection, while flexible employees without fixed jobs can freely choose whether to participate in the insurance, and adverse selection may occur; that is, whether adverse selection occurs depends on occupation. However, the occurrence of moral hazard is related to the income. When the income is low, the high medical expenses caused by moral hazard cannot be borne, and there is basically no moral hazard problem; on the other hand, when the income is high, moral hazard will occur in order to get better medical effect and service. Therefore, this paper chooses the third way to separate moral hazard and adverse selection.

This article focuses on the economic effect of medical insurance on employees who only have basic medical insurance. This group of people is also an economically vulnerable group, whose resistance to disease risk is weak. Without health insurance, if they suffer from major diseases, the economic impact on families will be very strong, and it is likely to result in active or passive abandonment of treatment. By purchasing UEBMI, the risk of high medical expenses will be transferred to medical insurance agencies, which will pay part of the medical expenses in case of illness, stimulating medical demand, and increasing medical expenses. However, due to the limited level of financing for UEBMI, the insured population still needs to bear a certain proportion of medical expenses. Therefore, with the increase of the total medical expenses, the self-paid expenses of the insured may also increase. Since the original intention of UEBMI is to solve the problem of "medical treatment is difficult and expensive," how much of a role does UEBMI play when employees suffer from diseases? Eventually does it reduce or increase the medical burden of employees? This requires analyzing the economic effects of UEBMI.

On the other hand, the reasons for medical expenses increasing include moral hazard effect and adverse selection effect, in addition to the decrease in the price actually paid by patients, which stimulates medical demand, that is, the release of normal medical demand. Moral hazard effect is the unreasonable increase of medical expenses caused by information asymmetry, which is manifested as excessive medical treatment, minor illness, collusion between doctors and patients, and prescribing "big prescriptions." Adverse selection effect is that people with poor health are more willing to buy medical insurance, which leads to an increase in the number of illnesses and an unreasonable increase in medical expenses. Considering that when the insureds' income level is low, they do not have enough financial ability to bear the "high" medical expenses, they will not take the initiative to increase medical expenses. Therefore, when seeing a doctor, they will be limited to reasonable treatment, and there is basically no moral hazard. Only when the insureds' income level is high, they have sufficient financial strength to enjoy better services, pursue better treatment, and thus generate moral hazard. At the same time, considering that the basic medical insurance for urban employees needs to take enterprises as the carrier, which is internally mandatory, employees of enterprises cannot freely choose whether to participate in the insurance. At this time, there is no adverse selection. On the other hand, flexible employees without fixed jobs can freely choose whether to participate in the insurance, and this will inevitably lead to the result of "bad money drives out good money" and there will be adverse selection. Therefore, based on the economic effect of UEBMI, this paper analyzes the mechanism of medical cost growth, distinguishes moral hazard effect and adverse selection effect by income heterogeneity analysis and occupation heterogeneity analysis, and provides theoretical foundation for the implementation of the UEBMI policy in the future.

2. Data, Variables, and Models

2.1. Data and Variables. The data used in this paper comes from the China Health and Nutrition Survey (CHNS), an international collaborative project between the Population Center at the University of North Carolina and the National Institute for Nutrition and Health (NINH, former National Institute of Nutrition and Food Safety) at the Chinese Center for Disease Control and Prevention (CCDC). CHNS has 10 phases of tracking data. This paper uses 4 phases of tracking data from 2006 to 2015. The latest data was released in 2018, involving about 7,200 families with over 30,000 interviewees in 15 provinces.

When measuring the economic burden of urban workers, this paper chooses "total medical expenses" and "self-paid medical expenses" as the explained variables. The explanatory variables include the processing variables "whether to participate in UEBMI or not" and period variables and their interaction. According to [17], the control variables include the population characteristics, family characteristics, and other health characteristics of the insured. The specific variable settings are shown in Table 1.

In this paper, after eliminating samples with obvious anomalies of key variables and missing variables, merging the subdatabases, and deleting the mismatched samples, 83,837 samples remained. Because the CHNS questionnaire started to include questions related to the UEBMI in 2009, only the three periods of data in 2009, 2011, and 2015 were available in this study. In order to accurately investigate the implementation effect of the UEBMI and compare the effects before and after the purchase of UEBMI, this paper also retains the data of the previous period, that is, the data of

Table 1: Variable description and assignment.

Variable settings	Variable description	Variable assignment
Medical burden		
Total medical expenses	Total medical expenses	Adjusted to 2015 by CPI = total medical expenses * (1 − medical insurance payment ratio), adjusted to 2015 by CPI
Self-paid medical expenses	Self-paid medical expenses	
Insured variable		
UEB	Whether to participate in the basic medical insurance for urban employees	Participating = 1, not participating = 0
Demographic characteristics		
Age	Age of interviewee	
Age^2	The square of age	The square of age
Male	Respondents are male	Male = 1, female = 0
Marital status	Marital status of interviewees	Unmarried = 0; divorced, widowed, separated = 1; married = 2
Single	Unmarried	Unmarried = 1, others = 0
Married	Married	Married = 1, others = 0
Others	Divorce, widowhood, or separation	Divorce, widowhood, or separation = 1, others = 0
Education level	Education level of interviewees	Illiteracy = 0, primary school = 1, junior high school = 2, senior high school and above = 3
Illiteracy	Illiteracy	Illiteracy = 1, others = 0
Primary	Primary school	Primary school = 1, others = 0
Junior	Junior high school	Junior high school = 1, others = 0
High	High school and above	High school and above = 1, others = 0
Nation	Ethnic minorities	Minority = 1, Han = 0
Occupation	Interviewee's occupation	No job = 0, ordinary worker = 1, professional or management work = 2
Unemployed	No job	No job = 1, others = 0
Ordinary workers	Ordinary workers	Ordinary employees = 1, others = 0
Senior management	Professional or management work	Professional or management work = 1, others = 0
Town	Permanent address is in town	Urban or town = 1, rural = 0
Family characteristics		
Family size	Number of households	
Any other relatives	Are there any other relatives?	Yes = 1, none = 0
Household income per capita	Household income per capita	Adjusted to 2015 by CPI
Health characteristics		
Smoking	Smoking or not	Smoking and still smoking = 1, others = 0
Alcohol	Do you drink alcohol?	Almost every day or 3-4 times a week = 1, others = 0
Illness or injury	Have you been sick or injured in the past four weeks?	Yes = 1, no = 0
Previous medical history	Previous medical history	Have been diagnosed as suffering from or having suffered from one or more of the seven diseases below: hypertension, diabetes, myocardial infarction, stroke or transient ischemia, tumor, fracture, and asthma = 1, none = 0

2006, with 40054 remaining samples. In order to analyze the net effect of UEBMI, this paper takes the samples that did not purchase any medical insurance in the previous period and only purchased the UEBMI in the next period as the treatment group, and takes the samples that did not purchase any medical insurance in the two periods as the control group. At this time, there are 1860 samples left, with 930 samples in each period, including 426 samples in the treatment group and 504 samples in the control group. Descriptive statistical results of these samples are shown in Table 2.

The results reported in Table 2 show that before the purchase of UEBMI, the total medical expenses of the treatment group were far less than those of the control group. However, after the purchase of insurance, the medical expenses of the control group decreased slightly, while the medical expenses of the treatment group increased greatly, from 278.8 yuan to 1274 yuan, exceeding the data of the control group. The change direction of self-paid medical expenses is consistent with the total medical expenses except that after purchasing insurance, the self-paid medical expenses of the treatment group are still less than those of the control group. None of the above results are significant. They seem to indicate that insurance has not reduced but increased the insured's economic burden, which means a countereffect and may even cause us to doubt the function of UEBMI. However, due to the differences in risk awareness, health level, and tendency to seek medical treatment between the groups who buy insurance and those who do not, Table 2 does not control other variables, so the results need to be further verified. Of course, the possibility that there will be some data exceptions in the table cannot be ruled out, because of the difference in the caliber of the respondents who filled in the survey. This may have happened when they were interviewed; the interviewers filled in the diploma they had not obtained in the first period, and they filled in the diploma they had obtained in the second period. This paper uses the Heckman sample selection model to empirically analyze the economic effect of UEBMI, and thus evaluate the economic effect of medical insurance more objectively.

2.2. Model Constructing. A lot of medical expense values are zero, which might be caused by unnecessary medical treatment, choosing not to seek medical advice because of the medical costs, or the inconvenience of seeking medical advice. In this case, direct estimation will lead to biased results, while Heckman sample selection model can correct the selective bias caused by the phenomenon of sample self-selection; that is, the model can correct the selective bias in estimation caused by the nil expenditure. On the other hand, Heckman sample selection model does not have to determine whether the two processes of "whether medical expenditure occurs" and "if it occurs, how much will pay" are independent of each other. Therefore, this paper constructs Heckman sample selection model to estimate the economic effect of UEBMI. When examining the impact of UEBMI on medical expenditure, considering that the increase of medical expenditure is mostly caused by the progress of medical technology and the rising price of medicine, in order to control the common time trend of the treatment group and the control group, this paper adopts the panel structure of difference in difference (DID) according to [5] and sets the sample selection model as follows:

$$P\left(I_i = 1\right) = P\left(\beta_0 + \beta_1 \text{treat}_i + \beta_2 \text{time}_t + \beta_3 \text{treat}_i \times \text{time}_t + \beta_4 X_{\text{tid}} + \delta_s + \varepsilon_{\text{tid}} > 0\right). \tag{1}$$

Equation (1) is a selection equation, considering the influence of treatment variable, time variable, control variables, and provincial variable on the dependent variable. It uses probit model to calculate the probability of positive medical expenses for the sample i. The expenditure equation for the second step is:

$$\ln\left(\text{pay}_{\text{tid}} | I_i = 1\right) = \beta_0' + \beta_1' \text{treat}_i + \beta_2' \text{time}_t + \beta_3' \text{treat}_i \times \text{time}_t + \beta_4' X_{\text{tid}} + \rho\sigma_2\lambda_i + \delta_s' + \varepsilon_{\text{tid}}'. \tag{2}$$

Equation (2) can estimate the effects of various factors on medical expenses. In (1) and (2), pay_{tid} is the dependent variable, which can be total medical expenses or self-paid medical expenses for sample i in period t. The dummy variable treat_i indicates whether UEBMI is purchased for sample i. The samples that purchased UEBMI are classified as the treatment group with a value of 1, and the samples that did not purchase the UEBMI are classified as the control group with a value of 0. Its coefficient β_1' reflects the difference between the treatment group and the control group in the first phase, that is, the group difference. The dummy variable time_t represents the time variable: the value is 0 when all samples did not purchase any medical insurance in the first period and 1 when some samples purchased UEBMI in the second period. Its coefficient β_2' reflects the difference in the control group between Phase 1 and Phase 2, that is, the time difference, which includes the increase in the price of medical expenses. treat $\times$ time is the interactive effect of the two variables: its value is 1 only when both variables equal 1; otherwise, it is 0. The difference in difference controls both the group effect and the time effect and can solve the endogeneity problem well. Its coefficient β_3' excludes the effect of rising medical prices and measures the net effect of UEBMI. The calculation principle of DID is shown in Table 3. X_{tid} are the control variables, including age, gender, nationality, marital status, education level, occupation, permanent address, income, previous medical history, smoking, and drinking. Whether there are any other relatives is also added as the control variable in the selection equation. δ_s is a provincial dummy variable. The sample size is small after processing, and the sample size is insufficient after controlling the municipal variable; thus, only the provincial variable is controlled. ρ is the correlation coefficient of ε_{tid} and $\varepsilon_{\text{tid}}'$. σ_1 is the standard deviation of equation (1). σ_2 is the standard deviation of equation (2). λ_i is the inverse Mills ratio.

3. Empirical Results and Explanations

3.1. The Overall Impact of Medical Insurance on Medical Expenses. Table 4 reports the results of the Heckman sample selection model. The results indicate that after purchasing the UEBMI, the probability of positive medical expenses of the insured decreases by 2.09%, and the result is not significant, which means that the UEBMI may slightly reduce the utilization of medical services. The reason may be that the insureds absorb more health knowledge and realize the importance of healthcare due to medical insurance; then, the number of illnesses decreases, which leads to the reduction of medical services utilization. It may also be because the medical expenses rise due to medical insurance. Even if the insured has medical insurance to reimburse part of the medical expenses, the actual amount paid in the end is higher than that before the insurance, which makes the

Table 2: Differences between treatment group and control group.

Variable	Previous period				Subsequent period		
	(1) Full sample	(2) Treatment group	(3) Control group	(4) T value	(5) Treatment group	(6) Control group	(7) T value
Total medical expenses	799.369	278.8	846.5	1.418	1274	781.2	−1.131
Self-paid medical expenses	623.33	223.7	846.5	1.567	516.7	734.5	0.658
Age	47.749	45.88	46.67	0.775	48.84	49.47	0.618
Male	0.487	0.512	0.466	−1.382	0.512	0.466	−1.382
Marital status	1.688	1.688	1.671	−0.387	1.742	1.661	−1.949*
Unmarried	0.106	0.127	0.109	−0.832	0.094	0.095	0.0700
Married	0.794	0.815	0.780	−1.311	0.836	0.756	−2.998***
Others	0.100	0.059	0.111	2.834***	0.070	0.149	3.788***
Education level	1.962	2.246	1.708	−8.059***	2.317	1.677	−9.887***
Illiteracy	0.144	0.087	0.202	4.983***	0.059	0.204	6.565***
Primary school	0.131	0.085	0.159	3.431***	0.101	0.167	2.919***
Junior high school	0.346	0.324	0.367	1.376	0.305	0.377	2.301**
High school and above	0.380	0.505	0.272	−7.505***	0.535	0.252	−9.247***
Nationality	0.101	0.085	0.115	1.541	0.085	0.115	1.541
Occupation	0.627	0.660	0.534	−2.781***	0.847	0.506	−7.236***
Unemployed	0.511	0.533	0.520	−0.396	0.430	0.554	3.793***
Ordinary workers	0.351	0.275	0.427	4.875***	0.293	0.387	3.001***
Senior management	0.138	0.192	0.0540	−6.712***	0.277	0.060	−9.447***
Town	0.557	0.610	0.512	−3.022***	0.610	0.512	−3.022***
Family size	3.461	3.300	3.605	3.466***	3.232	3.647	4.365***
Any other relatives	0.959	0.974	0.96	−1.173	0.958	0.944	−0.932
Household income per capita	12280.28	12125.36	8450.34	−5.614***	18724.76	10788.13	−9.816***
Smoking	0.281	0.254	0.304	1.693*	0.261	0.300	1.318
Alcohol	0.123	0.115	0.131	0.735	0.127	0.117	−0.451
Illness or injury	0.096	0.075	0.117	2.148**	0.082	0.105	1.194
Previous medical history	0.178	0.188	0.137	−2.111**	0.223	0.173	−1.931*

Table 3: The calculation principle of DID.

	Phase 1 (time = 0)	Phase 2 (time = 1)	Difference
Treatment group (treat = 1)	$\beta_0' + \beta_1'$	$\beta_0' + \beta_1' + \beta_2' + \beta_3'$	$\beta_2' + \beta_3'$
Control group (treat = 0)	β_0'	$\beta_0' + \beta_2'$	β_2'
Difference	β_1'	$\beta_1' + \beta_3'$	β_3' (DID)

insured choose not to seek medical treatment until suffering from serious illness, thus reducing the utilization of medical services. However, for the insureds who have incurred medical expenses, the expenses they actually paid rose sharply. The net effect of UEBMI led to a 234% increase in total medical expenses, which is significant at a 5% confidence level. On the other hand, self-paid medical expenses equal the total medical expenses minus the reimbursement amount of medical insurance. In case of the increase in the total medical expenses, after deducting the reimbursement amount of medical insurance, UEBMI still contributed to a 110.64% increase in self-paid medical expenses, although the result is not significant.

3.2. Robustness Test. In order to ensure the reliability of the above results, this paper reuses the fixed effect model to test the impact of UEBMI on total medical expenses and self-paid medical expenses. The results are shown in Table 5.

The results of robustness test are similar to those of Heckman sample selection model. The expenses paid by the insured who incurred medical expenses will increase significantly. The net effect of UEBMI led to an increase of 180.39% in total expenses and 83.86% in self-paid medical expenses.

4. The Mechanism Analysis of Medical Expenses Growth

This paper argues that there are three reasons for the sharp increase in total medical expenses and self-paid medical expenses caused by UEBMI: (1) The release of normal medical needs: because UEBMI reduces the medical prices, some insureds who once cannot afford healthcare can now seek medical attention, which increases their medical expenses. (2) The result of adverse selection: that is, people with poor health are more inclined to buy medical insurance, so the number of illnesses increases and the medical expenses increase. (3) The result of moral hazard: that is, after purchasing medical insurance, consumers can enjoy medical services at a lower price; then, they are not very sensitive to

Table 4: Empirical results of Heckman sample selection model.

Variable	Logarithm of total medical expenses		Logarithm of self-paid medical expenses	
	(1) Selection equation	(2) Expenditure equation	(3) Selection equation	(4) Expenditure equation
Interaction effect (Treat × time)	−0.0209 [0.0206]	1.206** [0.6120]	−0.0209 [0.0206]	0.745 [0.5823]
Logarithm of income	0.00143 [0.0053]	−0.252* [0.1296]	0.00143 [0.0053]	−0.228* [0.1234]
Previous medical history	0.0373*** [0.0126]	−0.0759 [0.4803]	0.0373*** [0.0126]	0.0961 [0.4622]
Illness or injury	0.255*** [0.0143]	−5.599 [4.3940]	0.255*** [0.0143]	−4.275 [4.2515]
Any other relatives	−0.0326 [0.0259]		−0.0326 [0.0259]	
Inverse Mills ratio		−15.51 [10.9397]		−12.08 [10.5715]
Constant		19.29* [9.9237]		16.15* [9.6066]
Provinces	Control	Control	Control	Control
Sample size	1836	213	1836	213

Note:the selection equations of models (1) and (3) are estimated by probit model, which gives marginal effect. The standard errors are shown in brackets, and the standard errors of models (2) and (4) are obtained by bootstrap method. The model also controls the variables of age, gender, nationality, marital status, education level, occupation, permanent address, smoking, and drinking. $^{*}P < 0.1$, $^{**}P < 0.05$, and $^{***}P < 0.01$.

the price of medical services, so they generally have the psychological tendency of "overconsumption," and the consumption motivation of "the more the better" [18], such as overexamination, overmedication, and other behaviors, resulting in an increase in medical expenses. The contribution to medical expenses of these three reasons can be analyzed by income heterogeneity and occupation heterogeneity.

4.1. Income Heterogeneity Analysis. In this paper, household income per capita is ranked. The bottom third of households are classified as low-income families, the middle third of households are classified as middle-income families, and the top third of households are classified as high-income families. The results in the above table show that after purchasing UEBMI, low-income and middle-income families are less likely to incur positive medical expenses, but the results are not significant. The probability of positive medical expenses in high-income families will increase slightly, and the results are also not significant. The results indicate that UEBMI plays a very limited role, and it does not effectively change the utilization rate of medical services of the insureds. The results in Table 6 indicate that it is true that medical insurance leads to an increase in medical expenses. Even if the insured has medical insurance to reimburse part of the medical expenses, the actual amount paid in the end is higher than that before the insurance, which makes the insured with lower income choose not to seek medical treatment without serious illness, thus reducing the utilization of medical services.

For the insureds who have incurred medical expenses, the coefficients of interaction effect are not significant, which indicates that the role of medical insurance is limited. There is no significant release of normal medical demand, no significant increase in the utilization rate of medical services, no significant increase in medical expenditure, and no significant reduction in self-paid medical expenditure. However, the role of UEBMI varies widely among families with different incomes. Low-income families are most likely to "become poor due to illness and return to poverty due to illness." Because medical insurance can help those most in need, it can release the demand of patients who originally "cannot afford healthcare," resulting in an increase of 0.61% in total medical expenses and a decrease of 63.98% in self-paid medical expenses. Normal medical demand has changed little, but the UEBMI has played an important role in economic compensation for low-income families. Middle-income families can pay medical expenses without medical insurance, so the increase in medical expenses mainly comes from moral hazard, leading to an increase of 114.47% in total expenses and 63.56% in self-paid medical expenses. On the contrary, the medical expenses paid by higher-income families decrease, because they pay more attention to daily healthcare, the probability of serious illness decreases, and the corresponding medical expenses decrease too.

4.2. Occupation Heterogeneity Analysis. The "Decision on Establishing the System of Basic Medical Insurance for Urban Employees" clearly requires workers who have a regular job to "be forced" to participate in UEBMI with the unit as the carrier. In this case, the insureds cannot freely choose whether to participate in the insurance according to their health status, and there is no adverse selection. However, those who have no fixed work, that is, flexible employees, can freely choose whether to participate in medical insurance and can also freely choose to participate in medical insurance for urban employees or medical insurance for urban and rural residents. In other words, this group of people is likely to choose whether to participate in

Table 5: Regression results of fixed effect model.

Variable	Logarithm of total medical expenses		Logarithm of self-paid medical expenses	
	Coefficient	Standard error	Coefficient	Standard error
Interaction (treat × time)	1.031*	0.5557	0.609	0.5274
Treatment effect (treat)	−0.504	0.392	−0.544	0.3721
Time effect (time)	0.224	0.3448	0.206	0.3273
Provinces	Control		Control	
Sample size	213		213	

*Statistical significance at the 10% level. Control variables include age, square of age, gender, nationality, marital status, education level, occupation, permanent address, income, previous medical history, smoking, and drinking.

Table 6: Release effect of normal medical needs.

	Variable	Low-income families		Middle-income families		High-income families	
		(1) Selection equation	(2) Expenditure equation	(3) Selection equation	(4) Expenditure equation	(5) Selection equation	(6) Expenditure equation
Explained variable: logarithm of total medical expenses	Interaction effect	−0.0398	0.00611	−0.0337	0.763	0.00776	−0.0949
	(Treat × time)	[0.0544]	[2.6589]	[0.0312]	[1.4655]	[0.0369]	[1.9022]
	Treatment effect	0.0254	−0.114	0.0157	0.379	0.00504	−1.28
	(Treat)	[0.0347]	[1.2680]	[0.0218]	[0.9869]	[0.0280]	[1.2413]
	Time effect	−0.0095	0.442	0.00968	1.186	−0.0228	1.207
	(Time)	[0.0249]	[0.6081]	[0.0233]	[0.8388]	[0.0302]	[1.4551]
	Constant term		2.706		9.027		35
	(_ cons)		[23.4859]		[13.3360]		[34.0406]
Explained variable: logarithm of self-paid medical expenses	Interaction effect	−0.0398	−1.021	−0.0337	0.492	0.00776	−0.554
	(Treat × time)	[0.0544]	[2.5011]	[0.0312]	[1.4032]	[0.0369]	[1.7911]
	Treatment effect	0.0254	−0.194	0.0157	0.324	0.00504	−1.352
	(Treat)	[0.0347]	[1.2274]	[0.0218]	[0.9537]	[0.0280]	[1.1713]
	Time effect	−0.0095	0.45	0.00968	1.259	−0.0228	0.961
	(Time)	[0.0249]	[0.5956]	[0.0233]	[0.8217]	[0.0302]	[1.2927]
	Constant term		3.438		8.901		26.84
	(_ cons)		[22.7362]		[12.9894]		[30.8461]
	Provinces	Control	Control	Control	Control	Control	Control
	Sample size	453	64	710	82	632	67

Note: the selection equations of models (1), (3), and (5) are estimated by probit model, which gives marginal effect. The standard errors are in brackets, and the standard errors of models (2), (4), and (6) are obtained by bootstrap method. The control variables of the expenditure equation include age, square of age, gender, nationality, marital status, education level, occupation, permanent address, income, previous medical history, smoking, and drinking. The control variables of the selection equation also add whether there are other relatives.

insurance according to their own health status, resulting in adverse selection. The empirical results in Table 7 show that the medical expenses of samples with fixed jobs, that is, the mandatory participants, reduced slightly, while the total medical expenses of those who have no fixed job, that is, the flexible employees, significantly increased by 364.6%, and the self-paid medical expenses increased by 153.96%. The results of income heterogeneity analysis show that medical expenses only increased by 0.61% due to the release of normal demand. Then, the increase in medical expenses can be mainly attributed to adverse selection and moral hazard, of which moral hazard led to an increase of 114.47% in total medical expenses and 63.56% in self-paid medical expenses. For flexible employees, adverse selection led to an increase of 249.52% in total medical expenses and 90.4% in self-paid medical expenses.

Table 7: Adverse selection and moral hazard effect.

	Variable	Having a regular job (1) Selection equation	(2) Expenditure equation	No fixed work (3) Selection equation	(4) Expenditure equation
Explained variable: logarithm of total medical expenses	Interaction effect	0.0117	−1.185	−0.0408	1.536*
	(Treat × time)	[0.0248]	[1.5332]	[0.0338]	[0.8333]
	Treatment effect	0.00655	−1.218	0.0048	−0.557
	(Treat)	[0.0178]	[0.8718]	[0.0244]	[0.5428]
	Time effect	−0.0197	0.826	−0.00391	0.124
	(Time)	[0.0175]	[0.9482]	[0.0221]	[0.4453]
Explained variable: logarithm of self-paid medical expenses	Interaction effect	0.0117	−1.146	−0.0408	0.932
	(Treat × time)	[0.0248]	[1.4467]	[0.0338]	[0.7869]
	Treatment effect	0.00655	−1.328*	0.0048	−0.538
	(Treat)	[0.0178]	[0.7902]	[0.0244]	[0.5396]
	Time effect	−0.0197	0.769	−0.00391	0.115
	(Time)	[0.0175]	[0.9180]	[0.0221]	[0.4404]
	Provinces	Control	Control	Control	Control
	Sample size	898	78	933	135

*Statistical significance at the 10% level. The selection equations of models (1) and (3) are estimated by probit model, which gives marginal effect. The standard errors are in brackets, and the standard errors of models (2) and (4) are obtained by bootstrap method. The control variables of the expenditure equation include age, square of age, gender, nationality, marital status, education level, occupation, permanent address, income, previous medical history, smoking, and drinking. The control variables of the selection equation also add whether there are other relatives.

5. Conclusions

By constructing Heckman sample selection model, this paper finds that after purchasing UEBMI, the medical expenses of the insureds increase greatly. The net effect of UEBMI led to an increase of 234% in total medical expenses and 110.64% in self-paid medical expenses. According to the results, UEBMI not only fails to play an important role in the economic compensation function, but also increases the economic burden of the insureds. In fact, there are three reasons for the increase of medical expenses: the release of normal medical demand, adverse selection, and moral hazard. This paper holds that when the insured gets a low income, the moral hazard is not a problem, and the increase of medical expenses can mainly be attributed to the release of normal medical demand, resulting in an increase of 0.61% in medical expenses. Flexible employees without a fixed job can freely choose whether to participate in insurance or not; thus, there may be adverse selection problems. On the other hand, workers with fixed jobs are forced to take the unit as the carrier to participate in UEBMI, and basically there is no adverse selection problem; thus, the increase in medical expenses can be attributed to moral hazard. Therefore, this paper concludes that moral hazard led to an increase of 114.47% in total medical expenses and 63.56% in self-paid medical expenses. For flexible employees, adverse selection led to an increase of 249.52% in total medical expenses and 90.4% in self-paid medical expenses.

This paper finds that the problems of adverse selection and moral hazard are very prominent in UEBMI, and puts forward some suggestions as follows: First, Hierarchical Treatment Model should be promoted to control the growth of medical expenses. In order to reduce patients' medical expenses and ease their medical burden, we can use medical insurance to speed up the process of Hierarchical Treatment Model, guide insureds to "seek downward medical treatment," and determine a scientific payment system [19]. Second, flexible employees should be guided to participate in the UEBMI. Due to the limited conditions of participating in insurance, weak awareness of participating in insurance, and difficulties in transfer and connection, the participation rate of flexible employees is not high [20]. For the sake of guiding them to actively participate in insurance, we can increase the publicity of medical insurance and health policies and build carriers of communities, labor dispatch companies, and trade associations. Because compulsory insurance is an effective way to solve the problem of adverse selection, flexible employees are required to purchase group insurance on a carrier basis, which means adopting internal compulsory insurance, to form a de facto compulsory insurance to solve the problem of adverse selection [21].

Data Availability

The raw data used to support the findings of this study can be obtained upon application to the website of China Health and Nutrition Survey. The processed data are available upon request from the corresponding author.

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

Impact of the Business Structure on Solvency of Property-Liability Insurance Companies and Its Mediating Effect

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It is an important objective for insurers to optimize their business structures to prevent business risks. This paper examines the solvency risk management in property-liability insurance companies from the perspective of business structure optimization. We construct a logical framework to explain the impact of the business structure on solvency through profitability and reinsurance behavior of property-liability insurance companies. By constructing a mediating effect model, we tested 35 Chinese-funded property-liability insurance companies and 18 foreign-funded property-liability insurance companies in China's insurance market from 2009 to 2015. Two major results were found as follows: first, the impact of the business structure on solvency is positively significant in small Chinese-funded insurance companies as well as foreign-funded insurance companies, while it is insignificant in large Chinese-funded insurance companies. Second, the mediating effect test shows that the intermediary channel of profitability does not exist, while the intermediary channel of reinsurance exists, and the reinsurance fully mediated the relationship between business structure and solvency only in foreign-funded insurance companies. Therefore, we suggest that small Chinese-funded insurance companies should actively develop nonauto insurance and improve the risk diversification effect of the diversified business structure. On the contrary, foreign-funded insurance companies should give play to their differentiated advantages and continue to concentrate on the operation of nonauto insurance in China's insurance market. Besides, the above two types of companies should attach more importance to the positive role of reinsurance in solvency risk management in their business development strategies.

1. Introduction

As we all know, insurance is a "social stabilizer" and "economic booster," and the key to give full play to the economic compensation function of insurance is the insurance product supply. Optimizing the product supply of insurance companies can not only meet the diversified needs of risk transfer of social and economic units but also help to improve the risk prevention and control ability of insurance companies themselves. In China's insurance industry's "11th Five-Year Plan," "12th Five-Year Plan," and "13th Five-Year Plan" (The "11th Five-Year Plan" of China's insurance industry refers to the *Outline of the "11th Five-Year" Plan for the Development of China's Insurance Industry*, which sets forth policies and measures for the development of China's insurance industry from 2006 to 2010, including its development direction, expected goals, and targets. The "12th Five-Year Plan" and "13th Five-Year Plan" of the insurance industry refer to the *Outline of the 12th Five-Year Plan for the Development of China's Insurance Industry* and the *Outline of the 13th Five-Year Plan for the Development of China's Insurance Industry*, respectively.), business structure optimization of property-liability (P/L) insurance companies has been repeatedly taken as the top priority in the reform and development of China's insurance market. For one thing, the overdependence on auto insurance business in Chinese-funded P/L insurance companies is not conducive to the diversification of their own operating risks and reduces the industry's overall resistance to market risks. For another thing, due to the initial operating restrictions, foreign-funded P/L insurance companies (According to the *Regulations on the Administration of Foreign-Funded Insurance Companies* issued by the China Banking and Insurance Regulatory Commission, foreign-funded companies include both wholly foreign-owned P/L insurance companies established in China and joint-venture P/L insurance companies with more than 25% foreign shares. Therefore, this paper divides the research samples into foreign-funded and Chinese-funded P/L insurance companies according to the above provisions.) cannot display their ambitions in China's auto insurance market and have to turn to the nonauto insurance business.

Therefore, a series of reform measures for auto insurance business have been implemented gradually. For example, the foreign-funded insurance company was allowed to enter the compulsory traffic accident liability insurance (CTALI) market from 2012; the second round of market-oriented reform of commercial auto insurance rate was executed from 2015. In 2018, the China Banking and Insurance Regulatory Commission (CBIRC) began to require insurers to strictly follow the regulations reported to the regulatory authorities in handling fees in practice. Under this background, Chinese-funded and foreign-funded P/L insurance companies chose different business development strategies, and their business structures began to change.

As shown in Figure 1, after foreign-funded P/L insurance companies entered the CTALI market in 2012, the proportion of auto insurance businesses increased, while large Chinese-funded P/L insurance companies (Referred to the practice of Guo and Wang, this paper divides large and small Chinese-funded insurance companies based on the median premium income. Insurers whose premium income is greater than the median of their premium income are considered as large companies, while those whose premium income is less than the median of their premium income are considered as small companies.) actively seized the opportunities after the release of the "New Ten Policies" (In 2014, the State Council of the People's Republic of China issued *Several Opinions on Accelerating the Development of the Modern Insurance Service Industry*, referred to as the "New Ten Policies.") to accelerate the development of their nonauto insurance business, and the proportion of nonauto insurance businesses increased gradually. However, small Chinese-funded P/L insurance companies still maintained their development strategy of auto insurance, and the proportion of nonauto insurance business is still on the decline.

In most countries, solvency regulation is the core tool used in insurance regulatory systems. Especially in China, it is one of the three regulatory pillars in the insurance industry, and it is the major risk prevention method for insurance companies. The P/L insurance companies should not threaten their own solvency when developing nonauto insurance or auto insurance business. In December 2016, the CBIRC issued *Guidelines on Insurance Product Development for Property-Liability Insurance Companies*, which clearly pointed out that an insurer shall comprehensively consider

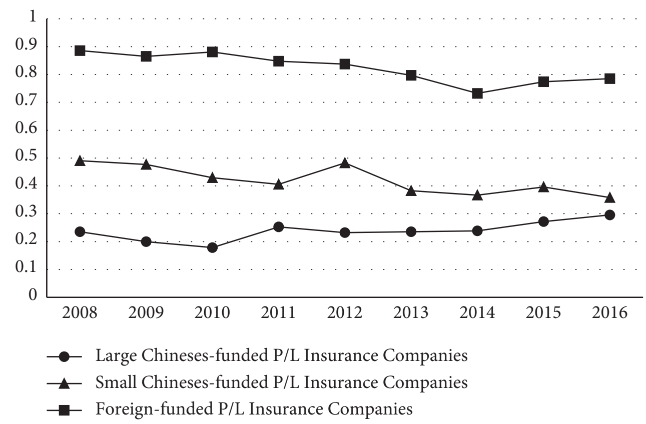

Figure 1: The changing trend of the average proportion of nonauto insurance business of P/L insurance companies in China. Data source: through 2009–2017 China Insurance Statistical Yearbook collation.

its underwriting capacity, division of risk units, reinsurance support, and other factors in the development of insurance products and shall not endanger its solvency and financial soundness.

Therefore, is there any impact of the business structure on solvency in P/L insurance companies? Are there any differences in these impacts between Chinese-funded and foreign-funded P/L insurance companies in China? If the answers of the above questions are both yes, through which channels the business structure affects the solvency among different companies? To answer all these questions, this paper discussed the impact of business structures on solvency in different P/L insurance companies through the profitability channel and the reinsurance channel by building an intermediary model.

2. Literature Review and Research Hypothesis

In early years, scholars mainly focused on the factors that influence the solvency in insurance companies. For example, Harrington and Nelson [1] empirically examined the factors that influence the solvency of insurers and found that factors such as premium surplus ratio, asset structure, and business structure all affect the insurers' solvency. Zhu et al. [2] pointed out that business quality was an important factor that affects the solvency of an insurer. Recently, more and more studies have begun to explore the influence of the business structure on the insurers' solvency. Jiang and Liu [3] came out with the conclusion that unbalanced product mix had a negative impact on the solvency.

There are two main streams on the mechanism of how the business structure affects the insurers' solvency. One is the profitability channel, and the other is the reinsurance channel as we can see as follows.

2.1. *The Impact of the Business Structure on Solvency through the Profitability Channel.*

According to the synergistic effect theory first put forward by the American enterprise strategic management expert Ansoff [4], business diversification can reduce costs, increase sales, and thus improve corporate earnings. The development of nonauto insurance business by P/L insurance companies can increase their profitability by sharing resources with auto insurance business. Therefore, according to the synergistic effect theory, the transformation of P/L insurance companies from a single business structure to a diversified business structure is conducive to improving their profitability.

However, according to the principal-agent theory proposed by Berle and Means in the 1930s, diversified business structure also means that, for the enterprise management level of diversification, as a result of the information asymmetry, diversification is likely to increase the insurance company's supervision and control difficulty and reduce the effectiveness of the enterprise management strategy and decision-making thereby weakening the profitability of the insurance company.

On the basis of the above theories, many scholars have studied the impact of business structure diversification on profitability of P/L insurance companies but reached inconsistent conclusions. Teyssier [5], Meador et al. [6], and Pervan and Pavic Kramaric [7] proved that the diversification of business structure has a positive effect on the profitability of P/L insurance companies. However, studies conducted by Hoyt and Trieschmann [8], Cummins and Nini [9], Cummins et al. [10], and Shim [11] all support that business diversification will reduce the profitability of P/L insurance companies. Elango et al. [12] even believed that there may be a complex nonlinear relationship between the two.

In the literature on factors affecting the solvency of insurance companies, many scholars have found that the profitability is an important factor, and the improvement of profitability helps to enhance the solvency of P/L insurance companies. Ambrose and Seward [13] considered the profit margin, company size, investment return, and other internal factors of P/L insurance companies as important variables affecting their solvency. Leadbetter and Dibra [14] found that the financial market turmoil and the decline of the profitability of the industry were catalysts for the solvency insufficiency of Canadian P/L insurance companies from 1960 to 2005. Kleffner and Lee [15] studied the reasons for the low incidence of insolvency of P/L insurance companies in Canada, found that only the measure of profitability, namely, return on assets, was a significant indicator, and pointed out that this conclusion was consistent with many studies taking P/L insurance companies in the United States as samples. Yakob et al. [16] also found in their study of life insurance companies that the improvement of profitability can enhance the solvency. Li and Lu [17] studied the solvency crisis of P/L insurance companies and solutions from the perspective of performance analysis based on the data of 13 Chinese-funded and foreign-funded P/L insurance companies and pointed out that the low return on assets was an important reason for the solvency crisis of Chinese-funded P/L insurance companies. Zhu et al. [2] argued that the actual solvency was affected by changes in owners' equity, while the profitability had a direct impact on such changes. The authors further studied the influence of 8 internal factors and 3 external factors on solvency by taking 10 P/L insurance companies in China as samples and found that return on assets was significantly positively correlated with solvency. Zheng [18] selected the data of insurance companies in China from 2007 to 2012, found that the net interest rate on assets was significantly positively correlated with the solvency of insurance companies, and proposed that insurers should enhance their solvency from the aspects of product structure and profitability improvement. Based on the data of 14 China's P/L insurance companies from 2012 to 2017, Li and Gu [19] did not find a significant correlation between the net profit margin of P/L insurance companies and solvency and pointed out that P/L insurance companies should reduce the loss ratio and asset-liability ratio, rather than excessively pursue the improvement of profitability to enhance solvency.

To sum up, changes in the business structure of P/L insurance companies will affect their profitability, which is an important factor affecting their solvency. Therefore, we put forward the first hypothesis.

Hypothesis 1. The business structure of a P/L insurance company affects its solvency through the profitability channel.

2.2. The Influence of the Business Structure on Solvency through the Reinsurance Channel. The business structure of an insurance company will affect its reinsurance behavior. Many research studies on insurers' reinsurance behavior have found that business structure is an important determinant. Mayers and Smith believed that the increase of business concentration of insurance companies would increase the cash flow volatility and the probability of insufficient solvency, and reinsurance was an important means to solve the insolvency caused by the above factors [20]. Based on the panel data of insurance companies in Croatia, Curak et al. [21] found that when the business structure of insurance companies is more concentrated, insurance companies tend to increase the proportion of reinsurance ceding so as to transfer more risk to the reinsurance companies. However, Mankaï and Belgacem [22] believed that P/L insurance companies could gain economic benefits from specialized operations so as to reduce their demand for reinsurance, and empirical studies with the American P/L insurance companies as samples also proved that business concentration was significantly negatively correlated with reinsurance rate.

In the empirical studies on reinsurance demand of insurance companies in China, most of the research conclusions support that the more concentrated the business structure of insurance companies is, the lower their reinsurance demand will be. Wu et al. [23] used the fixed effect model to conduct an empirical study on P/L insurance companies in China from 2001 to 2007 and found that business concentration was significantly positively correlated with the reinsurance ceding ratio of P/L insurance companies, indicating that business concentration was an important consideration in reinsurance decision-making. Zhao and Wu [24] used the quantile regression method to study the relationship between business concentration and reinsurance demand of P/L insurance companies and found that, except for the extreme positions (0.05 and 0.95), business concentration of P/L insurance companies was negatively correlated with reinsurance demand in general. The more dispersed the business structure of an insurance company is, the more professional reinsurance services are needed due to the limitations of professional knowledge, information, and management experience. When Chen and Ding [25] empirically tested the impact of business concentration on reinsurance demand of P/L insurance companies in China, they found that the more concentrated the business structure is, the lower the reinsurance ceding ratio will be. The authors further pointed out that this is closely related to the fact that most of the business structures of P/L insurance companies in China are concentrated in auto insurance, and the risk of auto insurance business is lower than that of nonauto insurance business such as liability insurance and cargo transportation insurance, so the reinsurance demand is also lower.

Reinsurance is an important means of risk transfer for insurance companies. The control of underwriting capacity is an important factor affecting the solvency of an insurance company. On the one hand, insurance companies can purchase reinsurance to transfer insurance risks that they cannot bear to reinsurance companies so as to improve their solvency. On the other hand, a high reinsurance ratio means the increase of reinsurance premium and the decrease of underwriting income, which is not conducive to the accumulation of corporate capital and may have an adverse impact on solvency. Lin et al. [26] and Liang and Huang [27] studied how insurance companies determine the optimal reinsurance ceding ratio to ensure their solvency. Most empirical studies based on Chinese data have found that an increase in the reinsurance cession ratio can improve the solvency of insurance companies. Zhu et al. [2] and Huang and Wang [28] found in their empirical studies based on Chinese data that increasing reinsurance ratio can enhance the solvency of insurance companies.

To sum up, the business structure of P/L insurance companies will affect their reinsurance ceding ratio, and the increase of reinsurance ceding ratio can enhance their solvency. Therefore, we propose the second hypothesis of this paper.

Hypothesis 2. The business structure of a P/L insurance company affects its solvency through the reinsurance channel.

According to the above analysis, profitability and reinsurance behavior are important channels for P/L insurance companies' business structure to affect solvency. The specific influence mechanism of the business structure of P/L insurance companies affecting solvency is shown in Figure 2.

3. Research Design

3.1. The Data Source. The research samples of this paper are the P/L insurance companies in China from 2009 to 2015. The sample period is selected from 2009, mainly because the solvency adequacy ratio data obtained on the website of China's Insurance Industry Association began in 2009 at the earliest. The reason why 2015 is chosen as the cutoff date is that China's insurance industry has officially implemented the "China Risk-Oriented Solvency System" since 2016, so there will be a difference between the calculation of solvency adequacy ratio after 2016 and before 2016. Therefore, in order to ensure the consistency and comparability of the research samples, the sample cutoff date is selected as 2015. The sample data are from the database of CSMR (China Stock Market & Accounting Research Database) and China Insurance Yearbook from 2009 to 2016. The solvency adequacy ratio data are manually sorted out from the annual reports of various insurance companies published on the website of the Insurance Industry Association. The macrodata are obtained from the website of the National Bureau of Statistics of the People's Republic of China. In this paper, policy-based P/L insurance companies (such as China Export and Credit Insurance Corporation), Lloyd's, professional insurance companies, and captive insurance companies are deleted, and the key indicators of this paper are winsorized by 1%. Table 1 reports descriptive statistics of the main variables in the full sample and the subsample of Chinese-funded and foreign-funded P/L insurance companies.

3.2. Variable Selection

3.2.1. Explained Variable

(1) Solvency. In this paper, according to Bian and Wang [29], solvency adequacy ratio was selected to reflect the solvency of P/L insurance companies. Solvency adequacy ratio is the ratio of "actual capital" to "minimum capital" of an insurer, which reflects an insurer's ability to fulfill its policy liability. The larger the solvency adequacy ratio is, the stronger the insurer's solvency is.

3.2.2. Explanatory Variable

(1) Business Structure. In this paper, the definition of the business structure of P/L insurance companies is based on the following three aspects: first, the difference of risk characteristics between auto insurance and nonauto insurance: different from the auto insurance, the types of risks insured by the nonauto insurance are more complex and special, and even many risks have the characteristics of long tail, such as liability insurance and catastrophe insurance. Once the loss occurs, it will bring huge indemnity payout to the P/L insurance company. Therefore, it is more difficult for P/L insurance companies to underwrite and settle claims for nonauto insurance objects, and the compensation volatility is relatively large.

Second, refer to the definition of the business structure in the banking industry. A bank's business structure usually refers to the proportion of noninterest income or interest income in the bank's income structure. At the beginning of its development, the banking industry also relied on interest income as its main source of income. However, drived by the needs of social and economic development, the income

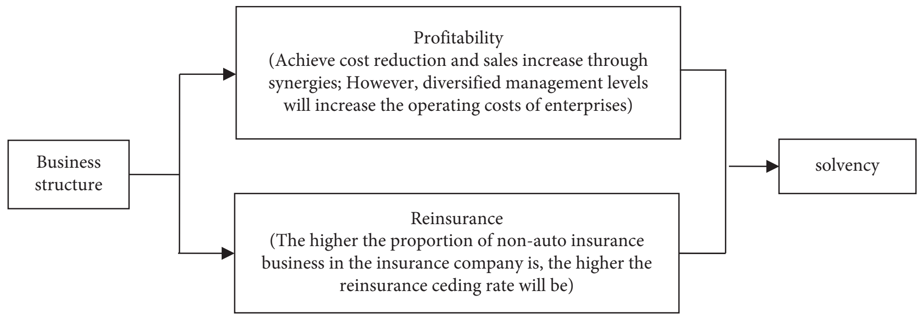

Figure 2: The transmission path of the impact of the business structure of P/L insurance companies on solvency.

Table 1: Descriptive statistics.

	Variable	Sample size	Mean value	Standard deviation	Minimum value	Maximum value
Full sample	Solvency	325	18.91	67.63	0.52	898.4
	Nonauto	451	0.486	0.357	0.013	1
	Roa	448	−0.017	0.067	−0.399	0.299
	Rein	450	0.228	0.234	0	0.971
	Size	448	8.079	1.660	5.188	13.59
	Loss	393	0.438	0.431	0	6.880
	Lev	448	0.616	0.211	0.018	1.297
	Geodiv	450	0.609	0.362	0	0.959
	Invest	440	0.651	0.196	0.137	0.985
	GDP	454	12.90	0.758	10.99	13.52
	Interest	454	2.412	0.694	1.022	3.325
Sample of Chinese-funded P/L insurance companies	Solvency	209	14.30	50.10	0.52	315.5
	Nonauto	273	0.270	0.196	0.013	0.971
	Roa	270	−0.006	0.056	−0.399	0.084
	Rein	272	0.113	0.103	0	0.734
	Size	270	8.910	1.541	6.189	13.59
	Loss	235	0.435	0.159	0	0.779
	Lev	270	0.644	0.201	0.018	0.959
	Geodiv	273	0.778	0.284	0	0.959
	Invest	264	0.267	0.169	0.015	0.762
	GDP	275	12.90	0.767	10.99	13.52
	Interest	275	2.423	0.685	1.022	3.325
Sample of foreign-funded P/L insurance companies	Solvency	116	27.21	90.77	1.077	898.4
	Nonauto	178	0.817	0.289	0.053	1
	Roa	178	−0.035	0.077	−0.308	0.299
	Rein	178	0.404	0.267	0.001	0.971
	Size	178	6.817	0.834	5.188	9.325
	Loss	158	0.442	0.653	0	6.880
	Lev	178	0.574	0.219	0.020	1.297
	Geodiv	177	0.349	0.315	0	0.922
	Invest	176	0.473	0.169	0.053	0.863
	GDP	179	12.90	0.746	10.99	13.52
	Interest	179	2.396	0.709	1.022	3.325

structure of banks began to shift from interest income to noninterest income, and the business structure of banks shifted from centralization to diversification. The business operation status of P/L insurance companies in China is similar to that of the banking industry. Their profit model is also shifting from the traditional auto insurance business to actively explore nonauto insurance business.

Third, in view of the existing literature on the definition of P/L insurance company business structure and the status quo of P/L insurance company's business structure in China, based on the current situation that the auto insurance business accounts for as high as 66.97% in China's P/L insurance market, Hao [30] pointed out that it is more reasonable to measure the business structure by the proportion of the largest insurance in the premium income, compared with the previous studies to measure the business structure of P/L insurance companies by using the Herfindahl index or entropy index.

This paper focuses on the problem of the business structure of China's P/L insurance companies. Therefore, we define the business structure as the proportion of nonauto insurance business, that is, the proportion of the nonauto insurance business income in the total premium income.

3.2.3. Intermediary Variables

(1) Profitability. This paper uses the return on assets to measure the profitability of a P/L insurance company. Return on assets is one of the most widely used indicators to measure the profitability of insurance companies. Return on assets represents the ability of an enterprise to obtain income of all its assets and comprehensively reflects the profitability and input-output status of an enterprise.

(2) Reinsurance. This paper uses the reinsurance ratio to reflect the reinsurance behavior of insurance companies. The reinsurance ratio of an insurance company is equal to the ratio of the premium ceded by the insurance company and the income from insurance business. The larger the reinsurance ratio is, the greater the proportion of insurance risks that the insurance company distributes through reinsurance.

3.2.4. Control Variables. Based on the relevant research on solvency and availability of the data, this paper controls other factors that may affect the solvency of P/L insurance companies, such as the company's own characteristics, daily business activities, and macroeconomic factors. Specifically, it includes the following variables.

(1) The Company Size. This paper uses the natural logarithm of the total assets of P/L insurance companies as the measurement index of company size. Company size is an important microfactor affecting the solvency of insurance companies. Larger insurers are able to take advantage of economies of scale, with richer cash flows and greater solvency. In addition, compared with large insurance companies, small insurance companies are more likely to suffer from solvency crisis because regulators are less likely to wind down and liquidate large insurance companies.

(2) Loss Ratio. The loss ratio is the ratio of claims to premium income. Too high a loss ratio will result in a large outflow of cash flow and a reduction in the solvency reserves made up of capital, total reserves, and unallocated earnings, thus reducing solvency [17]. The empirical studies of Li and Gu [19] all confirm that an increase in the loss ratio of an insurance company will significantly reduce its solvency.

(3) Financial Leverage. Corporate financial leverage is usually measured by asset-liability ratio, which is equal to the ratio of total liabilities and total assets. Asset structure has a great impact on an insurer's solvency, and asset-liability ratio is an important reflection of the asset structure of an insurer. Yakob et al. [16] found that the asset-liability ratio was significantly negatively correlated with the insurer's solvency. However, Harrington and Nelson [1] believed that the asset-liability ratio is a reflection of a company's long-term solvency. Since long-term liabilities do not need to be paid in the short term, on the contrary, it will improve the cash flow of an insurance company. Therefore, the higher the asset-liability ratio is, the stronger the solvency of an insurance company will be.

(4) Geographic Diversification. We use the complement of the Herfindahl index of premium income across 23 provinces, 4 municipalities directly under the central government, and 5 autonomous regions as the geographic diversification measure. The formula to calculate the geographic diversification is as follows:

$$\text{geodiv}_t = 1 - \sum_{i=1}^{n} \left(\frac{\text{income}_{i,j,t}}{\text{income}_{i,t}} \right)^2, \quad (1)$$

where the $\text{income}_{i,j,t}/\text{income}_{i,t}$ refers to the proportion of the i-th P/L insurance company's premium income from the j-th province, municipality and city specifically designated in the state plan to the total premium income of the i-th P/L insurance company in the period t.

The larger geodiv is, the more geographically diversified the P/L insurer is. Insurance companies implement the strategy of geographic diversification and diversify risks within the geographical scope, which may also have a certain impact on their solvency, just as business diversification.

(5) Stable Investment Assets. Referring to the practice of Sun and Cui [31], this paper uses the proportion of less risky investment assets such as cash, time deposit, and real estate investment in the investment portfolio of insurance companies to measure the proportion of stable investment assets of P/L insurance companies. Zhu et al. [2] pointed out that the solvency of aggressive and conservative companies is different. The higher the proportion of stable investment assets is, the smaller the investment risk an insurance company faces and the less likely the insurance company is to have a solvency crisis. However, on the contrary, according to the investment principle of "high risk brings high return," less investment risk means lower investment return, and lower investment return is not conducive to the improvement of solvency of insurance companies.

(6) Gross Domestic Product. In addition to the above microfactors, the impact of macroeconomy on the insurers' solvency is also very important. In this paper, the natural log of GDP is selected as the control variable and put into the model.

(7) Market Interest. The level of market interest rate will affect the return on investment of an insurer, thus affecting its solvency adequacy ratio. This paper refers to the practice of Peng and Zeng [32] to represent the market interest rate with the Shanghai Interbank Offered Rate.

The definitions of the main variables selected in this paper are shown in Table 2.

3.3. Model Specification. According to Baron and Kenny's [33] stepwise test regression coefficient method for the judgment of mediating effect, the setting of the mediating effect model needs to be divided into three steps.

Table 2: Main variable definitions.

Variable type	Variable name	Variable definitions
Explained variable	Solvency	Solvency, solvency adequacy ratio
Explanatory variable	Nonauto	Business structure, proportion of nonauto insurance income to total premium income
Intermediary variable	Roa	Profitability, the return on assets
	Rein	Reinsurance, the ratio of ceding premium to income from insurance business
Control variable	Size	Company size, natural log of total assets
	Loss	Loss ratio, the ratio of claims to premium income
	Lev	Financial leverage, the ratio of total liabilities to total assets
	Geodiv	Geographic diversification, Herfindahl index
	Invest	Stable investment assets, the proportion of stable investment assets in total assets
	GDP	Gross domestic product, the natural log of GDP
	Interest	Market interest, Shanghai Interbank Offered Rate

Step 1. Regression of independent variables to dependent variables.

Step 2. Regression of independent variables to intermediary variables.

Step 3. Simultaneous regression of independent variables and intermediary variables to dependent variables.

According to the above theoretical hypothesis, the business structure of P/L insurance companies may affect their solvency through two ways: profitability and reinsurance behavior. In this section, the stepwise regression method is used to examine the ways in which the business structure of P/L insurance companies affects solvency.

$$\text{solvency}_{i,t} = \alpha_0 + \alpha_1 \text{nonauto}_{i,t} + \alpha_2 \text{control}_{i,t} + \mu_{i,t}, \tag{2}$$

$$m_{i,t} = \beta_0 + \beta_1 \text{nonauto}_{i,t} + \beta_j \text{control}_{i,t} + \varepsilon_{i,t}, \tag{3}$$

$$\text{solvency}_{i,t} = \varphi_0 + \varphi_1 \text{nonauto}_{i,t} + \varphi_2 m_{i,t} + \varphi_j \text{control}_{i,t} + \omega_{i,t}, \tag{4}$$

where $\text{solvency}_{i,t}$ is the solvency adequacy ratio of the ith P/L insurer in period t, $\text{nonauto}_{i,t}$ is the proportion of nonauto insurance business of the ith P/L insurer in period t, and $m_{i,t}$ is the intermediary variable. $\text{control}_{i,t}$ is a series of control variables including company size, loss ratio, financial structure, geographic diversification, and stable investment assets. $\varepsilon_{i,t}$, $\mu_{i,t}$, and $\omega_{i,t}$ are the residual terms, respectively.

First, the regression coefficient α_1 in model (2) is tested. If α_1 is significant, further verification will be carried out; otherwise, the test is terminated. On the basis of the significance of α_1, the regression coefficient β_1 in model (3) and the regression coefficients φ_1 and φ_2 in model (4) were further verified. If coefficients β_1 and φ_2 were both significant at the same time, there was a mediating effect.

4. Empirical Process and Result Analysis

4.1. Descriptive Statistics of Variables. Table 1 lists the descriptive statistical results of the relevant variables. In the sample period, the average solvency adequacy ratio of P/L insurance companies is 18.91, and the average proportion of nonauto insurance business is 0.486. In general, the proportion of auto insurance business is still relatively high.

According to the subsample descriptive statistics, the average solvency adequacy ratio of Chinese-funded P/L insurance companies is 14.30, which is lower than the average solvency ratio of foreign-funded P/L insurance companies of 27.21. The average proportion of nonauto insurance business of Chinese-funded P/L insurance companies is 0.270, while the average proportion of nonauto insurance business of foreign-funded P/L insurance companies is as high as 0.817. Consistent with the above analysis, the business structure of Chinese-funded P/L insurance companies is mainly focused on auto insurance business, while that of foreign-funded P/L insurance companies is mainly focused on nonauto insurance business. In terms of return on assets, it is consistent with the findings of Hao [30] that the average return on assets of P/L insurance companies in China is negative. However, the average return on assets of Chinese-funded P/L insurers is −0.006, which is better than the average of foreign-funded P/L insurers, which is −0.035. As for reinsurance ceding, the average reinsurance rate of Chinese-funded P/L insurance companies is 0.113, which is lower than that of foreign-funded P/L insurance companies, which is 0.404. As for the geographical diversification, the average degree of Chinese-funded P/L insurance companies is 0.778, which is much larger than that of foreign-funded P/L insurance companies, which is only 0.349. In terms of financial leverage, the average financial leverage of Chinese-funded P/L insurance companies is 0.644, higher than the average of foreign-funded P/L insurance companies. In terms of stable investment assets, the average value of foreign-funded P/L insurance companies is 0.473, while the average value of Chinese-funded P/L insurance companies is 0.267, indicating that foreign-funded P/L insurance companies are relatively more stable in the insurance fund investment.

4.2. Basic Result of the Impact of the Business Structure on Solvency. Table 3 empirically tests the regression results of the impact of the business structure on solvency through the panel fixed effect model. Column (1) in Table 3 shows the empirical results of the full sample, and columns (2) and (5) show the

Table 3: The impact of the business structure of P/L insurance companies on solvency.

Variables	Full sample (1)	Chinese-funded (2)	Large Chinese-funded (3)	Small Chinese-funded (4)	Foreign-funded (5)
Nonauto	182.025∗∗∗ (5.871)	126.532∗∗∗ (4.900)	0.866 (0.078)	160.839∗∗∗ (3.938)	278.471∗∗∗ (4.166)
Size	18.535∗∗ (2.076)	1.793 (0.271)	4.471∗∗∗ (3.626)	8.991 (0.595)	62.998∗∗ (2.608)
Loss	0.149 (0.020)	−60.020∗∗∗ (−2.817)	−3.999 (−0.764)	−91.854∗∗ (−2.328)	0.087 (0.008)
Lev	−73.310∗∗ (−2.538)	−78.083∗∗∗ (−3.096)	−15.031∗ (−1.954)	−94.661∗∗ (−2.412)	−87.942 (−1.407)
Geodiv	−70.265∗∗ (−2.387)	2.667 (0.089)	−16.284 (−0.480)	−1.647 (−0.034)	−134.927∗∗ (−2.306)
Invest	44.680 (1.528)	6.151 (0.287)	5.245 (1.011)	−0.498 (−0.013)	77.744 (0.993)
GDP	−0.084 (−0.022)	2.798 (0.990)	0.036 (0.071)	5.021 (0.847)	−3.097 (−0.355)
Interest	−2.745 (−0.611)	2.069 (0.599)	−0.401 (−0.659)	6.828 (0.914)	−8.441 (−0.830)
Constant	−139.510 (−1.574)	−7.210 (−0.111)	−14.112 (−0.448)	−92.191 (−0.706)	−510.204∗∗ (−2.313)
Sample size	318	203	110	93	115

Note. (1) ∗∗∗ means $p < 0.01$, ∗∗ means $p < 0.05$, and ∗ means $p < 0.1$. (2) Below the estimated coefficient () is a robust standard error.

regression results of Chinese-funded and foreign-funded P/L insurance companies. Columns (3) and (4) in the table, respectively, show the regression results of large and small Chinese-funded P/L insurance companies.

In the regression results of the whole sample, the proportion of nonauto insurance business is significantly positively correlated with solvency at 1% level; that is, increasing the proportion of nonauto insurance business can improve the solvency of P/L insurance companies. As for the Chinese-funded P/L insurance companies, the proportion of nonauto insurance business is significantly positively correlated with solvency at 1%, indicating that the increase of the proportion of nonauto insurance business in the business structure will significantly enhance their solvency. The regression results of foreign-funded P/L insurance companies also show that the proportion of nonauto insurance business is significantly positively correlated with their solvency at 1%; that is, more concentrated business structure of foreign-funded P/L insurance companies in nonauto insurance business can enhance their solvency.

Columns (3) and (4) in Table 3 show the regression results of large and small Chinese-funded P/L insurance companies. In the regression results of large Chinese-funded P/L insurance companies, the proportion of nonauto insurance business is not significantly correlated with their solvency; that is, the change of business structure has no significant impact on their solvency. As for small Chinese-funded P/L insurance companies, the regression results show that the proportion of nonauto insurance business is significantly positively correlated with their solvency at 1%; that is, increasing the proportion of nonauto insurance business and reducing the concentration of the business structure of small Chinese companies can significantly enhance their solvency.

4.3. Mediating Effect Test of Profitability and Reinsurance Behavior Based on the Stepwise Regression Method

4.3.1. The Mediating Effect of Profitability. The above basic regression results show that the regression coefficient α_1 is significant only for small Chinese-funded P/L insurance companies and foreign-funded P/L insurance companies, but not for large Chinese-funded P/L insurance companies. Therefore, according to the testing process of mediating effect, this section only needs to test the mediating effect of the above two samples based on models (2) and (3).

Table 4 reports the mediating effect test results of small Chinese-funded and foreign-funded P/L insurance companies, respectively. Columns (1) and (2) in Table 4 are the panel fixed effect regression results of the mediating effect model for small Chinese-funded companies. The proportion of nonauto insurance business has no significant positive impact on profitability of small Chinese-funded companies. After controlling for the effect of nonauto insurance business proportion on solvency, the coefficients of profitability are positive, but not significant. Therefore, the mediating effect of profitability of small Chinese-funded companies is not significant, which does not support theoretical Hypothesis 1. This may be because small Chinese-funded P/L insurance companies have developed nonauto insurance businesses in the short term, which, due to the limited scale of nonauto insurance businesses, have not played the synergistic effect of improving profitability. In addition, in the early stage, the expansion of new businesses requires a lot of upfront costs,

Table 4: Mediating effect test of profitability based on the stepwise regression method.

Variables	Small Chinese-funded		Foreign-funded	
	Roa (1)	Solvency (2)	Roa (3)	Solvency (4)
Roa		121.422 (0.684)		175.666 (1.171)
Nonauto	0.004 (0.101)	160.285∗∗∗ (3.908)	0.067∗ (1.701)	269.925∗∗∗ (4.022)
Size	0.094∗∗∗ (7.469)	0.044 (0.002)	0.053∗∗∗ (4.563)	50.830∗ (1.936)
Loss	0.062∗ (1.691)	−92.206∗∗ (−2.327)	−0.015∗ (−1.961)	3.051 (0.262)
Lev	−0.047 (−1.352)	−92.620∗∗ (−2.343)	−0.120∗∗∗ (−3.593)	−65.867 (−1.011)
Geodiv	−0.073∗ (−1.738)	4.206 (0.085)	0.031 (0.977)	−131.055∗∗ (−2.241)
Invest	0.049 (1.483)	−6.124 (−0.153)	0.046 (1.157)	71.231 (0.909)
GDP	−0.000 (−0.063)	4.761 (0.798)	0.005 (0.842)	−4.059 (−0.464)
Interest	−0.012∗ (−1.723)	8.173 (1.054)	−0.004 (−0.643)	−7.559 (−0.742)
Constant	−0.691∗∗∗ (−5.795)	−22.829 (−0.138)	−0.459∗∗∗ (−4.375)	−416.230∗ (−1.776)
Sample size	104	93	155	115

Note. (1) ∗∗∗ means $p < 0.01$, ∗∗ means $p < 0.05$, and ∗ means $p < 0.1$. (2) Below the estimated coefficient () is a robust standard error.

including manpower and infrastructure investment. Therefore, the effect of improving profitability is not achieved in the short term.

Columns (3) and (4) in Table 4, respectively, show the regression results of foreign-funded P/L insurance companies. The results show that the coefficient of nonauto insurance business ratio of foreign-funded P/L insurance companies is significantly positive at the level of 10%; that is, the increase of nonauto insurance business ratio can significantly enhance their profitability. After controlling the influence of the nonauto insurance business ratio to solvency, the coefficient of profitability is positive, but not significant. Although the auto insurance business has an adverse impact on profitability, the foreign-funded P/L insurance companies have not let this negative effect to further weaken their solvency. This conclusion does not support theoretical Hypothesis 1 either. As for foreign-funded P/L companies, because of their lack of market experience and data accumulation in China's auto insurance business and their marketing network layout is difficult to develop in a short period of time, the increase of the proportion of auto insurance business does not bring profit growth. Instead, the increase in input costs and compensation expenses leads to a decline in profitability.

4.3.2. The Mediating Effect of Reinsurance Behavior. As shown in the previous research conclusions, only the regression α_1 of small Chinese-funded and foreign-funded P/L insurance companies is significant in the regression results of model (1). This section also only needs to conduct the following intermediary effect test of the above two samples.

Table 5 shows the regression results of the mediating effect of reinsurance behavior. The empirical results show that the nonauto insurance business ratio to the reinsurance rate of small Chinese-funded companies is significantly positive at 5%, indicating that when the proportion of nonauto insurance business is relatively high, the diversification of the business structure will increase, and small Chinese-funded companies will tend to buy more reinsurance to transfer risks. This is because the source and carrier of risks in nonauto insurance business are more complex than those in auto insurance business, and some risks may even bring huge compensation liability once they occur. With limited capital strength, small Chinese-funded companies are more inclined to transfer risks by means of reinsurance when the nonauto insurance business income increases. The regression results of column (2) in Table 5 show that the impact of reinsurance on their solvency is significantly positive at 1%, so the mediating effect of reinsurance behavior does exist, which supports theoretical Hypothesis 2.

From the empirical results in columns (3) and (4) of Table 5, the nonauto insurance business ratio to the reinsurance ratio of foreign-funded P/L insurance companies is significantly positive at 1%, indicating that when the nonauto insurance business accounts for a relatively high proportion, foreign-funded P/L insurance companies will increase their reinsurance ratio. When the proportion of nonauto insurance business increases, foreign-funded P/L

Table 5: Mediating effect test of reinsurance based on the stepwise regression method.

Variables	Small Chinese-funded		Foreign-funded	
	Rein (1)	Solvency (2)	Rein (3)	Solvency (4)
Rein		303.340∗∗∗ (5.950)		287.030∗∗∗ (3.135)
Nonauto	0.181∗∗ (2.279)	107.043∗∗∗ (3.126)	0.373∗∗∗ (5.547)	166.836∗∗ (2.285)
Size	−0.005 (−0.208)	12.104 (0.990)	−0.010 (−0.482)	54.491∗∗ (2.349)
Loss	−0.110 (−1.520)	−46.726 (−1.425)	0.020 (1.594)	−6.465 (−0.583)
Lev	−0.042 (−0.616)	−84.070∗∗ (−2.645)	−0.068 (−1.177)	−67.155 (−1.120)
Geodiv	0.106 (1.283)	−30.085 (−0.762)	−0.026 (−0.476)	−94.173 (−1.644)
Invest	0.097 (1.481)	−24.628 (−0.776)	−0.196∗∗∗ (−2.841)	131.323∗ (1.713)
GDP	0.005 (0.407)	3.009 (0.626)	−0.002 (−0.177)	−3.257 (−0.391)
Interest	−0.020 (−1.384)	13.547∗∗ (2.204)	−0.009 (−0.858)	−9.605 (−0.989)
Constant	0.073 (0.310)	−129.676 (−1.226)	0.354∗ (1.968)	−516.865∗∗ (−2.456)
Sample size	104	93	155	115

Note. (1) ∗∗∗ means $p < 0.01$, ∗∗ means $p < 0.05$, and ∗ means $p < 0.1$. (2) Below the estimated coefficient () is a robust standard error.

insurance companies will increase the reinsurance ceding ratio in order to prevent excessive concentration of risks, which is consistent with the research conclusions of Curak et al. [21].

Further empirical test results show that the coefficient of reinsurance and solvency of foreign-funded P/L insurance companies is significantly positive at 1% level, which further confirms that the intermediary effect of reinsurance behavior exists. This conclusion supports theoretical Hypothesis 2. Foreign-funded P/L insurance companies pay great attention to the management of solvency. Although the newly developed auto insurance business has a negative impact on profitability, foreign-funded P/L insurance companies can still avoid the negative impact of the decline in profitability on solvency by strengthening the reinsurance ceding management.

4.3.3. Multiple Mediating Effects of Profitability and Reinsurance Behavior Based on the Bootstrap Method. Although the stepwise regression method used above is one of the commonly used mediating effect testing methods, in recent years, scholars began to have positive and negative views on the stepwise regression method. Firstly, the stepwise regression method has the lowest testing force on the mediating effect among all the methods. In other words, it is difficult to test the significance of the mediating effect with the stepwise regression method, which is likely to cause inaccurate results. However, scholars who support the stepwise regression method believe that, on the contrary, if the results of stepwise regression have reached a significant level, the disadvantage of low test power is more likely to prove the existence of the mediating effect. Wen and Ye [34] pointed out that if the results of the stepwise regression method were significant, the results were better than other mediating effect testing methods. Secondly, the question of complete mediation and partial mediation: due to the influence of sample and total effect size, the results of the complete mediating effect obtained by the stepwise regression method are not accurate. Preacher and Hayes [35] pointed out that when the total effect value is small and the sample size is small, the result obtained is prone to a complete mediating effect, but the probability of the complete mediating effect in reality is very low. With the development of statistical and analysis software and the development of the mediating effect model, bootstrap method has become a new method to test the mediating effect.

Therefore, this paper uses Amos 21.0 to test the mediating effect and influence degree of the profitability and reinsurance behavior of P/L insurance companies on the basis of stepwise regression. In this paper, the deviation correction percentile bootstrap method was used to conduct repeat sampling for 200 times and select 95% confidence interval to test the mediating effect of profitability and reinsurance behavior.

Table 6 reports the results of the bootstrap test of multiple mediating effects for small Chinese-funded P/L insurance companies. It can be seen from Table 6 that the path coefficient of nonauto insurance business proportion

Table 6: Test results of the multiple mediating effect bootstrap method (small Chinese-funded companies).

	Effect value	p value	BootCI floor	BootCI ceiling
Nonauto⟶roa	0.028	0.073	0.001	0.062
Roa⟶solvency	134.145	0.516	−187.747	453.438
Nonauto⟶rein	0.293	0.013	0.138	0.426
Rein⟶solvency	177.770	0.055	63.832	274.988
Nonauto⟶solvency (direct effect)	50.832	0.052	7.077	122.259
Nonauto⟶solvency (indirect effect)	55.875	0.017	14.503	100.759
Nonauto⟶solvency (total effect)	106.706	0.007	36.008	204.508

affecting profitability is 0.028, which is significant at 10% level, but the path coefficient of profitability affecting solvency is not significant. Therefore, the mediating effect of profitability is not significant.

From the perspective of the path of "business structure-reinsurance behavior-solvency," the path coefficient of the business structure influencing reinsurance behavior is 0.293, which is significant at the level of 5%. The path coefficient of reinsurance affecting solvency is 177.770. The results in Table 6 also show that the mediating effect value of reinsurance is 55.875, which is significant at the level of 5%. The direct effect value of the business structure on solvency is 50.832. Based on the above analysis, it can be seen that the mediating effect of profitability is not significant, and the mediating effect of reinsurance is significant, which is a partial mediating effect and accounts for 52.36% of the total effect.

Table 7 reports the test results of the bootstrap method of multiple mediating effects for foreign-funded P/L insurance companies. The results in Table 7 show that the path coefficient of the business structure affecting profitability is 0.175, with a significance level of 10%, while the path coefficient of profitability affecting solvency is not significant.

From the perspective of reinsurance behavior, the path coefficient of the business structure affecting solvency is 0.384 at 1%, and the path coefficient of reinsurance ratio affecting solvency is 150.306 at 1%. In addition, the mediating effect value of reinsurance is 53.127, with a significance level of 1%. The direct effect of the business structure on solvency is not significant. To sum up, the mediating effect of profitability is not significant, while the mediating effect of reinsurance is significant and complete.

Table 8 reports the test results of the bootstrap method with multiple mediating effects for large Chinese-funded P/L insurance companies. As shown in Table 8, the total effect of the business structure on solvency is not significant, and the direct effect of the business structure on solvency is not significant either. In addition, the p value of the mediating effect of the business structure on solvency is 0.614. Therefore, neither profitability nor reinsurance behavior has a significant mediating effect for large Chinese-funded P/L insurance companies.

5. Robustness Test

5.1. Robustness Test of "Heteroscedasticity-Sequence Correlation-Cross-Section Correlation". Driscoll and Kraay [36] proposed that the panel data may have problems of cross-section correlation and heteroscedasticity. To solve the above problems, this paper adopted the method proposed by Hoechle [37] to conduct robustness test on the previous empirical model.

Table 9 reports the robustness test result of the impact of the business structure on solvency, and its conclusion is consistent with the above. The increase in the proportion of nonauto insurance business can significantly enhance the solvency of the small Chinese-funded P/L and foreign-funded P/L insurance companies.

Tables 10 and 11, respectively, report the robustness test results of the mediating effect of the profitability and reinsurance behavior. The results show that the increase in the proportion of nonauto insurance business of small Chinese-funded companies cannot improve their solvency by affecting their profitability, and the positive impact of the business structure of small Chinese-funded companies on their solvency is realized through the reinsurance channel. The mediating effect of profitability does not exist for foreign-funded P/L insurance companies either. The increase in the proportion of nonauto insurance businesses will increase their reinsurance rate and thus enhance their solvency, which is consistent with the previous conclusions.

5.2. Endogeneity Test. In order to test the robustness of the model, the instrumental variable method is further used in this paper. In this paper, the one-phase lag (L. nonauto) of the business structure was used as the instrumental variable to carry out the two-stage generalized moment estimation. Table 12 shows the endogenous test of the impact of the business structure on solvency. The conclusions are consistent with the previous conclusions. Small Chinese-funded and foreign-funded P/L insurance companies can significantly enhance their solvency by increasing the proportion of nonauto insurance business.

Tables 13 and 14, respectively, show the endogeneity test results of the mediating effect of the profitability and reinsurance behavior. The increase in the proportion of nonauto insurance business of small Chinese-funded P/L insurance companies cannot significantly improve their profitability and thus affect their solvency, but it can significantly increase their reinsurance rate and thus enhance their solvency.

For foreign-funded P/L insurance companies, the impact of the business structure on their solvency still exists through increasing the reinsurance rate, and the intermediary channel of profitability does not exist. The

Table 7: Test results of the multiple mediating effect bootstrap method (foreign-funded companies).

	Effect value	p value	BootCI floor	BootCI ceiling
Nonauto⟶roa	0.175	0.026	0.138	0.205
Roa⟶solvency	−26.147	0.587	−219.477	53.473
Nonauto⟶rein	0.384	0.006	0.321	0.461
Rein⟶solvency	150.306	0.005	26.757	329.816
Nonauto ⟶solvency (direct effect)	−4.064	0.776	−44.945	16.516
Nonauto ⟶solvency (indirect effect)	53.127	0.004	17.376	120.390
Nonauto ⟶solvency (total effect)	49.063	0.002	22.316	126.871

Table 8: Test results of the multiple mediating effect bootstrap method (large Chinese-funded companies).

	Effect value	p value	BootCI floor	BootCI ceiling
Nonauto⟶roa	0.029	0.010	0.013	0.049
Roa⟶solvency	32.230	0.771	−30.190	107.613
Nonauto⟶rein	0.186	0.019	0.120	0.266
Rein⟶solvency	−11.631	0.030	−25.495	−3.908
Nonauto⟶solvency (direct effect)	0.302	0.955	−8.862	5.837
Nonauto⟶solvency (indirect effect)	−1.230	0.614	−3.238	2.234
Nonauto⟶solvency (total effect)	−0.928	0.746	−7.821	3.970

Table 9: Robustness test of the impact of the business structure on solvency.

Variables	Full sample (1)	Chinese-funded (2)	Large Chinese-funded (3)	Small Chinese-funded (4)	Foreign-funded (5)
Nonauto	182.025∗∗ (3.103)	126.532∗∗∗ (6.068)	0.866 (0.057)	160.839∗∗∗ (6.025)	278.471∗ (2.237)
Size	18.535 (1.789)	1.793 (0.432)	4.471∗∗ (3.690)	8.991 (0.727)	62.998∗∗ (2.685)
Loss	0.149 (0.025)	−60.020∗∗∗ (−5.125)	−3.999 (−0.838)	−91.854∗∗ (−3.195)	0.087 (0.011)
Lev	−73.310∗∗∗ (−3.769)	−78.083∗∗ (−2.817)	−15.031∗ (−1.943)	−94.661∗∗∗ (−4.471)	−87.942 (−1.857)
Geodiv	−70.265∗∗∗ (−4.010)	2.667 (0.185)	−16.284 (−0.517)	−1.647 (−0.087)	−134.927∗∗∗ (−3.966)
Invest	44.680 (1.280)	6.151 (0.415)	5.245 (1.830)	−0.498 (−0.019)	77.744 (1.242)
GDP	−0.084 (−0.067)	2.798∗∗∗ (5.654)	0.036 (0.157)	5.021∗∗∗ (4.128)	−3.097 (−0.687)
Interest	−2.745 (−0.928)	2.069 (1.470)	−0.401 (−0.750)	6.828∗∗ (3.606)	−8.441 (−0.969)
Constant	−139.510 (−1.174)	−7.210 (−0.139)	−14.112 (−0.472)	−92.191 (−0.989)	−510.204 (−1.752)
Sample size	318	203	110	93	115

Note. (1) ∗∗∗ means $p < 0.01$, ∗∗ means $p < 0.05$, and ∗ means $p < 0.1$. (2) Below the estimated coefficient () is a robust standard error.

Table 10: Robustness test of the mediating effect of profitability.

Variables	Small Chinese-funded		Foreign-funded	
	Roa (1)	Solvency (2)	Roa (3)	Solvency (4)
Roa		121.422 (0.629)		175.666 (1.930)
Nonauto	0.004 (0.334)	160.285∗∗∗ (6.300)	0.067∗ (1.905)	269.925∗ (2.311)
Size	0.094∗∗∗ (8.122)	0.044 (0.002)	0.053∗∗∗ (13.306)	50.830∗∗ (2.809)

Table 10: Continued.

Variables	Small Chinese-funded		Foreign-funded	
	Roa (1)	Solvency (2)	Roa (3)	Solvency (4)
Loss	0.062 (1.335)	−92.206∗∗ (−3.024)	−0.015∗∗ (−2.915)	3.051 (0.446)
Lev	−0.047∗ (−1.975)	−92.620∗∗∗ (−5.693)	−0.120∗∗∗ (−9.098)	−65.867 (−1.261)
Geodiv	−0.073∗∗ (−3.015)	4.206 (0.195)	0.031 (1.221)	−131.055∗∗∗ (−4.449)
Invest	0.049∗∗∗ (3.772)	−6.124 (−0.172)	0.046 (1.824)	71.231 (1.151)
GDP	−0.000 (−0.161)	4.761∗∗∗ (4.440)	0.005∗∗ (3.473)	−4.059 (−0.979)
Interest	−0.012 (−1.586)	8.173∗ (1.956)	−0.004∗∗ (−2.945)	−7.559 (−0.892)
Constant	−0.691∗∗∗ (−10.439)	−22.829 (−0.146)	−0.459∗∗∗ (−9.258)	−416.230 (−1.727)
Sample size	104	93	155	115

Note. (1) ∗∗∗ means $p < 0.01$, ∗∗ means $p < 0.05$, and ∗ means $p < 0.1$. (2) Below the estimated coefficient () is a robust standard error.

Table 11: The robustness test of the mediating effect of reinsurance behavior.

Variables	Small Chinese-funded		Foreign-funded	
	Rein (1)	Solvency (2)	Rein (3)	Solvency (4)
Rein		303.340∗∗∗ (9.093)		287.030∗∗ (2.455)
Nonauto	0.181∗∗ (2.822)	107.043∗∗∗ (4.723)	0.373∗∗∗ (4.787)	166.836∗ (2.350)
Size	−0.005 (−0.413)	12.104∗ (1.970)	−0.010 (−0.909)	54.491∗∗ (3.338)
Loss	−0.110 (−1.471)	−46.726∗ (−1.959)	0.020∗∗∗ (4.191)	−6.465 (−0.689)
Lev	−0.042 (−1.246)	−84.070∗∗∗ (−5.609)	−0.068 (−1.481)	−67.155 (−1.602)
Geodiv	0.106∗ (2.114)	−30.085 (−1.036)	−0.026 (−0.654)	−94.173∗∗∗ (−4.316)
Invest	0.097∗∗ (3.489)	−24.628 (−1.286)	−0.196∗∗ (−3.362)	131.323∗ (1.968)
GDP	0.005 (0.732)	3.009∗∗∗ (4.598)	−0.002 (−0.476)	−3.257 (−0.904)
Interest	−0.020∗∗ (−2.835)	13.547∗∗∗ (7.028)	−0.009 (−1.363)	−9.605 (−1.335)
Constant	0.073 (0.837)	−129.676∗∗ (−2.916)	0.354∗∗ (3.486)	−516.865∗ (−2.092)
Sample size	104	93	155	115

Note. (1) ∗∗∗ means $p < 0.01$, ∗∗ means $p < 0.05$, and ∗ means $p < 0.1$. (2) Below the estimated coefficient () is a robust standard error.

Table 12: The endogeneity test of the impact of the business structure on solvency.

Variables	Full sample (1)	Chinese-funded (2)	Large Chinese-funded (3)	Small Chinese-funded (4)	Foreign-funded (5)
Nonauto	8.498∗∗∗ (4.384)	4.680 (1.500)	1.315 (0.423)	11.401∗∗ (2.113)	7.151∗∗ (2.077)
Size	1.208∗∗ (2.290)	1.045∗ (1.946)	1.127 (1.333)	−0.765 (−1.022)	−2.773 (−1.459)

Table 12: Continued.

Variables	Full sample (1)	Chinese-funded (2)	Large Chinese-funded (3)	Small Chinese-funded (4)	Foreign-funded (5)
Loss	2.265∗∗	−4.897∗	−4.718	−3.349	2.307∗∗
	(2.420)	(−1.675)	(−1.281)	(−0.940)	(2.217)
Lev	−36.804∗∗∗	−25.562∗∗∗	−13.810∗	−28.709∗∗∗	−53.457∗∗∗
	(−8.976)	(−7.280)	(−1.870)	(−7.580)	(−6.475)
Geodiv	−5.667∗∗	−1.943	−26.446	3.556	−9.079∗
	(−2.271)	(−0.790)	(−1.441)	(1.097)	(−1.870)
Invest	7.853∗∗	7.374∗∗	10.873	2.927	−15.720∗∗
	(2.423)	(2.249)	(1.620)	(0.937)	(−1.980)
GDP	−0.089	−0.124	0.246	−0.192	−0.130
	(−0.162)	(−0.246)	(0.525)	(−0.239)	(−0.120)
Interest	0.046	0.286	0.298	0.997	0.985
	(0.065)	(0.575)	(0.735)	(1.018)	(0.743)
Constant	18.708∗	13.957	22.406	24.317∗∗	67.337∗∗∗
	(1.817)	(1.353)	(1.555)	(2.149)	(3.376)
Sample size	297	186	105	81	111

Note. (1) ∗∗∗ means $p < 0.01$, ∗∗ means $p < 0.05$, and ∗ means $p < 0.1$. (2) Below the estimated coefficient () is a robust standard error.

Table 13: The endogeneity test of the mediating effect of profitability.

Variables	Small Chinese-funded		Foreign-funded	
	Roa (1)	Solvency (2)	Roa (3)	Solvency (4)
Roa		−1.419		21.500
		(−0.130)		(1.406)
Nonauto	0.009	11.423∗∗	0.118∗∗∗	3.691
	(0.275)	(2.115)	(5.623)	(0.969)
Size	0.031∗∗∗	−0.721	0.072∗∗∗	−4.241∗
	(3.714)	(−0.936)	(6.000)	(−1.847)
Loss	0.050	−3.270	−0.011	2.522∗∗∗
	(1.553)	(−0.925)	(−1.484)	(2.692)
Lev	−0.052∗∗	−28.785∗∗∗	−0.148∗∗∗	−50.749∗∗∗
	(−2.261)	(−7.578)	(−4.161)	(−5.613)
Geodiv	−0.022	3.525	−0.032	−8.451∗
	(−1.139)	(1.108)	(−1.165)	(−1.763)
Invest	0.028	2.962	0.002	−16.328∗∗
	(1.151)	(0.941)	(0.038)	(−2.128)
GDP	−0.001	−0.192	0.003	−0.258
	(−0.157)	(−0.239)	(0.550)	(−0.244)
Interest	−0.010	0.989	−0.004	1.036
	(−1.444)	(1.019)	(−0.645)	(0.796)
Constant	−0.222∗∗	23.972∗	−0.555∗∗∗	80.860∗∗∗
	(−2.346)	(1.926)	(−4.827)	(3.649)
Sample size	83	81	135	111

Note. (1) ∗∗∗ means $p < 0.01$, ∗∗ means $p < 0.05$, and ∗ means $p < 0.1$. (2) Below the estimated coefficient () is a robust standard error.

Table 14: The endogeneity test of the mediating effect of reinsurance behavior.

Variables	Small Chinese-funded		Foreign-funded	
	Rein (1)	Solvency (2)	Rein (3)	Solvency (4)
Rein		19.319∗∗∗		33.709∗∗∗
		(2.707)		(7.702)
Nonauto	0.177∗	8.137∗	0.384∗∗∗	−2.656
	(1.941)	(1.699)	(5.482)	(−0.667)

Table 14: Continued.

Variables	Small Chinese-funded		Foreign-funded	
	Rein (1)	Solvency (2)	Rein (3)	Solvency (4)
Size	−0.013 (−0.807)	−0.557 (−0.838)	−0.009 (−0.268)	−2.291 (−1.440)
Loss	−0.014 (−0.192)	−3.067 (−0.958)	0.009 (0.738)	1.748 ∗ (1.703)
Lev	0.166∗ ∗ ∗ (2.831)	−32.062∗ ∗ ∗ (−8.109)	0.106 (0.862)	−57.352∗ ∗ ∗ (−7.195)
Geodiv	−0.091 ∗ (−1.673)	5.402 ∗ (1.788)	−0.207∗ ∗ (−2.279)	−2.781 (−0.693)
Invest	0.012 (0.281)	2.709 (0.950)	−0.664∗ ∗ ∗ (−4.692)	7.687 (1.116)
GDP	−0.004 (−0.335)	−0.099 (−0.141)	0.006 (0.295)	−0.339 (−0.392)
Interest	−0.017 (−1.338)	1.328 (1.398)	−0.004 (−0.179)	1.282 (1.178)
Constant	0.224 (1.300)	19.940∗ ∗ (2.058)	0.428 (1.248)	49.977∗ ∗ ∗ (3.024)
Sample size	83	81	135	111

Note. (1) ∗ ∗ ∗ means $p < 0.01$, ∗ ∗ means $p < 0.05$, and ∗ means $p < 0.1$. (2) Below the estimated coefficient () is a robust standard error.

conclusion of this paper is still valid after endogeneity test.

6. Conclusions and Implications

This paper studies the theoretical mechanism of the impact of the business structure on solvency of P/L insurance companies and conducts an empirical test based on the manually collected solvency adequacy data of P/L insurance companies from 2009 to 2015 by using a mediating effect model.

The results show the following: first, the business structure of P/L insurance companies with different ownerships and different scales has different impacts on solvency. The increase in the proportion of nonauto insurance business of small Chinese-funded companies will significantly enhance their solvency, but not for large Chinese-funded companies. The increase in the proportion of auto insurance business of foreign-funded P/L insurance companies will significantly reduce their solvency.

Second, through the stepwise regression method, we empirically test the mediating effect of profitability and reinsurance behavior. It is found that no matter for small Chinese-funded companies or foreign-funded companies, the mediating effect of profitability does not exist. When the business structure of nonauto insurance business is relatively high, P/L insurance companies tend to increase the reinsurance ceding ratio to enhance their solvency.

Third, the bootstrap method was further used to estimate the multiple mediating effects of profitability and reinsurance behavior and their influence degree. It was found that the mediating effect of profitability did not exist. However, the mediating effect of reinsurance in small Chinese-funded companies is a partial mediating effect, and the mediating effect value is 55.875, accounting for 52.36% of the total effect, while the mediating effect of reinsurance behavior in foreign-funded P/L insurance companies is a complete mediating effect, and the effect value is 53.127.

In view of the above conclusions, this paper puts forward the following suggestions.

Firstly, in the background of China's insurance industry supply-side reform, small Chinese-funded companies should seize the opportunity and actively adjust their business development strategies to prevent the adverse impact on solvency caused by the excessive concentration of underwriting risks in the auto insurance business. As we all know, compared with auto insurance business, nonauto insurance business has more complex risk sources and risk carriers and higher requirements for underwriting and claim settlement. Therefore, small Chinese-funded P/L insurance companies should actively introduce talents related to the product design, claim settlement, and risk control of nonauto insurance and strengthen the training of employees on nonauto insurance knowledge. In addition, small Chinese-funded companies should abide by the *Guidelines on Insurance Product Development for Property-Liability Insurance Companies*, attach importance to reinsurance ceding work, transfer the risks and responsibilities higher than the company's ability to bear to reinsurance companies through appropriate reinsurance arrangements, control the accumulation of liabilities and the amount of loss compensation, and enhance their solvency.

Secondly, the development of foreign-funded companies' auto insurance business in China's insurance market does not enhance their solvency by improving their profitability, which may be related to the fact that foreign-funded companies lack market experience and data accumulation in China's auto insurance business, and the marketing network layout is difficult to develop in a short period of time. Foreign-funded companies in China should prudently and selectively develop their auto insurance business, give full play to their advantages in characteristic claim service and high-priced auto underwriting, take the road of differentiated competition, and improve the profitability of auto insurance business. Alternatively, foreign-funded P/L insurance companies can choose to unswervingly operate nonauto insurance business. Foreign-funded P/L insurance companies can reduce the policy acquisition cost through professional and centralized operation, give full play to the advantages of nonauto insurance business, and provide better risk management services for customers.

Finally, insurance regulatory authorities need to innovate the supervision mode of nonauto insurance business and conduct regular inspection of reinsurance ceding of nonauto insurance business of P/L insurance companies to prevent solvency risks.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Value Preferences and Intergenerational Differences of Tourists to Traditional Chinese Villages

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Tourist values determine the behavior of tourists. To pinpoint the behaviors and preferences of tourists, it is necessary to explore their value orientation and intergenerational differences. The exploration is of great significance to the activation of tourism in traditional villages. After analyzing the value of tourists to two traditional villages (Hongcun and Xidi), this paper investigated the value preferences and intergenerational differences of tourists of four generations to traditional villages, using means-end chain (MEC) theory and hard laddering. Through a questionnaire survey on tourists born in the 1960s, 1970s, 1980s, and 1990s, the authors established 36 MEC value chains of 18 classes. The results show that the post-60s traditional village tourists are a generation of wisdom-loving learners, who prefer the values of wisdom and self-improvement; the post-70s and 80s tourists are a generation of beauty lovers with a strong sense of belonging, who prefer the values of beautiful world, inner harmony, and sense of belonging; the post-90s tourists are a generation of inclusive advocators of diversity, with no special value preference. These results provide theoretical support and practical enlightenment for the market segmentation of traditional village tourism and the protection and activation of traditional villages.

1. Introduction

Traditional villages are the basic units of rural China and the living fossils of traditional culture [1]. In June 2019, the Chinese Ministry of Housing and Urban-Rural Development, in association with other departments, released the fifth batch of Chinese traditional villages. In total, 6,819 traditional villages are being protected in China. The main protective method is to activate tourism to these villages [2]. The ancient village tourism and rural tourism are an important means to activate and protect traditional villages [3]. Driven by the boom of domestic tourism, the purpose of traditional village tourism has shifted from sightseeing to both sightseeing and vacation. Thanks to unique regional cultures, improving infrastructure, better public services, and new business products, traditional villages are attracting more and more tourists of different generations.

At present, fruitful results have been achieved on the description of the behavior features of tourists to traditional villages. However, there is a lack of in-depth research on the intergenerational differences of tourists. The Travel Industry Association of America (TIA) considered intergenerational analysis as the most common and effective approach for dividing the population and segmenting the market. Tourists of different generations vary significantly in behavior features and preferences [4]. A good understanding of the intergenerational differences in tourist behaviors helps to mine the deep-seated inducers of their tourism behaviors and preferences [5]. On this basis, it is possible to accurately predict the value preferences of tourists of different generations [6] and segment the market to provide products and services tailored to their needs, thereby promoting the sustainable development of traditional village tourism. The tourists' pursuit of value is the fundamental determinant of their travel behaviors [7]. Therefore, this paper analyzes the values of tourists of different generations to traditional villages through hard laddering, a technique of means-end chain (MEC), and tries to disclose the value preferences and intergenerational differences between traditional village tourists.

2. Literature Review

2.1. Traditional Village Tourism. The development of traditional villages as travel destinations is always accompanied by the game between core stakeholders, dormant stakeholders, and marginal stakeholders. There are differences and interconnections between these stakeholders [8]. Culture and environment are their common focuses [9]. The government plays a decisive role in the development of traditional village tourism [10], which suffers the greatest impact from community and residents [11]. Being the owners of traditional villages, the residents determine how well the tourism of these villages develops with their satisfaction, support, and active participation [12–17]. Therefore, the active involvement of the community can promote the sustainable development of tourism in traditional villages [18, 19], enhance community capacity [20], spur community development [21, 22], and underpin the good interaction between community and tourism. Hence, the development of traditional village tourism is not only a game, but also the symbiosis of multiple stakeholders.

Symmetrical reciprocity and integrated symbiosis are the optimization objectives of the symbiosis systems for traditional villages [23, 24], such as the "community participation + enterprise operation" model of stakeholders [25], the typical model of valley economy in mountainous regions [26], the diversified mixed effect model of market game [27], and the synchronized/asynchronized "urbanization + community participation + protection zone" model [28].

During the game and symbiosis of stakeholders in the development of traditional village tourism, the space of traditional villages is evolving into two social spaces, namely, tourist area and resident area, with the continued growth of tourist immigrants and tourists. Some traditional villages have developed into small towns [10], creating new ethnic cultures [29]. In this process, the spatial social order has also been reorganized: the niche space of community populations is replaced by tourist populations, which occupy the core area of traditional villages [30]. Driven by tourism interests, the tertiary industry-centered land urbanization has taken place around some traditional villages. The population is dominated by residents and tourism practitioners. Under the influence of outside cultures, the original residents of traditional villages are increasingly urbanized and modernized [31], and the rural culture is shifting from traditional farming culture to modern culture [32].

In the development of traditional village tourism, culture is the soul and resources are the body [33]. The tourism resources of traditional villages include the local environment, village shape, human landscape, and local culture [34–37], which embody the history, culture, and artistic value of traditional villages [38]. This precious heritage wins the favor of tourists. With the emerging demand from niche markets of tourism, new businesses spring up in the tourism industry. For example, the sketching tourism, research tourism, sports tourism, and gourmet tourism in traditional villages are very popular among tourists [39, 40]. Being the subjects of traditional village tourism, tourists attach the greatest importance to the authenticity of architecture and cultural relics [41, 42], and their primary travel motives are experiencing traditional culture, sightseeing, and family trips [43–46]. The existing studies on the niche markets of tourism in traditional villages mostly discuss the consumption behaviors of overseas tourists, female tourists, and sketching tourists [47–49], as well as the trend and seasonal variation of tourism demand [50]. However, there is not yet any discovery about the niche markets, value preferences, or intergenerational differences of traditional village tourists of different generations.

2.2. Theory of Generations. Based on anthropology, Mannheim [51] proposed the theory of generations, which holds that people born in the same period have the same position in the historical process of social development and form common values, thinking patterns, and behavioral features, as they experience the same major external events. The theory of generations is composed of three progressive concepts: the site of generation, the realistic sense of generation, and the intrageneration division. This theory has been further verified, extended, and improved by many scholars [52–54], who found that different generations differ markedly; the intrageneration values are relatively stable and directly affect future behaviors and attitudes [55]; intragenerational personalities and features are predictable [6].

Foreign researchers have relied on the theory of generations for empirical analysis of tourist preferences for consumption behaviors and intergenerational differences. Most of them tackled the behaviors and preferences of tourists in two or three generations [6, 56–63]. In recent years, researchers from countries and regions like South Korea, the United States, and Taiwan have explored the intergenerational differences in the travel behaviors of strait tourists from Chinese mainland [4]. Nevertheless, the research results are not necessarily valid, because the researchers adopted the division rules for foreign generations and did not know much about the situation in Chinese mainland. In China, the studies on the generational behaviors of domestic tourism consumers mainly deal with the behavior differences between tourists born in the 1980s and 1990s [64, 65]; the differences in the impression of destinations between the tourism consumers born in the 1950s, 1960s, and 1970s [66]; and the description of the behavior differences between tourism consumers across generations [5, 67], female tourism consumers [68], domestic tourism consumers in scenic spots [69], and tourists searching for tourism information [70]. However, the sample sizes are relatively small, without many samples on the national scale.

3. Research Design

This paper designs a questionnaire survey based on hard laddering. All the questions were extracted from the literature and in-depth interviews (Table 1). In 2019, the authors

Table 1: The As, Cs, and Vs of traditional village tourists born in the 1960s, 1970s, 1980s, and 1990s.

Attributes (As)	Consequences (Cs)	Values (Vs)
A1, ancient architecture	C1, culinary experience	V1, inner harmony
A2, water system of traditional village	C2, harmony between man and nature	V2, satisfaction
A3, local delicacies	C3, gaining experience	V3, self-improvement
A4, environment of traditional village	C4, ecological protection	V4, sense of belonging
A5, local traditional culture	C5, spirit of workmanship	V5, wisdom
A6, engravings/couplets	C6, wisdom of the ancients	V6, sense of security
A7, lifestyle of residents	C7, cultural experience and inheritance	V7, beautiful world
A8, family tours	C8, picturesque landscape	V8, long-lasting life
A9, native products	C9, escaping from reality	V9, cleanness
A10, layout of traditional village	C10, idyllic life	V10, joy
A11, natural landscape around traditional village	C11, neatness	—
—	C12, beauty	—
—	C13, shopping experience	—
—	C14, novel experience	—
—	C15, lodging experience	—
—	C16, photo taking and sharing	—

The categories of "attribute, consequence, and value" are determined based on the first-hand data obtained from the soft-step progressive interview.

conducted a stratified sampling [71] on weijuan.com. Taking generation, gender, and residence as control variables, the questionnaire survey targets 60s, 70s, 80s, and 90s tourists who had traveled to traditional villages in the previous 12 months. The occupation and education of the respondents were also taken into account. A total of 642 questionnaires were recovered, including 600 valid ones (Table 2).

The data analysis was carried out in four steps, as suggested by Reynolds and Olson [72], Gong [73], Kim et al. [74], and Richter and Bokelmann [75] for hard laddering. The correlation between attribute (A) and consequence (C) was obtained through questionnaire survey. The questionnaire is divided into three layers to design questions. First, visitors are asked to choose the attribute motivation of rural tourism, then to choose the possible results caused by the attribute motivation, and finally to choose the value motivation caused by the results. In the questionnaire, there is a blank item after each C_i item, and the respondents are asked to fill in the result caused by A_i (multiple choices can be made), so as to establish a connection. Firstly, the frequency of each attribute (A) motive, consequence (C) motive, and value (V) motive was counted, so it was with the number of consequence-value connections. Secondly, the As, Cs, and Vs were tabulated, and the frequency of A-C and C-V connections was quantified. We counted the occurrence times of A_i, C_i, and V_i in the questionnaire, respectively, to calculate the frequency. According to the results of the questionnaire, the frequency of the occurrence of A_i was marked as N_{Ai}, and then the number of the results C_j brought by A_i (the data obtained from the questionnaire) was counted and marked as n_{Cj}, so the quantitative relationship between A_i and C_j could be expressed as n_{cj}/N_{Ai}. The quantitative relationship between C and V was similar to this. Thirdly, the cut-off point for analysis was determined based on the quantified data of A-C and C-V connections. Finally, the data above the cut-off point was plotted into a hierarchical value map (HVM) of MEC value chains. Each row of the HVM was analyzed, revealing the value preferences and intergenerational differences of traditional village tourists.

4. Results

According to the survey data, two interconnected matrices were set up for the A-C connections (Table 3) and C-V connections (Table 4) selected by these respondents, and the cut-off point of the analysis was set to 50% (any data greater than or equal to 49.5% were treated as equal to 50%). The data above the cut-off point of 50% were selected to build the HVM, forming MEC value chains (A-C-V). In the HVM, the connections between A, C, and V are shown in percentages, reflecting the proportion of tourists to each connection [75]. The percentages help to determine the important Cs and Vs [76]. According to the criteria of the 50% cutoff point, 75 or more of the 150 questionnaires selected attribute motivation to be marked, respectively, as follows: A4, traditional village environment atmosphere ($n = 101/67.3\%$); A5, local traditional culture ($n = 96/64.0\%$, 64.0%); A3, local characteristic food ($n = 95/63.3\%$, 63.3%) motivation; A1, attribute motivation of ancient building and B&B ($n = 88/58.7\%$, 58.7%); A10, pattern of traditional villages ($n = 76/50.7\%$, 50.7%).

4.1. MEC Value Chains of the Post-60s Traditional Village Tourists. A total of 150 post-60s tourists were surveyed. According to the survey data, two interconnected matrices were set up for the A-C connections (Table 3) and C-V connections (Table 4) selected by these respondents. The number of A-C connections (Table 5) and C-V connections (Table 6) being selected by the respondents was counted and used to prepare the HVM for the MEC value chains (A-C-V) of the post-60s tourists (Figure 1).

Based on 50% of the cut-off point to build hierarchical value map (HVM), six MEC value chains have been formed, including three attributes such as ancient building, local traditional culture, and local characteristics food; four consequences such as the wisdom of the ancients, spirit, culture and heritage, and dining experience; and four values such as wisdom, self-improvement, satisfaction, and happiness.

Table 2: Demographic statistics of respondents in traditional villages ($n = 600$).

Population information		Percentage
Gender	Male	52.0
	Female	48.0
Generation	Post-60s	25.0
	Post-70s	25.0
	Post-80s	25.0
	Post-90s	25.0
Education	Junior high school	2.0
	Senior high school or secondary technical/vocational school	19.0
	Undergraduate college/junior college	75.0
	Graduate school and above	4.0
Occupation	Civil servant	5.8
	Manager of enterprise/public institution	27.0
	Staff member/worker	40.2
	Self-employed	11.2
	Education/research/cultural practitioner	9.3
	Freelancer	4.0
	Student	1.5
	Others	1.0

Table 3: C motives of the post-60s traditional village tourists.

A-C	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	n
C1	—	—	65	—	—	—	—	2	18	—	—	85
C2	19	15	—	15	16	3	—	3	—	24	23	118
C3	34	25	37	23	39	23	17	10	9	24	10	251
C4	15	31	10	40	19	11	15	3	7	26	28	205
C5	54	18	—	21	18	25	9	3	2	17	6	173
C6	55	22	15	24	35	18	12	2	1	21	7	212
C7	30	17	28	34	48	19	31	5	8	31	12	263
C8	22	32	—	36	20	—	—	5	—	18	33	166
C9	11	11	—	—	17	13	11	3	—	—	7	73
C10	18	19	31	41	25	13	36	3	6	25	25	242
C11	16	13	23	30	17	13	18	3	5	9	13	160
C12	8	17	11	19	10	7	9	2	3	9	22	117
C13	—	—	12	12	—	—	8	3	22	—	—	114
C14	14	10	17	19	24	8	17	2	12	17	13	153
C15	8	5	—	10	10	3	16	1	3	13	—	138
C16	9	4	17	14	10	4	6	1	8	9	18	100

n is the number of connections. C_{ij} is the amount of C_j caused by A_i.

Table 4: V motives of the post-60s traditional village tourists.

C-V	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10
C1	25	60	—	—	9	10	—	—	—	41
C2	36	33	21	33	16	23	—	34	—	17
C3	22	52	58	30	46	27	42	24	—	23
C4	—	—	—	30	32	39	76	53	55	25
C5	21	39	53	24	57	—	39	27	—	10
C6	—	37	—	35	82	—	—	—	—	30
C7	—	—	75	57	62	33	—	—	—	41
C8	29	48	22	22	30	19	63	35	—	17
C9	26	26	—	28	—	29	—	—	—	17
C10	56	48	—	44	20	—	73	56	40	29
C11	—	42	—	—	—	33	—	—	70	—
C12	28	28	—	—	—	—	52	29	31	21
C13	11	32	—	19	—	—	—	—	12	23
C14	20	47	—	15	28	23	27	16	—	25
C15	14	27	—	16	—	32	—	—	18	11
C16	11	32	—	—	—	—	—	—	—	34
n	299	551	229	353	382	268	372	274	226	364

n shows the number of occurrences of C_i to V_j.

Table 5: A-C connections of the post-60s traditional village tourists (cutoff point = 50%).

A-C	A1	A3	A5
C1	—	65/95 (68.4%)	—
C5	54/88 (61.4%)	—	—
C6	55/88 (62.5%)	—	—
C7	—	—	48/96 (50.6%)

Percentage = n/N, where N is the total number of respondents recognizing an A (A_i) and n is the number of respondents agreeing that A (A_i) can produce a C (C_i).

Table 6: C-V connections of the post-60s traditional village tourists (cutoff point = 50%).

C-V	V2	V3	V5	V10
C1	60/75 (80.0%)	—	—	41/75 (54.7%)
C5	—	53/104 (51.0%)	57/104 (54.8%)	—
C6	—	—	82/103 (79.6%)	—
C7	—	75/122 (61.5%)	62/12 (50.8%)	—

Percentage = n/N, where N is the total number of respondents recognizing a C (C_i) and n is the number of respondents agreeing that C (C_i) can reflect a V (V_i).

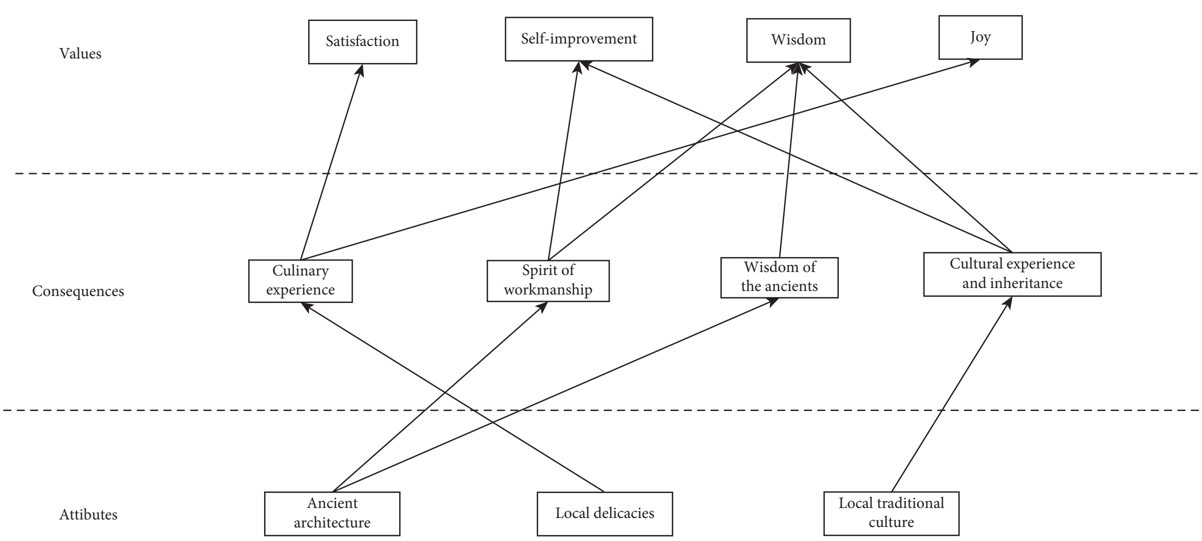

Figure 1: The HVM of the post-60s tourists to traditional villages (including correlated factors only) (cutoff point = 50%).

According to relevant literature, 50% cut-off point is used to construct HVM diagram, including two aspects: 1. If the total number of respondents choosing A, C, or V is less than 50% (i.e., 75 respondents), 50% is lower than the cut-off point. 2. The proportion of association relationship in A-C matrix, N_{Cj}/N_{Ai}, is lower than 50%, and it is also lower than 50% of the cut-off point. The above two cases are not identified in the HVM diagram, and only the association relationship above 50% is listed in the HVM diagram to improve the typicality of MEC chain. For example, only A1, A3, A4, and A5 have more than 75 respondents selected for attribute A, so other attributes are not marked in the HVM diagram. The value of N_{Cj}/N_{Ai} greater than 50% is C1 (A3-C1), C5 (A1-C5), C6 (A1-C6), C7 (A5-C7). Other paths are not marked.

The V of job comes from the pursuit of the post-60s tourists for the A of local delicacies and the C of culinary experience. In traditional Chinese culture, food is the paramount necessity of the people. Since the beginning of the 21st century, gourmet tourism has become the main travel motive for tourists [77, 78]. Tourists perceive the culture of destinations by experiencing food, which affects the travel experience [79]. Through the culinary experience of enjoying local delicacies, the post-60s tourists gain physical and psychological Vs like joy and satisfaction (local delicacies—culinary experience—satisfaction).

HVM results show that the V of wisdom stems from the pursuit of the post-60s tourists for spirit of workmanship, wisdom of the ancients, and cultural experience and inheritance. For those born in the 1960s, the traditional culture of rural tourism destinations can bring them cultural experience, and the ancient buildings can help them appreciate the craftsman spirit and the wisdom of the ancients, which are conducive to enhancing their cultural identity and acquiring more knowledge. The post-60s tourists are nurtured by traditional Chinese culture. Patriotism and heroism are their typical values [80]. Our findings are consistent with the literature. The nostalgic feelings encourage them to travel to traditional villages. Traveling through the ancient architecture, the tourists perceive the wisdom of the ancients in planning and design and the spirit of workmanship exemplified by the builders. Such an experience satisfies their pursuit of the V of wisdom.

In addition, the post-80s tourists, like those born in the 1970s, realize the V of sense of belonging through the pursuit of the A of local traditional culture and the C of cultural experience, and inheritance exploration and learning are important motives for tourists [81]. Apart from the spirit of workmanship, the post-60s tourists learn the knowledge about traditional culture and ancient architecture and broaden their horizons [82–84]. In this way, they realize the V of self-improvement.

4.2. MEC Value Chains of the Post-70s Traditional Village Tourists. A total of 150 post-70s tourists were surveyed. According to the survey data, two interconnected matrices were set up for the A-C connections (Table 7) and C-V connections (Table 8) selected by these respondents. The number of A-C connections (Table 9) and C-V connections (Table 10) being selected by the respondents was counted and used to prepare the HVM for the MEC value chains (A-C-V) of the post-70s tourists (Figure 2).

It can be observed that the post-70s tourists pursue five As (ancient architecture, environment of traditional village, natural landscape around traditional village, local traditional culture, and local delicacies), six Cs (wisdom of the ancients, ecological protection, idyllic life, picturesque landscape, cultural experience and inheritance, and culinary experience), and seven Vs (wisdom, beautiful world, inner harmony, self-improvement, satisfaction, joy, and sense of belonging), which constitute eleven MEC value chains.

Like the post-60s tourists, the post-70s tourists realize the Vs of satisfaction and joy through the pursuit of the A of local delicacies and the C of culinary experience.

The V of wisdom stems from the pursuit of the post-70s tourists for the A of ancient architecture and the C of wisdom of the ancients. Going through the reform and opening-up, the post-70s tourists experienced the enrollment expansion of colleges and employment. Through diligent learning and hard work, these tourists achieved their goals of work, income, and life [85]. As a result, they generally believe in “knowledge can change your fate.” Meanwhile, the post-70s tourists are deeply influenced by traditional culture in society and family. Therefore, they pay more attention to the V of wisdom embodied in ancient architecture, during travel to traditional villages.

The V of self-improvement originates from the pursuit of the post-70s tourists for the A of local traditional culture and the C of cultural experience and inheritance. The Chinese education advocates “reading ten thousand books and traveling ten thousand miles.” Both reading and traveling are important for human development. Traveling can improve the capacity of the tourists [86] and sublimate the inner motives to higher needs, thereby promoting personal development [87]. The post-70s tourists believe that, through traditional village tourism, they can fully and deeply understand and recognize local traditional culture and customs, acquire new knowledge, broaden their horizons, and gain experience. In other words, travel to traditional villages both enriches their lives and increases their knowledge [82–84], thus helping them realize the V of self-improvement. At the same time, the post-70s tourists have a higher spiritual demand for traditional culture [88]. They personally feel the importance of inheriting local traditional culture to the development of the Chinese culture. This feeling results in the confidence in their culture, and a strong sense of belonging (local traditional culture—cultural experience and inheritance—sense of belonging).

The V of beautiful world derives from the post-70s tourists’ pursuit of the As of environment of traditional village and natural landscape around traditional village and the Cs of ecological protection, idyllic life, and picturesque landscape. In traditional Chinese culture, nature is the source of human life, and tourism bridges human and nature [89]. Besides, traditional Chinese philosophy emphasizes

Table 7: C motives of the post-70s traditional village tourists.

A-C	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	*n*
C1	—	—	89	—	—	—	—	6	25	—	—	120
C2	24	27	—	26	19	9	—	2	—	27	34	168
C3	31	17	34	19	48	9	22	4	13	17	14	228
C4	22	29	18	54	24	6	13	3	5	20	39	233
C5	38	15	—	14	20	21	7	2	6	29	6	158
C6	50	23	16	22	35	23	19	3	8	31	11	241
C7	23	16	18	30	63	11	27	4	8	24	17	241
C8	15	23	—	40	18	—	—	2	—	12	58	168
C9	7	10	—	—	13	5	5	1	—	—	10	51
C10	19	30	34	50	28	3	34	4	14	22	44	282
C11	11	15	11	25	6	4	8	3	1	12	17	113
C12	8	17	9	19	10	9	6	1	5	10	26	120
C13	—	—	13	6	—	—	1	1	28	—	—	49
C14	15	13	29	12	29	4	26	5	12	16	8	169
C15	8	6	—	13	9	—	29	—	6	8	—	79
C16	10	11	23	15	15	2	7	1	14	13	21	132

n is the number of connections.

Table 8: V motives of the post-70s traditional village tourists.

C-V	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10
C1	34	78	—	—	17	16	—	—	—	56
C2	65	35	33	35	28	25	—	35	—	26
C3	33	49	69	29	37	17	37	20	—	26
C4	—	—	—	33	33	40	86	46	56	32
C5	23	27	48	23	58	—	31	30	—	16
C6	—	41	—	36	86	—	—	—	—	32
C7	—	—	74	61	57	28	—	—	—	42
C8	46	29	22	26	11	16	87	41	—	33
C9	21	11	—	16	—	13	—	—	—	13
C10	61	37	—	45	21	—	67	45	33	41
C11	—	34	—	—	—	27	—	—	50	—
C12	31	23	—	—	—	—	51	27	27	28
C13	17	25	—	10	—	—	—	—	8	24
C14	36	53	—	32	23	23	24	20	—	40
C15	21	28	—	24	—	22	—	—	27	18
C16	15	49	—	—	—	—	—	—	—	46
n	403	519	246	370	371	227	383	264	201	473

n is the number of connections.

Table 9: A-C connections of the post-70s traditional village tourists (cutoff point = 50%).

A-C	A1	A3	A4	A5	A9	A11
C1	—	89/104 (85.6%)	—	—	—	—
C4	—	—	54/94 (57.4%)	—	—	—
C6	50/78 (64.1%)	—	—	—	—	—
C7	—	—	—	63/107 (58.9%)	—	—
C8	—	—	—	—	—	58/87 (66.7%)
C10	—	—	50/94 (53.2%)	—	—	44/87 (50.6%)

Percentage = n/N, where N is the total number of respondents recognizing an A (A_i) and n is the number of respondents agreeing that A (A_i) can produce a C (C_i).

Table 10: C-V connections of the post-70s traditional village tourists (cutoff point = 50%).

C-V	V1	V2	V3	V4	V5	V7	V10
C1	—	78/99 (78.8%)	—	—	—	—	56/99 (56.6%)
C4	—	—	—	—	—	86/116 (74.1%)	—
C5	—	—	—	—	58/101 (57.4%)	—	—
C6	—	—	—	—	86/109 (78.9%)	—	—
C7	—	—	74/118 (62.7%)	61/118 (51.7%)	—	—	—
C8	—	—	—	—	—	87/103 (84.5%)	—
C10	61/117 (52.1%)	—	—	—	—	67/117 (57.3%)	—

Percentage = n/N, where N is the total number of respondents recognizing a C (C_i) and n is the number of respondents agreeing that C (C_i) can reflect a V (V_i).

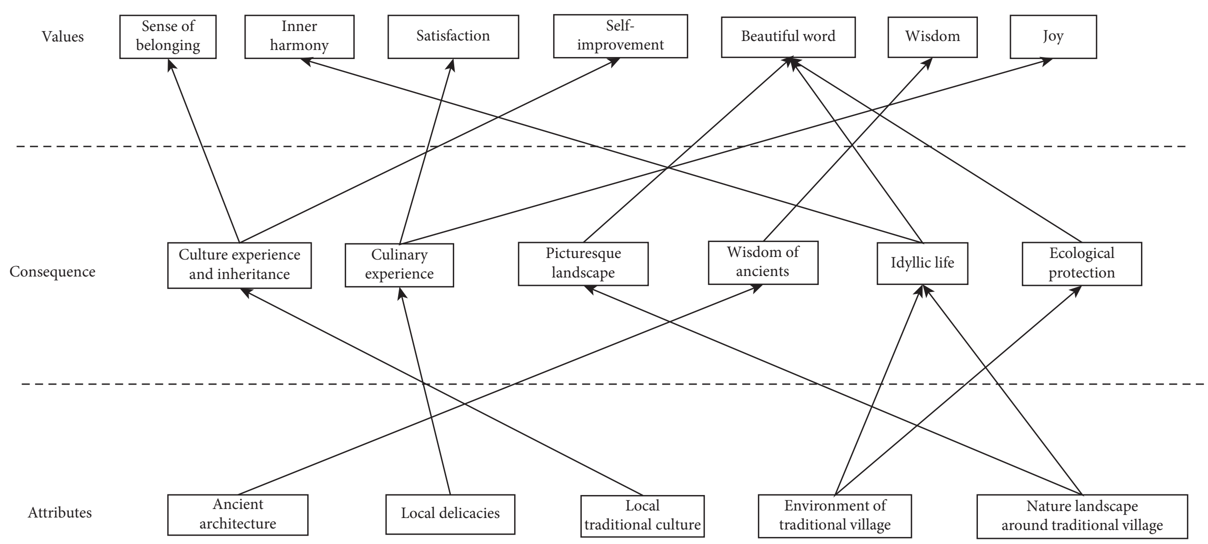

Figure 2: The HVM of the post-70s tourists to traditional villages (including correlated factors only) (cutoff point = 50%).

that the harmony between human and nature, human and society, and body and soul can promote spiritual cultivation [90]. The environment, surrounding natural landscape, and idyllic life of traditional villages reflect the philosophy of ecological protection and produce a beautiful environment with a picturesque landscape, which satisfies the appreciation and love of the post-70s tourists for human-nature harmony and beautiful sceneries, as well as their pursuit of a beautiful world [82, 83, 91, 92]. Traveling in such a picturesque landscape helps to cultivate their spirits.

Most post-70s tourists live in cities. They long to temporarily escape from the environment of daily life and work [93]. The tranquil environment (environment of traditional village—idyllic life—inner harmony) and natural landscape (natural landscape around traditional village—idyllic life—inner harmony) of traditional villages can relieve the pressure of work and life [94] and ensure the harmony between human and nature [95], realizing the V of inner harmony.

4.3. MEC Value Chains of the Post-80s Traditional Village Tourists. A total of 150 post-80s tourists were surveyed. According to the survey data, two interconnected matrices were set up for the A-C connections (Table 11) and C-V connections (Table 12) selected by these respondents. The number of A-C connections (Table 13) and C-V connections (Table 14) being selected by the respondents was counted and used to prepare the HVM for the MEC value chains (A-C-V) of post-60s tourists (Figure 3).

Table 11: C motives of post-80s traditional village tourists.

A-C	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	n
C1	—	—	93	—	—	—	—	4	46	—	—	143
C2	37	23	—	29	17	10	—	3	—	18	32	169
C3	31	21	29	25	47	14	16	5	13	25	23	249
C4	30	38	15	54	21	2	23	5	9	17	47	261
C5	51	14	—	15	14	11	8	2	10	23	7	155
C6	40	25	16	21	41	15	16	3	8	23	13	221
C7	38	26	25	29	75	19	23	9	21	22	16	303
C8	18	28	—	42	17	—	—	5	—	14	49	173
C9	5	11	—	—	11	—	6	3	—	—	10	46
C10	21	27	31	57	24	4	42	6	16	18	40	286
C11	9	18	22	23	9	1	13	2	6	12	26	141
C12	15	20	16	27	11	2	10	4	5	8	36	154
C13	—	—	23	4	—	—	6	2	36	—	—	71
C14	23	13	28	11	20	2	16	10	16	9	11	159
C15	21	10	—	24	20	3	26	3	7	15	—	129
C16	23	12	44	24	11	7	9	5	16	15	29	195

n is the number of connections.

Table 12: V motives of post-80s traditional village tourists.

C-V	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10
C1	31	90	—	—	10	17	—	—	—	73
C2	60	25	29	41	19	20	—	31	—	36
C3	32	42	78	21	51	19	37	19	—	25
C4	—	—	—	34	22	37	85	53	53	30
C5	28	32	49	21	69	—	35	19	—	19
C6	—	30	—	50	96	—	—	—	—	30
C7	—	—	83	66	69	40	—	—	—	38
C8	61	37	22	22	14	26	88	37	—	48
C9	14	17	—	16	—	19	—	—	—	15
C10	54	62	—	55	15	—	84	51	26	50
C11	—	33	—	—	—	37	—	—	66	—
C12	38	27	—	—	—	—	69	30	35	35
C13	8	43	—	9	—	—	—	—	12	37
C14	21	51	—	20	27	23	35	21	—	43
C15	27	37	—	37	—	50	—	—	31	32
C16	25	66	—	—	—	—	—	—	—	70
n	399	592	261	392	392	288	433	261	223	581

n is the number of connections.

Table 13: A-C connections of post-80s traditional village tourists (cutoff point = 50%).

A-C	A1	A2	A3	A4	A5	A11
C1	—	—	93/112 (83.0%)	—	—	—
C4	—	38/76 (50.0%)	—	54/102 (52.9%)	—	—
C5	51/93 (54.8%)	—	—	—	—	—
C7	—	—	—	—	75/113 (66.4%)	—
C8	—	—	—	—	—	49/84 (58.3%)
C10	—	—	—	57/102 (55.9%)	—	—

Percentage = n/N, where N is the total number of respondents recognizing an A (A_i) and n is the number of respondents agreeing that A (A_i) can produce a C (C_i).

It can be observed that the post-80s tourists pursue six As (ancient architecture, local traditional culture, environment of traditional village, natural landscape around traditional village, water system of traditional village, and local delicacies), six Cs (spirit of workmanship, cultural experience and inheritance, ecological protection, idyllic life, picturesque landscape, and culinary experience), and seven Vs (wisdom, beautiful world, inner harmony, self-improvement, satisfaction, joy, and sense of belonging), which constitute seven MEC value chains.

Like the post-60s and post-70s tourists, the post-80s tourists realize the Vs of satisfaction and joy through the pursuit of the A of local delicacies and the C of culinary experience.

Table 14: C-V connections of post-80s traditional village tourists (cutoff point = 50%).

C-V	V1	V2	V3	V4	V5	V7	V10
C1	—	90/103 (87.4%)	—	—	—	—	73/103 (70.9%)
C4	—	—	—	—	—	85/121 (70.2%)	—
C5	—	—	—	—	69/107 (64.5%)	—	—
C7	—	—	83/130 (63.8%)	66/130 (50.8%)	69/130 (53.1%)	—	—
C8	61/111 (55.0%)	—	—	—	—	88/111 (79.3%)	—
C10	—	62/123 (50.4%)	—	—	—	84/123 (68.3%)	—

Percentage = n/N, where N is the total number of respondents recognizing a C (C_i) and n is the number of respondents agreeing that C (C_i) can reflect a V (V_i).

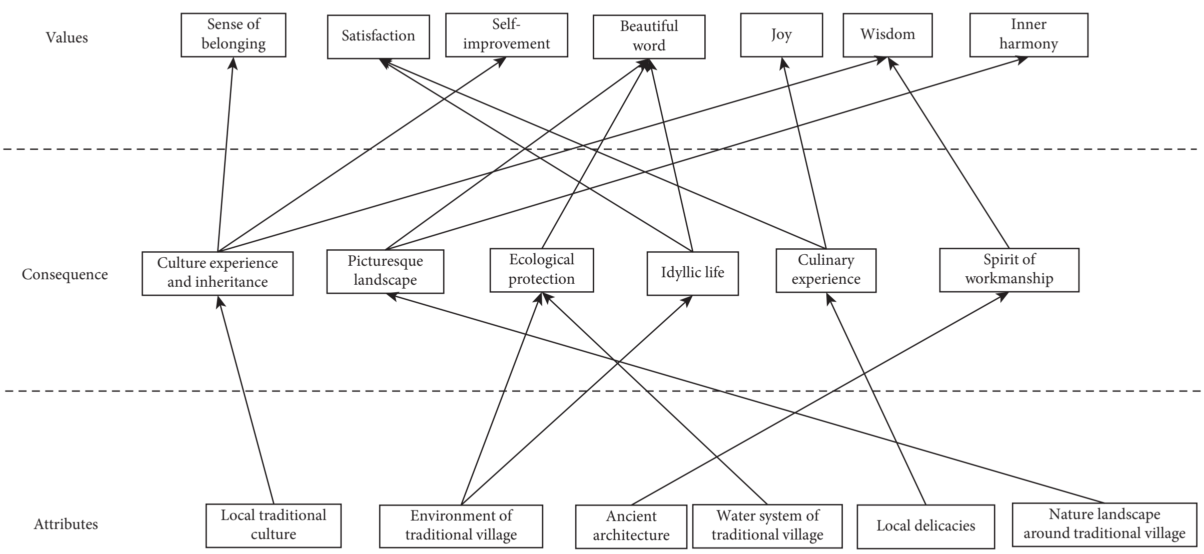

Figure 3: The HVM of post-80s tourists to traditional villages (including correlated factors only) (cutoff point = 50%).

The V of wisdom comes from the pursuit of the post-80s tourists for the As of ancient architecture and local traditional culture and the Cs of spirit of workmanship and cultural experience and inheritance. The post-80s tourists have the same Vs as the post-60s and post-70s tourists but differ from the latter in As and Cs.

The post-80s tourists achieved personal success through hard work and diligent learning [96]. Like the post-70s tourists, they believe that knowledge has the power to change one's fate and are deeply influenced by traditional culture. During travel through traditional villages, the post-80s tourists highlight the V of wisdom reflected by the spirit of workmanship among the builders of ancient architecture and perceive the V of wisdom of the ancestors of the Chinese nation in the creation and inheritance of the traditional culture.

In addition, the post-80s and post-70s tourists both realize the value of "belonging" (V4) by pursuing the attribute of "local traditional culture" (A5) and the result of "cultural experience and inheritance" (C7). In other words, the post-80s and post-70s tourists share the same MEC value chain (A5⟶C7⟶V4). Similarly, tourists born in the 60s and 70s have realized the value of "self-improvement" (V3) by pursuing the attribute of "local traditional culture" (A5) and the result of "cultural experience and inheritance" (C7). The post-60s and post-70s share the same MEC value chain (A5⟶C7⟶V3).

The V of beautiful world stems from the post-80s tourists' pursuit of the As of environment of traditional village, natural landscape around traditional village, and water system of traditional village, as well as the Cs of ecological protection, idyllic life, and picturesque landscape. In their views, the water system, environment, and surrounding natural landscape of traditional villages, plus the idyllic life of residents, protect the eco-environment and nurture a beautiful environment with picturesque landscape, providing them with the chance to realize the V of beautiful world [82, 83, 91, 92]. Hence, the post-80s tourists can cultivate their spirit by traveling to traditional villages.

The post-80s tourists share the same motive of escaping from daily routines as the post-70s tourists [93]. The environment of traditional village and natural landscape around traditional village (environment of traditional village—idyllic life—inner harmony; natural landscape around traditional village—picturesque landscape—inner harmony) set the stage for an idyllic life in the picturesque landscape, which relieves pressure [94] and realizes the V of inner harmony.

4.4. MEC Value Chains of the Post-90s Traditional Village Tourists

4.4. MEC Value Chains of the Post-90s Traditional Village Tourists. A total of 150 post-90s tourists were surveyed. According to the survey data, two interconnected matrices were set up for the A-C connections (Table 15) and C-V connections (Table 16) selected by these respondents. The

Table 15: C motives of post-90s traditional village tourists.

A-C	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	n
C1	—	—	96	—	—	—	—	1	40	—	—	137
C2	31	20	—	33	15	2	—	6	—	19	37	163
C3	37	20	31	31	47	9	30	5	12	23	16	261
C4	26	30	11	60	25	4	22	7	7	23	39	254
C5	48	12	—	22	24	7	12	4	7	32	8	176
C6	37	15	18	33	40	14	26	3	8	35	18	247
C7	37	31	23	35	65	8	31	11	12	26	19	298
C8	11	27	—	37	15	—	—	8	—	18	61	177
C9	6	7	—	—	15	1	10	6	—	—	9	54
C10	27	31	35	49	19	4	46	7	18	25	54	315
C11	15	15	24	33	14	3	21	4	11	14	18	172
C12	16	20	18	38	14	3	22	1	8	16	32	188
C13	—	—	18	13	—	—	8	6	32	—	—	77
C14	18	14	27	16	35	4	16	6	17	13	14	180
C15	22	11	—	20	12	2	24	3	5	10	—	109
C16	20	18	43	23	23	5	20	8	14	21	36	231

n is the number of connections.

Table 16: V motives of post-90s traditional village tourists.

C-V	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10
C1	31	88	—	—	18	15	—	—	—	69
C2	51	41	37	29	27	26	—	33	—	32
C3	39	62	81	27	52	34	34	17	—	33
C4	—	—	—	33	37	41	79	55	54	39
C5	31	34	53	28	75	—	28	20	—	20
C6	—	51	—	47	95	—	—	—	—	32
C7	—	—	95	61	73	42	—	—	—	51
C8	45	35	30	23	27	25	85	48	—	40
C9	23	16	—	21	—	22	—	—	—	16
C10	66	46	—	52	25	—	82	58	36	50
C11	—	50	—	—	—	47	—	—	62	—
C12	30	41	—	—	—	—	70	43	33	49
C13	19	38	—	16	—	—	—	—	14	35
C14	26	51	—	26	30	19	36	23	—	44
C15	25	33	—	31	—	33	—	—	32	35
C16	28	68	—	—	—	—	—	—	—	65
n	414	654	296	394	459	304	414	297	231	610

n is the number of connections.

number of A-C connections (Table 17) and C-V connections (Table 18) being selected by the respondents was counted and used to prepare the HVM for the MEC value chains (A-C-V) of post-90s tourists (Figure 4).

It can be observed that the post-90s tourists pursue six As (ancient architecture, local traditional culture, environment of traditional village, natural landscape around traditional village, lifestyle of residents, and local delicacies), six Cs (spirit of workmanship, cultural experience and inheritance, ecological protection, picturesque landscape, idyllic life, and culinary experience), and six Vs (wisdom, beautiful world, inner harmony, self-improvement, satisfaction, and joy), which constitute twelve MEC value chains.

Like the previous three generations, the post-90s tourists realize the Vs of satisfaction and joy through the pursuit of the A of local delicacies and the C of culinary experience.

Similar to the post-60s and post-80s tourists, the post-90s tourists achieve the V of wisdom through the search for the As of ancient architecture and local traditional culture, as well as the Cs of spirit of workmanship and cultural experience and inheritance. These tourists are pragmatic, innovative, and aggressive [97, 98]. They are curious about the unknown and good at learning [99]. The ancient architecture embodies exquisite craftsmanship, superb technology, and wisdom of the ancestors of the Chinese nation in the creative culture. All these factors inspire the post-90s tourists to have a deeper understanding of the wisdom in the spirit of workmanship among ancient architecture builders and the wisdom of the ancestors. Moreover, the post-90s tourists can acquire knowledge through travel and realize the V of self-improvement (ancient architecture—spirit of workmanship—self-improvement; local traditional culture—cultural experience and inheritance—self-improvement).

For the post-90s tourists, the V of beautiful world originates from the As of environment of traditional village and natural landscape around traditional village and from

Table 17: A-C connections of post-90s traditional village tourists (cutoff point = 50%).

A-C	A1	A3	A4	A5	A7	A11
C1	—	96/121 (85.7%)	—	—	—	—
C4	—	—	60/100 (60.0%)	—	—	—
C5	48/82 (58.5%)	—	—	—	—	—
C7	—	—	—	65/101 (64.4%)	—	—
C8	—	—	—	—	—	61/90 (61.8%)
C10	—	—	—	—	46/79 (58.2%)	54/90 (60.0%)

Percentage = n/N, where N is the total number of respondents recognizing an A (A_i) and n is the number of respondents agreeing that A (A_i) can produce a C (C_i).

Table 18: C-V connections of post-90s traditional village tourists (cutoff point = 50%).

C-V	V1	V2	V3	V5	V7	V10
C1	—	88/101 (87.1%)	—	—	—	69/101 (68.3%)
C4	—	—	—	—	79/116 (68.1%)	39
C5	—	—	53/104 (51.0%)	75/90 (72.1%)	—	—
C7	—	—	95/132 (72.0%)	73/132 (55.3%)	—	—
C8	—	—	—	—	85/106 (80.2%)	—
C10	66/126 (52.4%)	—	—	—	82/126 (65.1%)	—

Percentage = n/N, where N is the total number of respondents recognizing a C (C_i) and n is the number of respondents agreeing that C (C_i) can reflect a V (V_i).

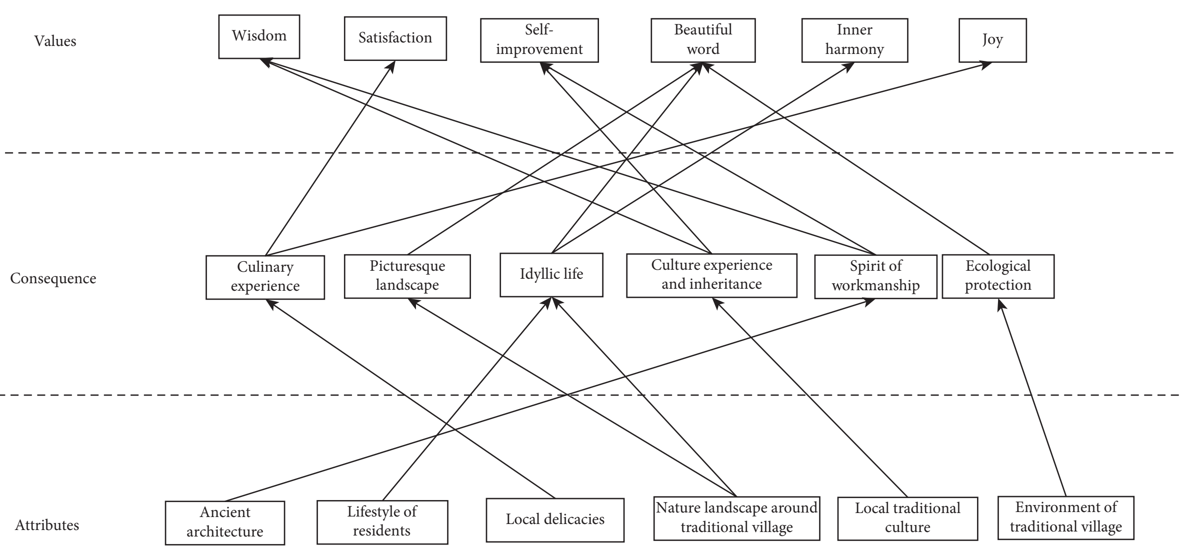

Figure 4: The HVM of post-90s tourists to traditional villages (including correlated factors only) (cutoff point = 50%).

Table 19: The MEC value chains of traditional village tourists.

	Attributes	Consequences	Values	60s	70s	80s	90s
MEC1	Ancient architecture	Wisdom of the ancients	Wisdom	✓	✓	—	—
MEC2	Ancient architecture	Spirit of workmanship	Wisdom	✓	—	✓	✓
MEC3	Local traditional culture	Cultural experience and inheritance	Wisdom	✓	—	✓	✓
MEC4	Environment of traditional village	Ecological protection	Beautiful world	—	✓	✓	✓
MEC5	Environment of traditional village	Idyllic life	Beautiful world	—	✓	✓	—
MEC6	Natural landscape around traditional village	Picturesque landscape	Beautiful world	—	✓	✓	✓
MEC7	Natural landscape around traditional village	Idyllic life	Beautiful world	—	✓	—	✓
MEC8	Water system of traditional village	Ecological protection	Beautiful world	—	—	✓	—
MEC9	Lifestyle of residents	Idyllic life	Beautiful world	—	—	—	✓
MEC10	Environment of traditional village	Idyllic life	Inner harmony	—	✓	✓	—
MEC11	Natural landscape around traditional village	Idyllic life	Inner harmony	—	✓	—	✓

Table 19: Continued.

	Attributes	Consequences	Values	60s	70s	80s	90s
MEC12	Natural landscape around traditional village	Picturesque landscape	Inner harmony	—	—	✓	—
MEC13	Lifestyle of residents	Idyllic life	Inner harmony	—	—	—	✓
MEC14	Ancient architecture	Spirit of workmanship	Self-improvement	✓	—	—	✓
MEC15	Local traditional culture	Cultural experience and inheritance	Self-improvement	✓	✓	✓	✓
MEC16	Local delicacies	Culinary experience	Satisfaction	✓	✓	✓	✓
MEC17	Local delicacies	Culinary experience	Joy	✓	✓	✓	✓
MEC18	Local traditional culture	Cultural experience and inheritance	Sense of belonging	—	✓	✓	—

the Cs of ecological protection and picturesque landscape. These As and Cs are commonly pursued by the previous three generations. Besides, this V also stems from the A of idyllic life yearned by the post-70s tourists. Out of curiosity, the post-90s tourists choose to experience the lifestyle of residents in traditional villages and find that the idyllic lifestyle of "getting up at sunrise and going to bed at sunset" is exactly what they have imagined about a beautiful world (lifestyle of residents—idyllic life—beautiful world).

In the meantime, as the previous two generations, the post-90s tourists are eager to temporarily escape the environment of daily life and work [99] and have a taste for the rural lifestyle [100]. The surrounding natural environment of traditional villages and the lifestyle of residents jointly create a slow and idyllic life, which eases the tourists' stress [94] and offers the V of inner harmony (lifestyle of residents—idyllic life—inner harmony; natural landscape around traditional village—idyllic life—inner harmony).

5. Conclusions and Discussion

5.1. Conclusions. According to the HVMs of traditional village tourists born in the 1960s, 1970s, 1980s, and 1990s, there are 36 MEC value chains of 18 classes for traditional village tourists (Table 19).

5.1.1. Intergenerational Preferences and Differences of Vs. The post-60s, post-70s, post-80s, and post-90s tourists pursue seven Vs, i.e., beautiful world, inner harmony, wisdom, self-improvement, satisfaction, joy, and sense of belonging. The four generations of tourists share the following MEC value chains: local delicacies—culinary experience—satisfaction (MEC16); local delicacies—culinary experience—joy (MEC17); local traditional culture—cultural experience and inheritance—self-improvement (MEC15). Therefore, satisfaction, self-improvement, and joy are the Vs commonly pursued by the four generations. Furthermore, the self-improvement realized through local traditional culture is a pursuit of culture, while the satisfaction and joy brought by local delicacies are Vs on spiritual level. The research results show that tourism can bring happiness, satisfaction, and self-improvement to tourists. This conclusion is applicable to the four generations from the post-60s to the post-90s, and there will be no difference in the values pursued by rural tourism due to generational differences.

The MEC value chains show that the post-60s tourists to traditional villages prefer the two Vs of wisdom and self-improvement; the post-70s and post-80s prefer the three Vs of beautiful world, inner harmony, and sense of belonging. The post-90s tourists like all the Vs favored by the traditional village tourists of the previous three generations, a sign of the diversity and inclusiveness of the post-90s tourists [101].

5.1.2. Intergenerational Preferences and Differences of As. The post-60s, post-70s, post-80s, and post-90s tourists pursue seven As, i.e., ancient architecture, local delicacies, local traditional culture, environment of traditional village, natural landscape around traditional village, water system of traditional village, and lifestyle of residents. Specifically, ancient architecture refers to the ancient buildings and the homestays with local cultural features transformed from ancient architecture within the traditional villages; environment of traditional village refers to the atmosphere of human-nature harmony in traditional villages; natural landscape around traditional village refers to the natural landscape involving artificial or natural plants in the surroundings of traditional villages; lifestyle of residents refers to the slow and idyllic lifestyle of "getting up at sunrise and going to bed at sunset."

Ancient architecture, local delicacies, and local traditional culture are the common As of the four generations of tourists. The post-80s tourists prefer the A of water system of traditional village; the post-90s tourists prefer the A of lifestyle of residents, reflecting their curiosity; the post-70s, post-80s, and post-90s tourists prefer the As of environment of traditional village and natural landscape around traditional village.

5.1.3. Intergenerational Preferences and Differences of Cs. The post-60s, post-70s, post-80s, and post-90s tourists to traditional villages have seven Cs: idyllic life, cultural experience and inheritance, culinary experience, picturesque landscape, ecological protection, spirit of workmanship, and wisdom of the ancients.

Among the seven Cs, culinary experience, and cultural experience and inheritance are shared by all four generations. The post-70s, post-80s, and post-90s tourists prefer three Cs, namely, ecological protection, picturesque landscape, and idyllic life. This is because they wish to temporarily leave the stressful environment of daily life and work [99] and take a rest in the slow and idyllic life with superior ecological conditions. The post-60s and post-70s tourists prefer the C of wisdom of the ancients. Deeply affected by traditional Chinese culture, these two generations are attracted by the wisdom of our ancestors crystallized in the buildings, environment, and layout of traditional villages. The post-60s, post-80s, and post-90s prefer the spirit of workmanship among the builders of ancient architecture. Many ancient buildings in traditional villages are works of art, reflecting the Chinese culture and the craftsmanship of excellence. The research results show that tourists in these three ages will be motivated to explore the spirit of craftsmanship because of the ancient buildings in traditional villages.

According to the hierarchical value map (HVM) of tourists in traditional villages and the results of MEC chain research, we believe that the attributes of traditional villages produce the tourism consequence of traditional villages, and the tourism value of traditional villages is realized through the experience of the tourism consequence of villages. Meanwhile, the ultimate tourism value reflects the spiritual needs of tourists. It also affects the protection of traditional village attributes and their reuse in sustainable tourism development, so that attributes⟶consequence⟶value⟶attributes form a cycle of mutual influence and interaction of the transmission of village protection and activation model. In this process, the attribute of traditional villages is the basis of tourism activation, and the tourism consequence of traditional villages is the guidance of tourism activation. The tourism value of traditional villages, which reflects tourists' tourism values and value pursuit, is the core of tourism activation. It is also an important factor affecting the sustainable development of traditional village tourism.

5.2. Discussion. This paper collects 600 samples of traditional village tourists across China and explores the tourism values behind the tourist behaviors through hard laddering. The main findings are as follows:

(1) From value preferences, it can be learned that the post-60s traditional village tourists are a generation of wisdom-loving learners, the post-70s and 80s tourists are a generation of beauty lovers with a strong sense of belonging, and the post-90s tourists are a generation of inclusive advocators of diversity.
(2) From the root and source, this paper summarizes the essence of the sustainable development of traditional villages: realizing the ultimate values of tourists, such as joy, wisdom, satisfaction, sense of belonging, self-improvement, inner harmony, and beautiful world, through careful protection of the following attributes of traditional villages: local delicacies, local traditional culture, ancient architecture, lifestyle of residents, environment of traditional village, and natural landscape around traditional village.
(3) The MEC theory proved to be effective for the study of different types of tourists to traditional villages, the discovery of the value preferences and intergenerational differences of such tourists, and the accurate prediction of their intergenerational preferences, providing theoretical support and practical enlightenment to the product development and marketing of the niche markets of traditional village tourism.
(4) The research results help to activate the traditional village tourism, adapt to the latest changes in the tourism market, and inherit and innovate the traditional culture of traditional villages. After experiencing the traditional culture, the tourists are very likely to spread the culture voluntarily. Besides, the tourists can affect the culture of traditional villages during travel. Through these pathways, it is possible to inherit and renovate the traditional culture in traditional villages, enhance the confidence in traditional culture, and promote rural revitalization.

The contribution of this research lies in the in-depth study of the value preferences and intergenerational differences of traditional village tourists born in the 1960s, 1970s, 1980s, and 1990s and the subdivision of traditional village tourism market into different generations, providing theoretical support to and bridge the research gap of the product development for the niche markets of traditional village tourism.

Due to space limitations, this paper only analyzes the MEC value chains above the cut-off point (50%). The MEC value chains below that point were not considered. Besides, the authors did not deeply explore the relationship between the tourist values and the protection and activation of traditional villages. Adding the intergenerational values of traditional village tourists, the future work will try to establish a model for the protection and activation of traditional villages and to safeguard the key attributes or activities of traditional villages.

Finally, several suggestions were presented for the activation of traditional village tourism:

(1) To revive the attributes and values of traditional villages, it is necessary to marketize the tourist values of traditional villages like satisfaction, self-improvement, wisdom, and joy, which are the results of ancient architecture, local delicacies, environment of traditional village, and local traditional culture.
(2) The following attributes of traditional villages should be protected with special care: local delicacies, local traditional culture, ancient architecture, lifestyle of residents, environment of traditional village, and natural landscape around traditional village.
(3) Considering the MEC value chains of post-60s, post-70s, post-80s, and post-90s tourists, it is important to design tourism products meeting the market needs of different generations, making the tourism products of traditional villages livelier.
(4) It is necessary to establish a government-led, villager-dominated, and market-driven mechanism to activate the traditional villages. Under the mechanism, it would be possible to develop new tourism businesses and products for traditional villages, carry out marketization targeted at specific groups of tourists, and improve the service level, laying the basis for rural revitalization and sustainable development of traditional villages.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Convergence of City Relational Network, Production Sector Structure, and Regional Development

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There is a strong correlation between government intervention and urban production structure in China. Particularly, the outputs of the cities partly come from the economic rent of city relational network (CRN), which is a unique regional policy and administrative hierarchy. In order to analyze the gravity flows of CRN under the nonmarket mechanism, we attempt to build a new gravity model that adopts the production sector. The new gravity produces relational data with direction, which makes it possible to use social network analysis (SNA) and overcome the endogeneity of the linear model. The empirical results show that (1) modified new gravity model can effectively capture the distribution of CRN gravity flows and the convergence of regional development in China, (2) the CRN, which especially stems from the government financial intervention, increases the share of nontradable sectors in cities, and (3) adjustment of the production sector leads to the difference of CRN gravity flows, so asymmetric flows distribution leads to the heterogeneity of regional economic performance. Cities with higher share of nontradables have relatively slower productivity growth in long-term.

1. Introduction

City relational network (CRN) is the network formed by the flows of people, logistics, and capital between regions. The economic rent of CRN is an important nonmarket source of outputs of Chinese cities, which is very different from urban governance in the market-oriented countries. For instance, despite the withering of tradable production sector, many undeveloped cities receive supports from regional coordination policies (e.g., transfer payment, industrial support, and preferential policy on infrastructure construction) and the income earned by migrant workers. In addition, the relocation of administrative officials and targeted support will also change the production sector. As a result, urbanization picks up speed in underdeveloped regions, which is featured by the expansion of the nontradable production sector. In other words, the relative structure of the production sector is altered by the economic rent of CRN. If the economic rent of CRN leads to a larger proportion of nontradable sectors, its long-term productivity will be slower than that of other cities with a larger proportion of tradable sectors. As a result, the regional development gap will be widened.

The two phenomena work together to reshape the regional economic trend. The correlations between Chinese cities have moved beyond the research scope of iceberg transport cost or nearest neighbor distance in new economic geography or spatial econometrics. The cities form a complex network involving interactions between people, logistics, and capital flow. Against this backdrop, this paper attempts to build a new gravity flow model for CRN, and reexamine the correlations of China's CRN through social network analysis (SNA). The research focuses on how the asymmetric changes of tradable and nontradable production sectors in different regions influence the convergence of regional development.

The asymmetric changes in the productivity of tradable and nontradable sectors in different regions have slowed down the convergence of regional development and even widened the development gaps. In developed regions, a large share of the production sector is tradable; the productivity of tradable production sector increases faster than the nontradable production sector [1, 2]. Therefore, the tradable production sector attracts labor from other local sectors, and also draws high-skilled people from underdeveloped regions, causing a gradual decline of the tradable sector in underdeveloped regions. In addition, whether migrant workers make a living in other regions or return to their hometown for work, their surplus income leads to the phenomenon of Engel's consumption cycle, which stimulates the demand for nontradable products in their hometown, such as retail goods, real estate, and other services. In underdeveloped regions, the employment ratio of the nontradable production sector is further magnified by the local government's push for urbanization. The withering tradable sector and expanding nontradable sector in underdeveloped regions will tilt the balance of regional development [3, 4]: the relatively slow growth of the productivity of the nontradable sector adds to the difficulty for underdeveloped regions to catch up with developed regions. To overcome the imbalance of regional development, China has rolled out a series of top-down policies to balance the development across regions. The earliest policy is the Great Western Development Strategy, followed by the Northeast Area Revitalization Plan, and the Rise of Central China Plan. The ongoing urbanization process is also driven by many incentive policies [5]. The scale of a city is closely related to the local government. For example, many underdeveloped regions have issued various urbanization policies to attract population inflow. As a result, the employment ratio of the nontradable sector in these regions is poised to rise. By contrast, megacities like Beijing take lots of measures (e.g., tightening land supply) to limit the city scale. To sum up, the interregional trade of tradable products and the economic rent of CRN have both restructured regional production sector, and thus affected the convergence of regional development.

Under the combined effects of interregional trade and the economic rent of CRN, the relations between cities in China gradually form a complex network with multiple directions. However, there is hardly any report that discusses regional development based on the features of CRN, from the perspective of production sector restructuring. The few studies on regional economic convergence and spatial correlations mainly focus on the flow of factors [6], government roles [5], agglomeration economy, and even the reversal of enterprise agglomeration by the Internet [7]. Of course, some scholars have explored the close correlations between the employment and product price of tradable/nontradable sector and regional productivity. The prices of nontradable products usually depend on the local market. In some parts of the nontradable sector, however, the rise of productivity will suppress the product prices. The price reduction mechanism clearly differs from the price drop of nontradable products induced by the economies of scale [8, 9]. Trade liberalization can transmit product prices from the tradable sector to the nontradable sector [10, 11]. He and Zhou [12] confirmed that international trade liberalization will squeeze out a portion of the formal employment in tradable and nontradable sectors, and promote the nonformal employment in the nontradable sector more effectively than that in the tradable sector. Similar studies have made great progress in the field of interregional trade. For instance, Shao et al. [13] empirically tested the close association between the regional linkage of economic development cycles and the trade of domestic value chain in China, and claimed that the division of labor in the value chain network is an important reason for the differences between the eastern region and the central/western region in internal and external spatial features. Using indices like the proportion and added value of service industry, Tang et al. [14] discovered the growing regional imbalance of the service industry in China: the eastern region is increasingly powerful, while the western region falls further back. In fact, the growing imbalance mentioned by Tang et al. [14] mainly refers to the widening gap of tradable service industry between regions.

Considering the current features of urbanization and the economic rent of CRN, it is difficult to fully explain the regional economic and social phenomena of China solely from traditional theoretical angles, such as free flow of factors. This paper attempts to build a statistical model based on the gravity flows in CRN, and uses the model to depict the structural features and convergence trend of the regional production sector, trying to make the analysis results more objective and accurate. Currently, the trade of tradable products between regions is usually measured by trade quality and trade intensity. The data on these attributes only reflect a side of the urban production sector. To fully analyze the complex interregional network of people flow, logistics, and capital flow, a good option is to replace the attribute data with relational data [15]. However, the replacement brings another problem: featured by relevance and directivity, the relational data go against the independence assumption in the measurement theory. Fortunately, this problem can be solved by the statistical methods related to social network analysis. Taylor et al. [16] and Fagiolo [17] shed new light to the academia through the topology inference of international trade and financial relational network; their estimation of parameter values and inference of relational network parameters (e.g., degree centrality and betweenness centrality) have won wide recognition. In recent years, great advancement has been made concerning the unobserved individual heterogeneity and network flow modeling for social and economic networks.

This work makes two marginal contributions. On the one hand, while the traditional gravity model centers on population size or per-capita gross domestic product (GDP), this paper modifies the gravity parameters, and introduces new variables into the benchmark gravity model (e.g., the ratio between tradable and nontradable sectors), creating directed gravity flows in the urban relational network. Our novel statistical model facilitates further research into the economic rent of CRN, breaks through the limitations of the proximity assumption in spatial econometric theory, and makes up for the lack of direction attributes in traditional data. Moreover, fitting tests were carried out by maximum likelihood estimation (MLE) and the iterative weighted least squares (IWLS) method derived from the Newton-Raphson method. The results show that our CRN gravity flow model and its method can effectively capture city structural changes and regional convergence trend of China. Previously, Li et al. [18] deduced the provincial spatial spillover effect through social network analysis combined with the Granger causality test of vector autoregressive (VAR) model. This combined approach is similar to the network graph statistics of Wasserman and Faust [19], and Scott [20]. However, the approach only vaguely selects the lag orders and processes the dynamic changes of spatial links, failing to explain the economic implication that affects sector adjustment and regional development. In this paper, the start and end point flows are quantified for each link in the CRN, and the gravity model is corrected. These practices are inspired by the modeling ideas of Fagiolo [17], and Kolaczy and Csárdi [21] on national trade networks, as well as the use of gravity model by Liu et al. [22] to disclose the spatial clustering of energy consumption in China.

On the other hand, the empirical results show that the gravity flows to a city from other cities directly rely on the employment structure of that city (employment ratio of tradable sector to nontradable sector), and tend to increase significantly over time. This means that compared with underdeveloped cities, developed cities with a high share of tradable sector witness relatively fast growth in CRN gravity inflows. For simplicity, the tradable sector and nontradable sector are collectively referred to as the two sectors. Moreover, the per-capita GDP ratio between two cities increases with their employment structure ratio, that is, the two-sector employment ratio of a city divided by that of the other city. Therefore, the economic rent of CRN can increase the CRN gravity flows and the scale of nontradable sector in cities, pushing up the portion of that sector in the employment structure. Nevertheless, the cities with a high presence of nontradable sector are slower in the rise of overall productivity than those with a high presence of tradable sector, because the products of nontradable sector cannot be traded. The relatively slow growth of productivity in such cities would slow down the convergence of regional development. In addition, the growing productivity of the nontradable sector will lower the prices of some nontradable products, making the product between productivity and price in the nontradable sector unstable. As a result, it is not a feasible way for underdeveloped regions to expand the employment in cities only by improving the productivity of the nontradable sector.

The remainder of this paper is organized as follows: Section 2 models the adjustment of the urban production sector, and puts forward theoretical propositions; Section 3 presents ridge regression; Section 4 establishes a model of CRN gravity flows; and Section 5 summarizes the main findings.

2. Benchmark Theories of Urban Production Structure

Our theoretical model was constructed in reference to the ideas of Gollin et al. [3] concerning the equilibrium between such three sectors as the agricultural sector, the tradable production sector, and the nontradable production sector. The core of their research is to address the Dutch disease of resource-based country in the urbanization. However, our two sector model considers the structural adjustment and regional growth of only two urban production sectors, namely, tradable sector and nontradable sector. More importantly, the economic rent of CRN was introduced to the model, in the light of the unique urbanization background and regional development in China. The economic rent of CRN is manifested by the following phenomena: the cities on high administrative levels or large economic scales tend to concentrate lots of public resources (such as better health care and education). These cities earn much more through the attraction of people flow, logistics, and capital flow than the competitive market. Meanwhile, the economic rent of underdeveloped cities comes from the regional policy support by the central government, such as fiscal transfer, land supply, and preferential terms on infrastructure construction. Apparently, the economic rent of CRN has a close correlation with the variation in CRN gravity flows, and exerts an influence on the production sector adjustment and employment structure of cities. The urban production sector provides two types of outputs:

(1) Nontradable products

Nontradeable products refer to private services (local retail, transportation, education, and health) and other industrial products that cannot be traded in the national market. The price P_u of such products depends on the endogeneities of the local market. Due to the nontradability, the growth rate of productivity of nontradable sectors is lower than that of tradable sectors.

(2) Tradable products

Tradable products refer to industrial products and tradable services that can be traded in the national market at a competitive price p_k^*. These products can kick off complex competition and cooperation between the tradable sectors of different cities.

Suppose individuals have a log linear utility function over the two products: tradable products (c_k), and nontradable products (c_u):

$$u = \lambda_k \ln c_k + \lambda_u \ln c_u, \tag{1}$$

where λ_k and λ_u are the income elasticities for products from different sectors, here $\lambda_k \in (0, 1)$; $\lambda_u \in (0, 1)$; $\lambda_k + \lambda_u = 1$. The utility function is homothetic. Unlike other industrial structure change models, our model about the adjustment of the two sectors in cities can obtain nonhomothetic results, without needing to assume that the demand is nonhomothetic. Production of the two sectors in cities can be, respectively, described as

$$Y_k = A_k L_k^{1-\alpha}, \tag{2}$$

$$Y_u = A_u L_u^{1-\alpha}. \tag{3}$$

The functional form shows the existence of diminishing marginal products of labor in each production activity. A_k

and A_u are the productivities of tradable and nontradable sectors, respectively; L_k and L_u are the proportions of the labor of tradable and nontradable sectors to the total labor, respectively ($L_k + L_u = 1$); the value of α is identical across all sectors.

The price p_k^* of tradable products is determined by the competitive market in interregional trade, while the price P_u of nontradable products is determined endogenously by the local market. If q is income for an individual, the budget constraint for the individual is

$$p_k^* c_k + p_u c_u = q. \tag{4}$$

Considering the special background of urbanization and regional development in China, our theoretical model also takes account of the economic rent of CRN; so, the total income (flow) in the city from the economic rent of CRN is denoted by R, which is taken as given by individuals and producers. The economic rent of CRN is not fully regulated by the market. For example, the underdeveloped cities enjoy the extra nonmarket outputs, which comes from support policies like fiscal transfer, industrial subsidies, and preferential policy on infrastructure construction.

Economic rent of CRN changes the proportion of nontradable and tradable structures, and finally affects urban flow and outputs. For simplicity, we assume that the amount R is distributed equally across all individuals. Although this assumption is not the case, inequality in the distribution does not change the basic results, as shown in the Gollin's [3] Web Theory.

Given the log-linear utility, the optimal choice for a consumer is for the expenditure share of income on nontradable products to equal its weight λ_u in the utility function. The ideas of deduction are consistent with Gollin et al. [3]. Given that urban nontradables are only produced in the local market, total expenditure on them must equal the sum of production and the income from R. Let θ ($0 < \theta < 1$) be the proportion of CRN economic rent in nontradable sectors, so

$$\lambda_u q = \theta R + p_u Y_u. \tag{5}$$

The larger θ is, the greater the role of government power in nontradable sectors is. The tradable products can be produced for the economy as a whole, traded from the rest of the nation. In addition, the city has the income partly from R, assuming balanced trade yields the following condition

$$\lambda_k q = (1-\theta)R + p_k^* Y_k. \tag{6}$$

Since labor can flow freely between sectors, the wage rates of the sectors are equal in the equilibrium state. Then, the partial derivatives of formulas (2) and (3) satisfy

$$(1-\alpha) p_k^* A_k L_k^{-\alpha} = (1-\alpha) p_u A_u L_u^{-\alpha}. \tag{7}$$

From formulas (5)–(7), it can be derived that

$$L_u^{1-\alpha} = \frac{\left[(1-\theta)\lambda_u - \theta\lambda_k\right] \cdot R}{P_u A_u \left[1 - \lambda_u \left(P_k^* A_k / P_u A_u\right)^{1/\alpha}\right]}, \tag{8}$$

$$L_k^{1-\alpha} = \frac{\left[(1-\theta)\lambda_u - \theta\lambda_k\right] \cdot R}{P_k^* A_k \left[\left(P_u A_u / P_k^* A_k\right)^{1/\alpha} - \lambda_u\right]}. \tag{9}$$

Let $\rho = (1-\theta)\lambda_u - \theta\lambda_k$ be a constant combination between the consumption of the products from different sectors; $\tau = (P_k^* A_k / P_u A_u)$ be the productivity-price product (PPP) ratio of the two sectors, that is, the PPP of the tradable sector divided by that of the nontradable sector. Then, formulae (8) and (9) can be rewritten as

$$L_u = \left[\frac{\rho R}{P_u A_u \left(1 - \lambda_u \tau^{1/\alpha}\right)}\right]^{(1/1-\alpha)}, \tag{10}$$

$$L_k = \left\{\frac{\rho R}{P_k^* A_k \left[(1/\tau)^{1/\alpha} - \lambda_u\right]}\right\}^{(1/1-\alpha)}. \tag{11}$$

From formulas (10) and (11), we have:

$$\begin{aligned} &(i)\ \frac{\partial L_u}{\partial R} > 0,\\ &\frac{\partial L_u}{\partial \tau} > 0,\\ &\frac{\partial L_u}{\partial (P_u A_u)} > 0, \end{aligned} \tag{12}$$

$$\begin{aligned} &(ii)\ \text{if } (1/\tau)^{1/\alpha} - \lambda_u > 0, \text{then } \frac{\partial L_k}{\partial \tau} > 0, \frac{\partial L_k}{\partial (P_k^* A_k)} < 0,\\ &\frac{\partial L_k}{\partial R} > 0. \end{aligned} \tag{13}$$

The following can be derived from formulae (12) and (13):

(i) The adjustment of employment structure in cities depends on CRN economic rent (R), PPP ($P_k^* A_k$ or $P_u A_u$), and the PPP ratio of the two sectors (τ); the share of the nontradable sector in the employment structure (L_u) increases with CRN economic rent (R).

(ii) If underdeveloped regions choose to expand urban employment scale solely by increasing the productivity A_u of the nontradable sector, the long-term effect will be very limited. The reason is that undeveloped cities have a high share of the nontradable sector; the rise of productivity A_u of this sector will drag down.

(iii) R, τ and $P_k^* A_k$ have uncertain impacts on the share of the tradable sector in the employment structure (L_k). The specific impacts depend on the original endowments of the cities. If $(1/\tau)^{1/\alpha} - \lambda_u > 0$ or $(1/\tau)^{1/\alpha} - \lambda_u < 0$, the variations in R, τ, and $P_k^* A_k$

have different impacts on the adjustment of L_u. This further indicates that the change of the tradable sector involves complicated and intertwined issues like agglomeration economy, regional trade development, and the economic rent of CRN.

3. CRN Economic Rent and Adjustment of Urban Production Structure

3.1. Construction of Variables and Indicators. The statistical samples are selected from 277 cities in China. The original data from 2003 to 2018 are from China Urban Statistical Yearbook, Wind database, and China Stock Market & Accounting Research Database. According to the ruling period of the two central governments, the statistical process is divided into two stages, 2004–2011 and 2012–2018. The Economic rent of CRN reflects the government intervention. Government intervention is measured by the ratio of fiscal expenditure to fiscal revenue (FEFR) in this paper. If there is a bigger FEFR in the city from 2004 to 2011, it means that the greater the government intervention, the greater the economic rent of CRN. The other covariates (urban features) are geographical location, income endowment, financial status, urban size, and agglomeration, and the specific construction process is shown in Table 1.

Considering the availability of data and following the principle of statistical yearbooks, the tradable sector was divided into the following parts: mining; manufacturing; information transmission, computer services, and software industry; finance and insurance industry; geological investigation, water conservation, and management industry; transportation, warehousing, post and telecommunications industry; scientific research and integrated technology services; cultural, sports, and entertainment industry; and neighborhood service and other service industry. The nontradable sector was divided into the following parts: wholesale and retail trade; accommodation and catering; real estate; rental and commercial services; educational and cultural broadcasting; and social services and public management.

All variables of 277 cities are preliminarily counted, and the detailed results are shown in Table 2.

3.2. Ridge Regression. In order to overcome the endogeneity of the traditional regression model, ridge regression, a classical machine learning technology, is used to analyze the relationship between covariates and dependent variables. As a data-driven algorithm, the basic idea of ridge regression is to reduce the regression coefficient to zero, so as to minimize the sum of RSS of regression model and penalty, so as to select a better set of covariates. The estimated values of ridge regression coefficients are obtained by minimizing the following equation:

$$R = \sum_{i=1}^{n}\left[\left(L_i - C_0 - \sum_{j=0}^{13}\left(\beta_j X_{ij}\right)\right]^2 + \lambda \sum_{j=0}^{13}\beta_j^2, \qquad (14)$$

L_i is the employment ratio of the two sectors in the city i, X_{ij} is one of the features (shown in Table 2) in the city i, and λ is the tuning parameter. Minimizing formula (14) to get the estimated coefficient of ridge regression, the 10-fold Cross Validation is used to obtain the λ. After the variables are standardized, the change of MSE is shown in Figure 1. The figure on the left (MSE-A) describes the process of the ridge regression model in analyzing the data from 2004 to 2011, and the figure on the right (MSE-B) describes the data processing from 2012 to 2018. The minimum value of prediction model error is selected for Cross Validation, and estimation is shown in Table 3.

Best λ and MSE are small, and the empirical model of Ridge regression is effective. From the estimation of the whole sample in the whole period, the coefficients of FEFR ($X9$) are all negative, indicating that there is a linear correlation between the increase of government intervention and the declining share of tradable sector (nontradable sector increase), which indicates that China's economic rent of CRN has indeed affected the regional production structure. In fact, in the past 10 years, regional policy has become the main guiding ideology of China's high-level decision-making.

There is a nonlinear relationship between the productivity growth and production structure. In the initial stage, the coefficient of urban productivity growth ($X13$) is negative (−0.383,−0.403, and −0.307) and becomes positive later, which means that during 2004–2011, the rapid increase of urban productivity and the increasing share of nontradable sectors appeared simultaneously, but this short-term effect did not appear again in 2012–2018. This indirectly shows that the economic rent generated by China's regional policy can promote the growth of less-developed regions and employment in nontradable sectors in the short term, but in the long run, the productivity growth of nontradable sectors is relatively slower, and the growth of developed regions with higher proportion of tradable sectors will be higher, which leads to the complex convergence in different regions.

On the interaction term, FEFR×Income endowment ($X9 \times X3$) and FEFR×Productivity growth ($X9 \times X13$) are negative. Specifically, the impact of one unit of productivity improvement on production structure (tradables/nontradables) is $-0.017 \times \mathrm{X9}$ and $-0.030 \times \mathrm{X9}$. Therefore, the more the government intervention, the higher the nontradable share.

4. Robust Analysis from CRN Gravity Flows

In order to make the results in the previous section more robust, we use the method of combining urban gravity flows and social network analysis (SNA) to carry out further analysis. This statistical technology of SNA can effectively solve the endogeneity of linear model, especially the endogeneity of mutual causality. Mainly, we construct a new Gravity model to obtain direction data.

Table 1: Description of indicators.

Variable	Specific indicators	Construction details
Geographical location	North or south areas ($X0$)	Taking qinling_huaihe river as the boundary, the cities in the north and the south are divided, with 0 for the north and 1 for the south.
	Region ($X1$)	According to China's traditional four regions, the cities in the eastern region are set as 4, the cities in the northeast are set as 3, the cities in the central region are set as 2, and the cities in the western region are set as 1.
	Port ($X2$)	The port city is set as 4, other cities in coastal provinces are set as 3, cities in central and northeast China are set as 2, and other cities are set as 1.
Income endowment	The initial level of regional economic development ($X3$)	Natural logarithm of GDP per capita in 2003.
Financial status	Credit growth ($X4$)	Expressed by the growth rate of loan scale.
Human capital	Scale and proportion of college students ($X5$)	Divide the number of university students and the total population of the city at the end of the year, and then take the logarithm.
Transportation condition	The volume of freight transport ($X6$)	Logarithm of highway freight volume.
Investment	Investment in fixed assets ($X7$)	Logarithm of total investment in fixed assets of the whole society.
Urban scale growth	Construction land growth ($X8$)	It refers to the growth rate of the horizontal projected area of the land enclosed by the construction land boundary determined by the administrative department of urban planning.
Government intervention	FEFR ($X9$)	It is expressed as fiscal expenditure divided by fiscal revenue.
Urban size	Population ($X10$)	Measured by the population of the municipal district, then getting logarithm.
Agglomeration	Specialization ($X11$)	The proportion of the population in the industry with the largest number of employment in the total employment, that is, $VI_m = \max_n (p_{mn})$; here, p_{mn} is expressed as the employment proportion of sector n in city m.
	Diversification ($X12$)	The reciprocal of Hirshman herfindahl index, that is, $WI_m = 1/\sum p_{mn}^2$
Productivity growth	Per capita GDP growth rate ($X13$)	GDP per capita of this year/GDP per capita of last year.
Production structure	Ratio of tradable production sectors to nontradable production sectors (L)	Employment in tradable sectors/employment in nontradable sectors.

Table 2: Basic statistical description.

Variable	N	Mean	sd	Median	min	Max	se
$X1$	277	2.542	1.232	2	1	4	0.074
$X2$	277	2.318	0.978	2	1	4	0.059
$X3$ (YUAN)	277	11167.702	8317.554	8628.74	2373	47693	500.658
$X4$	277	1.173	0.026	1.174	1.103	1.276	0.002
$X5$	277	154.222	200.571	82.591	1.533	1169.47	12.051
$X6$ (10000 ton)	277	6891.56	5878.329	5332.5	678.625	52693.375	353.195
$X7$ (100 million)	277	911.6201.348	9373978.262	5979325.914	71.196	6997.831	563227.767
$X8$	277	1.18	0.634	1.069	0.93	7.665	0.038
$X9$	277	2.595	1.369	2.217	0.95	9.229	0.082
$X10$ (10 thousand)	277	146.825	173.504	98.881	19.473	1405.829	10.425
$X11$	277	0.303	0.105	0.274	0.126	0.718	0.004
$X12$	277	6.649	2.045	6.816	1.923	21.241	0.087
$X13$	277	1.131	0.025	1.132	1.049	1.219	0.002
L	277	1.057	0.619	0.905	0.291	3.776	0.037

Note: these data are raw data without logarithmic processing.

4.1. Statistics on Gravity Flows. In CRN, complex flow links have been formed by the complicated trade network, traffic network, and people-to-people interactions between cities. The flows in CRN are a composite form of people flow, logistics, and capital flow. Therefore, it is reasonable to adopt the gravity model to analyze the evolution trends of CRN's flow changes and spatial relational structure. Referring to the handling of the gravity model by Kolaczy and Csárdi [21], and Liu et al. [22], this paper derives from the above basic theories that the CRN flows are affected by PPP π, city scale Q, city distance d, and employment ratio l of the two sectors.

Then, the gravity flow from city j to city i in CRN can be expressed as

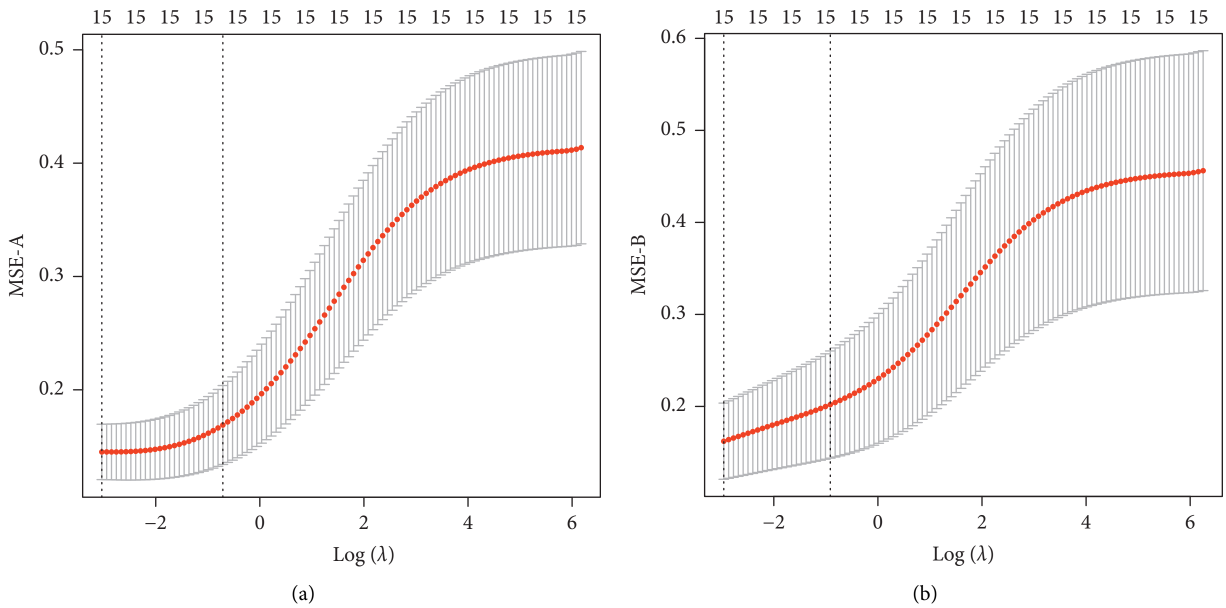

Figure 1: Relationship between tuning parameter and test error.

Table 3: Ridge regression result.

	2012~2018			2004~2011		
(Intercept)	−1.336	−1.243	−1.330	−1.501	−1.383	−1.521
*X*0	−0.098	−0.099	−0.098	−0.192	−0.201	−0.199
*X*1	0.006	0.006	0.006	−0.001	−0.002	−0.001
*X*2	−0.014	−0.015	−0.015	−0.041	−0.045	−0.044
*X*3	0.259	0.261	0.257	0.298	0.308	0.302
*X*4	−1.670	−1.685	−1.672	1.436	1.474	1.492
*X*5	0.029	0.028	0.029	0.060	0.060	0.060
*X*6	0.081	0.078	0.080	0.021	0.020	0.022
*X*7	−0.067	−0.069	−0.068	−0.120	−0.133	−0.133
*X*8	0.012	0.013	0.013	0.010	0.011	0.011
*X*9	−0.042	−0.010	−0.027	−0.078	−0.035	−0.049
*X*10	0.021	0.022	0.021	0.072	0.078	0.079
*X*11	3.746	3.742	3.743	1.776	1.799	1.802
*X*12	0.016	0.016	0.016	−0.082	−0.082	−0.083
*X*13	0.850	0.846	0.893	−0.383	−0.403	−0.307
$X3 \times X9$		−0.005			−0.006	
$X9 \times X13$			−0.017			−0.030
Best lamda	0.052	0.052	0.052	0.063	0.048	0.048
MSE	0.259	0.259	0.259	0.118	0.116	0.117

Note: All variables are taken as the average of the corresponding stage (2012–2018, or 2004–2011). Dependent variable is L. The Variables were standardized.

$$f_{ij} = \sigma_{ij}\frac{\left(l_i Q_i \pi_i\right)^{1/2} \cdot \left(l_j Q_j \pi_j\right)^{1/2}}{d_{ij}^2},$$
$$\sigma_{ij} = \frac{\pi_i}{\pi_i + \pi_j}, \tag{15}$$

where Q_i and Q_j are the scales of cities *i* and *j*, respectively, which are represented by population; π_i and π_j are the PPPs of cities *i* and *j*, respectively, which are represented by per-capita GDP; d_{ij} is the geographical distance between cities *i* and *j*, which is measured by the actual expressway distance between them on Baidu Map; σ_{ij} and σ_{ji} are CRN gravity coefficients, which reflect the contributions of cities *i* and *j* to the gravity flow f_{ij} between them, respectively. Through the use of gravity coefficient, gravity flows of CRN has directionality, which is defined the relational data in this paper. The advantage of relational data is more realistic because the flows of Beijing to Zhengzhou are obviously different from that of Zhengzhou to Beijing. In addition, social network analysis (SNA) is carried out through relational data, and the endogenous problem of regression is not considered.

Considering the availability of CRN data and the complexity of computation, 39 representative cities on different levels were selected from different regions to discuss the CRN of China: Beijing, Xingtai, Changzhi, Chifeng, Fuxin, Siping, Qiqihar, Shanghai, Yancheng, Suqian, Hangzhou, Lishui, Huainan, Putian, Pingxiang, Heze, Zhengzhou, Kaifeng, Wuhan, Huangshi, Changsha, Hengyang, Yongzhou, Guangzhou, Shaoguan, Shenzhen, Shantou, Nanning, Qinzhou, Chengdu, Zhangzhou, Zunyi, Kunming, Zhaotong, Xi'an, Weinan, Lanzhou, Tianshui, and Xining.

To capture the latest spatial correlations and sector restructuring laws of Chinese cities, this paper sorts out and models the CRN gravity flows of the 39 cities in 2003, 2011, and 2018, using 1482 gravity flow data each year. These 39 cities evenly divide Chinese cities into three development levels and even geographical distribution. The years 2003 and 2011 are the turning time for the adjustment of the central governments, respectively. Based on the data availability of existing variables, the latest is 2018. The basic data used to measure the CRN gravity flows were collected from *China Statistical Yearbooks* and *China City Statistical Yearbooks*, and processed by social network analysis (SNA) method. Table 4 presents the variables and their meanings

Table 4: Relevant variables.

Name	Abbreviation	Meaning
Employment structure of city *i*	lnemployment_*i*	Employment ratio between the two sectors in city i
Employment structure of city *j*	lnemployment_*j*	Employment ratio between the two sectors in city j
Scale of city *i*	lncitysize_*i*	Population of the districts administered by city i
Scale of city *j*	lncitysize_*j*	Population of the districts administered by j
Employment structure ratio between the two cities	lnemployment_*ij*	Employment structure of city *i* divided by that of city j
Distance between the two cities	lndistance_*ij*	Expressway distance between cities *i* and *j* on Baidu Map
Per-capita GDP ratio between the two cities	ln*gdp_ij*	Per-capita GDP of city *i* divided by that of city j
Gravity flow from city *j* to city *i*	$\ln f_{ij}$	$f_{ij} = \sigma_{ij}\left(\left(l_i Q_i \pi_i\right)^{1/2} \cdot \left(l_j Q_j \pi_j\right)^{1/2} / d_{ij}^2\right)$

involved in the empirical analysis. For the lack of space, the statistical results of these variables are not fully displayed. Any interested reader can contact the authors for the full results or the source code.

4.2. Gravity Flows and CRN. The processing of gravity flows is the core work of CRN analysis. The modeling and prediction of CRN topology were carried out mainly based on the ideas of Kolaczy and Csárdi [21] on SNA. The difference lies in gravity coefficient σ; a pseudo count was added to the flow data, making the latter more in line with independent Poisson's distribution; further, the Newton–Raphson algorithm was optimized to a certain extent.

Here, a CRN is represented by $G = (V, E)$. G is a directed graph, because each gravity flow is directed from the start point to the end point. The edges in G are also referred to as links. This research focuses on the start-end point matrix $F = [f_{ij}]$ composed of the gravity flows from node i to node j. This matrix is also known as gravity flow matrix.

In CRN, each directed edge was assigned a weight, which was calculated by multiplying each f_{ij} with 5 and then divided by the minimum value of $F = [f_{ij}]$. Since 39 city nodes on different levels were selected, there were $39 \times 38 = 1,482$ CRN gravity flows each year. The relations between the city nodes in 2003, 2011, and 2018 can be visualized as Figures 2–4, respectively. Note that the size of each circle reflects the total gravity flow of the corresponding city; the white and light blue parts of the circle represent the gravity inflow and gravity outflow, respectively; the link width stands for the flow from the start point to the end point.

Figures 2–4 show that, as time goes on, the inflow of gravity flow to cities in the south is generally better than that in the north, especially in cities with strong innovation ability and prosperous tradable sectors such as Shenzhen, Guangzhou, and Hangzhou, while the inflow to cities in the north is relatively weak, although some national central cities (such as Zhengzhou) performed well.

Judging by the size of the circles in CRN, central cities like Shenzhen, Guangzhou, Shanghai, Hangzhou, Xi'an, Zhengzhou, and Changsha had very large gravity flows, while the vast majority of central and western cities and other prefectural-level cities had very small gravity flows; the latter cities also faced a high share of outflow.

Among the cities with large gravity flows, Shenzhen had always maintained a very large flow. Hangzhou saw a gradual increase in the inflow-outflow ratio. The city achieves eye-catching gravity flow and economic vibrance as a result of its digital economic boom in the recent decade. The inflow-outflow ratio of Guangzhou decreased to a certain extent, which has much to do with the transformation and upgrading of traditional industries, and the replacement of low-end industries with high-end ones. Despite that, Guangzhou still boasted a large gravity flow. As a national central city, Zhengzhou had a relatively large gravity flow, but its inflow-outflow ratio first increased and then decreased. In recent years, the inflow-outflow ratio of Shanghai dropped a little bit. As for Beijing, the gravity flow was not as large as expected; an important reason is the high proportion of nontradable sector in the employment structure, especially the headquarters of central enterprises or public management departments of government organs; of course, there are some ambiguities about the statistical data of the parts of nontradable sectors.

5. Testing and Analysis of CRN Gravity Flow

The gravity flows obtained by formula (15) agree well with the city development in China. However, the gravity model f_{ij} needs more supports from theoretical and empirical tests. After all, it is not as naturally acceptable as Newton's law of Gravitation. Therefore, the MLE of independent Poisson's distribution was adopted to further test and correct the model.

To further quantify and correct the gravity flow model, this paper selects the MLE to derive that model. Similar to logistic regression, the MLE uses the IWLS method derived from the Newton–Raphson method. After the count form had been set, the CRN flow f_{ij} was assumed to obey independent Poisson's distribution. The mean function of f_{ij} can be defined as

$$\mu_{ij} = E\left(f_{ij}\right) = m_D\left(\phi_{ij}\right) m_S\left(c_{ij}\right). \tag{16}$$

Then, the benchmark log linear model with Poisson's distribution can be expressed as

$$\ln f_{ij} = \alpha_0 + \alpha_1 \ln m_D\left(\phi_{ij}\right) + \alpha_2 \ln m_S\left(c_{ij}\right), \tag{17}$$

where $m_D(\varphi_{ij})$ is the relative value of an economic variable between cities i and j (e.g., the per-capita GDP ratio $m_1(\varphi_{ij})$ and the employment structure ratio $m_2(\varphi_{ij})$; c_{ij} is a vector representing the separation attribute of the relationship between the two cities, e.g., distance or cost. To further highlight the CRN correlations and economic rent issue,

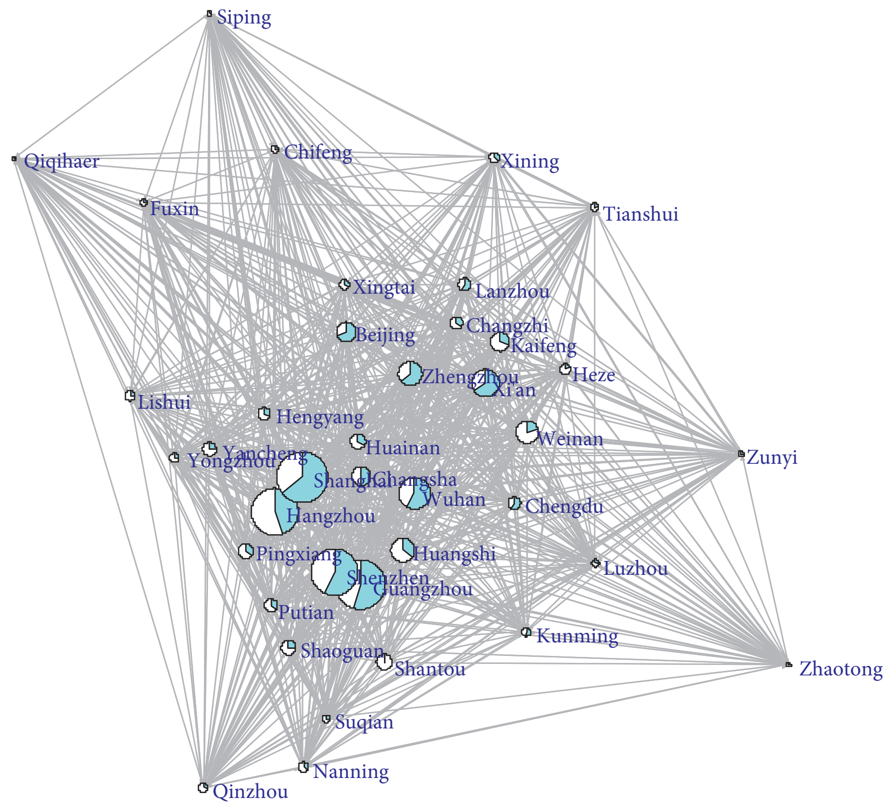

Figure 2: Visualized CRN gravity flows in 2003.

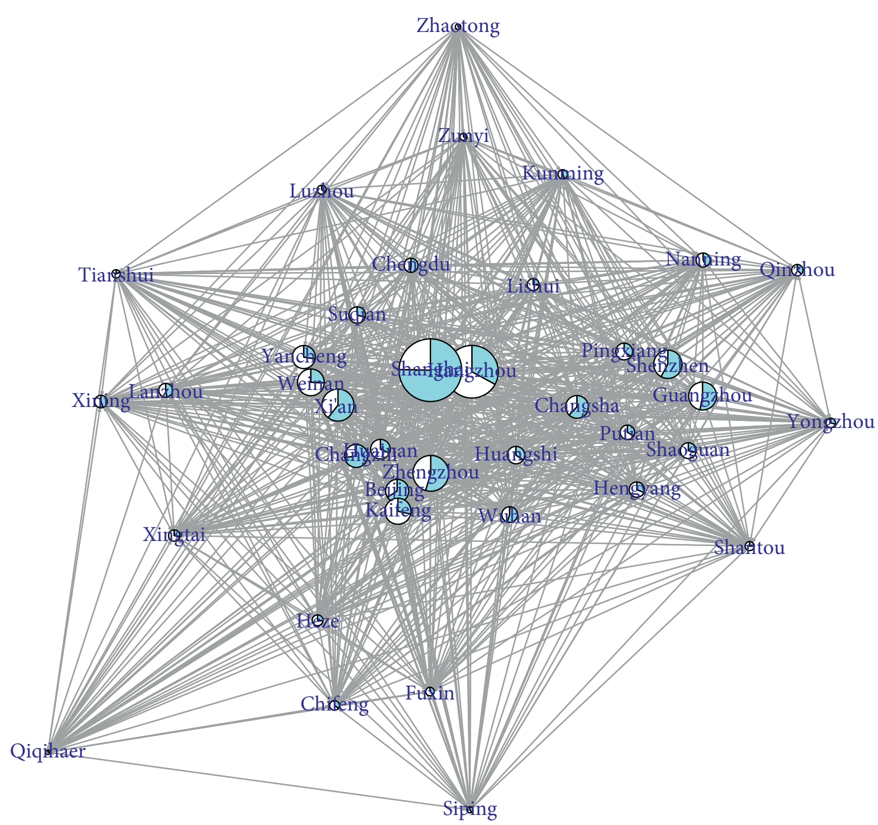

Figure 3: Visualized CRN gravity flows in 2011.

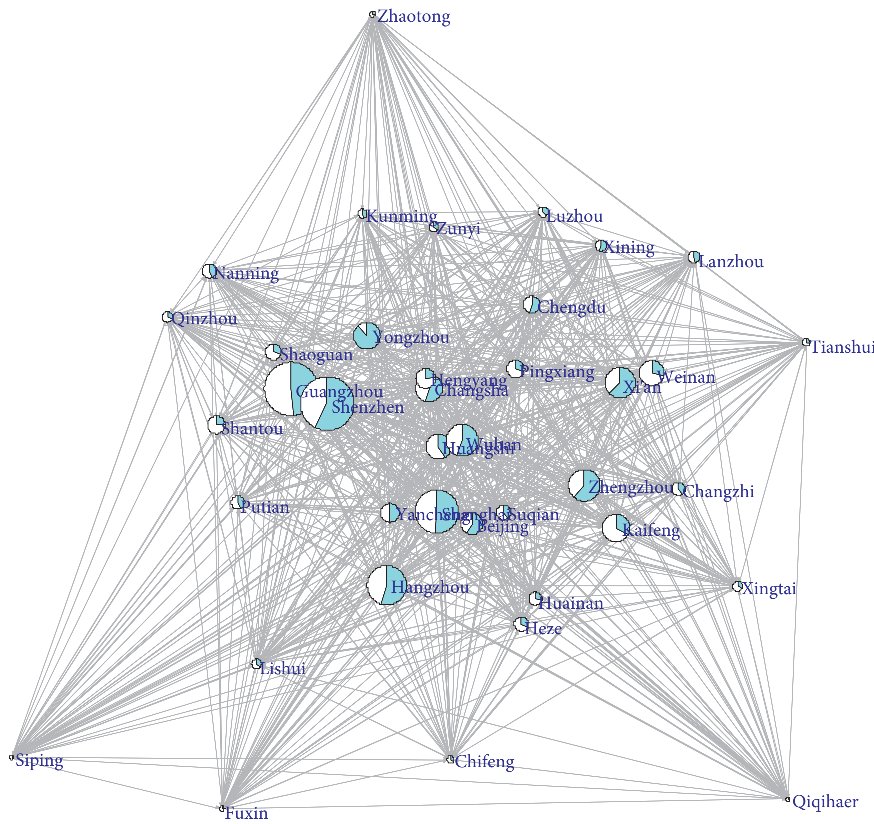

Figure 4: Visualized CRN gravity flows in 2018.

generalization is necessary to test the GRN gravity flow model, including the assumption of the independence between start point effect and end point effect. The generalized linear model can be expressed as

$$\ln \mu_{ij} = \ln h(i) + \ln h(j) + \beta_1 \ln m_1(\phi_{ij}) + \beta_2 \ln m_2(\phi_{ij}) + \beta_3 \ln m_S(c_{ij}), \tag{18}$$

where $h(i)$ and $h(j)$ are the attributes of economic variables of cities i and j, respectively. During the empirical test, these attributes were parametrized, such as taking the logarithms. Since f_{ij} is an independent variable with Poisson distribution and the mean of $\mu_{ij} = E(f_{ij})$, the most reasonable derivation approach is the MLE. Following the ideas of Poisson's distribution and MLE, the log-likelihood function in Poisson's distribution related to μ can be established as

$$\eta(\mu) = \sum_{i,j\in\ell\times\ell} f_{ij} \ln \mu_{ij} - \mu_{ij}. \tag{19}$$

Substituting formula (19) into formula (18), the MLE values of $h(i)$, $h(j)$, β_1, β_2, and β_3 can be obtained by making their partial derivatives zero. Then,

$$\widehat{\mu}_{ij} = \ln \widehat{h}(i) \cdot \ln \widehat{h}(j) \exp\left[\widehat{\beta}_1 \ln m_1(\phi_{ij}) + \widehat{\beta}_2 \ln m_2(\phi_{ij}) + \widehat{\beta}_3 \ln m_S(c_{ij})\right]. \tag{20}$$

According to the conclusions of Kolaczy and Csárdi [21], the unique solutions of $\widehat{\mu}_{ij}, \widehat{\beta}_1, \widehat{\beta}_2$ and $\widehat{\beta}_3$ can be estimated well under nonextreme conditions. Although $\ln \widehat{h}(i)$ and $\ln \widehat{h}(j)$ could be overparametrized and generate redundant degrees of freedom (DOFs), the core conclusions will not be affected, because the MLE approach of our model uses the IWLS method derived from the Newton–Raphson method (similar to logistics regression). In addition, internalities and multicollinearity were largely overcome by adopting the data on directed relations in our log linear model, as well as the IWLS method derived from the Newton–Raphson method in the glm () function of R language. Furthermore, the mean of per-capita GDP ratio between the two cities $\kappa_{ij} = E(gdp\_ij)$ was estimated under similar principles. The fitted results are listed in Tables 5 and 6.

Table 5: Results of generalized linear model for mean CRN flow.

Explanatory variables	$\ln\mu_{ij}$ (2003)	(2011)	(2018)
C	2.585*** (17.866)	2.529*** (16.638)	2.506*** (16.191)
lnemployment_i	0.061*** (3.534)	0.093*** (3.567)	0.094** (3.035)
lnemployment_j	0.051** (2.948)	0.068** (2.576)	0.075* (2.439)
lncitysize_i	0.144*** (11.007)	0.134*** (10.033)	0.151*** (10.555)
lncitysize_j	0.092*** (7.544)	0.101*** (7.764)	0.086*** (6.321)
lngdp_ij	0.019*** (3.909)	0.030** (3.068)	0.028** (2.753)
lndistance_ij	−0.161*** (−20.552)	−0.164*** (−20.847)	−0.163*** (−20.640)
DOF		1,481	

Table 6: Results of generalized linear model for per-capita GDP ratio.

Explanatory variables	$\ln\kappa_{ij}$ (2003)	(2011)	(2018)
C	1.272*** (5.985)	1.009*** (4.509)	1.156 *** (5.225)
lncitysize_i	0.117*** (9.160)	0.097*** (6.933)	0.118 *** (8.496)
lncitysize_j	−0.126 *** (−9.168)	−0.101*** (−6.928)	−0.127 *** (−8.596)
lnemployment_ij	0.062* (2.274)	0.098 ** (3.148)	0.068* (2.435)
lndistance_ij	0.001 (0.151)	0.001 (0.111)	0.0004 (0.042)
DOF		1,481	

Note: In Tables 5 and 6, "***," "**," "*," and "." represent the significance at the levels of 0.1%, 1%, 5%, and 10%, respectively; the bracketed numbers are Z-scores; Columns (2003), (2011), and (2018) report the generalized linear estimation results on each Poisson's distribution for 2003, 2011, and 2018, respectively.

The empirical results in Table 5 show that, among the estimations of the generalized linear model for mean CRN flow μ_{ij} each year, the coefficients of explained variables like city scale, distance, and employment structure were very significant. When the employment ratio of the two sectors in city i, i.e., the employment structure ln employment_i of city i, increased, the mean gravity flow from city j to city i would rise; When that ratio in city j increased, the mean gravity flow from city j to city i would rise, too, but by a much smaller amplitude. In 2003, 2011, and 2018, the coefficients of ln employment_i were 0.061, 0.093, and 0.094, respectively, while the coefficients of ln employment_j were 0.051, 0.068, and 0.075, respectively. However, the employment structures of the two cities had a common feature: with the elapse of time, the employment ratio of the two sectors contributed more and more to CRN gravity flow. This means developed cities with a high portion of tradable sector tend to witness a relatively fast growth of gravity flow. This trend became increasingly prominent in recent years.

According to the fitted results on mean per-capita GDP ratio in Table 6, the coefficient of distance, one of the three explained variables, was not significant, but the coefficients of CRN gravity flow and employment structure ratio were significantly positive. In 2003, 2011, and 2018, the coefficients of employment structure ratio were 0.062, 0.098, and 0.068, respectively. This directly supports the expectation that the productivity will grow relatively fast in cities with a large share of the tradable sector. For underdeveloped cities with a heavy presence of the nontradable sector, two results could be deduced: on the one hand, CRN economic rent could expand the scale of the nontradable sector, increasing its share in employment structure; since the products of this sector are not tradable, the overall productivity of the cities dominated by the nontradable sector will grow slowly than the cities with a large share of tradable sector; as a result, the regional development will converge at a slower speed. On the other hand, the rising productivity of the nontradable sector will reduce the prices in some parts in that sector; Thus, underdeveloped regions could not effectively expand urban employment scale solely by improving the productivity of the nontradable sector.

Next, we further test the reliability of the results and the performance of the model shown in Tables 5 and 6. The left subgraph of Figure 5 shows the relationship between the fitting value $\widehat{\mu}_{ij}$ of the generalized linear model (e.g. formula (18)) and the statistical CRN gravity flows f_{ij}. Because the dynamic range of the involved values is very wide, the two groups of data are processed in the form of double logarithm coordinates. Prediction effect of the model is better when CRN gravity flow is large,

The right side of Figure 5 shows the comparison between the relative error and CRN gravity flows, also using the double logarithmic coordinates. It can be seen clearly in the figure that $\log[(f_{ij} - \widehat{\mu}_{ij})/f_{ij}] \leq 0$ accounts for most of the proportion, that is, the relative error of model on CRN gravity flows is very small, and the relative error does not change greatly with the CRN gravity flows. This means that it

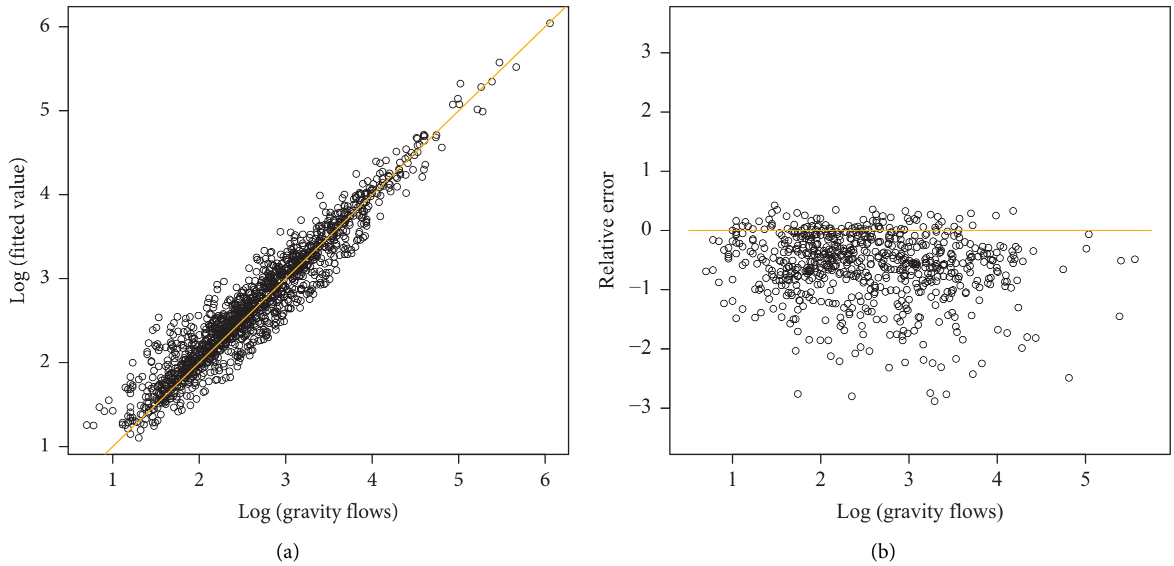

Figure 5: Model error on CRN gravity flows. Note: The abscissa uses natural logarithm, and the solid line reference system distribution of the left and right figures is $y = x$ and $y = 0$, respectively.

is effective to analyze the structure adjustment and regional development of China's urban production sector by using the New Gravity model.

6. Conclusions

In China, the policies on new urbanization and balanced regional development have created a highly interactive network between people flow, logistics, and capital flow. Against this backdrop, a CRN gravity flow model was constructed through a social network analysis on the gravity flows between Chinese cities in different regions and on different levels, coupled with the data on other directed relations. The authors drew the following conclusions:

First, this paper establishes a statistical model of CRN gravity flows with the characteristics of urbanization in China, and proves the effectiveness of the model in analyzing the correlations and flow trend of CRN. Unlike traditional gravity models centering on population or per-capita GDP, our new gravity flow model includes novel variables like the ratio between the two sectors and the gravity coefficient. Besides, a generalized linear model was built on the data of directed relations for fitting. The estimated coefficients of the model were very significant, and the relative error was reasonable.

Second, the slowing convergence of regional development in China is directly driven by the relative adjustment of the production sector: the proportion of the tradable sector continues to increase in developed cities, while that of nontradable sector keeps growing in redeveloped regions. Compared with underdeveloped cities, developed cities have a high share of the tradable sector, a fast-growing CRN gravity inflow, and a rapid increase of productivity; these advantages became increasingly obvious in recent years. This paper offers sufficient theoretical and empirical statistics about the close correlation between the gravity inflow of a city and the employment ratio of that city, i.e., the ratio between the two sectors. Based on the relevant data, the coefficients of the employment ratio were 0.061, 0.093, and 0.094 in 2003, 2011, and 2018, respectively; the coefficient increased clearly over time. Therefore, underdeveloped regions could not effectively expand urban employment scale solely by improving the productivity of the nontradable sector.

In recent years, the accelerated urbanization process in China has brought about complex changes to the people flow, logistics, and capital flow in CRN. The spatial correlations bred by CRN economic rent have moved beyond the research scope of nearest neighbor distance in new economic geography or spatial econometrics. Therefore, our new CRN gravity flow model can effectively process directed flows and optimize the relevant algorithms, greatly promote the construction of equal and high-quality cities for all residents, and provide the theoretical foundation for coordinating regional development and pursuing collaborative development of future smart cities. Despite selecting 39 representative cities in a well-connected CRN, this paper does not consider a massive amount of data network maps (e.g., degree centrality, betweenness centrality, and closeness centrality). At present, this model can only consider the special CRN in China. Next, we will discuss the feasibility of this model using more data from more countries.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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Research Article

A Beacon of Space and Time: Detailed Depiction of Human Space in the Xiong'an New Area Guided by Material Cultural Heritages

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In April 2017, the Chinese government announced a plan to establish a national new district: the Xiong'an New Area (hereinafter referred to as Xiong'an). Xiong'an plays a major role in optimizing the layout of Beijing-Tianjin-Hebei city cluster, promoting the rapid development of regional cities and cultivating new drivers of innovative economy. As a result, Xiong'an is recognized in China as a millennium plan and a project with national significance. At this time, the scientific and forward-looking preliminary research work from more different fields will become important support to ensure the healthy development of Xiong'an. Taking the material cultural heritages of Xiong'an as a beacon, this paper makes a detailed depiction of the forms and features of the human space in Xiong'an in different stages during the ancient times. Multiple instruments were combined to realize the depiction, including archeological methods, geographical methods, and sociological methods. The results show that, on the vast North China Plains, with Baiyangdian Lake as the center, different social, political, and cultural factors have a huge impact on the social conditions, humanities activities, and heritage survival. Finally, based on the existing heritages, a visual projection was established between the ancient human space and the spatial distribution of potential heritages and used to predict the probability distribution of potential heritages in Xiong'an. The research results provide a scientific and forward-looking guide for the protection of material cultural heritages in the upcoming massive construction of Xiong'an.

1. Introduction

1.1. The Xiong'an New Area. In April 2017, the Chinese government announced a plan to establish a national new district: the Xiong'an New Area (hereinafter referred to as Xiong'an) [1]. Lying at the heart of Central Hebei Plains, eastern China's Hebei Province, Xiong'an is located right at the center of the triangle between Beijing (political center of China), Tianjin (economic center of northern China), and Shijiazhuang (seat of Hebei Province) (Figure 1). It is the hub of transport and functional, economic, and cultural exchanges between the three cities. The planning and construction of Xiong'an have profound realistic and historical significance for redistributing Beijing's noncapital functions, renovating the development model of populous economic-intensive areas, optimizing the layout and spatial structure of Beijing-Tianjin-Hebei urban cluster, cultivating innovative drivers of economy, and promoting the rapid development of regional cities [2]. On a larger scale, Xiong'an plays a major role in perfecting and balancing the layout and development of the three dominant urban clusters in China: Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta [3]. That is why Xiong'an is recognized in China as a millennium plan and a project with national significance [2].

Xiong'an has a unique geographical environment. It is situated at a core area to the east of the Taihang Mountains, where the alluvial fan of the Daqing River converges with that of the Hutuo River [4]. The landform is dominated by plains, basins, and depressions. There are two large depressions in Xiong'an, namely, Baiyangdian and Wen'an (Figure 1). The rivers and lakes form a continuous corridor of wetlands [5], including the east-west transverse tributaries of the Daqing River and the large lakes from Baiyangdian to Wen'an in the middle and lower reaches of the river (e.g.,

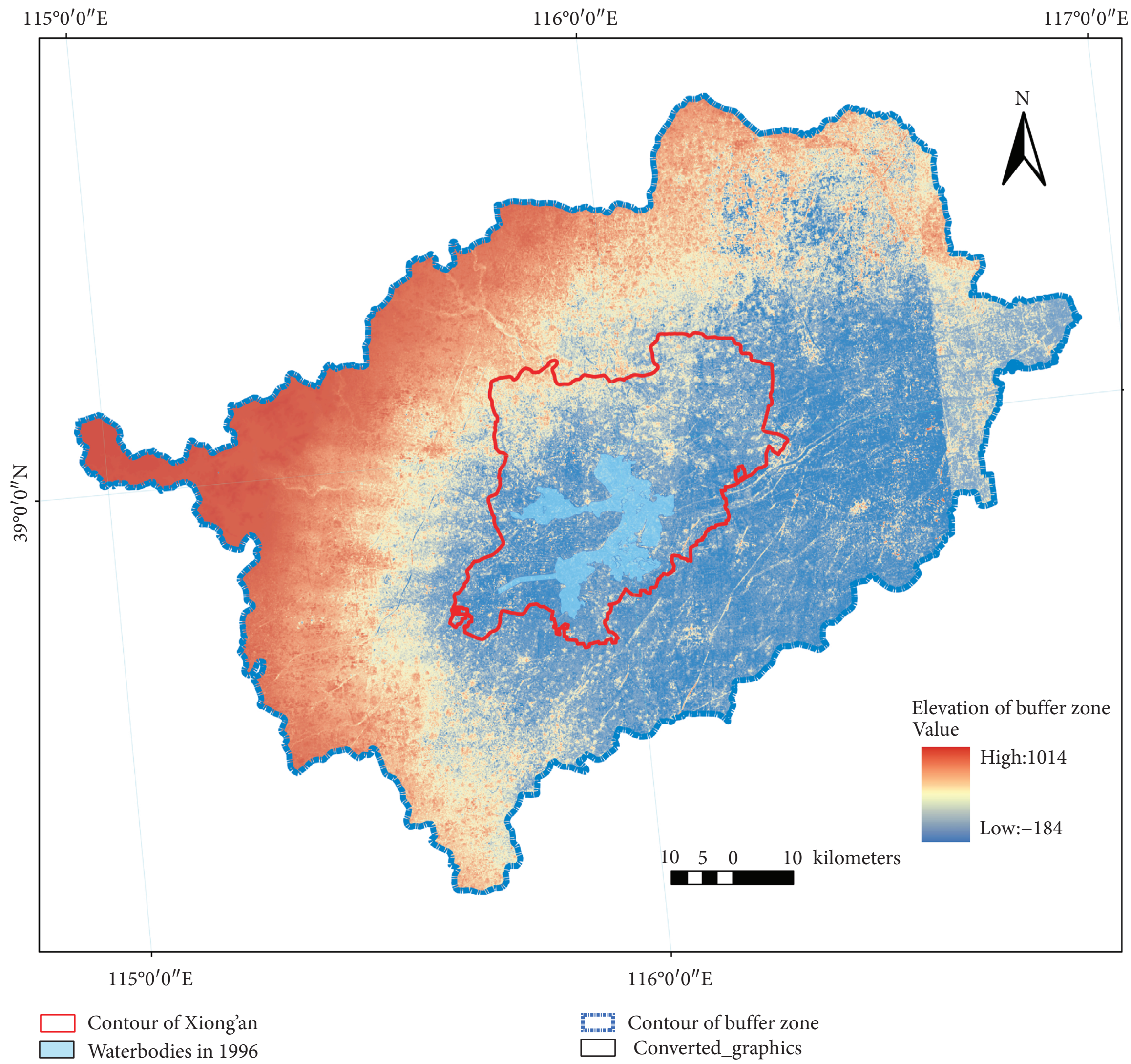


Figure 1: Topographic map of Xiong'an and its surrounding buffer zone.

Baiyangdian Lake, Wuguan Lake, and Desheng Lake). In the flood season, the flood water cannot be easily discharged in this corridor, causing frequent floods in history [6]. Therefore, the wetland corridor becomes a natural barrier to the north-south traffic in the Central Hebei Plains.

On the microscale, Xiong'an belongs to the north of Baiyangdian Depression. With an elevation of about 7–19 m, the entire area can be divided by the Rongcheng-Xiongxian line into the northwest highland and the southeast lakes and depressions (Figure 2). The southern margin of the northwest highland surrounds the northern Baiyangdian in three directions along the line from Anxin and Rongcheng to Xiong'an; the southeast lakes and depressions mainly refer to Baiyangdian Lake and a part of Wen'an Depression, which are crisscrossed by many ancient river channels and linear high banks [7].

From the perspective of time, the core of the geographic environment of Xiong'an is how the plains and depressions interact with the water in Baiyangdian. The evolution of the lake provides an important clue for the mesoscale shaping of the human space variation in Xiong'an. In the late early Holocene (10,000–7,500 years ago), the ancient Baiyangdian gradually appeared and went through several cycles of expansion and shrinkage. Eventually, the contiguous water area was reduced into the multiple small waterbodies today [8] (Figures 3(a)–3(c)). As a result, early humans had the chance to enter the realm of the ancient Baiyangdian. In the following thousands of years, Baiyangdian expanded and shrank several times. The lake dried up in Han Dynasty and reappeared later. In general, the water area continued to reduce. In the 1990s, the water area variation of Baiyangdian was accurately captured by the emerging satellite mapping technology. The data show that the water area of the lake is greatly affected by basin management and natural rainfall (Figures 3(d)–3(f)) [9]. Referring to the data, it is possible to perceive how the water area of the ancient Baiyangdian changed and understand the ensuing human-water interactions: when the water level drops, people occupy the exposed land; when the water level rises, people retreat to highland. Currently, the water area of Baiyangdian is basically stable, roughly the same as it was in 1996 (Figure 3(e)).

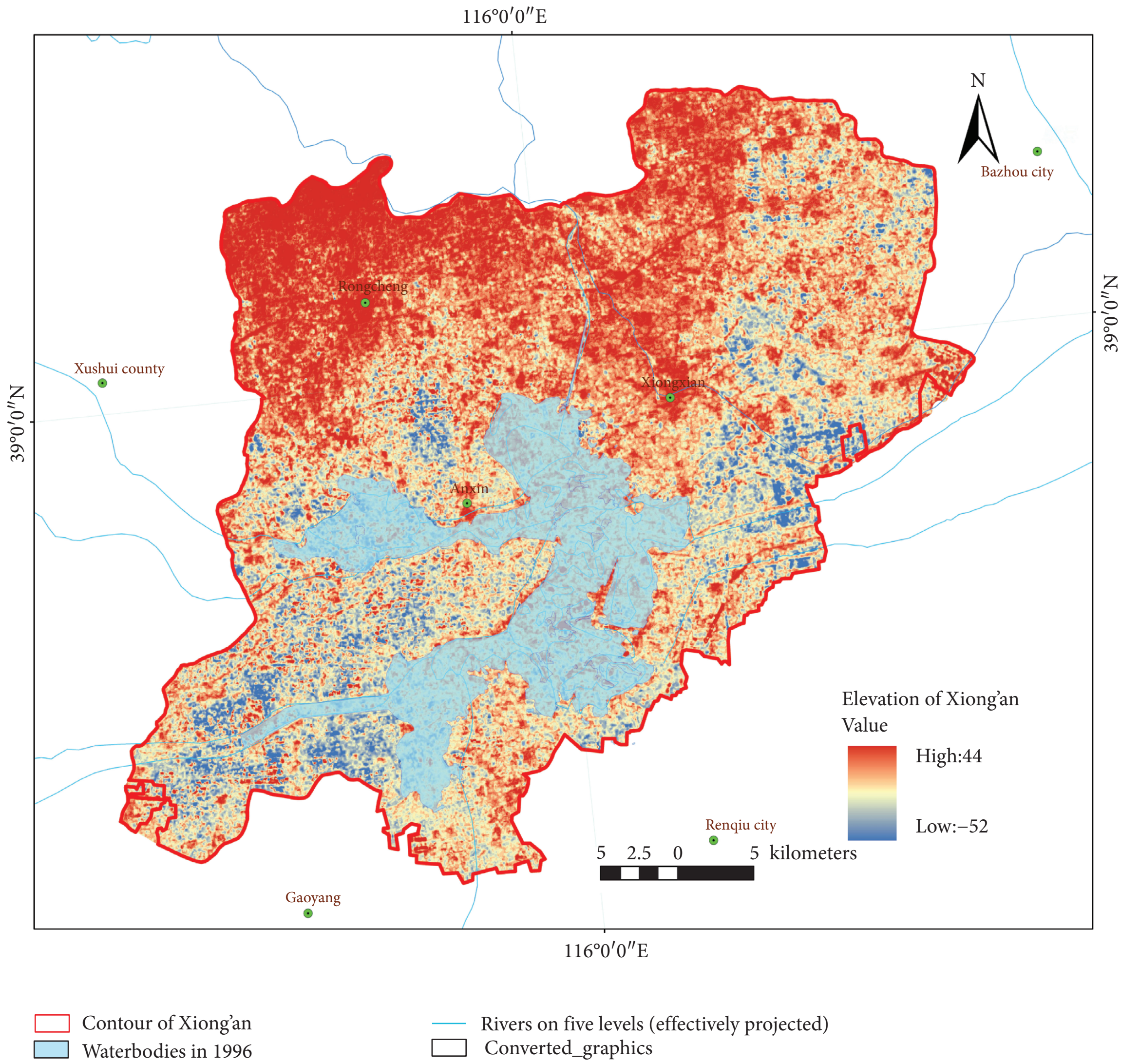


Figure 2: Topographic map of Xiong'an.

1.2. Problem Statement. Xiong'an covers a vast area: the startup area is about 100 km^2, the midterm development area around 200 km^2, and the long-term control area roughly 2,000 km^2. The magnificent planning and rapid construction are bound to reshape the geographic environment, urban structure, economy, and culture in the region fundamentally and quickly. Since the announcement of the plan, the government has been engaging in basic work like resource survey, afforestation, and river improvement in a prudent, systematic, and comprehensive manner, aiming to build a future city with high quality and standard [10]. Scholars also investigated and evaluated the evolution trend and sustainable development potential of Xiong'an, from the aspects of expansion and evolution of regional cities [11], simulation of urban function transfer [12], landscape Pattern Evolution [13], and evaluation of the ecosystem [14], which provided theoretical support for the future construction of Xiong'an. So far, the construction of transport infrastructure has been kicked off, including expressways and high-speed rails. In future, Xiong'an will enter the phase of large scale urban construction. At this time, the scientific, forward-looking, and comprehensive preliminary research work from more different fields will become important support to ensure the healthy development of Xiong'an.

Regarding the archeology of material cultural heritages, the government has clearly defined the principle of "archeology first, groundbreaking second." Archeological investigations in Xiong'an were initiated early in 2017. The material cultural heritages of the region have been extensively surveyed and excavated [15]. Scholars have conducted relevant studies in a larger scale of time and space from the perspectives of cultural evolution [16], types of artifacts [17], and distribution of settlements [18]. However, the existing studies mainly focus on the macro history of the North China Plains or specific heritages. There is no technical result on the scale of Xiong'an that accurately guides heritage protection and planning construction. In terms of depth, almost no scholar has discussed the relationship between complex social factors and heritage survival. This is attributed to the lack of effective analysis tools in the field of

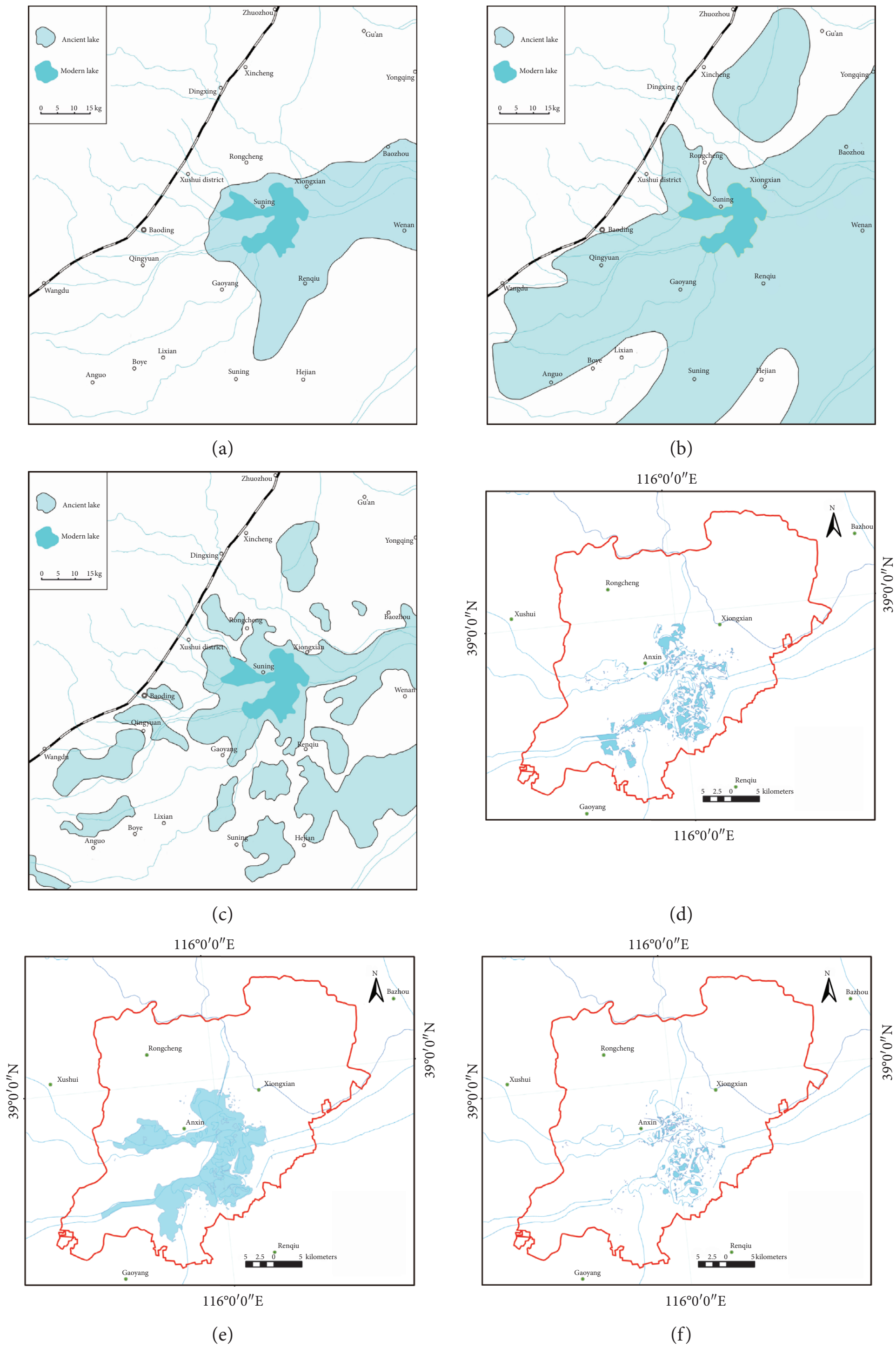


FIGURE 3: Water area variation of Baiyangdian. *Note.* Figures 3(a)–3(c) were plotted based on expansion and shrinkage of Baiyangdian in the past 10,000 years; Figures 3(d)–3(f) were plotted based on satellite images. (a) Baiyangdian revived in the early Holocene. (b) Baiyangdian expanded extremely in the middle Holocene. (c) Baiyangdian Lake disintegrated and shrank in the late Holocene. (d) Water area in 1992. (e) Water area in 1996. (f) Water area in 2002.

heritage protection. Heritage protection involves a lot of complex social factors. Some factors are quantitative, and some are qualitative. The traditional approaches of multi-factor relationship analysis, namely, correlation analysis [19], regression analysis [20], and structural equation [21], cannot easily handle complex sociological issues, which have a small sample size, multiple concurrent causes and consequences, and qualitative variables. The relationship between social factors and heritage survival is the combined result of multiple concurrent causes and consequences. That is, the same phenomenon might be generated along several different paths. The causality is not linear and correlated, but complex and syncretistic.

Researchers in other fields of sociology have long noticed the issue of multiple concurrent causes and consequences and developed the qualitative comparative analysis (QCA), which overcomes the limit of traditional statistical analysis. The QCA examines the relationship between conditions and consequences from the angle of set theory, draws the causality of the topic from a small sample set using the Boolean algorithm, and investigates the composite paths and impact intensities of the causes for complex social phenomena [22]. Liu et al. [23] further proposed the fuzzy set QCA (fsQCA), which breaks through the limitations of binary variable analysis and adapts well to the depiction of complex continuous variables. Since then, QCA and its related methods have been widely adopted in economic operation [24], social employment [25], and work policy [26]. If it is introduced to study the relationship between social factors and heritage survival, the QCA can effectively disclose the composite paths and impact intensities of the causes for complex social phenomena, facilitating the deduction of the spatiotemporal distribution law of potential heritages in Xiong'an under the effect of multiple factors. The latter issue needs to be solved urgently before the construction of Xiong'an.

1.3. Research Aim. Taking the material cultural heritages of Xiong'an as a beacon, this paper makes a detailed depiction of the forms and features of the human space in Xiong'an in different stages during the ancient times. Based on geographical and sociological theories, the authors attempted to establish a visual projection between the ancient human space and the spatial distribution of potential heritages and relied on the projection to predict the probability distribution of potential material cultural heritages. The research results provide a scientific and forward-looking guide for the protection of material cultural heritages in the upcoming massive construction of Xiong'an.

2. Research Scope, Data, and Methods

2.1. Research Scope and Data. The time span was defined as the period from the Neolithic Age to the founding of New China. The spatial range belongs to two scales: (1) the administrative region of Xiong'an, which covers all the material cultural heritages in the region, was taken as the core area to be meticulously depicted (Figure 2); (2) the area extending from the core area to the neighboring counties by roughly the same distance was defined as the buffer zone (Figure 1). On the mesoscale, the core area is suitable for high-precision depiction. The buffer zone, covering the macro distribution trend of broader heritages, makes up for the defects of the systemic deficiencies of the core area.

The data were prepared based on the latest archeological results of material cultural heritages in Xiong'an. At the same time, the Atlas of Chinese Cultural Relics [27] was taken as a reference to ensure the consistency and completeness of the macro-trend research of material cultural heritages in terms of statistical caliber and archeological depth.

2.2. Research Methods. Multiple tools were synthetized in this research, including methods of archeology, geography, and sociology. This section focuses on the QCA and the technical flow. Archeological and geographical methods were not introduced, as they are very common.

QCA. The QCA is a sociological research method proposed by the American sociologist C. C. Ragin in 1987. Drawing on the idea of the set theory, the QCA integrates the merits of traditional quantitative research and qualitative research and examines the composite paths and influence mechanisms of the complex factors affecting social phenomena [28]. Currently, four QCA methods are available for solving difference cases. Among them, fsQCA is a configuration analysis instrument based on the comparison of multiple cases [29]. It is often used to test the relationship between the dependent variable (outcome variable) and the combination of multiple specific conditions. The condition combination with the highest coverage and consistency is called the optimal combination. Each condition combination (outcome combination) reflects the influence of different combinations between conditional variables on the outcome, when a single variable does not constitute a necessary condition of the outcome. This method can recognize the common configuration between multiple cases and provide multiple equivalent paths for the same outcome, i.e., the multiple combinations between several equivalent antecedents that lead to the same outcome. The fsQCA applies to the cases with complex conditional variables that have complex values. The value ranges of these variables often contain a median and cannot be simplified as 0 or 1 [30]. This paper selects fsQCA as the analytic tool, in view of the complexity and qualitative values of the factors affecting the social evolution in Xiong'an in the ancient times.

By summing up the historical data, seven key factors affecting the development of each dynasty in ancient Xiong'an were selected as the conditional variables: population situation, location importance, war turbulence, business exchange, agricultural prosperity, folk culture, and water area. In addition, the social development and heritage number in the corresponding stage were taken as the outcome variables. After that, the conditional and outcome variables were subjected to six-level calibration and value assignments, according to the value assignment standard in Table 1 and the indirect calibration method. The optional values include 0, 0.2, 0.4, 0.6, 0.8, and 1 [31]. Next, the consistency and explanatory power of each variable were calculated by QCA. The consistency can be calculated by

$$\text{Consistency}\left(X_i \le Y_i\right) = \frac{\sum\left[\min\left(X_i, Y_i\right)\right]}{\sum X_i}. \tag{1}$$

The coverage can be calculated by [32],

Table 1: Fuzzy set values of each variable.

Variables		Signs	Values
Conditional variables	Population situation	PS	PS refers to the presence of regional population; PS is affected by two factors, namely, the population size and population stability of Xiong'an in each dynasty; the greater the values of the two factors, the closer the PS to 1; otherwise, the closer the PS to 0
	Location importance	LO	LO refers to the location level of Xiong'an in the state in each dynasty; LO is closely associated with the distance from Xiong'an to the central city cluster of the state and the status of Xiong'an in political, economic, war, and cultural activities of the state; the higher the location level, the greater the importance, and the closer the LO to 1; otherwise, the closer the LO to 0
	War turbulence	TU	TU refers to the extent of the impact of war on Xiong'an in each dynasty; in principle, the growing number, duration, and scale of wars have a rising impact on the society and create a greater turbulence; in this case, the TU approximates 1; otherwise, the TU approximates 0
	Business exchange	BU	BU refers to the commercial prosperity of Xiong'an in each dynasty; the index contains the state-to-state large border trade and the daily trade between civilians; the more prosperous the commerce, the closer the BU to 1; otherwise, the closer the BU to 0
	Agricultural prosperity	AR	AR refers to the agricultural development in Xiong'an in each dynasty; the better the development, the closer AR to 1; otherwise, the closer AR to 0
	Folk culture	CU	CU refers to the folk culture development in Xiong'an in each dynasty; the better the development, the closer CU to 1; otherwise, the closer CU to 0
	Water area	WA	WA refers to the water area of Baiyangdian; the larger the water area, the closer the WA to 1; otherwise, the closer the WA to 0
Outcome variables	Social development	SO	SO refers to the social prosperity of Xiong'an in each dynasty; the more prosperous the society, the closer SO to 1; otherwise, the closer SO to 0
	Heritage number	HN	HN refers to the number of heritages of Xiong'an in each dynasty; the more the number, the closer the HN to 1; otherwise, the closer the HN to 0

$$\text{Consistency}\left(X_i \leq Y_i\right) = \frac{\sum\left[\min\left(X_i, Y_i\right)\right]}{\sum Y_i}, \qquad (2)$$

where X_i is the degree of membership in set X; Y_i is the degree of membership in set Y; $(X_i \leq Y_i)$ is the subset relation in question; and "min" dictates selection of the lower of the two scores.

The necessary or sufficient conditions were examined for each variable, and the explanatory power of each condition for each outcome was measured. If consistency is greater than 0.9, the condition is a necessary condition of the outcome. If the fuzzy set score of the condition is smaller than that of the outcome and the consistency is greater than 0.8, then the condition is a sufficient condition of the outcome [33]. Coverage measures the explanatory power of a condition for an outcome. The greater the coverage, the more the explanatory power. Finally, the combination of conditions was analyzed, and the combination path of various conditions was comprehensively investigated.

Technical flow. The technical flow of our research can be summarized as follows. Guided by material cultural heritages, geographic spatial analysis [34] was supplemented by historical data and modern research results to visualize the state and trend of heritage distribution and depict the human space with a high accuracy. Next, QCA was performed to further analyze the necessity and configuration of the multiple factors that affect the ancient social development and existing heritage number in Xiong'an. Finally, based on the existing material cultural heritages, the spatial range of each type of potential heritages was calculated, using the theories of Kriging [35], spatial accessibility [36], and spatial relationship of settlements [37]. The time sequence and type probability of heritages were assigned by the QCA results, producing the final probability distribution of potential heritages. The main technical points and roadmap (Figure 4) are as follows:

(1) Archeology is a continuously updated dynamic process. The above probability distributions are all derived based on the current archeological information. With new discoveries in future, the distributions should be corrected and improved to approximate the truth.

(2) The social condition and behavior space of each type of heritages in each stage are the basis of prediction. The scope is determined in the following steps: taking each known heritage as the sign (dot or line), the mean spatial distance of the corresponding cultural behaviors is taken as the step length D. Then, the distance is expanded by D or $1.5\,D$ (the larger envelope scope) to estimate the scope of existence for adjacent potential heritages of the same type or correlated types. The heritage is the crux of the prediction for the distribution of each type of heritages. The prediction is particularly accurate based on the heritages before Qin dynasty, because they were not clearly divided into different types of heritage at that time.

(3) The probability, density, and level of the grid image are all positively correlated with the distance to cultural core (extremely high area of heritage density). Taking density as example, the denser the type

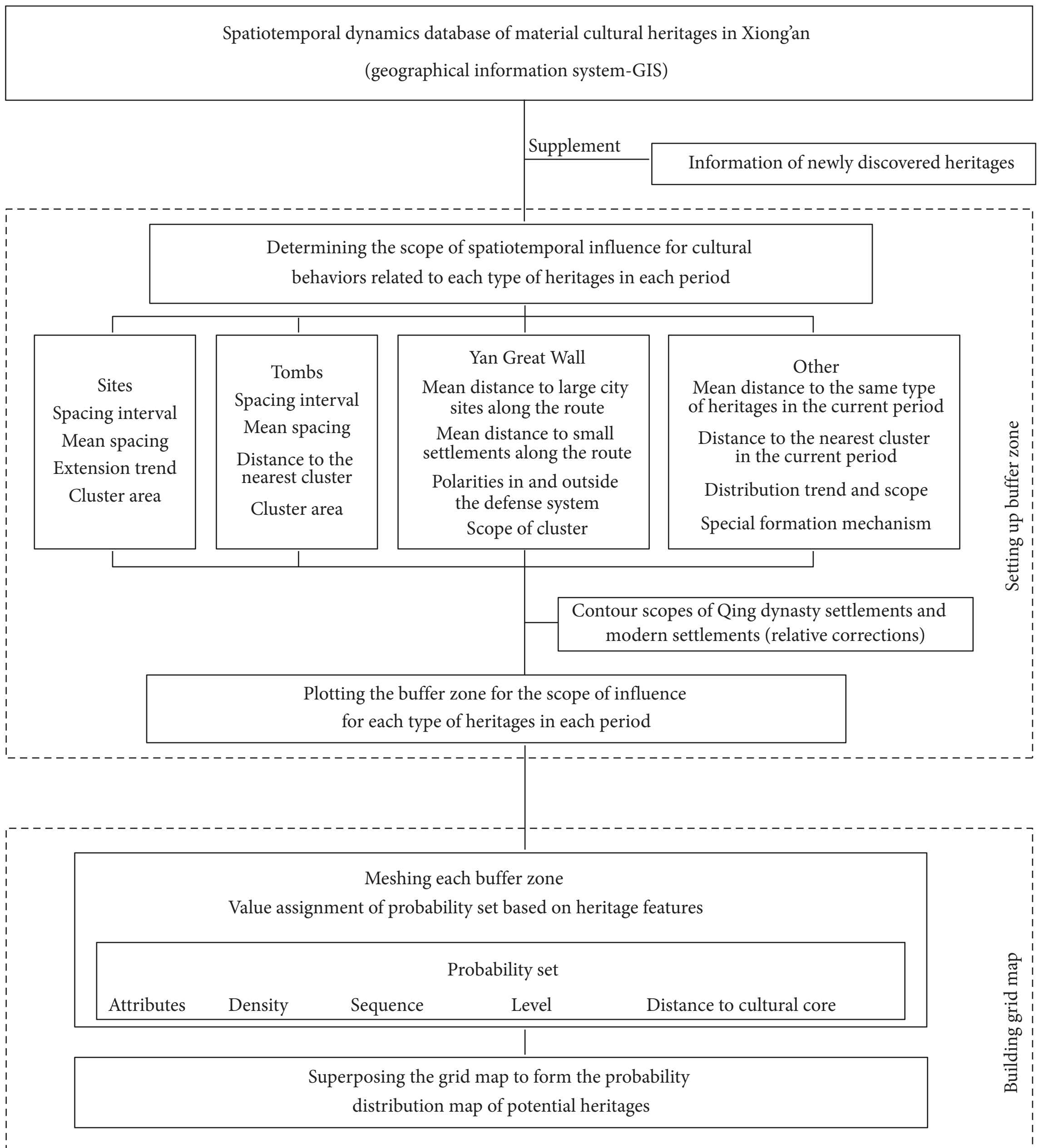


Figure 4: Technical roadmap.

of heritages in a period, the greater the probability of discovering potential heritages of the same type or correlated types in its surroundings. The time sequence and type probability of heritages were determined according to the factors affecting heritage number and the correlation between different types of heritages. The latter two were obtained through QCA.

(4) Because Qing Dynasty settlements well match modern settlements, the latter are adopted to assist the judgment of the distance from material cultural heritages (especially nonsite heritages) to adjacent settlement space. This facilitates the rough valuation of heritages under the lack of references.

3. Analysis

3.1. Statistical Analysis. The latest survey shows that Xiong'an has a total of 263 heritages, including 189 sites, 43 tombs, 15 ancient buildings, and 16 modern cultural relics. Besides, some heritages discovered in the last century but destroyed today are also included. Therefore, there are a total of 285 heritages in Xiong'an (Figure 5): 110 in Rongcheng, 85 in Anxin, and 90 in Xiongxian (Rongcheng, Anxin, and Xiongxian are three counties entirely or partly administered by Xiong'an). The latter two counties include the towns and townships under their administration.

As of 2019, Xiong'an had 3 national heritages, 9 provincial heritages, and 80 plus prefectural and county-level

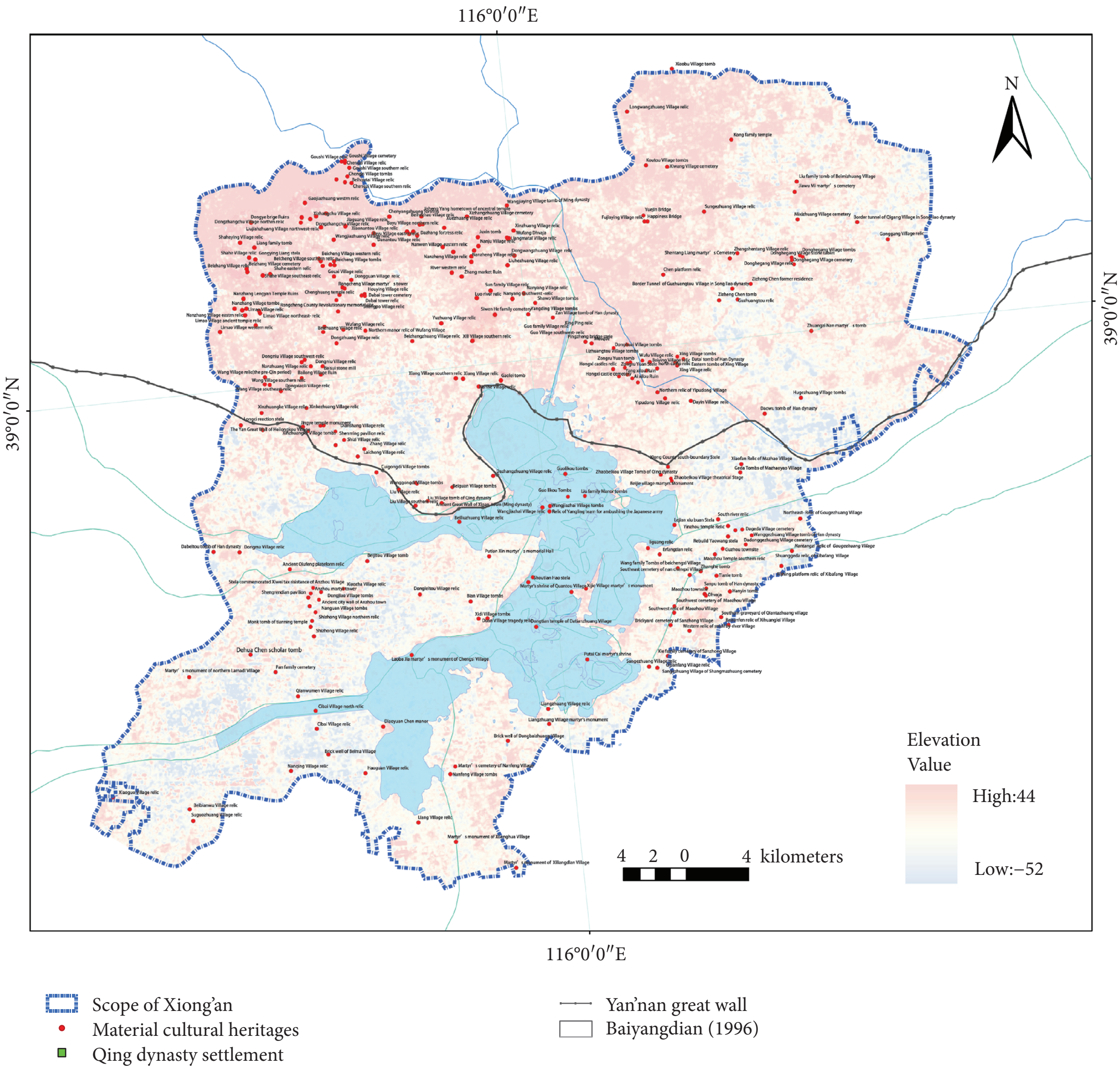


FIGURE 5: Distribution of material cultural heritages in Xiong'an.

heritages. These heritages mainly belong to sites, tombs, buildings, and revolutionary heritages. Most of them are sites (58%) and tombs (24%). The heritage distribution is basically the same in the three counties (Figure 6), a sign of the consistency in geography and culture. It is clear that Rongcheng boasts the largest number of sites, mainly because the high ground in the north is suitable for living.

With the elapse of time, the number of heritages oscillated significantly. Most of them were produced in the Spring and Autumn Period and Han Dynasty. Some were produced in Song Dynasty, Qing Dynasty, and the modern period. Very few were produced in Tang and Yuan Dynasties. The rest were produced in other periods (Figure 7). The time distribution density of heritages was slowly increasing, with local fluctuations. In modern times, numerous heritages were discovered in a short time. Without considering them, the time distribution density still rose in the modern period. Specifically, the number of material cultural

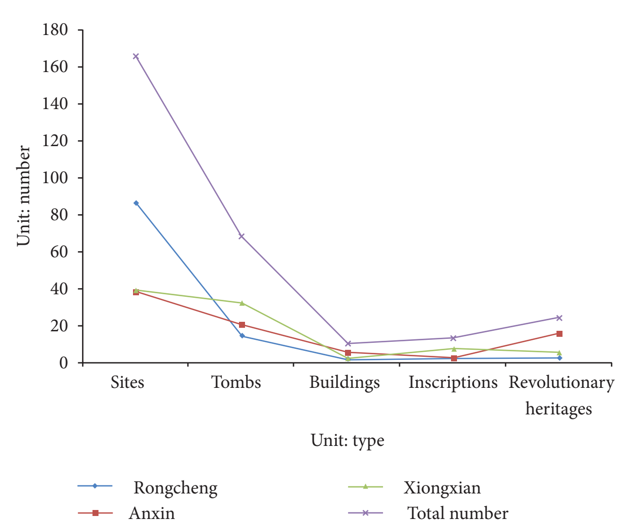


FIGURE 6: Number of material cultural heritages of each type.

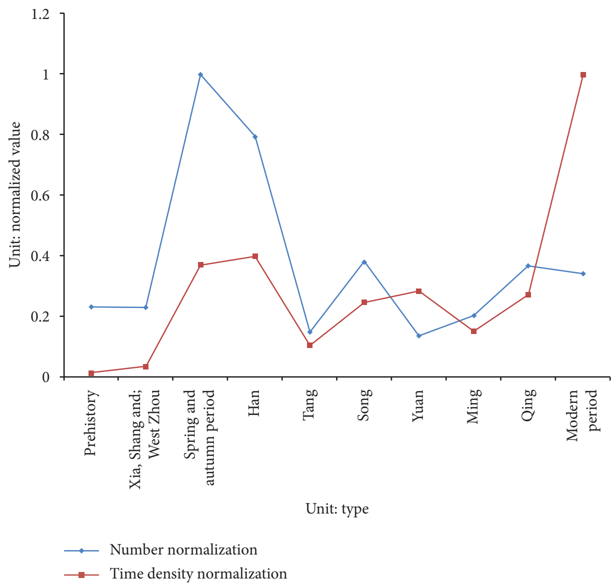


Figure 7: Mean time distribution density of heritages in each period (normalized).

heritages in Xiong'an remained stable and increased slowly before the East Zhou Dynasty, surged up from the Spring and Autumn Period to the Han Dynasty, nosedived in Tang Dynasty, steadily bounced back in Song Dynasty, slightly increased before plunging in Yuan and Ming Dynasties (in particular, Ming Dynasty had very few heritages, a stark contrast to its unification and vibrant culture; it is probably the result of the relatively small research scale), increased clearly in Qing Dynasty (a sign of advanced culture), and stayed at a moderate level in modern period.

3.2. Spatiotemporal Distribution. The heritages mainly concentrate in the northwest and middle parts of Xiong'an and almost encircle Baiyangdian Lake. Most heritages form three clusters, except a few scattered along the terrain or water surface in the northeast and south (Figure 8). The three clusters are as follows:

(1) There is a C-shaped cluster encircling the convex north margin of Baiyangdian Lake, which encompasses two belts of densely distributed heritages: the west belt starts from Rongcheng and spans to Dongxiaoli and Anxin in the south; the east belt extends from Rongcheng to Xiongxian in the east. This cluster is the core gathering area of material cultural heritages in Xiong'an. The two peak density nodes, namely, Rongcheng and Xiongxian, both fall in this cluster.

(2) There is also a medium density cluster centering on Mozhou Town, which lies on the east margin of Baiyangdian Lake.

(3) There is another dotted medium density cluster centering on Anzhou Town, which lies on the west margin of Baiyangdian Lake.

The three clusters are polarized in distribution trend. From the northwest to the southeast, the heritages exhibit a trend of integrating into Baiyangdian Lake; from the northeast to the southwest, the heritages are discretized at random. The superimposed elevation shows that the polarity is consistent with the lay of the land in Xiong'an. The above clusters agree well with the linear or dotted highlands.

On a small scale, individual heritages are attached to the relative highlands in the microscopic region. Only a few Han tombs appear in the low-lying areas of Baiyangdian Lake.

On a large scale, there are more heritages on the peripherals than in the middle of the buffer zone, except that the heritages are sparsely distributed in Gaobeidian and Gu'an in the north. The density distribution takes the shape of a bowl, i.e., high on the four sides and low at the center (Figure 9). However, the distribution is not continuous: an island-like area of ultrahigh median appears at the center of the bowl, and blank rings exist between the inside and outside. The island shape and symmetry of the ultrahigh median area indicate that Baiyangdian Lake, as the heterogenous element on the homogenous plains, exerts a cumulative disturbance to the normal social mode of Xiong'an, creating a unique cultural area. Judging by the type and distribution state of heritages, primitive heritages (Figure 10(b)), urban heritages (Figure 10(f)), and revolutionary heritages (Figure 10(g)) were the only types that made medium contributions. The other types of heritages made very little contributions. These three kinds of heritages are closely related to the attributes of Baiyangdian. The primitive heritages originated in the primitive society, thanks to the high elevation in the north of the lake; the urban heritages appeared as Xiong'an rose to prominence as a border trade hub during the Song Dynasty, because the Baiyangdian water system creates a natural border between Song and Liao; and the revolutionary heritages are the result of the fact that Baiyangdian is the only region in the Northern Hebei Plains that provides natural shelters for revolutionists. To sum up, the unique attributes and distribution pattern of heritages stem from the unique environment.

According to the sequence of evolution, the authors investigated the trend of the spatiotemporal distribution of heritages by drawing the ellipses of standard deviation [38] for the directional distribution of heritages in each and every stage, as well as the mean centers [39] (Figure 11). Throughout history, the ellipses cover the entirety of central Xiong'an. The superposition of the ellipses is close to a circle, with very weak polarity. This means the core distribution area of heritages is highly correlated with Baiyangdian Lake and testifies the fact that the polarities of heritage distributions in different periods cancel out each other after superposition. Therefore, important information could be covered up if the heritages of multiple stages are adhered together. To mine heritage information, a key prerequisite is to divide the history into multiple spatiotemporal slices.

The ellipses of different periods show significant differences in polarity and carry prominent features of the time.

In the Neolithic period, the ellipse is small and narrow and strongly skewed towards Baiyangdian Lake. In addition,

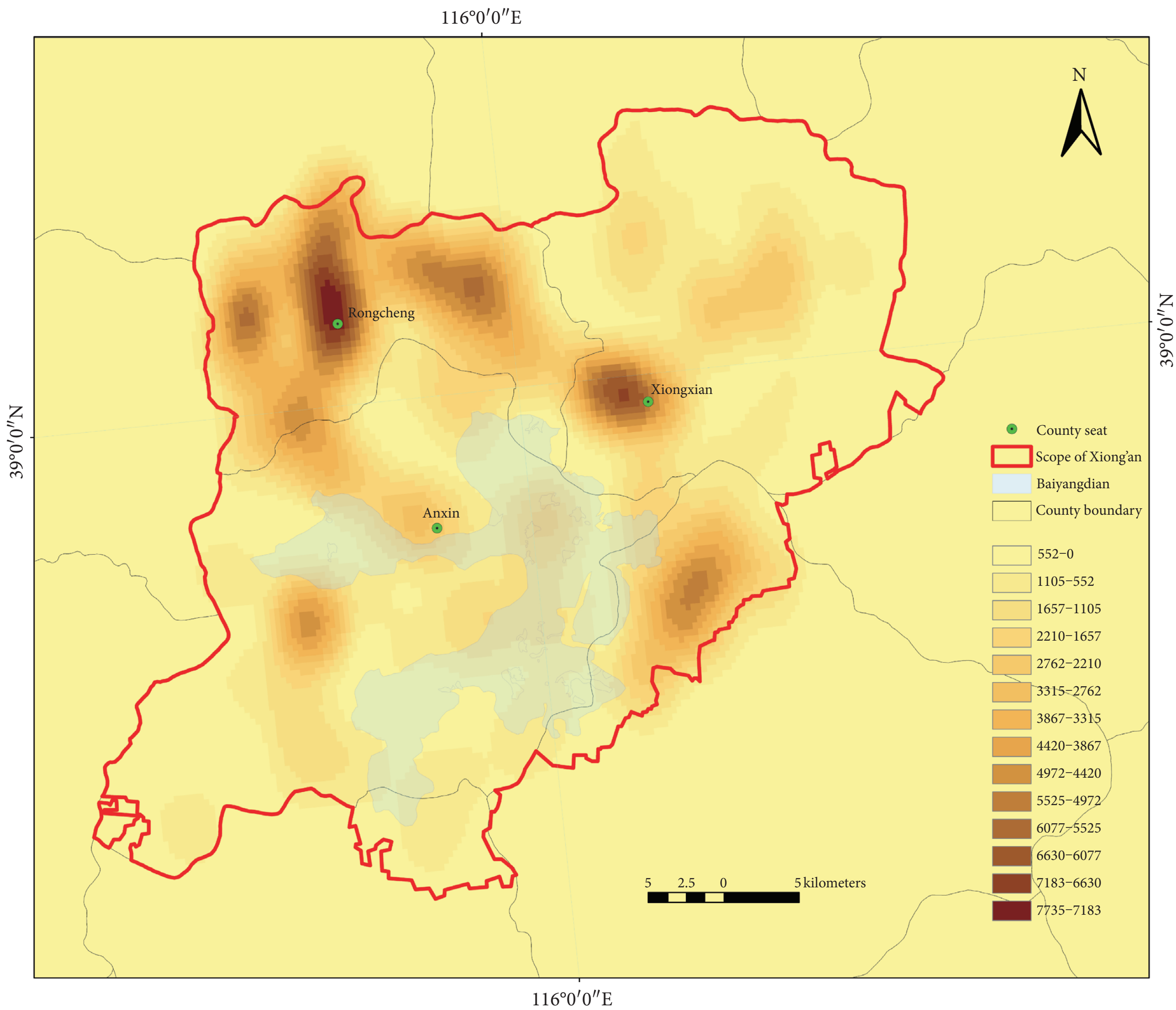


Figure 8: Density distribution of material cultural heritages.

it agrees well with the line from Rongcheng and Dongxiaoli to Anxin. The distribution center lies close to the Shangpo site in Rongcheng.

In Xia, Shang, and West Zhou Dynasties, the ellipse is of similar scale to that of the previous period. The location remains basically unchanged, still centering in Shangpo. However, there is a major change in directional polarity: the dominant axis becomes almost perpendicular to the northeast-southwest direction in the Neolithic period.

In East Zhou Dynasty, the ellipse expands and increases in directional polarity. The expansion takes place along the line from Rongcheng to Mozhou. The two places must have close correlations. The center of the ellipse is adjacent to Nanyang site.

In Han Dynasty, the ellipse expands significantly into a plump form, involving most of Baiyangdian Lake. The expansion in the east-west direction is further enhanced. The center shifts southward into Baiyangdian Lake, about 9 km to the then county seat (Guxian Village).

In Tang Dynasty, the ellipse has a moderate form but a rather large scale. From northeast to southwest, the ellipse spans across Baiyangdian Lake. The center moves to a place near downtown Anxin, which is related to the ultradiscrete distribution of heritages.

In Song Dynasty, the ellipse has a moderate form and a slightly smaller scale than that in Tang Dynasty. From northeast to southwest, the ellipse spans across the north and center of Xiong'an. The center falls at somewhere near the shore in the north part of Baiyangdian Lake, about 8 km to Xiongxian.

In Yuan Dynasty, the ellipse retreats to the northern highland of Xiong'an. The form is moderate, and major axis is in east-west direction. The center seems to be leaving Baiyangdian.

In Ming Dynasty, the ellipse is as plump as a circle, with a significantly reduced scale. However, it moves back to the hinterland of Xiong'an, centering at a similar place to the ellipse of Song Dynasty.

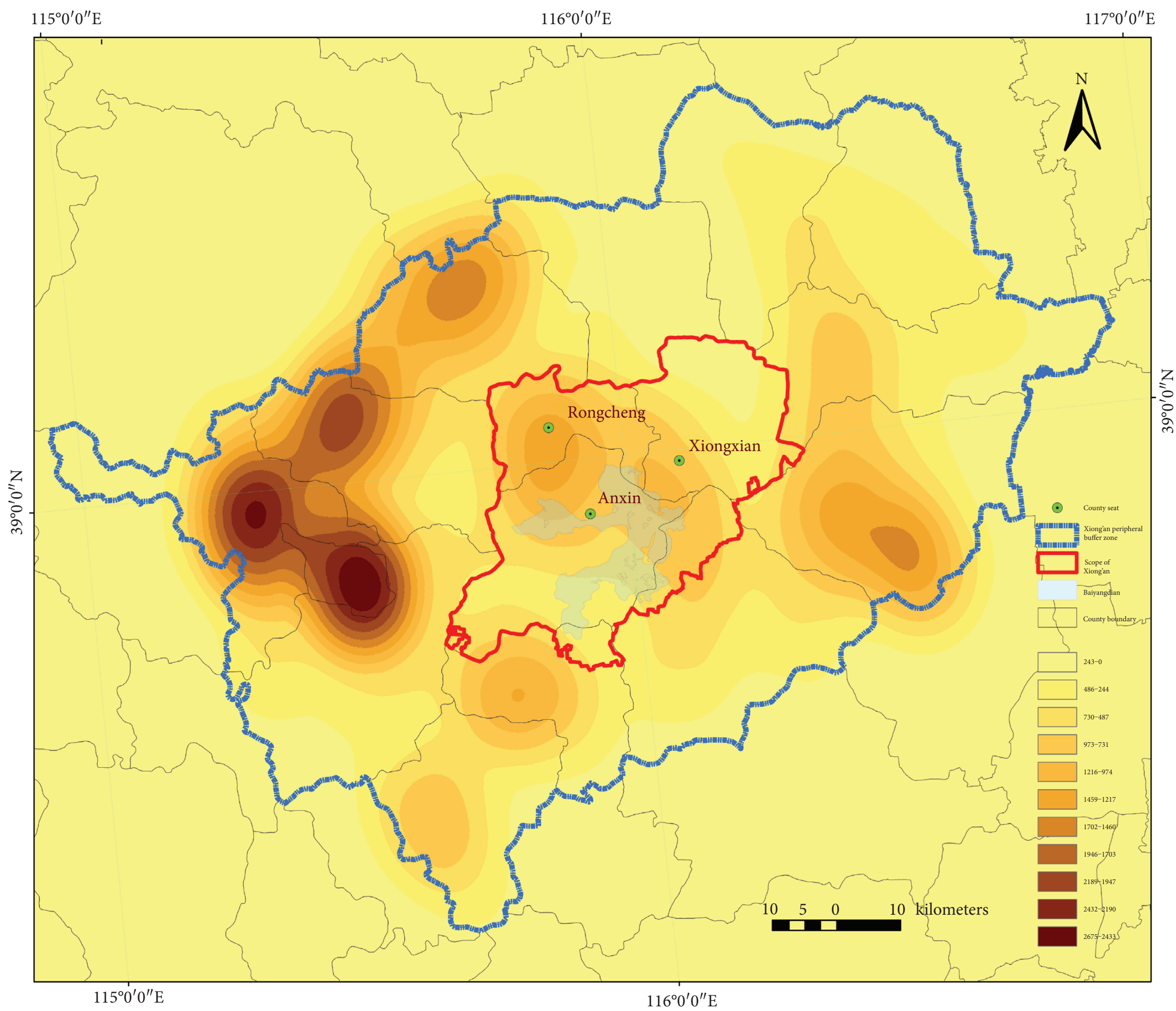
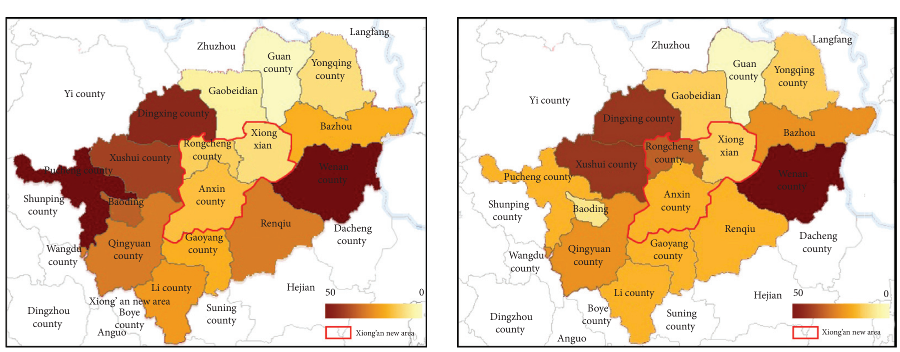


Figure 9: Density distribution of material cultural heritages in neighboring counties.



(a) (b)

Figure 10: Continued.

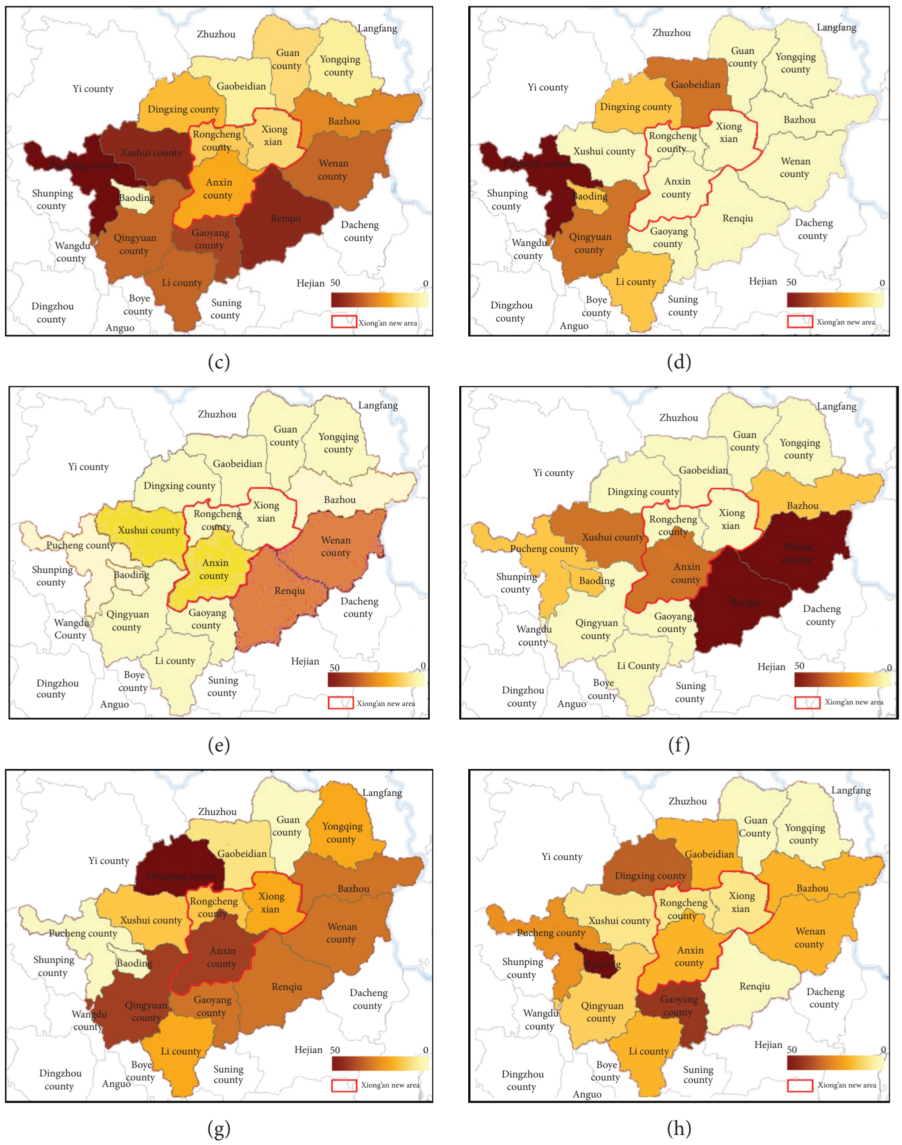


Figure 10: Number of heritages in and around Xiong'an. (a) All heritages. (b) Sites. (c) Tombs. (d) Bridges. (e) Inscriptions. (f) Cities. (g) Revolutionary heritages. (h) Buildings.

In Qing Dynasty, the ellipse has a moderate scale and polarity. The coverage is skewed slightly from the center to the northwest. The center moves close to the shores to the north of downtown Anxin.

During the Chinese People's War of Resistance against Japanese Aggression (hereinafter referred to as the War of Resistance), the ellipse is so large as to cover almost every inch of Baiyangdian Lake. The center lies deep in the lake. Moreover, the ellipse contour is highly in line with the water area.

3.3. Correlation Analysis. Referring to the local chronicles of Qing Dynasty and modern place names, the authors drew the distribution map of Qing Dynasty settlements. Besides, the contour map of modern settlements was plotted based on satellite images. Once the two maps were superimposed, it was learned that Qing Dynasty settlements are distributed similarly as the modern ones (except for being a little bit sparser in the northeast (Figure 12)), indicating that the pattern of modern settlements has been formed at least in the late phase of the reign by Emperor Qianlong.

In addition, the distribution patterns of material cultural heritages and Qing Dynasty settlements are very similar, but the latter fill up more blanks. Therefore, material cultural heritages mostly concentrate in the backbone area of densely populated settlements, proving the theoretical assumption that cultural activity is positively correlated with the probability distribution of settlements and population.

Furthermore, the distribution patterns of material cultural heritages and modern settlements are close to each other. The heritage density is positively correlated with settlement level. Most heritages appear on the edges or peripheries of villages and small towns. The heritages associated

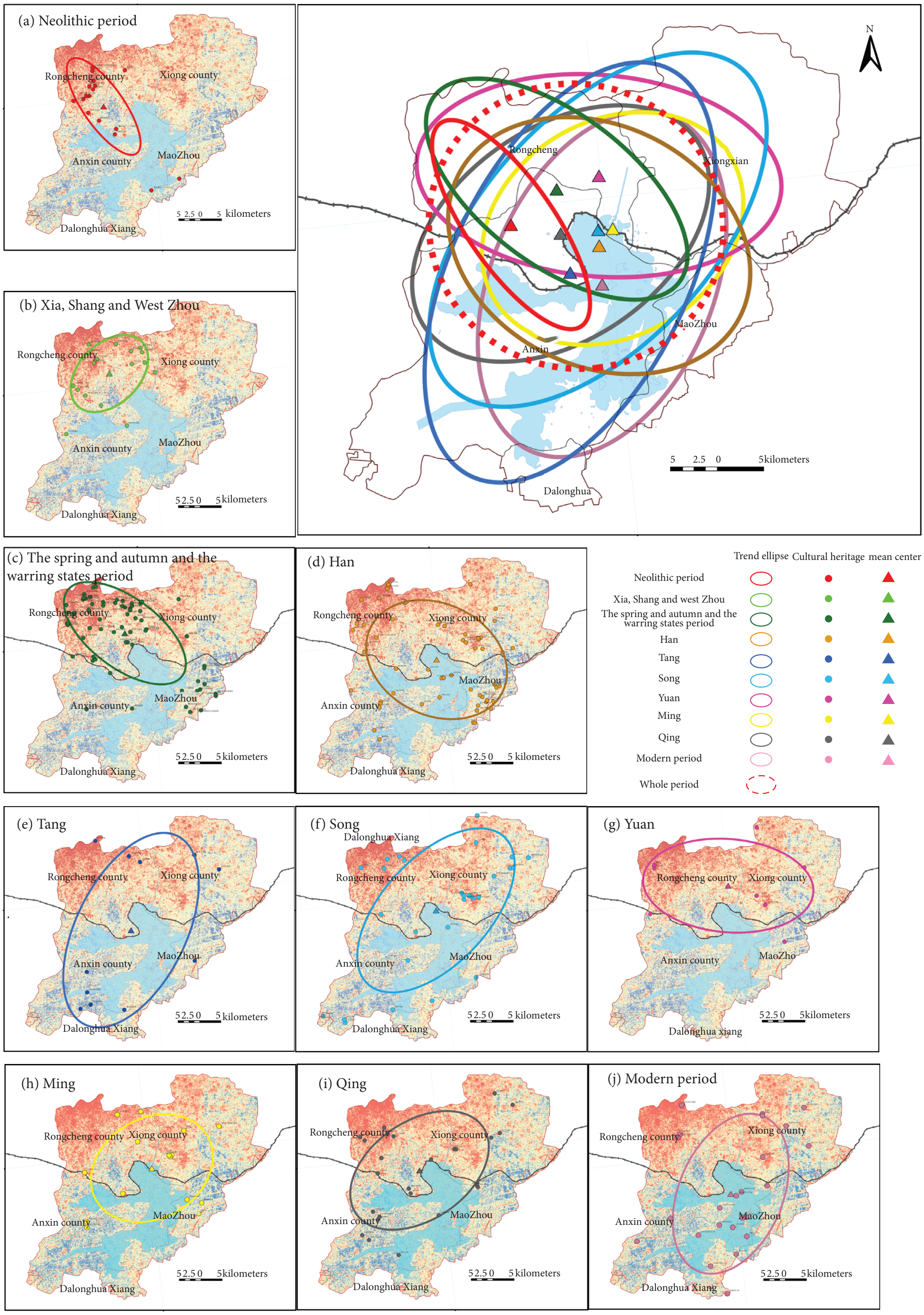


Figure 11: Spatiotemporal distribution trend of heritages in different periods.

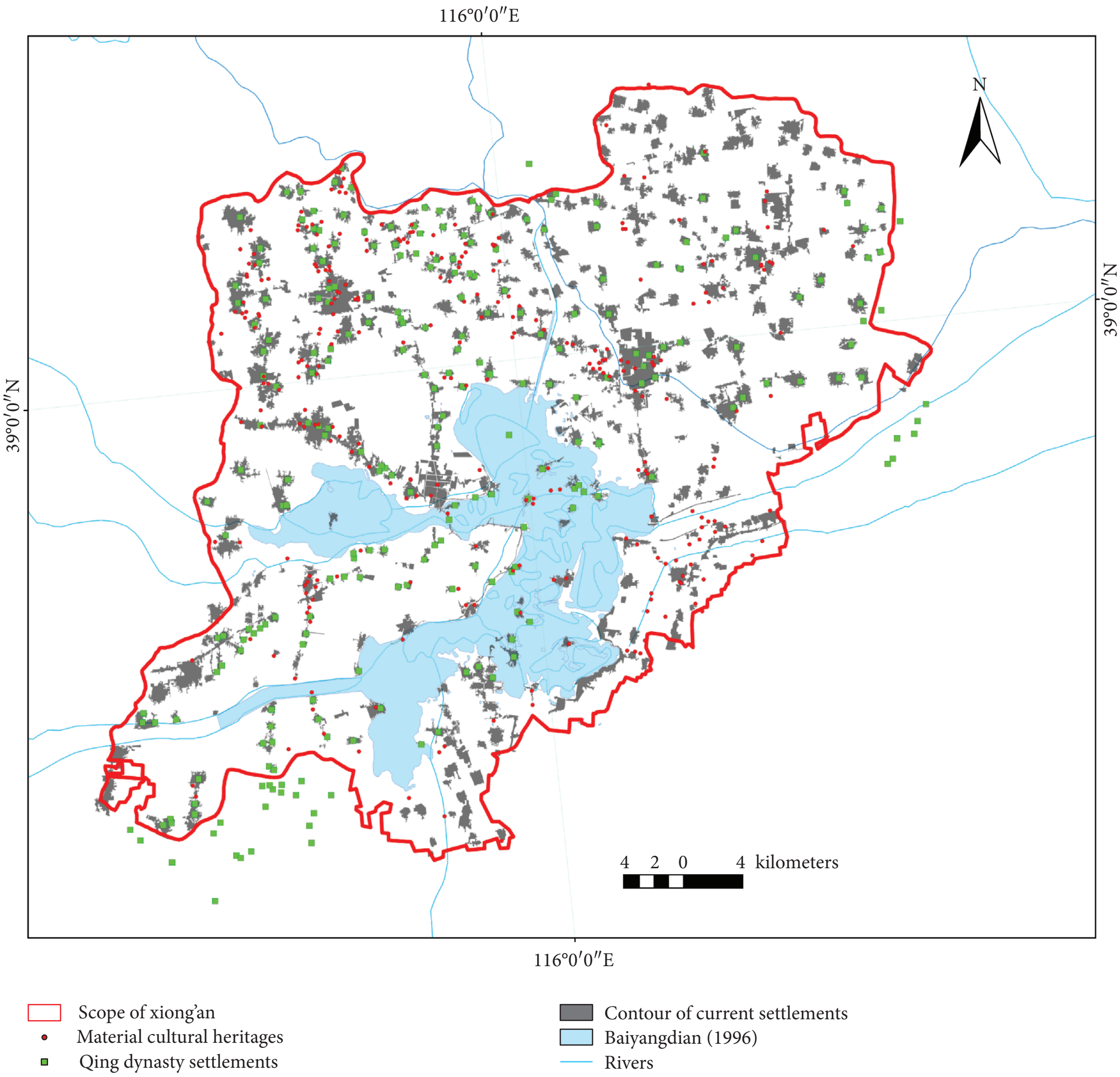


Figure 12: Superposition of material cultural heritages with Qing Dynasty and modern settlements.

with county seats or large towns are within the contours of these high-level localities. The wide dislocation indicates that, with heritages as the center, the settlements that evolved by the first law of geography will not grow homogenously in space. Another interpretation is that the settlements continue to accumulate and cover up most heritages; only those on the edges of the settlements can be found.

3.4. Analysis of Influencing Factors. The necessary conditions (Table 2) and variable combinations (Table 3) were calculated separately by fsQCA. For the outcome variable of SO, PS is the necessary condition, and LO, BU, AR, and CU are the sufficient conditions (Table 2), indicating that SO determines the development of ancient society, while the other single conditions play a weak role. For the outcome variable of HN, there is no necessary condition, and LO is the only sufficient condition. Thus, LO is the top influencing factor of HN. Looking back in history, whenever the LO of Xiong'an increased (e.g., East Zhou, Song, and Qing), advanced human activities appeared in the region, forming many high-level heritage carriers. Meanwhile, more low-level derivative heritage carriers emerged in the peripherals. The relatively small impact of PS may be related to the fact that many remains are not recognized as heritages. When the PS is high, the social prosperity and human activities

Table 2: Necessity of single variable.

Variable	Outcome: SO		Outcome: HN	
	Consistency	Coverage	Consistency	Coverage
PS	0.962963	0.896552	0.766667	0.793104
LO	0.851852	0.741935	0.866667	0.83871
TU	0.333333	0.5625	0.4	0.75
BU	0.851852	0.958333	0.633333	0.791667
AR	0.814815	1	0.566667	0.772727
CU	0.814815	1	0.633333	0.863636
WA	0.703704	0.703704	0.733333	0.814815

Table 3: Antecedent combinations for SO and HN.

Variable	SO			HN		
	Config. 1	Config. 2	Config. 3	Config. 4	Config. 5	Config. 6
PS	●	●	●	○	•	•
LO	•		•		●	●
TU	◦	◦	•	◦	◦	•
BU	•	•	◦	◦	•	◦
AR	•	•	◦	◦	•	◦
CU	•	•	◦	◦	•	◦
WA		•	•	●		•
Raw coverage	0.62963	0.518519	0.185185	0.2	0.5	0.2
Unique coverage	0.148148	0.037037	0.111111	0.133333	0.433333	0.1
Coverage consistency	1	1	0.833333	0.857143	0.882353	1
Solution coverage		0.777778			0.766667	
Solution consistency		0.954545			0.884615	

Note. ● or • means the condition exists; ○ or ◦ means the condition does not exist; blank means the condition in the combination either exists or does not exist; ● or ○ means the condition is a core condition; • or ◦ means the condition is an auxiliary condition.

could create many remains. However, most of them belong to ordinary people and are unqualified for heritage protection. Taking tombs as example, almost all heritage tombs belong to landlords and those of even higher social classes. These tombs are made with higher grade, better materials, and more exquisite burial items than those of ordinary people.

Further analysis shows that, for the outcome variable of SO, the overall coverage and consistency of the three condition combinations met the judgment criteria for significant conditions. Specifically, Config. 1 and Config. 2 have similar and strong explanatory powers for the outcome. The latter only adds one condition: the large AW. For the outcome variable of HN, the overall coverage and consistency of the three condition combinations also met the criteria. Among them, Config. 5 had a relatively strong explanatory power, the condition combination of Config. 5 is the same as that of Config. 1, and the two combinations are close in consistency. Therefore, SO can be promoted by the combination of high PS, strong LO, low TU, frequent BU, high AR, and rich CU. This condition combination is consistent with our intuition.

To sum up, the consistency of condition combination indicates that a prosperous society is more likely to produce and preserve material cultural heritages. This agrees with the inference about heritage survival from the probability theory [40]: for a region in a certain period, if a social state or cultural behavior is very active, the material carriers will be abundant, and the remains will be more likely to be discovered by the later generations. However, the difference in necessary conditions indicates that the conditional variables differ in importance: LO > PS > WA > BU = CU > AR. Based on this ranking, different weights can be assigned to the probability of each kind of potential heritages. In a certain period, if a heritage has a high correlation with the necessity of a factor, it should be assigned the probability weight corresponding to that factor.

4. Detailed Depiction of Ancient Human Space in Xiong'an

4.1. Prehistory (10,000 BC–2,000 BC). In the Paleolithic period (3 million BC–10,000 BC), the sites were mainly located in the northern mountains of North China, forming a ring around the Central Hebei Plains. There was no site in the hinterland of the plains. The nearest site to Xiong'an is Beibianqiao site, Laishui County, amidst the east hills of the Taihang Mountains. The remains are primarily the bones of deer and rats. It can be speculated that humans then mainly live in the mountains (Figure 11(a)).

In the early phase of early Neolithic period, a major discovery was made in the northwest Xiong'an at Nanzhuangtou site, Xushui District, Baoding, and at Beifudi site, Yi District, Baoding [27], which marks human entry into the plains before the east of the Taihang Mountains and the gradual shrinkage of the vast water area in Central Hebei Plains.

From the late phase of early Neolithic period to the early phase of Yangshao period (6,500 BC–4,700 BC), discovery of phase 1, Shangpo site, Rongcheng, and the underlying part of Liangzhuang site, Anxin, mark the entry of humans in the scope of Xiong'an. This unveils the human space evolution in the region. The two sites are located on the northern highland of Baiyangdian Lake and the discontinuous highland in the southern low-lying area, respectively. Combined with Nanzhuangtou site, the two sites exhibit a gradual convergence to Baiyangdian Lake in the northwest-southeast direction (Figure 11(a)). The trend is small-scale evidence on the large scale advancement of original heritages in North China from the Taihang Mountains to the southeastern plains. The elevation of Liangzhuang site is merely 7 m, suggesting that Baiyangdian Lake is then a network of lakes, depressions, and highlands, rather than a complete water area. Apart from animal remains, a lot of shells and fish bones are unearthed at these sites. This means humans have moved close to Baiyangdian Lake and made a living out of the lake. With Shangpo site as the center, sites like Gouxi and Beicheng appear in the north, while Beizhuang site appears in the south. The spacing between these sites is about 2 km. The settlements expand along the highland; that is, the primitive humans settled down in Shangpo and gradually reproduced and spread from that place, forming the Shangpo Cluster, Rongcheng. In the meantime, the underlying part of Liucun site appears deep in Baiyangdian

Lake between Shangpo and Liangzhuang, west to today's downtown Anxin. By spatial distribution, this site is an extended settlement of Shangpo Cluster.

In the early to middle phase of Yangshao period (4,800 BC–3,500 BC), Anxin Cluster, which centers on Liucun, slightly extended eastward, approaching the western shores of Baiyangdian today. In this cluster, the upper part of Liucun site is added above the underlying part. Compared with Shangpo Cluster, Anxin Cluster extended very slightly, as it is in the vicinity of Baiyangdian. During the same phase, Sangezhuang site on the southern shores also approached the lake, indicating the stability of water area and limitation of land area in the study area.

In the late phase of Yangshao period (3,500 BC–3,000 BC), many new sites emerged, including the upper part of Shangpo, the upper part of Gouxi, phase 1 of Wufang, and Dongniu. Anxin Cluster was further enriched and expanded significantly to Baiyangdian on the south.

During the Longshan period (2,600 BC–2,000 BC), several sites, namely, Bailong, Shenmingting, and Laicheng, appeared far to the south of Shangpo Cluster. These sites expanded along the highlands on the outer ring to the west of the southeastern depression (today's May 4th Farm) to Baiyangdian in the south and formed a clear linear correlation with Anxin Cluster. This trend is related to the cultural attraction of early settlements in Anxin [41] and signifies the growing ties with Baiyangdian.

In the Neolithic period, the ancient humans gradually migrated deep into Central Hebei Plains from the peripheral mountains. Along the rivers and lakes, they explored the depressions at the center and established scattered settlements on highlands. The primitive survival strategy is water-loving on the macroscale and water-hating on the microscale. Later, the settlements were expanded into a linear cluster along the C-shaped highland, approaching Baiyangdian in the south. The spatial spacing and development timing showcase the scale of the living space, resource control range, and evolution step length for primitive humans and precisely illustrate the form and shrinking trend of the water area of Baiyangdian.

4.2. Xia, Shang, and West Zhou Dynasties (2,070 BC–771 BC). In Xia and Shang Dynasties, phase 3 of Shangpo and phase 2 of Wufang appear in Shangpo Cluster. As for Anxin Cluster in the south, the sites also witness superposition and extend to the northwest. The northwest-extending part meets the south-expanding part of Shangpo Cluster at Dongxiaoli and phase 1 of Xingkezhuang. As a result, the south cluster grows plumper. In the meantime, the east cluster of the C-shaped highland starts to develop, giving birth to sites like Beizheng and Liangmatai. The cluster expands obviously to the east and merges with Baigou site 13 km in the northeast. It can be deduced from the above that Shangpo Cluster has evolved into a settlement network expanding from a large and stable core. Besides, the southward movement to water changes to the eastward and westward movements to land (Figure 11(b)). This proves the dominance of agriculture in the social production mode of Central Hebei Plains in Shang Dynasty [42]. Moreover, the time and spatial densities of new sites are much higher than those of previous ones, indicating that the fast population growth stimulates the expansion of settlement system to a wider scope of land.

Regional records start to appear in this period. At the transition from Xia Dynasty to Shang Dynasty, Yishi, a northern tribe under the rule of Shang, lived in the basin of ancient Yishui River (today's Juma River, a tributary of Daqing River). It can be deduced that Yishi entered the hinterland of Central Hebei Plains near Baiyangdian along the Yishui River from the Taihang Mountains and grew into the Shangpo Cluster. The social production of the tribe shifted from hunting, gathering, fishing, and animal husbandry to agriculture and planting. On a larger scale, the Chinese territory is dotted with civilizations, which expand from their core areas. Crisscrossed by rivers and lakes, the plains of Xiong'an provide a zone of engagement of different civilization circles. Archeological evidence suggests that Shangpo and the nearby areas in Xiong'an have diverse and complex cultural relics, which belong to different cultures. Xiong'an is a whirlpool, where cultures from all directions merge and intermingle, including the underlying part of Xiajiadian from the north, Yueshi from the east, Xia and Shang from the south, and Baiyan from Central Shanxi of the west.

4.3. The Spring and Autumn and the Warring States Period (770 BC–221 BC). In the Spring and Autumn and the Warring States Period, there was a significant growth of heritages in the west, north, and east sides of Shangpo Cluster. In particular, the number of heritages rockets up in the east part of the C-shaped highland. In the middle of that part, Nanyang site develops into the core of a new dense group, which spreads as far as Xingcun site in the west (within today's downtown Xiongxian). Xingcun site is the first beacon of human activities in Xiongxian and a sign of the initialization of the belt settlement system in the east part of the C-shaped highland. In the south, Anxin Cluster has only two additional heritages: Xidi tomb group and Beiliuzhuang site. The two new heritages approximate the northern shores of today's Baiyangdian. The latter even lies within the water area today. Therefore, this part of water area in Baiyangdian is very similar to that nowadays. On the other side of the lake, a dense group of heritages appear in Mozhou. The overall distribution trend seems to be related to the Rongcheng-Xiongxian settlement belt (Figure 11(c)).

In this period, Yan State builds the Southern Great Wall across the hinterland of Xiong'an [43]. The relevant sites agree well with the northern shore of today's Baiyangdian. Only the north end is partly within the water area. Hence, the lake is of similar form to that of today. The relationship between cities and lakes also reflects the fact that the construction principle of early Great Wall is correlated with the mode of city construction: digging trenches in the ground and piling up the excavated soil into walls. Historical documents testify that many of the isolated lakes along the south of the Great Wall are manually connected into a continuous barrier. It is the first attempt of mass transformation of nature for the purpose of defense.

Taking the Great Wall as the division line, except Mozhou, the heritages are rich and balanced in the north and scattered and few in the south. Considering the scale of each heritage, Nanyang site, which lies at the core of the east settlement belt, is huge in size and contains high-level ritual vessels. It is speculated by some to be the midterm capital of Yan State, Linyi. According to historical record, Yan State built three cities to guard itself against Zhao State, namely, Hunni (today's Anxin), Santai (today's Santai Town), and Gecheng (today's Anzhou Town, later occupied by Zhao). Gecheng is outside the Great Wall, while the other two cities are close to the inside of the wall. The three cities form a triangle centering on the western tip of today's Baiyangdian and protect the large opening of the lake to the southwest. This opening faces Nanyang site deep in Xiong'an from afar. The heavy defense and the abundant heritages in the north of the wall bear witness to the high social and political statuses of Nanyang, which promote the rapid development of regional settlements and culture.

The low presence of heritages in the south of the Great Wall is attributed to the low level of cultural development, since the region is a low-lying lake and swamp frontier far away from the center of Zhao State. The high density of heritages in Mozhou comes from the fact that the city originally belongs to Yan (later occupied by Zhao). The development of this city is backed up by the prosperous settlement system of Yan State. In addition, the flourish of settlements in Mozhou is supported by its critical geographical location: the roads from all directions converge in the city, the neck of the narrow wetland corridor. The city is a magnet to merchants and a strategic place during the wars. In the Warring States Period, the study area changed from centripetal growth to the confrontation state for the first time, and the local man-earth relationship shifted from water-loving to passive water-hating. Due to the confrontation between Yan and Zhao, the pure natural barrier of Baiyangdian was reinforced into the boundary of cultural cognition. Since then, the lake has been treated as administrative boundaries on different scales.

4.4. Han Dynasty (206 BC–220). In Han Dynasty, under the background of grand unification, the heritages break through the imbalanced development fueled by the polarity difference between north and south of the Yan Great Walls. The heritage distribution is more homogenous and extensive than ever before, and the scale of cultural space increases prominently. The traditional gathering place of heritages in the northern highland remains prosperous. In addition, a lot of heritages appear around and even in Baiyangdian, which used to have little heritages. In the northeast, the Rongcheng-Xiongxian (east) cultural belt has an abundance of heritages, primarily on the east and west of the seat for Zhuojun prefecture of Han Dynasty (today's Guxian Village) and Yiyi of Yan State. Meanwhile, the eastern node of the east belt, i.e., Xiongxian, sees further increase of heritages. In the southeast, Mozhou still boasts a high density of heritages, most of which are tombs. Thus, the city remains prosperous in this period. In the southwest, the area of today's Anzhou has three tombs and heritages, the result of the old Anzhou city being built in Han Dynasty. Deep in Baiyangdian, multiple sites, e.g., Dazhangzhuang, Dongdiantou, and Wangjiazhai, emerge, indicating that the lake keeps a low water level in Han Dynasty (comparable to the water level in dry season of 1992). The places of the above new sites are all key nodes in the settlement system of Xiong'an today. Since Han Dynasty, the cultural space and settlement system in the study area has been basically stable.

The material cultural heritages of Han Dynasty clearly fall into two categories: settlements and tombs. There are many tombs (31) in this period, accounting for 53.4% of all heritages. On the macroscale, the two types of heritages cluster separately and only overlap in local areas. On the microscale, settlements and tombs mutually repel each other; the mean spacing between settlements and tombs is about 500 m. Further, the tombs are all away from or on the edges of the early and modern settlements (Figure 11(d)). These laws are similar to the distribution pattern of Han Dynasty tombs around Xiong'an: the density and level of Han Dynasty tombs in Mancheng in the west are much higher than those in other places. Relevant studies confirm the spatial differentiation of settlements and tombs in Han Dynasty; Han Dynasty tombs have nurtured special spatial attributes. Furthermore, the wide distribution of numerous settlement sites and high-level tombs is microscale evidence on the then macro policy of the state: In Han Dynasty, Zhuojun prefecture was densely populated. The enfeoffment policies in the late phase of that dynasty bred many small landlords, who competed to stake claims to unowned land [44]. This coincided with the shrinkage of Baiyangdian. As a result, humans advanced into the receding water area to obtain more land from the hinterland of Baiyangdian.

4.5. Tang Dynasty (618–907). In Tang Dynasty, there were relatively few material cultural heritages. The few heritages can be categorized into two distinctive groups. The northern group was scattered on the northern boundary of Xiong'an. The southern group gathered in the nontraditional cultural gathering space in the southeast corner and tended to connect with Anzhou in the north. The traditional cultural gathering space in the hinterland was completely blank. The heritages are either sites or tombs, including one site and one tomb of Buddhist carved stones (Figure 11(e)).

In this period, the social, economic, and cultural development in Hebei can be roughly split into two phases by the An Lushan Rebellion. In the previous phase, the study area flourished in agriculture, planting, and animal husbandry, under the favorable policies from the central government. It is recorded that Mozhou had 99 lakes. Although the number is fictitious, it is greater than that that in any other age. At that time, the area must have had numerous large and interconnected lakes. The government diverted water to irrigate farmlands in the east, creating more than 200 hectares of new arable fields. As late as the reign of Emperor Xuanzong, the study area still constructed water conservancy projects and expanded farmlands. Therefore, the heritages in the study area ought to have developed towards Baiyangdian and survived to this day. However, this is not the case in reality. Hebei was the main battleground during the An Lushan Rebellion. The residents fled in masses, and the social economy was wrecked [45]. The administrative regions were also adjusted. Two regional centers formed in this phase: The southern part is located in Mozhou further in the south, with Anzhou Town (today's Gezhou, and Xingxian in Tang Dynasty) as the center. The northern part is located in Yizhou in the north, with Rongcheng (Youxian, Quanzhong County, etc.) as the center. Therefore, the polarized distribution of heritages coincides with the centroids of local spaces. Despite the vagueness of spatial semantics, it can be said that the heritage distribution of Tang Dynasty has something to do with the social situation in the late phase. Finally, Buddhist carved stones were discovered for the first time in the study area, taking up quite a portion in the local heritages. This reflects the boom of Buddhism in Tang Dynasty [46]. One of the Buddhist carved stones is found in Mozhou, which has profound links with Buddhism.

4.6. Song Dynasty (960–1127) and Liao Dynasty (907–1125). During the Song Dynasty, material cultural heritages were widely distributed, yet primarily along the southern shores and northern margin of Baiyangdian. In the south, Xiongxian Cluster witnesses extra remarkable heritage development, involving sites like Beiying and Aixilou and tunnels on Song-Liao borders. On the northeastern margin of that cluster, multiple sites appear in a string, including Qigang tunnels and tombs. If the two places are connected by a line (about 45°), which extends to the southwest across Baiyangdian in the southwest corner of Xiong'an, then the southern part is rich in sites, which are uniformly scattered along the shores of the lake. This feature is demonstrated by the previous ellipses (Figure 11(f)). The northern part has relatively few sites, which concentrate on the corner 4 km in the northwest of Rongcheng. The traditional gathering area in the south and east of Rongcheng is virtually blank. In Anxin, several heritages are available in today's Anzhou only, signifying the origin of the ancient city of Anzhou in northern Song Dynasty.

In this period, Xiong'an was situated exactly on the boundary between Song and Liao [47]. The strategic Waqiao Pass was within the seat of Xiongxian. It is when the name of Xiongzhou became famous across the county. Early on, the two sides were in a stalemate. Since the horsemen of Liao could move rapidly across the vast plains, the Song army built up a 400 km-long Great Wall on the Water in a few years, the largest water defense work in the region. Roughly at the same time, an Underground Great Wall of tunnels was established from Xiongxian to Bazhou. The two "Great Walls" complement each other, forming a complex stereo defense system. The heritage distribution in the south of the said connecting line is highly consistent with the defense system.

In 1005, Song and Liao signed a peace treaty, unveiling a century of peace [48]. Then, the study area was coadministered by the two parties. To facilitate trade and exchanges, four market towns were set up in Xiongzhou (today's Xiongxian), Bazhou, Anshu Military Town (today's Xushui), and Guangxin Military Town (northwest of Baoding). Xiongzhou was the largest among the four. In this way, Xiongzhou was transformed from a fortress on the frontier into a stage for cross border trade and ethnic fusion. The traces of cultural prosperity can be found even today. Many place names retain the character "wu" (literally "affair"), a symbol of trade function back then. For example, Mijiawu and Matouwu mean the affairs of grain and horse trades, respectively. The trade greatly promoted the development of settlement system in Xiongzhou. By contrast, the previous leader, Rongcheng Cluster, met a major setback. At that time, Rongcheng County was split into different parts. Liao designated a new Rongcheng on the north of Juma River, while Song relocated the county to Xiongzhou. That is why no heritage is found in the southern part of Rongcheng.

4.7. Yuan Dynasty (1271–1368). In Yuan Dynasty, there were only eight material cultural heritages. The distribution of them is rather unique. The traditional gathering place of culture in the northern highland is blank. Only three heritages appear on the line from Xiongxian to Mozhou in the southeast corner. The other five heritages are scattered on the peripherals of Xiong'an. For instance, the Tombstone of Duke Liang and Longci Ganying Inscription appear on the far end of the western outskirts of Rongcheng; Banzhuangtou and Donghegang tomb groups are the only heritages in and to the northeast of Xiongxian; Anxin in the south has no heritage.

During the transition from Jin Dynasty to Yuan Dynasty, the two sides fought fiercely in Hebei. Many residents were massacred. The massacre, coupled with the fleeing from war and the southward relocation of Jin military households, led to a more than 90% drop in regional population. The wars also forced wealthy and influential Han families in Hebei to stockade their villages. The common people looking for shelter became serfs. Therefore, the social order, production relationship, economy, and culture retrograde caused the significant decline in material cultural heritages. Considering the northward shift of ellipse center and the reduced scale of the ellipse (Figure 11(g)), it can be seen that Xiong'an, especially the peripherals of Baiyangdian, had a low activity of society and culture. Judging by attributes, inscriptions and sites make up the most of heritages. This is a typical feature of Yuan Dynasty: Due to the lack of surviving texts, inscriptions become the main basis for research. The contents of the inscriptions are mostly about the Mongolian rulers [49]. For example, the Tombstone of Duke Liang reports the rewards given to the military in Hebei [50]. The linear distribution of sites from Xiongxian to Mozhou holds evidence of the prominence of this channel. Historical records show that Xiongxian had a large number of temples in Yuan Dynasty. The Grand Temple of Mozhou, a provincial heritage now, was built in this period, attracting worshippers till this day. The above verifies the importance of the line from Xiongxian to Mozhou.

4.8. Ming Dynasty (1368–1644). In Ming Dynasty, the heritages concentrated in the hinterland and moved back to the traditional gathering places. The notable heritages include Yuan Chonghuan Tomb and Hongxilou site near Xiongxian Cluster, the ancient walls of Anzhou, and the Inscription of Temple Construction in Mozhou. The other heritages are scattered across the study area. The number of heritages is greater than that in Yuan Dynasty. Compared with Qing Dynasty, Ming Dynasty has relatively few and low-diversity material cultural heritages, although the two unified dynasties are similar in production state and level of culture development and close in time (Figure 11(h)).

At the beginning of this period, Hebei was sparsely populated. The central government relocated many people there from other places. During the Jingnan Campaign, especially the Baigouhe Battle, the regional culture was destroyed from the root, and most residents were killed or forced to flee [51]. After the reign of Emperor Yongle, almost every village was newly built by immigrants. Therefore, the human background is rather weak in the study area. When it comes to the early phase of Emperor Hongzhi, Baiyangdian was silted heavily after consecutive droughts, which attracted settlement development towards the lake area. The lakebed was turned into farmlands, and the central part was even used as a ranch. After that phase, huge changes took place in the environment. Baiyangdian began to grow into a boundless lake. The expansion of water area in the late phase checked and balanced the inward development of settlements in the early phase, such that several heritages appear to approach the lake from different directions.

In addition, the heritages are further differentiated into Buddhist sites, tombs of prominent personage, and city walls. Because the time is close to now, the heritages reflect the details of the then culture. Since the founder of Ming Dynasty used to be a monk, Buddhism is included in the national governance system. Temples spring up across China [52]. This explains why Ming Dynasty has more Buddhist heritages than any other period. The coexistence of Buddhist heritages and city sites holds testimony to the official recognition of the religion. The well-preserved tombs belong to officials known for their righteousness and frankness, two attributes hailed in the popular Neo-Confucianism of that dynasty. The two sites of city walls directly mirror the national policy of "building high walls."

4.9. Qing Dynasty (1636–1912). In Qing Dynasty, material cultural heritages existed broadly in Xiong'an. The high density areas were well correlated with the traditional gathering space and corresponded to the high-level nodes in today's settlement system. Anxin boasted half of all heritages in Xiong'an, way more than the other two counties. Gathering around Baiyangdian, the heritages have a large scale of spatial distribution and belong to various types, including Zhaobeikou Opera House, Sage Hall Pavilion, and Inscription of Royal Appointment of Tianzeng. The heritages of Rongcheng are crowded in a narrow range near today's downtown Rongcheng. The small scale of distribution involves Guandi Temple and Chenghuang Temple. Xiongxian sees discretized distribution of heritages, such as Xihuai Mosque and Chen Zizheng Tomb. The heritages in the latter two counties are mostly about local affairs and culture (Figure 11(i)).

In this period, the country was unified, and Xiong'an received much attention for its strategic location (near the capital) and natural endowments. At the beginning of Qing Dynasty, Baiyangdian was often flooded. Since it lied close to Beijing, the government spent much efforts to control the floods. The abundant water nurtured a beautiful landscape. The traditional eight sceneries of Xin'an, Rongcheng, and Xiongzhou contained a lot of water elements, attracting many senior officials. Thanks to the continuous improvements by Emperors Kangxi and Qianlong, Baiyangdian became a royal retreat of beautiful scenery, advanced farming and fishing, and excellent hunting ground. It is often compared to Mulan Paddock in the northern province of Rehe [53]. As a result, the cultural development of the lake was pushed to a climax. Four palaces were constructed around the main lake at the best scenic lookouts in the four directions, which delineated the core scenic area. The locations of the four palaces are significantly correlated with today's heritages, such as Zhaobeikou Opera House, Duncun Concert Hall (intangible cultural heritage), and stone remains of the palace in Juantou Village. On a larger scale, Baiyangdian palaces were part of the temporary imperial palace system across the country at that time and thus closely bound with royal power. The improvement of the location importance of Anxin directly promoted the cultural development in the surroundings of the lake (Anxin) over that of Rongcheng and Xiongxian.

In this period, the differentiation of material cultural heritages is even more clear. Different types of heritages carry richer and more refined information, involving almost every aspect, ranging from customs and religious beliefs to economic production. The balanced distribution demonstrates the sound social and cultural form in Qing Dynasty. Of course, this is partly attributed to the fact that the heritages are well preserved due to the short history. Further investigation shows that the material cultural heritages have rich and vivid local features, which increase from Baiyangdian to the peripherals. The heritages surrounding the lake seem to imply the social attributes of high levels, different from local attributes. Combined with legends, concerts, and dancing [54], the sense of high-level social attributes is evident, with an air of solemnity and magnificence. This is obviously the result of the intervention of royal culture into space.

4.10. War of Resistance and War of Liberation (1931–1945). During the Wars of Resistance and Liberation, the heritages in the study area mainly included martyrs cemeteries, cenotaphs, and war sites. They can be basically divided into two types: urban monuments marking the collective memory of a specific time and space, e.g., Rongcheng Martyrs Cemetery; historical event markers with clear spatiotemporal information, e.g., the site where Yanling Team ambushed Japanese army and Mijiawu Martyrs Cemetery. The latter type of heritages is located on the peripherals of main settlements back then and highly correlated with natural barriers (reed marshes) and artificial barriers (tunnels) (Figure 11(j)). The distribution shows how Chinese and Japanese armies were located and interacted in that period. At that time, Central Hebei Plains was occupied by the Japanese. The flat and bare terrain posed a severe challenge to the Chinese army. Interlaced by rivers and ditches and overshadowed by reed marshes, Baiyangdian provided the most reliable natural barrier for the Chinese army. The military and civilian therefore established a base area in the lake and launched guerrilla warfare against the Japanese. Mijiawu and other villages, which have fewer reed marshes around, resorted to the more extreme tunnel warfare. The tunnels in Mijiawu almost overlap with the tunnels on Song-Liao borders, a sign of direct inheritance of cultural behaviors. The above confrontation mode was formed through the innovative utilization and development of heterogenous environment against a homogenous background. The spatiotemporal attributes of Baiyangdian were transformed into the confrontational features of shielding and defense on the plains.

5. Prediction and Conclusions

In the probability distribution map of heritages (Figure 13), the extremely high area of heritage density appears at the center and two ends of the C-shaped high density belt, as well as places like Xiongxian, Anzhou, Mozhou, and Zangang. After the map is superimposed on the scope of planned construction for Xiong'an, the startup area of Xiong'an belongs to the central to southern part of the northern highland of Baiyangdian, just outside the extremely high area of heritage density. However, the startup area overlaps the high area of heritage density in many places.

(1) The eastern part of the startup area overlaps the medium association area extending from the extremely high area of Xiongxian. The important Anyang site and its influencing scope precisely are located in this area.

(2) The northwestern tip of the startup area overlaps the turning point of the south part in the C-shaped high density area, showing a high distribution probability of potential heritages.

(3) The southwestern belt and its nodes along Anxin of the startup area coincide with the south part in the C-shaped high density area and closely intertwine with the buffer zone of the Southern Great Wall built by Yan State. About one-third of the central part of the planned area falls on low probability zones and even blank zones, which favors the construction of Xiong'an. However, the startup area lies slightly to the east of this area and partly overlaps the medium area of the probability.

During future construction activities, archeologists should focus on the above three overlap areas, where surface or underground material cultural heritages potentially exist. The constructors of the startup area must fully consider the influence of the cultural sphere related to Nanyang site from the northeast. Besides, the peripheral extension area of the startup area overlaps the high and extremely high density areas in many places, such as Guigang, downtown Xiongxian, downtown Anxin, and Rongcheng and its east and west. All of them used to be medium and large urban settlements. It is very likely that heritages are discovered in these places. Before construction, geological surveys must be carried out in such places. Further away from the startup area, the special small towns will be built on the original sites. They partly overlap the high value areas (e.g., Anzhou) and a few low and medium value areas. The local governments should carefully arrange preliminary surveys, especially if the new towns are relocated or deviate from the original sites. However, the probability of discovering new heritages in these places is low, because of the small envelope area for prediction.

Guided by material cultural heritages, this paper makes a detailed depiction of the pattern and features of the human space in Xiong'an in different stages of history. It was learned that, on the vast North China Plains, the social and human activities of Xiong'an were greatly affected by complex social, political, and cultural factors. The influence is centered on the heterogenous element of Baiyangdian. On the macroscale, these factors are consistent in the influence of social development and heritage survival. On the microscale, there are sequence and type differences between the different conditions on heritage survival. Based on the spatial distribution of existing heritages, the authors dew a prediction map for the probability of potential material cultural heritages in Xiong'an. As Xiong'an is set to launch a massive construction campaign, our research results will provide forward-looking guidance for urban planning, urban design, and material cultural heritage protection. Of course, this research mainly concentrates on the macro level. In future, the authors will resort to techniques like the far infrared mapping with unmanned aerial vehicles and ground penetrating radar to make more accurate prediction of potential heritages in key blocks, including the first batch of planned construction areas and the areas with a high probability of heritage existence.

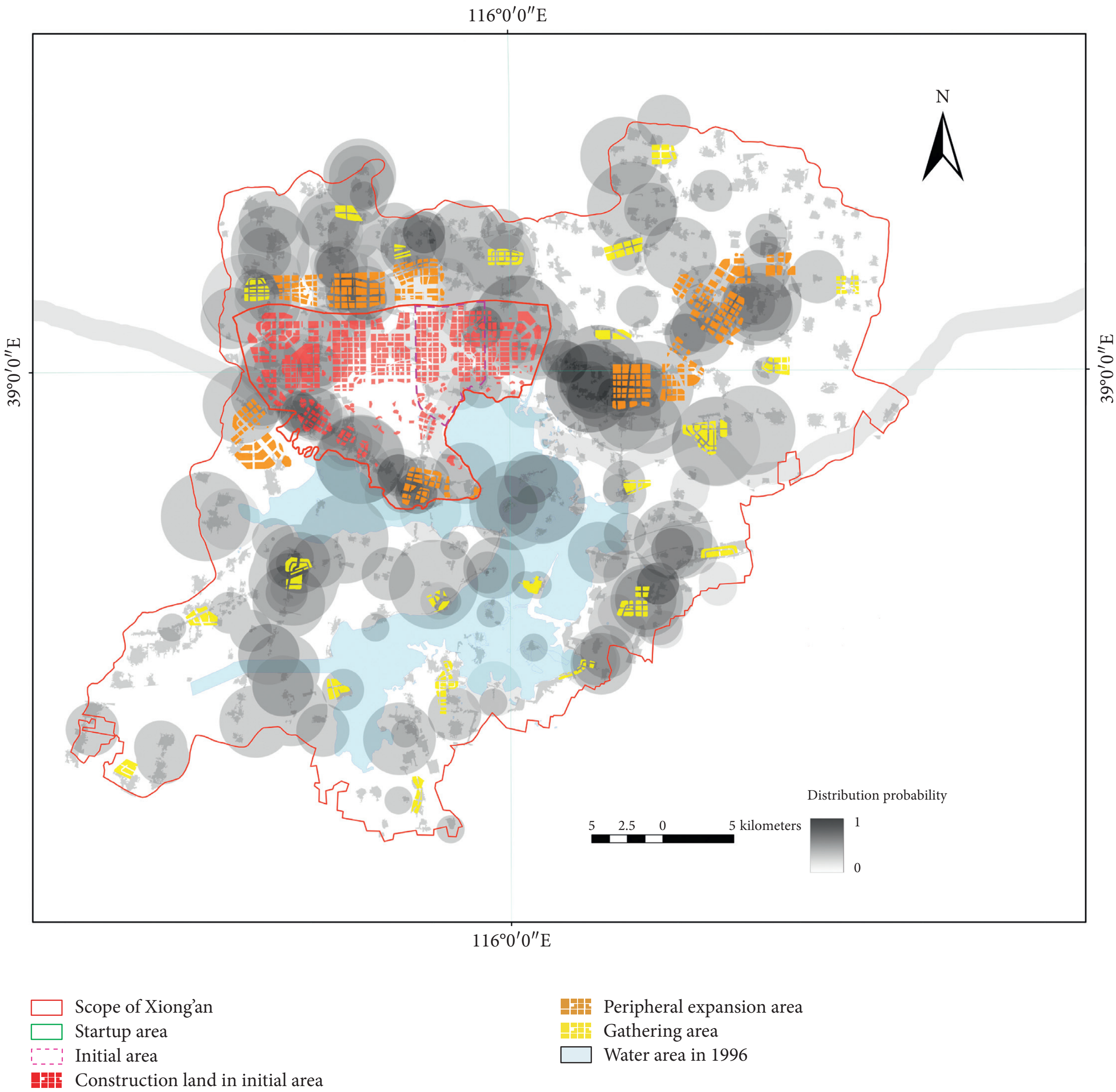


FIGURE 13: Superposition between planned construction land and probability distribution of material cultural heritages (the planning map of the startup area of Xiong'an was plotted according to the data from http://www.metaobao.cn/image/1168984132/).

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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Research Article

On the Transmission of COVID-19 and Its Prevention and Control Management

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The spread of an epidemic is a typical public emergency and also one of the major problems that humans need to tackle in the 21st century. Therefore, the research on the spread, prevention, and control of epidemics is quite an essential task. This paper first briefly described and analyzed the development of COVID-19 and then introduced the basic epidemic models and idealized the population in the epidemic area by dividing them into four categories (Classes S, E, I, and R). After that, it set the relevant parameters of the basic SEIR model and the modified one and worked out the relevant differential equations and iterative equations. According to the feature of the epidemic situation and the changes in the number of contacts in different units of time, the epidemic data were substituted into the iterative equations for data fitting with an *R* Package. Then, analysis was performed on the epidemiological features such as the transmission time and epidemic peak and the epidemic trend was evaluated. Finally, sensitivity analysis was conducted on the parameters (government control and recovery rate), and the results showed that measures such as government restrictions on travel (reducing the contacts between virus carriers and susceptible persons) can effectively control the scale of the outbreak.

1. Introduction

At present, there are 64 major infectious diseases in the world, spreading in 82 countries and regions. In addition to the well-known influenza, measles and dengue fever are spreading in more than 20 countries and regions [1]. For many years, infectious diseases have been a major test to the medical and health systems in various countries in the world.

In 2019, a type of viral pneumonia appeared in many countries around the world, with the characteristics of "human-to-human transmission" [2]. The pathogen was officially named severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) and the pneumonia caused by the virus was named coronavirus disease 2019 (COVID-19) by the Coronaviridae Study Group (CSG) of the International Committee on Taxonomy of Viruses (ICTV). Since the first case of pneumonia of unknown cause was reported on December 8, 2019, a total of 115,653,459 cases and 25,718,823 deaths have been reported worldwide as of March 6, 2021 [3].

Thanks to the active medical treatment and preventive and control measures, the epidemic situation in China was effectively contained and the economic and social order was being recovered in an orderly manner as early as April 2020. However, the epidemic was still spreading rapidly in countries and regions outside China, turning Europe and North America into the hardest-hit areas.

Since the outbreak of COVID-19, a number of studies have analyzed the development of the epidemic based on epidemic dynamics models and related data, interpreted the epidemic trends in different regions of China, and put forward recommendations for epidemic prevention and control [4, 5]. In addition, Zhan et al. [6] established a virus transmission spectrum using COVID-19 data in Chinese cities and evaluated the development of the epidemic in cities in Italy and South Korea. Zhuang et al. [7] estimated the basic transmission rate of COVID-19 in Italy and South Korea using the maximum likelihood method and forecasted the epidemic situation at the early stage. Li et al. [8] estimated the basic infection rates before and after Korea's prevention and control measures and analyzed the epidemic situation in Italy. Zheng et al. [9] used the state transition matrix model to analyze the development of the epidemic in South Korea and Italy. There are also studies that estimated the basic infection coefficient of COVID-19 [10–13], but most of them were carried out before March 5, 2020, earlier than the time when the epidemic broke out on a global scale and turned into a pandemic.

To prevent and control COVID-19, different countries have adopted different measures, resulting in different development trends of the epidemic. For example, due to large-scale gatherings, the number of confirmed cases of COVID-19 increased significantly in South Korea in mid-to-late February [14], and later, thanks to active prevention and control measures, the epidemic was effectively controlled. As of April 4, 2020, there had been 10,237 confirmed cases in South Korea. Italy had fewer COVID-19 patients than South Korea at the beginning of March 2020; but after that, the number of new confirmed cases per day remained high, and as of April 4, 2020, the total number of confirmed cases had reached 124,632, much higher than that in South Korea. In addition, the United States, Spain, France, Germany, the United Kingdom, and other countries were also experiencing a surge in the number of confirmed cases. The pandemic situation was very severe.

The susceptible-infected-recovered (SIR) model is a classic model for studying epidemic dynamics. It was established by Kermack and McKendrick in 1927 using the dynamic method [15]. Yu et al. proposed an SIR model based on time-varying parameters and predicted the development of the epidemic with time-varying parameters [16]. Based on the traditional SEIR model, Geng et al. predicted the development of the novel coronavirus (2019-nCoV) pneumonia epidemic by adding new parameters such as the rate of infection in the incubation period and the rate of change of infected population and evaluated the role of relevant interventions [17–19]. Yan et al. [20] introduced a time-delay process to construct an infectious disease model based on a time-delay dynamic system on the basis of the traditional dynamic model to predict the epidemic situation and evaluate the effectiveness of prevention and control measures. Bai et al. [21] established a nonautonomous dynamic model to predict the development trend of the epidemic by adding isolated susceptible persons and isolated latent persons into the SEIR model and proposed sensitivity analysis on effective regeneration number to emphasize the effectiveness of tracking isolation in epidemic prevention and control.

Based on the SEIR model, this study established and modified a basic SEIR epidemic model and performed data fitting and sensitivity analysis using an *R* Package. In order to realize the trend prediction of the epidemic, the prevention and control suggestions were put forward, and the feasibility of the measures was effectively evaluated, so as to provide a reference for the subsequent epidemic prevention and control.

2. Transmission and Distribution of SARS-CoV-2

2.1. Data Source. The data relating to COVID-19 in this paper were all extracted from the statistics published on the official website of the National Health Commission of the People's Republic of China [22] from January 23 to March 14, 2020, including the numbers of (new) confirmed and (new) suspected cases, deaths, discharged patients, people under medical observation, and people discharged from medical observation nationwide every day, used to construct the SEIR model and analyze the epidemic situation. Considering the rapid spread of SARS-CoV-2, government agencies actively took effective preventive measures, putting the virus transmission into a controlled state. After effective quarantines, many community residents were restricted from going out, and few people traveled across cities and provinces, putting the virus transmission into a highly controlled state.

2.2. Data Analysis. From the map of epidemic outbreaks in China in Figure 1 (from the official website of China Centers for Disease Control and Prevention), it can be seen that Hubei Province is in the darkest color, showing that Hubei was the hardest-hit area of COVID-19 in China. The first case of pneumonia with an unknown cause was also found in Wuhan, Hubei. This provided important information for the traceability investigation of the virus and the quarantine and observation of close contacts.

Figure 2 is a pie chart based on the epidemic data of various provinces in China posted on the official website of the National Health Commission as of 24:00 on March 13, 2020. From Figure 2, it can be clearly seen that Hubei Province had the most confirmed cases, followed by Guangdong Province and Henan Province. Due to the strict isolation and travel restriction measures implemented in China, as of mid-March, all provinces except for Hubei have been cleared of COVID-19 cases.

Then, based on the case data published on the official website of the National Health Commission, a line chart was drawn. It can be seen from Figure 3, with the strong intervention of the government, that the new cases across China were on a decreasing trend. In particular, the number of new confirmed cases reached the peak on February 12 and then gradually decreased; the number of new suspected cases reached the peak on February 5, and after medical observation, it gradually decreased; the number of recovered cases continued to increase, and the number of deaths gradually decreased. Later, various data also showed that the outbreak was basically contained.

3. Review of Common Epidemic Models

The basic mathematical model for an epidemic is a mathematical model constructed based on the characteristics of the epidemic, used to study the transmission speed, spatial range, and transmission routes of the epidemic so as to effectively prevent and control the epidemic.

According to the conditions of different individuals, the total population in the epidemic area can generally be divided into the following four categories:

(1) The susceptible: denoted as the *S* group, referring to the group of people who have not been infected in a

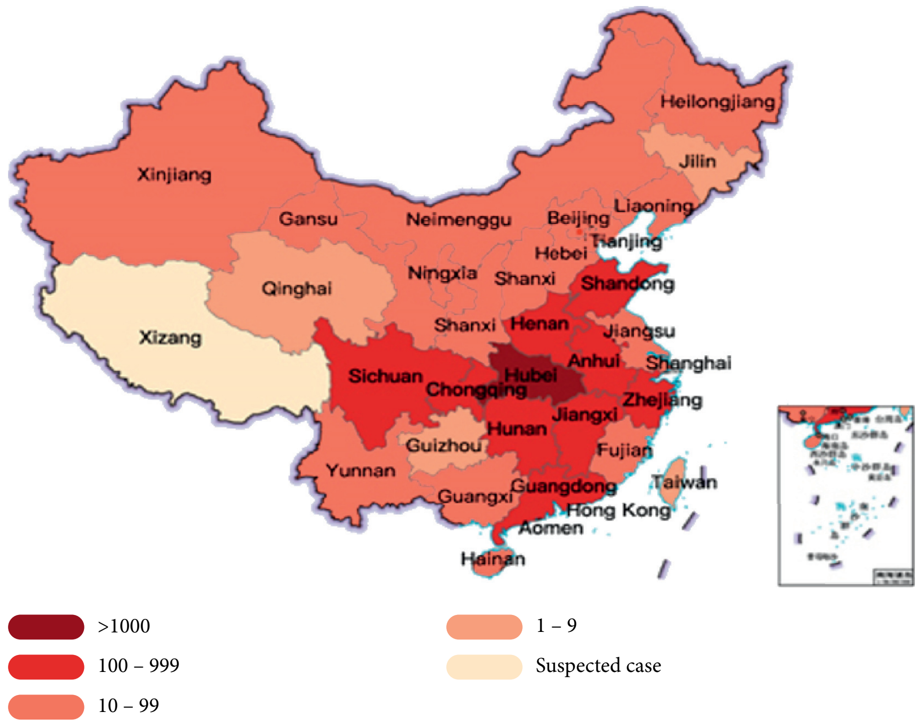

FIGURE 1: Epidemic outbreak map of China (as of 8:00 January 29, 2020).

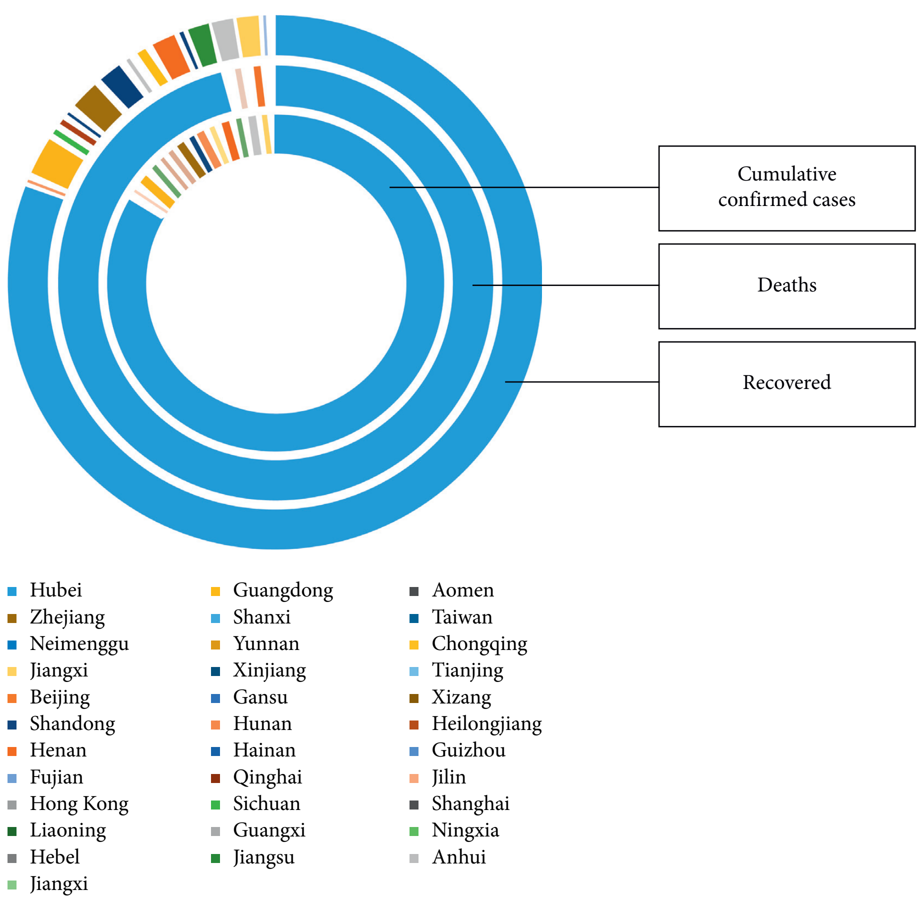

FIGURE 2: Distribution of COVID-19 cases by province.

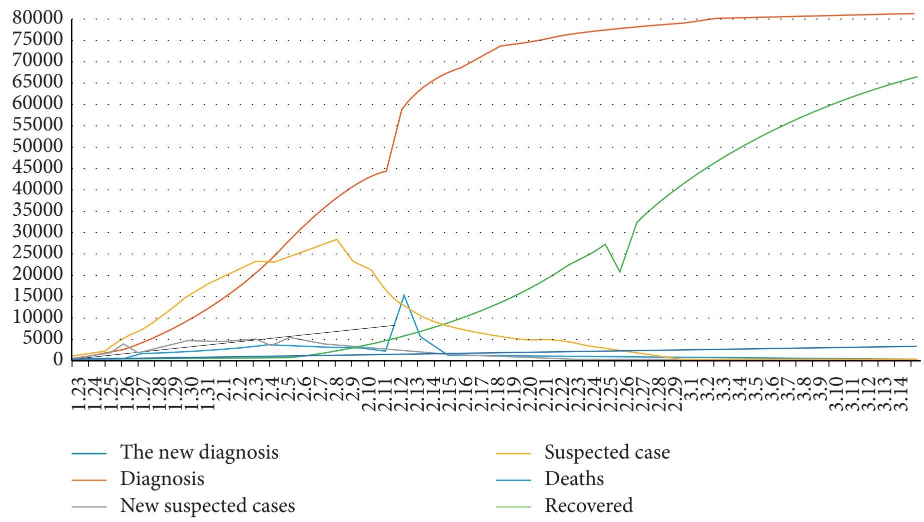

Figure 3: Line chart of COVID-19 cases (as of 24:00 March 14, 2020).

certain period of time but are susceptible to infection after contact with virus carriers.

(2) The exposed: denoted as the E group, referring to the group of people who have been in contact with the infectious and are in the latency stage of the disease. This is applicable to any infectious disease with a long latent period.

(3) The infectious: denoted as the I group, referring to the group of people who have been infected with the infectious disease and can spread the disease to the susceptible, and turn them into the recovered or infectious.

(4) The recovered, denoted as the R group, referring to the group of people who are cleared of the infectious disease and immune to the disease after being cured. If the immunity period is limited, the recovered will soon become the susceptible.

For the sake of intuitive and convenient research, Table 1 is a specific symbolic illustration diagram.

Suppose that the total population is N. During the outbreak of the epidemic, despite the prevention and control measures imposed by the government, there are still some individuals going out. Suppose the number of persons that each individual comes into contact with when going out is $C(t)$ and that the probability of such individual successfully spreading the virus to each contact is β, then there will be newly infected individuals. The birth rate and mortality rate of the population during the outbreak period are not taken into account in this study.

3.1. SI Model. The SI model is used for the situation in which the susceptible, after being infected with the disease, cannot be recovered. An example of such diseases is AIDS. The process is shown in Figure 4.

Suppose the population is divided into two groups—S and I—and the total population is equal to the sum of the number of people in the S group and the I group; then, the following equations can be established for the number of newly infected cases and the number of healthy susceptible people reduced:

$$\begin{cases} \dfrac{\mathrm{d}S}{\mathrm{d}t} = -\dfrac{C(t)\beta SI}{N}, \\ \\ \dfrac{\mathrm{d}I}{\mathrm{d}t} = \dfrac{C(t)\beta SI}{N}. \end{cases} \tag{1}$$

The original equations can be reorganized into the Bernoulli equations:

$$\frac{\mathrm{d}I}{\mathrm{d}t} - C(t)\beta I + \frac{C(t)\beta}{N} I^2 = 0. \tag{2}$$

And then there is

$$I(t) = \frac{NI_0}{I_0 + (N - I_0)e^{-C(t)\beta t}}. \tag{3}$$

3.2. SIS Model. The SIS model is used for the situation in which individuals, after being infected with and recovered from an infectious disease, will return to susceptible individuals, who are likely to be infected again. An example of such diseases is influenza. The process is shown in Figure 5.

The equations are established as follows:

$$\begin{cases} \dfrac{\mathrm{d}S}{\mathrm{d}t} = -\dfrac{C(t)\beta SI}{N} + \gamma I, \\ \\ \dfrac{\mathrm{d}I}{\mathrm{d}t} = \dfrac{C(t)\beta SI}{N} - \gamma I. \end{cases} \tag{4}$$

They can be simplified into

$$\frac{\mathrm{d}I}{\mathrm{d}t} - (C(t)\beta - \gamma)I + \frac{C(t)\beta}{N} I^2 = 0. \tag{5}$$

And it is solved as follows:

Table 1: Description of symbols.

Symbol	Description
N	Total population
σ	Infection rate (the probability of an exposed individual becoming an infected one)
$(1/\sigma)$	Average latent period
γ	Recovery rate
$(1/\gamma)$	Average duration of recovery (days)
$(\beta SI/N)$	Number of the infected
β	Transmission rate
$I(0)$	Initially infected persons
$E(0)$	Initial number of the exposed
$R(0)$	Initial number of the recovered
$C(t)$	Number of contacts per patient
$C(t_0)$	Initial number of contacts per patient
α	Recovery rate
β_2	Transmission rate of the exposed
$C(t_1)$	Number of the susceptible that the exposed come in contact with each day

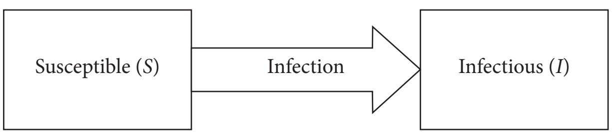

Figure 4: SI compartment chart.

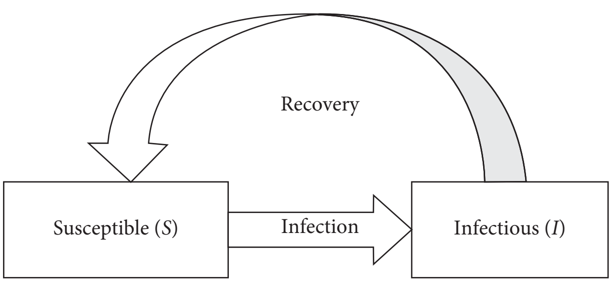

Figure 5: SIS compartment chart.

$$I(t) = \frac{NI_0((C(t)\beta - \gamma)/C(t)\beta)}{I_0 + (N((C(t)\beta - \gamma)/C(t)\beta) - I_0)e^{-(C(t)\beta-\gamma)t}}. \tag{6}$$

3.3. SIR and SIRS Models. The SIR model is used for the situation in which individuals, after being infected with an acute infectious disease and recovered, will have antibodies and obtain permanent immunity. Examples of such diseases are smallpox and measles. The process is shown in Figure 6.

The equations are established as follows:

$$\begin{cases} \dfrac{\mathrm{d}S}{\mathrm{d}t} = -\dfrac{C(t)\beta SI}{N}, \\ \dfrac{\mathrm{d}I}{\mathrm{d}t} = \dfrac{C(t)\beta SI}{N} - \gamma I, \\ \dfrac{\mathrm{d}R}{\mathrm{d}t} = \gamma I. \end{cases} \tag{7}$$

The SIRS model is used for the situation in which individuals, after being infected with an infectious disease and recovered, can be immune for only a limited period of time, and after that, they will become susceptible persons, with the risk of being infected again. The process is shown in Figure 7.

The equations are established as follows:

$$\begin{cases} \dfrac{\mathrm{d}S}{\mathrm{d}t} = -\dfrac{C(t)\beta SI}{N} + \alpha R, \\ \dfrac{\mathrm{d}I}{\mathrm{d}t} = \dfrac{C(t)\beta SI}{N} - \gamma I, \\ \dfrac{\mathrm{d}R}{\mathrm{d}t} = \gamma I - \alpha R. \end{cases} \tag{8}$$

3.4. SEIR Model. In the SEIR model, the infected patients will experience a latent period in the beginning, meaning that after contacting with a virus carrier, they will not show symptoms until after a period of time, and by then, they become the carriers of the pathogen. After being recovered, they will have antibodies and not be infected again. Examples of such diseases are COVID-19, SARS, and so on. The process is shown in Figure 8.

The equations are established as follows:

$$\begin{cases} \dfrac{\mathrm{d}S}{\mathrm{d}t} = -\dfrac{C(t)\beta SI}{N}, \\ \dfrac{\mathrm{d}E}{\mathrm{d}t} = \dfrac{C(t)\beta SI}{N} - \sigma E, \\ \dfrac{\mathrm{d}I}{\mathrm{d}t} = \sigma E - \gamma I, \\ \dfrac{\mathrm{d}R}{\mathrm{d}t} = \gamma I. \end{cases} \tag{9}$$

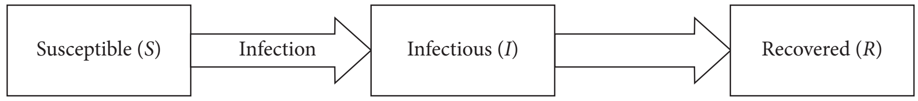

Figure 6: SIR compartment chart.

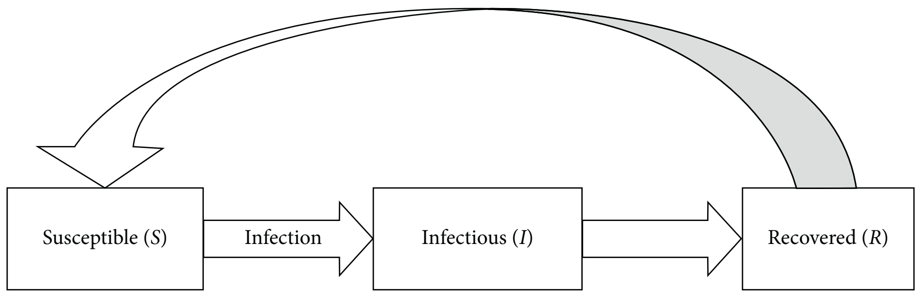

Figure 7: SIRS compartment chart.

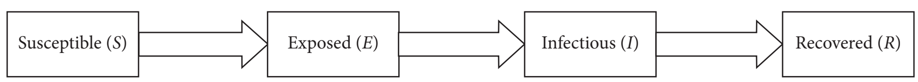

Figure 8: SEIR compartment chart.

From the above, it can be seen that it is actually a modified version based on the SIR model.

4. Prediction of COVID-19 Development Based on the SEIR Model

4.1. Basic Assumptions. COVID-19 has a latent period, so it is necessary to consider the individuals who have contacted the exposed. The following model assumptions are proposed for the transmission characteristics and changing trends of COVID-19 across China.

(1) This study is only intended to analyze and predict regional outbreaks within a short period of time, so it is assumed that the different groups of people are subject to conservation relations in the model, that is, $(t) + E(t) + I(t) + R(t) = \text{constant}$. What is more, the data used are those obtained after all provinces across China activated the first-level lockdown, so there is no population flow. Also, the inflow, outflow, births, and deaths of the population are not taken into account.

(2) It is assumed that the initial number of infected persons is 1.

(3) Individuals who have contacted the infected are put under medical observation for 14 days, during which time; they have no contact with the outside world.

(4) The individuals who are confirmed cases are completely quarantined and can no longer infect others.

(5) As mentioned above, if the COVID-19 patients, after being recovered, will no longer be isolated from others, the whole population can be divided into 4 groups of people, put in 4 independent compartments. The transforming relationships between them are shown in Figure 9.

In Figure 9, $(C(t)\beta IS/N)$ represents the rate at which the number of susceptible persons moves to the E group per unit of time; σE is the number of people diagnosed with COVID-19 per unit of time; and γI is the number of people recovered per unit of time. It should be noted that, based on our understanding of the actual situation, the exposed and infectious persons are both infectious. In the model, the patients refer to the individuals infected and hospitalized (including mobile cabin hospitals). The exposed, that is, the E group, actually includes those in the latent period and those who have been infected but have not been discharged from the hospital.

4.2. Parameters and Initial Value Setting.

(1) Total population N: the data of the total population was provided by the Hubei survey team of the National Bureau of Statistics of The People's Republic of China. As of the end of 2019, the permanent population of Hubei Pro was 59.27 million.

(2) Infection rate σ: according to the official website of the National Health Commission, based on the existing cases, the latent period of COVID-19 is about 7 days on average, but currently, the latent period has been extended. The duration of infection is $(1/\sigma)$, so it can be calculated that $\sigma = 0.143$.

(3) The determination of the expression of $C(t)$ [23].

(4) β value: the value fitted by Xu et al. [24] based on data and the actual situation is adopted, that is, $\beta = 0.074$.

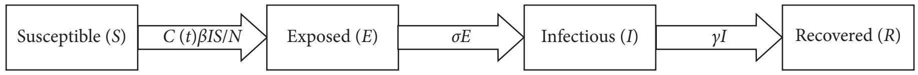

Figure 9: SEIR compartment chart.

4.3. General Model and Analysis

4.3.1. Modeling. According to the parameters, it can be found that S/N represents the proportion of people who are not infected; βI is the number of people who are contacted with and can be infected by patients, and γI is the number of people who have recovered. Then, based on the SEIR model, the daily increase in the number of people in each group can be expressed by the following equations:

$$\begin{cases} \dfrac{\mathrm{d}S}{\mathrm{d}t} = -\dfrac{C(t)\beta IS}{N}, \\ \dfrac{\mathrm{d}E}{\mathrm{d}t} = \dfrac{C(t)\beta IS}{N} - \sigma E, \\ \dfrac{\mathrm{d}I}{\mathrm{d}t} = \sigma E - \gamma I, \\ \dfrac{\mathrm{d}R}{\mathrm{d}t} = \gamma I. \end{cases} \tag{10}$$

The iterative formulas can be obtained as follows:

$$\begin{cases} S_n = S_{n-1} - \dfrac{C(t)\beta I_{n-1}S_{n-1}}{N}, \\ E_n = E_{n-1} + \dfrac{C(t)\beta I_{n-1}S_{n-1}}{N} - \sigma E_{n-1}, \\ I_n = I_{n-1} + \sigma E_{n-1} - \gamma I_{n-1}, \\ R_n = R_{n-1} + \gamma I_{n-1}. \end{cases} \tag{11}$$

The corresponding parameters are set as follows: the initial number of the infectious $I(0) = 1$, that of the exposed $E(0) = 0$, and that of the recovered $R(0) = 0$.

4.3.2. Model Solution and Analysis. Without travel restrictions, assuming that in the range of $N = 10000$, $C(t_0) = 20$, the result calculated by an *R* Package [25] is shown in Figure 10, where the inflection point of the epidemic appears at approximately two months and a half after the beginning of the outbreak. It can be seen that the numbers of the infectious and the exposed both increase first and then decrease and that the outbreak period is also relatively long. It can also be seen that the number of infected individuals does not conform to reality.

According to relevant reports, some exposed individuals who carry SARS-CoV-2 but do not show symptoms can still infect others. Therefore, the following improvements were made to the model.

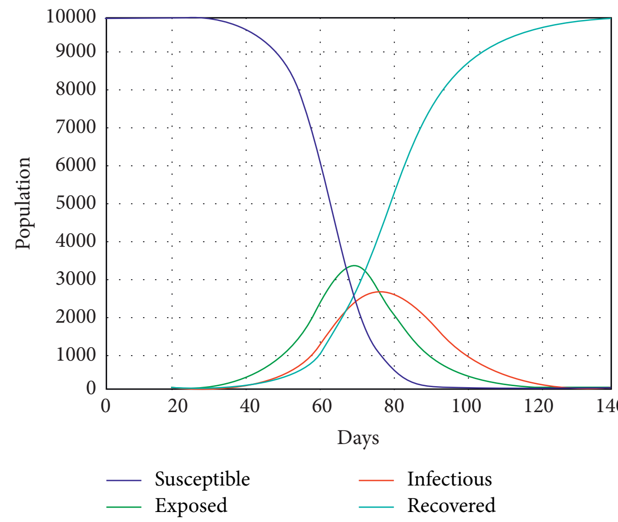

Figure 10: SEIR model fitting chart.

4.4. Model Improvement and Analysis

4.4.1. Modeling. The exposed and the infectious can both infect others. Suppose the contact rate among people is the same, and that the transmission rate is β, then the equations can be improved; that is, the daily increase in the number of people in each group can be expressed

$$\begin{cases} \dfrac{\mathrm{d}S}{\mathrm{d}t} = -\dfrac{C(t)\beta SI}{N} - \dfrac{C(t_1)\beta_2 ES}{N}, \\ \dfrac{\mathrm{d}E}{\mathrm{d}t} = \dfrac{C(t)\beta SI}{N} - \sigma E + \dfrac{C(t_1)\beta_2 ES}{N}, \\ \dfrac{\mathrm{d}I}{\mathrm{d}t} = \sigma E - \gamma I, \\ \dfrac{\mathrm{d}R}{\mathrm{d}t} = \gamma I. \end{cases} \tag{12}$$

The iterative formulas are as follows:

$$\begin{cases} S_n = S_{n-1} - \dfrac{C(t)\beta I_{n-1}S_{n-1}}{N} - \dfrac{C(t_1)\beta_2 E_{n-1}S_{n-1}}{N}, \\ E_n = E_{n-1} + \dfrac{C(t)\beta I_{n-1}S_{n-1}}{N} - \sigma E_{n-1} + \dfrac{C(t_1)\beta_2 E_{n-1}S_{n-1}}{N}, \\ I_n = I_{n-1} + \sigma E_{n-1} - \gamma I_{n-1}, \\ R_n = R_{n-1} + \gamma I_{n-1}. \end{cases} \tag{13}$$

According to the iterative formulas, the calculation results can be obtained.

4.4.2. Model Solution and Analysis. In the modified model, it can be seen from Figure 11 that the inflection point appears earlier, which, to a certain extent, verifies the feature that virus carriers can also infect others. This is also the reason why the epidemic situation is so difficult to contain.

4.5. Parameter Sensitivity Analysis

4.5.1. Sensitivity Analysis of $C(t_0)$. In 2.4, through statistical analysis, it is determined that $C(t_0) = 20$. Below is an analysis of the changes in the model results when $C(t_0)$ changes. This is to examine how a parameter affects the model results while other parameters remain unchanged. $C(t_0)$ represents the initial average number of contacts, which reflects the government's effort to control the epidemic.

(1) The Government Imposes Less Control. If the government imposes less control, the value of $C(t_0)$ will increase. Assuming that $C(t_0) = 30$, it can be seen from Figure 12 that the number of the exposed has increased significantly, so in the same area, the healthy population are more likely to get infected.

(2) The Government Imposes More Control. If the government imposes more control, then the value of $C(t_0)$ will decrease. Assuming that $C(t_0) = 10$, it can be seen from Figure 13 that the number of the exposed has decreased.

In the above two cases, the inflection point of the outbreak and the transmission period have changed, but not much. The above results also show that the government's travel restrictions can truly effectively control the spread of the epidemic by reducing the number of contacts.

4.5.2. Sensitivity Analysis of the Recovery Rate. It can be clearly seen from Figure 14 that if the recovery rate is increased to $\gamma = 0.5$, the number of patients will be greatly reduced, the inflection point will appear earlier, and the transmission period will be relatively shortened. From this, it can be concluded that early detection, early isolation, early treatment, and at the same time improving the recovery rate of the infectious are very important to ending the outbreak as soon as possible.

5. Prevention and Control Analysis

From the previous SEIR epidemic model, it is known that both the exposed and the infectious can infect others. Since the contact rate among people is the same and the transmission rate is β, the key to preventing and controlling the epidemic is to minimize $\beta S(t) - \gamma$, by taking the following actions:

(1) Reduce $S(t)$: Reduce the source of infection by reducing the number of the susceptible. The main

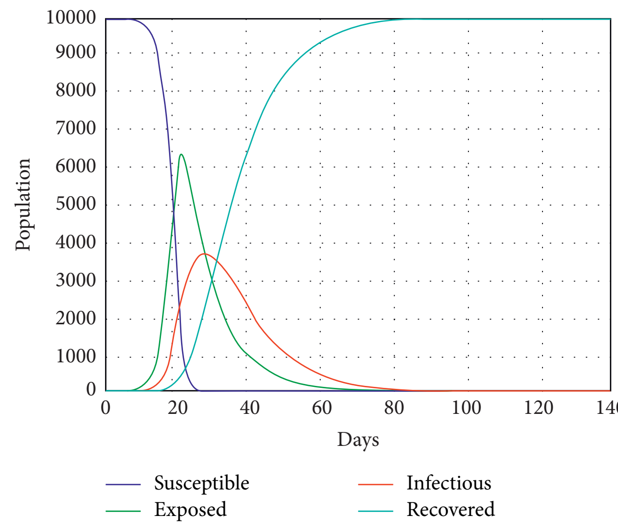

Figure 11: Fitting chart of the modified model.

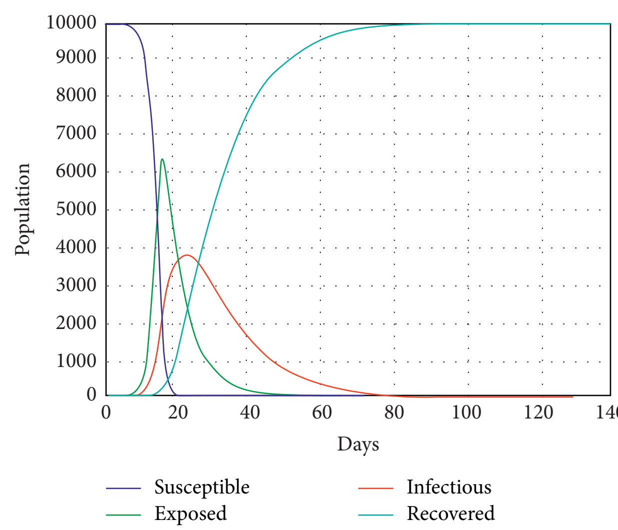

Figure 12: Fitting chart with more contacts per patient.

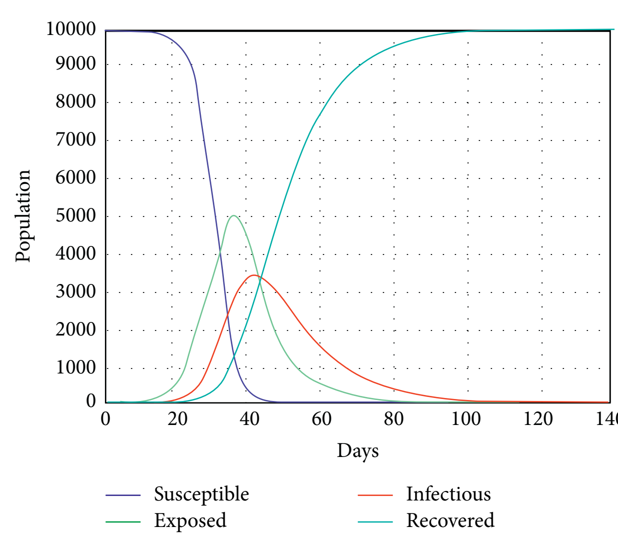

Figure 13: Fitting chart with fewer contacts per patient.

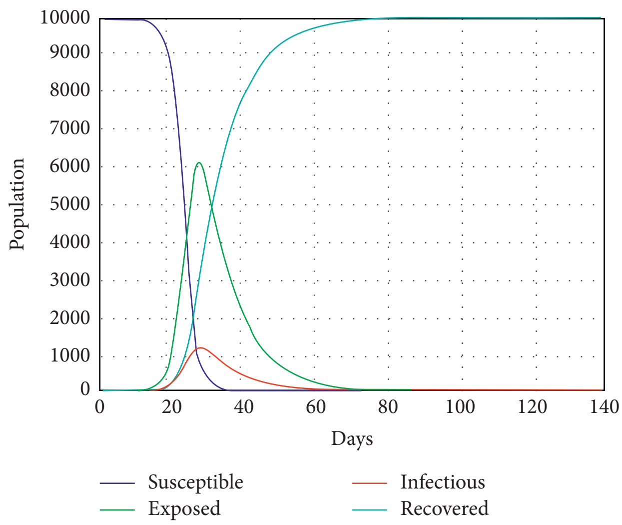

Figure 14: Fitting chart with a higher recovery rate.

methods are vaccination and isolation to prevent infection.

(2) Reduce $I(t)$: Currently, patients are treated in isolation to reduce further infections.

(3) Reduce the infection rate β: Further reduce individual contacts and improve sanitary conditions to block the spread of the virus. Common methods include frequent and scientific hand washing, wearing disposable gloves, wearing masks when going out, imposing community quarantine, and reducing public gatherings and shutdown of companies and schools.

(4) Increase the recovery rate γ: speed up treatment, increase the recovery rate, and increase the immune population. Common measures include actively looking for specific therapeutic drugs, developing vaccines, enhancing physical fitness, and improving individual immunity. At the government level, actions to take include simplifying the drug approval process and speeding up drug development and clinical trials.

The above analysis shows that, before the vaccine is successfully developed, the traditional isolation method is indeed one of the most effective ways to prevent and control the epidemic. However, specifically, different isolation methods should be applied to different areas. For high-risk areas, such as Wuhan, absolute isolation is required, while for nonrisk susceptible areas, real-time protective isolation is required, such as isolation of streets, communities, and villages without COVID-19 cases. In addition, for different people, different methods should also be applied, like the isolation of susceptible individuals, isolation of contacts, and quarantine of suspected patients.

For the infectious group in the model, all suspected patients should be received and treated as much as possible. Those with fever and close contacts should be isolated, reported, diagnosed, quarantined, and treated as early as possible. Just as President Xi emphasized during the investigation on the prevention and control of COVID-19, the Chinese must fight and win the battle against the epidemic by mobilizing all resources and blocking the spread of the virus.

6. Conclusions

This paper used the basic SEIR epidemic model and then obtained the results with an *R* Package using the data to describe the transmission pattern and development process of COVID-19. The main work done for this paper included acquiring the epidemic data from the official website, plotting relevant charts, performing data analysis, and understanding the relevant situation. In this outbreak, it was found that Hubei Province was the hardest-hit area. Then, the basic epidemic models were described, including the SI model, the SIS model, the SIR (SIRS) model, and the SEIR model. The SEIR model was given the greatest attention and applied to the outbreak of COVID-19. Differential equations and iterative equations were established, and with these equations, the final results were obtained. After comparison of the calculated results against the reality and considering the special feature of this epidemic, the equations were modified and calculations were performed again. The results obtained were more consistent with the reality. Sensitivity analysis was also performed on two parameters. Through comparison of the results and based on the actual situation, prevention and control recommendations were proposed.

Data Availability

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

Conflicts of Interest

The author declares no conflicts of interest.

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Research Article

What Is Affecting the Residents' Subjective Perception toward Objective Environment Quality?

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Environmental quality assessment is an important way to promote the improvement of urban environmental quality. Environmental performance is usually used to evaluate the improvement of environmental quality, and residents' satisfaction with environmental quality is also an important method to evaluate environmental improvement. At present, in many cities in China, the results of the two evaluation methods vary greatly. Residents' environmental satisfaction is not high in some cities with good environmental performance; however, in cities with poor environmental performance, residents' environmental satisfaction is higher. Here, based on the environmental subjective assessment of more than 4,600 independent samples from 56 cities in 2014, this paper constructed an index between subjective and objective scores for each sample and its city, separating the total samples into two groups. In order to analyze the differences between groups, firstly, the important factors driving the differences were extracted by random forest. Secondly, the key individual characteristics were identified by the model based on conditional inference tree. Finally, the regional heterogeneity was analyzed by nonmetric multidimensional scaling. The results show that population density is the main factor that affects the difference between subjective and objective evaluations. Furthermore, in those cities with low population density, investment increasing in transportation infrastructure helps to improve urban air quality, which can bring about more perceptual environmental optimization to people. As individuals, education is the key factor for residents when it comes to environment evaluation, but it is not a simple linear relationship. In terms of regional heterogeneity, the consistency of important factors among regions is not obvious, and the situation that "neighboring" cities share the same factors is not significant.

1. Introduction

1.1. Background. As the gathering place of industrial, commercial, and traffic pollution sources, cities have also become the main carrier of improving environmental quality. The pollutants produced by urban production and living account for 80–90% of the global pollutant production. As the basic administrative unit in China, the city's strategy of implementing environmental governance directly determines the level of urban environmental quality, and environmental quality evaluation is an important way to promote the improvement of urban environmental quality [1, 2]. To improve the quality of the environment, the Chinese government has issued new policies on the basis of existing environmental policies and regulations.

In 2013, the Air Pollution Prevention and Control Action Plan was released; the ministry of environmental protection and 31 provinces (autonomous regions and municipalities directly under the central government) signed the Target Responsibility Statement for the prevention and control of air pollution in 2014. Meanwhile, the Water Pollution Prevention and Control Action Plan was performed, and the newly revised Law of Environmental Protection came into effect. Releasing the soil pollution prevention and control plan and the law of environmental protection tax in 2016 and starting the environmental protection "Over Check" together with the law of environmental protection tax came into effect, making the environmental regulation further strengthened. However, there are still two contrasts of environmental quality: one contrast exists between pollutant emission reduction and environmental quality and the other exists between environmental performance and public perception of the environment [3].

According to the state of "the environment bulletin of China" (2013–2018) issued by the Ministry of Ecology and Environmental Protection, the average annual PM2.5 concentration has dropped from 72 μg/m3 to 47 μg/m3, the annual concentration of PM10 decreased from 118 μg/m3 to 81 μg/m3, the annual concentration of SO_2 reduced from 40 μg/m3 to 15 μg/m3, annual concentration of NO_2 dropped from 44 μg/m3 to 36 μg/m3, and CO annual average concentration decreased from 2.5 μg/m3 to 1.6 μg/m3 over the past five years. The annual concentration of O_3 increased from 139 μg/m3 to 169 μg/m3, chemical oxygen demand (COD) emissions decreased by 14.06%, and ammonia nitrogen emissions decreased by 43.22% (Statistical Yearbook of the Republic of China 2018). These data fully demonstrate that China's environmental protection work has achieved remarkable results. According to the official statistics of the effect of policy implementation, compared with 2015, the proportion of surface water with a quality of III or better increased by 8.9 percentage points, reaching 74.9% in 2019. The proportion of inferior surface water decreased by 6.3 percentage points to 3.4%. The concentration of PM2.5 in cities at or above the prefectural level that failed to meet the standards fell by 23.1 percent.

However, the public perception and media attention are in stark contrast. According to the "Environmental Quality Special Online Survey" organized by the "WOYAO Online Survey," more than 83% of the respondents believe that "the environmental pollution" situation around them is relatively serious or very serious. Before that, the OECD commissioned Gallup has surveyed 158 countries from 2006 to 2008, the relevance between pollutant emission level and environmental satisfaction was studied, especially during the happiness survey. It is proved that there is a strong positive correlation between pollutant emission reduction and environmental quality satisfaction, based on the level of country and city. The correlation coefficient is $r = 0.61$ [4].

Why is there such a big contrast between the environmental quality assessment based on public perception and the environmental quality assessment based on pollutant emission level in China? It has been modified in the article; other possible errors have been checked and corrected. What is the reason for this contrast?

In order to explain the reason for the contrast, this paper makes a comparative analysis of the regional pollutant emission level and the public environmental quality satisfaction using the data from a large-scale environmental satisfaction survey conducted at the city level in China through "WOYAO Online Survey" in August 2016. By carrying out comparative analysis of regional pollutant discharge levels and public environmental quality satisfaction, this paper tries to find out the regularity of contrast between the two and find the lack of environmental protection work. As a result, we can enrich theories and methods of environmental quality assessment and provide some references for China's environmental protection work and ecological civilization construction; it can also answer the above questions.

1.2. Definition of Environmental Quality. A large number of studies have characterized the environmental quality by the emission level of a certain pollutant or the comprehensive index of the emission level of various pollutants, such as sulfur dioxide, nitrogen dioxide, and sewage volume or PM10, PM2.5, and so forth. However, the Dictionary of World Economy and the Dictionary of Capitalism point out that environmental quality is an essential attribute of environmental system, represents the degree to which the overall or certain elements of the environment in a specific time or space satisfy human survival, reproduction, and socioeconomic development, and is a concept of environmental assessment that reflects the specific requirements of the population.

The study in [5] pointed out that "high environmental quality represents residents' high satisfaction and happiness towards the objective physical or social environment." The study in [6] argued that not only is environmental quality limited to pollutant emission level, but also it is a complicated issue involving subjective feelings, attitudes, and values that vary from a person to another. In 2002, an international academic conference on "livability" held in Bouwman reached a consensus about environmental quality. It defines environmental quality as an important component of quality of life, whose essence is residents' comfort of living environment [7]. ISO (the International Standardization Organization, 2000) comprehensively defines "quality" as "the degree to which an inherent set of features meets requirements." From the perspective of public goods, if "environment" is regarded as a public product, environmental quality can be understood as the objective level of a region's environment (i.e., the level of pollutant control) to meet the environmental needs of residents. Therefore, in combination with the original definition of "quality" as "the degree to which a set of inherent characteristics meet the needs" (ISO, 2000), "environment" is regarded as a public product, and "environmental quality" can be understood as the degree to which the objective level of an area's environment (the level of pollutant control) meets the environmental needs of residents.

1.3. Evaluation Methods of Environmental Quality. Environmental quality assessment activities began in the mid-1960s, and the United States was the first country to start environmental quality assessment. They had introduced, for example, the Green Composite Air Pollution Index and the Oak Ridge Air Quality Index for the first time. At that period, a single pollutant is mainly used to characterize the environmental quality and sulfur dioxide, nitrogen oxide, nitrogen dioxide, industrial waste gas, industrial smoke, and industrial waste water which are commonly used as indicators to measure the environmental quality. Subsequently, environmental quality assessment and theoretical research have been carried out in various countries. Among them, Japan takes environmental quality assessment as an important policy to implement. The reason is that a single index is too general or cannot fully reflect the overall picture of environmental quality in a region, and subsequent studies have integrated a variety of environmental pollutant emission indicators into a comprehensive index through different methods. For example, Rolf Fare and others constructed the environmental performance index with the list of toxic substances. With the development, more environmental indicators are included, such as PM10, PM2.5, CO_2, and greenhouse gases. There are also scholars who conduct environmental quality satisfaction surveys based on residents' perceptions and carry out environmental quality evaluation. As an important evaluation content of sustainable development, environmental quality evaluation is also evaluated from the relationship between environment, society, and economy. Many environmental quality evaluation indexes and methods are proposed from different perspectives and methods.

1.4. Literature on Subjective and Objective Evaluation of Environment. Until now, most studies on social indicators have focused on a single objective or subjective measurement. Although one indicator can help explain the other, relatively few empirical attempts have been made to combine the two methods in a single study. One of the important reasons is that the inclusion of subjective evaluation is a problem to be considered carefully, due to its value judgment property. It tends to become the focus of the debate rather than an effective way to measure pollution. Many of these factors, including personal and social characteristics such as age, income, education, and health status can act as "filters" that distort objective conditions by intervening between the objective world and an individual's assessment of the objective world. Thus, individual perception transforms what was initially seen as a universal objective condition into a highly individualistic interpretation of this objective condition. However, any definition of the quality of the living environment must include two basic elements: one is the internal psychophysiological mechanism that produces satisfaction and the other is the two dimensions of external phenomena associated with it. Meanwhile, both dimensions of environmental assessment strive to be objective because they strive to have effective, reliable, sensible, and useful repeatable measures [8]. Moreover, both are subjective because even technical assessments depend on human decisions about the dimensions to examine, the time and place of sampling, and the interpretation of the results. Many literatures have begun to draw meaningful conclusions through subjective and objective environmental assessments and many previous studies on environmental perception have been based on interviews with tourists, where issues such as recreational use, tourism infrastructure, and safety may interfere with the perception of major environmental factors [9]. This is also true of interviews with residents, where environmental perceptions may be strongly influenced by the culture in the landscape environment [10], local social and economic conditions (Xu et al., 2006), and information from the media [11].

Generally speaking, "environmental quality" has both subjective and objective attributes. Subjectivity refers to residents' perception of the environment, which can be represented by environmental satisfaction. For the convenience of expression, the measurement of environmental quality based on the emission level of environmental pollutants will be represented by the objective evaluation of environmental quality, while the measurement of satisfaction of environmental quality based on the subjective feelings of residents will be represented by the subjective evaluation of environmental quality in the following paper.

2. Data and Methods

2.1. Data Source. This paper adopts the Gallup survey method and covers 56 cities in 26 provinces (municipalities directly under the central government) in China, excluding Hong Kong, Macao, Taiwan, and other regions. The 56 cities include 24 provincial capitals and some prefecture-level cities in each province. The selection of other prefecture-level cities is mainly based on the stratified sampling method of per capital GDP ranking. The specific sampling method is as follows: If the population of the province is less than 50 million, the cities with the median ranking are selected. If the population of the province is more than 50 million, more than two cities will be selected in addition to the provincial capital cities, ranking the cities at 40% and 70%, respectively. In the surveyed cities, samples were taken according to different income levels, and 30–50 samples were selected according to different populations. As a result, 4660 valid samples were obtained. Among the 4660 samples, nonagricultural registered residents accounted for 70.05%, while agricultural registered residents accounted for 29.05% ,with 49.85% men and 50.15% women. In terms of education level, high school and below accounts for 27.22%, college, technical secondary school, and vocational high school account for 27.88%, and bachelor's degree and above accounts for 44.90%. The survey on environmental quality in the questionnaire includes five aspects: residents' perception and satisfaction with the overall environment, air quality, water quality, noise, and vegetation. Moreover, "1" means very dissatisfied, "6" means very qualified, and 10 means very satisfied. The subjective perception data of environmental quality in this paper are formed, and the overall evaluation results are shown in Figure 1.

2.2. Objective Evaluation. As mentioned in Table 1, in the process of evaluating the overall quality of the environment, single-dimensional indicators will produce the problem of overgeneralization, while multidimensional indicators lack a unified composition standard, resulting in different composition of comprehensive indicators and inconsistent evaluation results, which is not conducive to comparison. Also, the indexes are numerous, and the calculation is complex due to the shortage of result continuity. In this

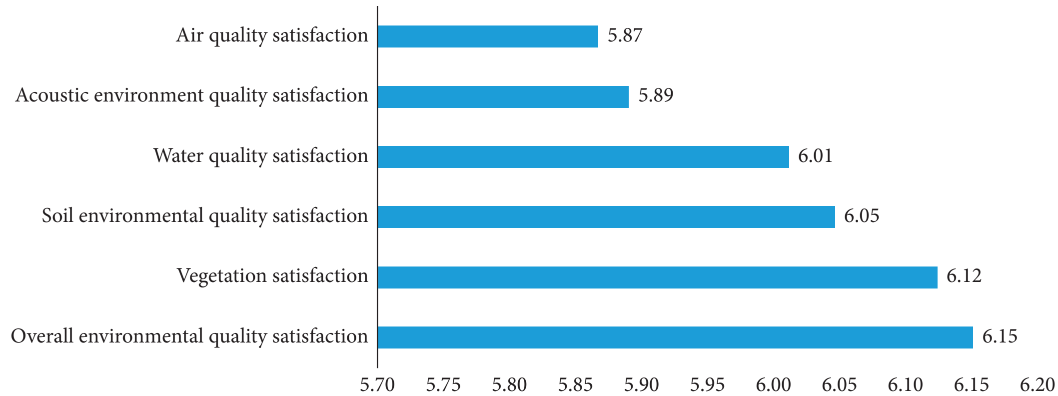

FIGURE 1: Environmental quality satisfaction score.

paper, since the objective evaluation system needs to be compared with the evaluation results of the supervisor, the environmental changes that are more easily perceived by residents in real life are mainly due to the pollution or purification level of water, gas, and solid. Hence, in order to make the results more comparable, this paper chooses three types of pollutants that are more easily perceived and pollution treatment level to construct system indicators. Based on the multidimensional analysis system, the weighted average method is used to calculate the objective evaluation index of environmental quality. The rating system is given in Table 2.

The pollutant emission data of each city mainly came from China Statistical Yearbook 2012–2015, China Environmental Statistical Yearbook 2012–2015, and China Urban Statistical Yearbook 2012–2015. In those three statistical yearbooks, air quality indicators include total SO_2 emissions, total NO_2 emissions, and PM10. Indicators of water environmental quality include total discharge of waste water and concentrated treatment rate of waste water. Meanwhile, the pollution treatment uses the solid waste treatment rate and the garbage disposal rate.

2.3. Random Forest. Random forest is a combination of tree classifiers, where each classifier is generated by using a random vector sampled independently from the input vector, and each tree casts a unit vote for the most popular class to classify an input vector. The method, which adds an additional layer of randomness to bagging [12], changes the algorithm utilizing averaging multiple deep decision trees and trains on different parts of the same training set with the goal of reducing the variance against overfitting. Besides, it is very user-friendly in the sense that it has only two parameters (the number of variables in the random subset at each node and the number of trees in the forest), and it is usually not very sensitive to their values. In the same manner as the decision tree, the random forest classifier uses the Gini index as an attribute selection measure to assess the impurity of an attribute concerning the classes. However, relationships between variables assessed by stochastic forest models are treated as a "black box" that requires advanced mathematical knowledge to explain.

The mechanism of random forest is beyond the scope of this study. In this paper, we mainly use the importance of random forest as the ranking of the importance of driving factors. Here are the definitions of the variable importance measures. The first measure is computed from permuting OOB data: For each tree, the prediction error on the out-of-bag portion of the data is recorded (error rate for classification and MSE for regression). Then the same is done after permuting each predictor variable. The differences between the two are then averaged over all trees and normalized by the standard deviation of the differences. If the standard deviation of the differences is equal to 0 for a variable, the division is not done (but the average is almost always equal to 0 in that case). The second measure is the total decrease in node impurities from splitting on the variable, averaged over all trees. For classification, the node impurity is measured by the Gini index. This method has been applied to study the relationship among climate change, energy consumption, and people's subjective perceptions or attributes [13].

2.4. Conditional Inference Tree (CTREE). The model of a conditional inference tree is another type of machine learning algorithm that can be used as a classifier and a regression. The "tree" refers to a hierarchical model of decisions and its results. The application of decision tree method in environmental assessment is still rare. Compared with random forest, the tree-based model has relatively clear, simple, and easy-to-understand rules. Because it does not need to optimize the geometry and internal network, it can be programmed faster than a random forest model. Furthermore, because most recursive partitioning algorithms are special cases of simple two-phase algorithms, the observations of a univariate partition are first partitioned recursively, and then a constant model is installed in each cell of the result partition. The most popular implementations of this algorithm are "CART" [14] and "C4.5" [15]. Similar to AID, both perform exhaustive searches for all possible segmentations to maximize the information measure of node impurities and select the covariates that display the best segmentation. However, there is a basic problem with this approach: there is no concept of statistical significance, so it is impossible to distinguish the significance and

Table 1: Comparison of environmental quality assessment methods.

Evaluative dimension	Name of index	Explanation	Advantage	Disadvantage
Unidimensional index	The air indicator	A unit of environmental pollutant such as sulfur dioxide, suspended matter concentration (SPM), carbon monoxide, carbon dioxide, and nitrogen oxides.	Single-dimensional indicators are straightforward and easy to understand, data availability is strong, continuity is strong, it is easy to compare and study, and local environmental problems are targeted.	In the process of evaluating the overall quality of the environment, there will be an overgeneralization problem.
	Water environment indicator	One kind of water pollutant is taken as the content of environmental assessment, such as industrial wastewater and chemical oxygen demand (COD).		
	Waste indicator	Hazardous waste is taken as the index of environmental evaluation, such as solid waste and liquid waste.		
	Forest environmental indicators	Forest coverage rate is the main index of environmental quality evaluation.		
	Other indicators	The utilization efficiency of a certain natural resource is taken as the index of environmental comprehensive evaluation.		
Multidimensional index	Comprehensive indicators for the discharge of various pollutants	A variety of environmental factors are integrated into a comprehensive indicator of environmental quality, such as industrial emissions, industrial waste water emissions, and industrial solid emissions.	The multidimensional environmental quality evaluation index can reflect the overall situation of environmental quality in a comprehensive way, which is conducive to an objective, fair, and reasonable comprehensive evaluation of environmental quality. It can also reflect the ability of sustainable development from the environmental dimension.	Due to the lack of unified criteria for the composition of multidimensional evaluation indicators, the composition of comprehensive indicators is different, and the evaluation results are inconsistent, which is not conducive to comparison. Because the indexes are numerous, the calculation is complex, causes the result continuity to be not good, and is disadvantageous to discover the historical regularity.
	Environmental sustainability indicators	Environmental quality is an important part of sustainable development. The relationships between environment and society, between environment and economy, between environment and ecology, and between environment and human development are evaluated.		
	Environmental quality satisfaction index	Taking residents' perceived environmental quality satisfaction as the evaluation index, the satisfaction data were obtained by means of questionnaire survey, including air quality satisfaction, water quality satisfaction, vegetation satisfaction, and acoustic environment satisfaction.		

Table 2: Objective evaluation system of environmental quality.

The first layer	The second layer
Air quality (35%)	SO_2 (33.3%) NO_2 (33.3%) PM10 (33.3%)
Water quality (30%)	Total discharge of wastewater (50%) Concentration rate of sewage treatment (50%)
Pollution treatment (35%)	Solid waste disposal rate (50%) Centralized rate of garbage disposal (50%)

insignificance of information measures. The conditional inference tree provides an integrated framework for embedding recursive binary division into the well-defined permutation test theory proposed by [16]. By doing so, multiple testing procedures are applied to determine whether any covariables and responses can be declared without a significant correlation, and the recursion is stopped when it is needed.

2.5. Nonmetric Multidimensional Scaling (NMDS). The nonmetric multidimensional scaling is a data analysis method that simplifies the research objects (samples or variables) of multidimensional space to lower-dimensional space for positioning, analysis, and classification, while retaining the original relationship between these objects [17]. It is applicable to the case where the exact similarity or heterogeneity data between the objects cannot be obtained, and only the hierarchical relationship data among them can be obtained. Its basic characteristic is to regard the similarity between objects or the data of phase as the monotone function of the distance among the points and replace the original data with new data columns of the same order on the basis of maintaining the order relation of the original data for metric multidimensional scaling analysis [18]. Put differently, when the data is not suitable for the analysis of variable-type multidimensional scale directly, the variable transformation is carried out, and then the variable-type multidimensional scale analysis is adopted. For the original data, it is called the nonmetric multidimensional scale analysis. Its characteristic is that, according to the species information contained in the samples, it is reflected in the multidimensional space in the form of points. Furthermore, the degree of difference between different samples is reflected by the distance among the points, and finally the spatial location map of samples is obtained.

3. Results

3.1. Evaluation Index and Ranking of Urban Environmental Quality. Based on the subjective and objective evaluation methods selected in the previous article, we calculated the subjective and objective environmental evaluation scores and rankings of each city, as shown in Figure 2. In Figure 2(a), the length of the blue column represents the objective ranking order, and orange represents the subjective ranking order. The column length in Figure 2(b) indicates the difference between the subjective ranking and objective ranking. The larger the value is, the lower the subjective ranking is compared with the objective ranking. In many cities, subjective and objective evaluations differ greatly, which is also consistent with the results of previous studies.

In order to measure the difference value of each sample, we subtracted the standardized objective score of the city where each sample was located from the standardized subjective score of each sample and constructed a new difference index *heter* in the following analysis. The samples were divided into groups greater than 0 and less than 0 by this index. Figure 3 shows the kernel density function graph of *heter*.

3.2. Extracting the Main Driving Factors. Based on the grouping of difference index, we add all characteristic factors of all samples into the model and extract the most important driving factors through random forest. In Figure 4, the importance of all relevant variables is ranked. The larger the value is, the more important the variable is. It can be found that population density is the most important factor by two different measures. Therefore, we can assume that population density has the greatest influence on urban environmental evaluation [19]. Since the two measures are only important references, the first four factors are selected from the two groups of species, and a total of eight factors (including coincidence) are selected as the most important elements which will be used as the basis for further CTREE analysis.

Further factor extraction was conducted for each city through random forest; we found that the occurrence frequency of education factor was the highest among the top three factors from a national perspective. In the 55 cities (due to missing data), 28 (51%) had educational factors in the top three influencing factors (see chart in dark red in Figures 5 and 6). Figures 5–7 show the distribution of the top three influencing factors in each province (Figure 7 shows the third most important factor). As mentioned in the previous article, the education factor has become the most frequent factor in many provinces. Among numerous studies on education and environmental quality, more and more scholars have found that there is no obvious direct relationship between education and mortality caused by air pollution [20, 21], and education interacts with other socioeconomic environments in complex ways in terms of influencing people's health and quality of life. Therefore, we can assume that there is not a general and monotonous relationship between the advantages and disadvantages of

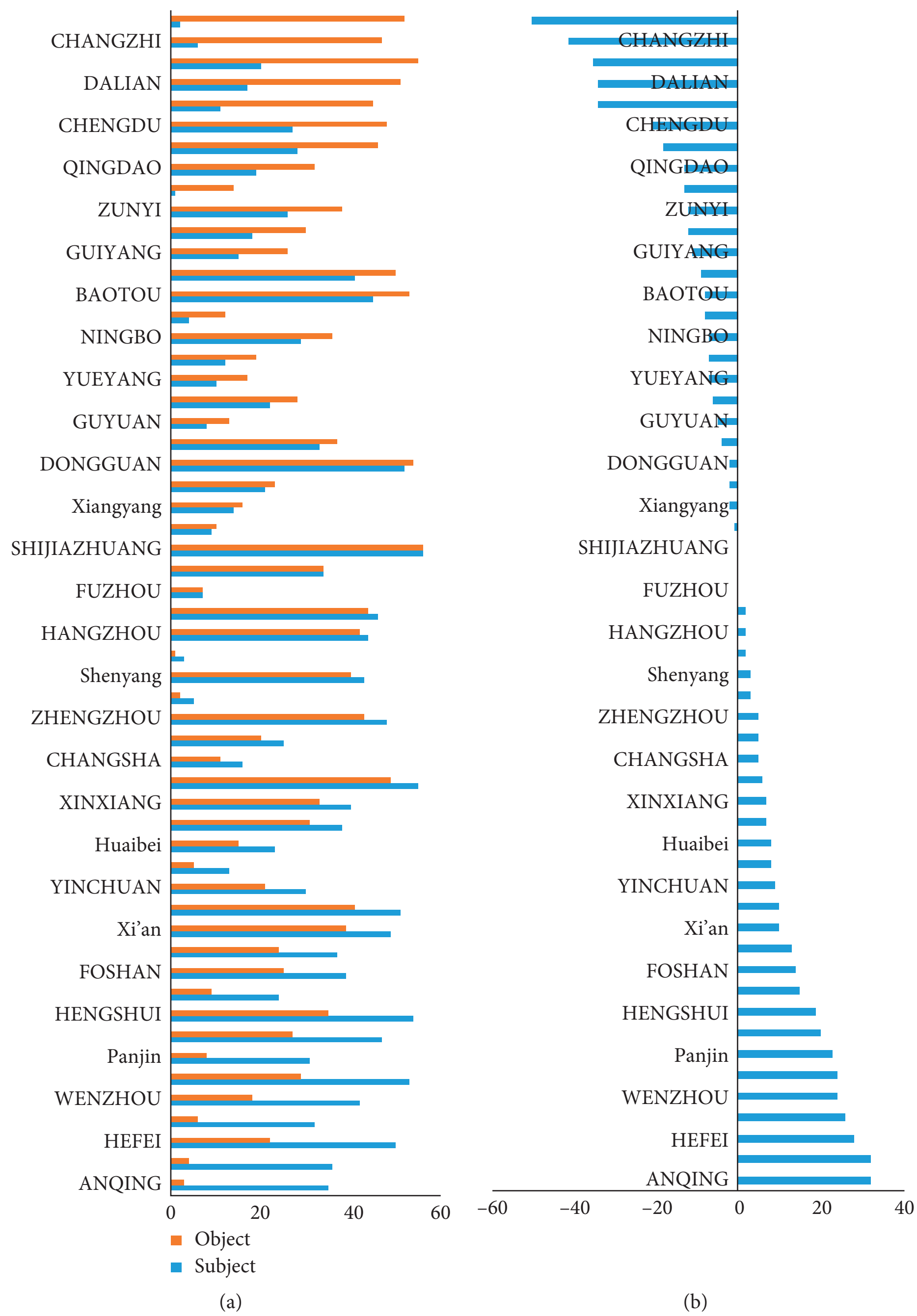

Figure 2: The subjective ranking and objective ranking and difference of environmental quality in each city.

urban evaluation among people with different educational levels. We will prove this by the conditional inference tree in the following passage.

3.3. Feature Classification Analysis. Based on the important driving factors of random forest extraction, we obtain the integral sample ($N = 4652$) of conditional inference tree. A stacked bar chart for each terminal node shows the percentage of individuals whose subjective evaluation is higher than the objective "1" (in black) or whose subjective evaluation is lower than the objective "0" (in light). Each tree has three layers. We set a 95% confidence interval as one of the conditions that the number of branches can be used as a node, so that each node reports the corresponding P value.

The most important variable in Figure 8 is population density, which is consistent with the screening results of random forest. Secondly, for the urban road area, we found that, in the group with moderate population density, node 11 completely divided the urban road area into two groups: "high, low" and "medium," while the group with high subjective evaluation accounting for the largest proportion was "medium." Then observe node 2 and node 5 and ignore the influence of education node 7. In the group of low

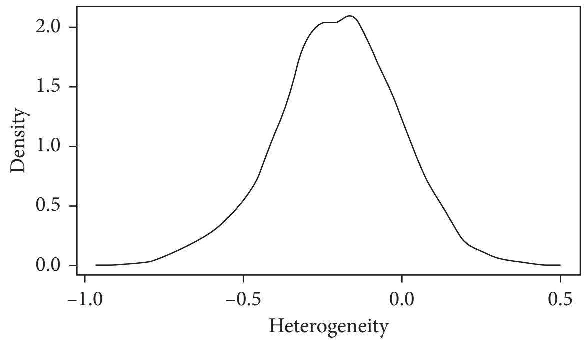

Figure 3: Differential exponential kernel density function diagram.

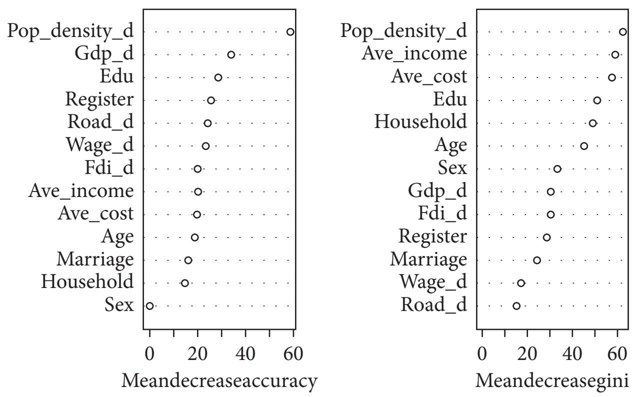

Figure 4: Factors in order of importance.

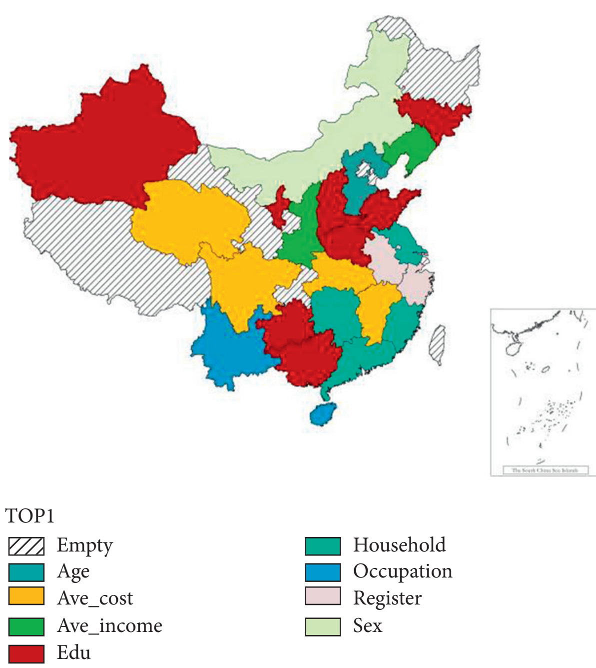

Figure 5: The top one factor in each province.

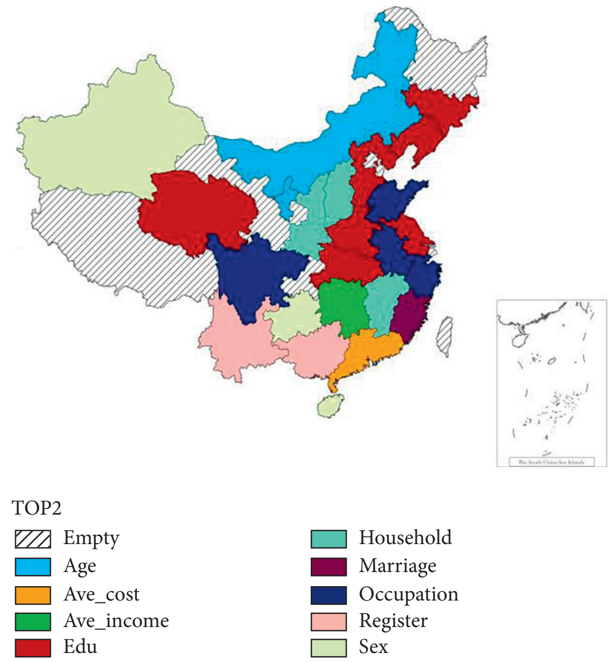

Figure 6: The second factor in each province.

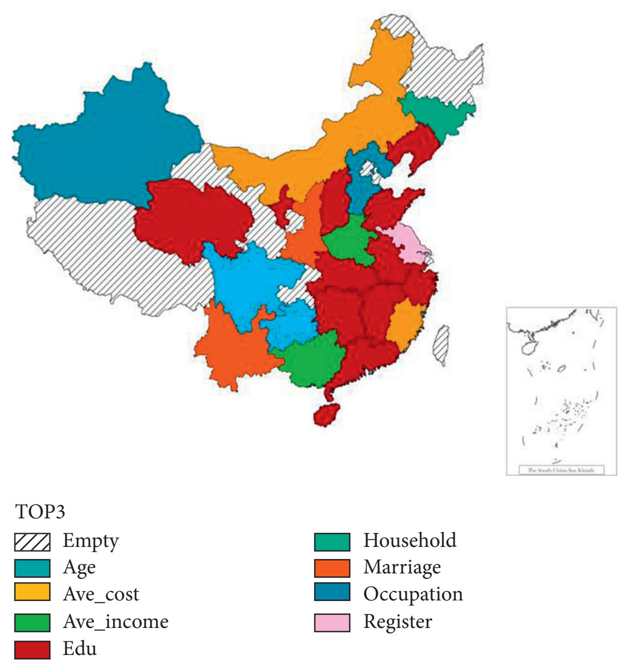

Figure 7: The third factor in each province.

population density and high urban road area (node 6), the percentage of people with higher subjective evaluation is significantly higher than that of other groups. The former shows that extreme population density and urban road area may not bring better subjective evaluation of environmental quality. The latter indicates that, in the case of lower population density, if the city has a larger urban road area, the probability of obtaining higher subjective evaluation is significantly higher than that of the group with lower road area. Hence, on the basis of previous researchers [22], we can draw the conclusion that, in cities with low population density, increased investment in transportation infrastructure can improve urban air quality, because it can bring people more perceived environmental optimization, which is also very consistent with our hypothesis.

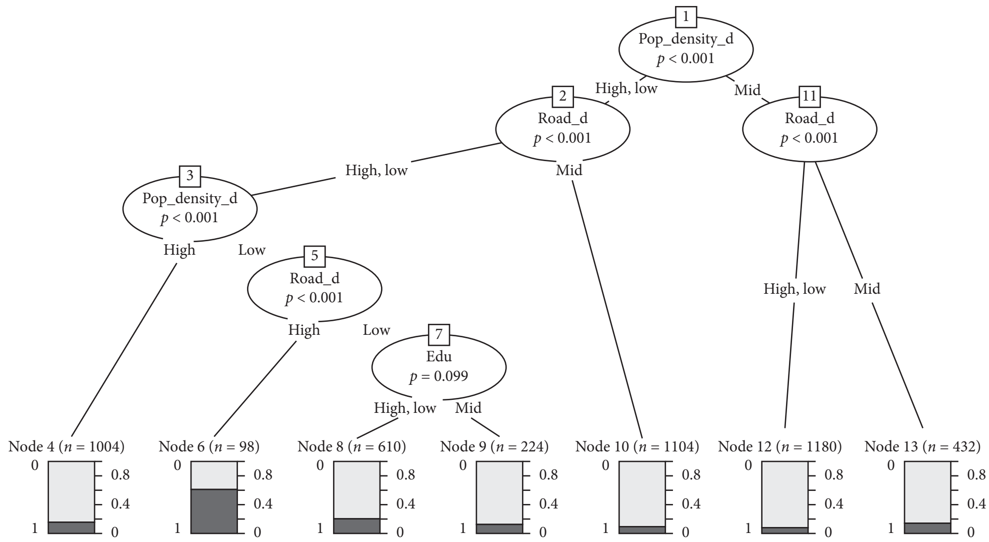

Figure 8: Conditional inference tree for all samples. Note: each node of the branch is numbered.

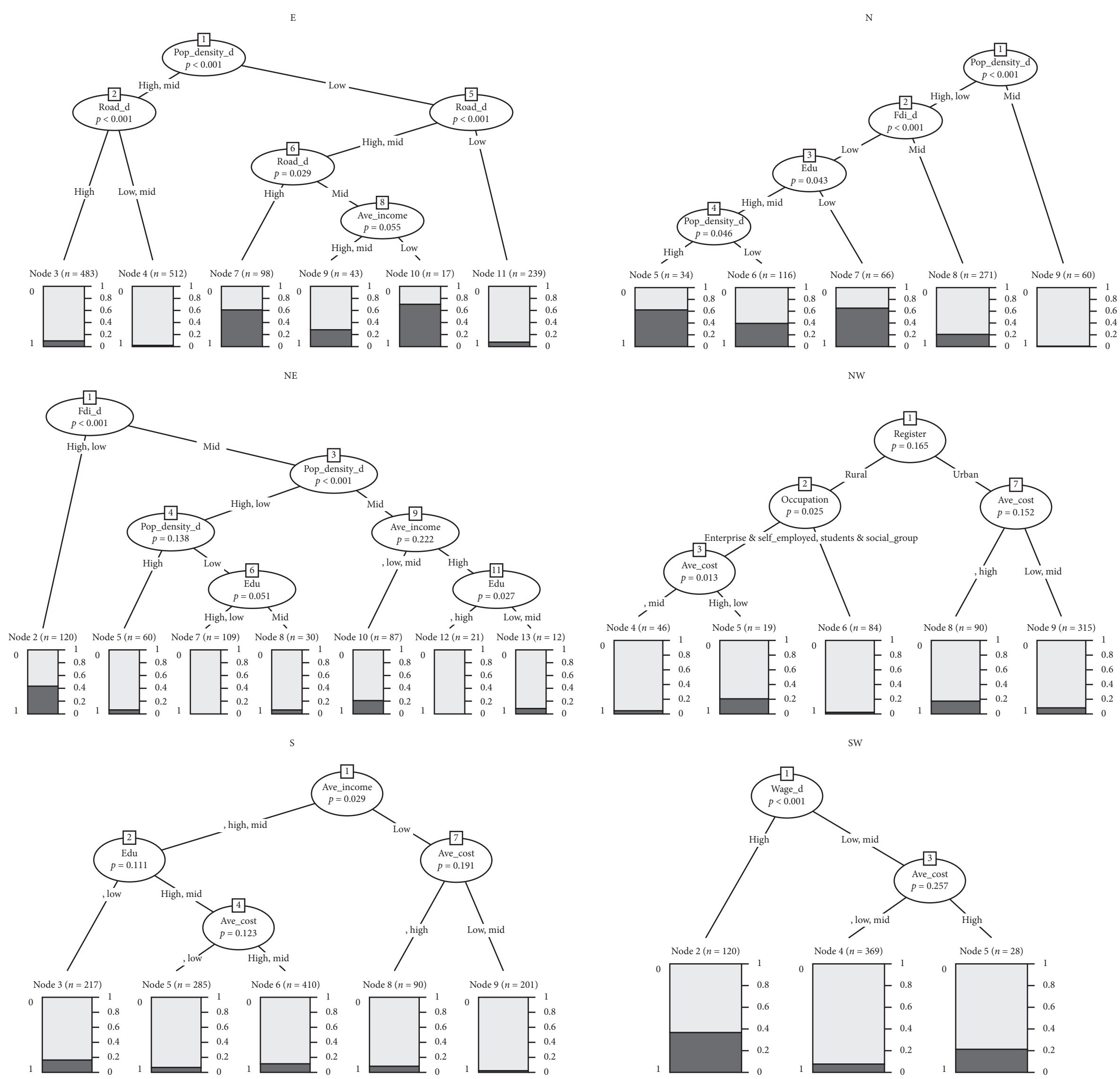

Figure 9: Conditional inference tree of six geographical regions.

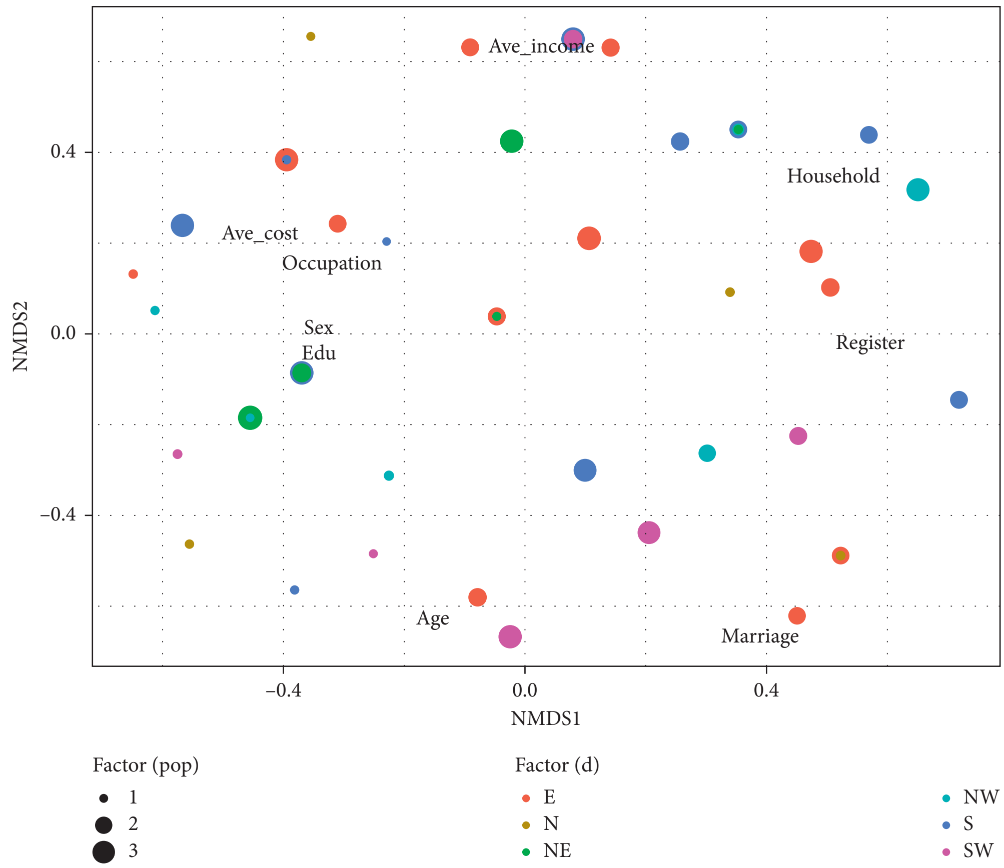

Figure 10: Nonmetric multidimensional scaling (NMDS) analysis of top significant factors. *Note.* (1) Pop represents the population of the city; the larger the circle, the larger the population. (2) Factor d represents the six regions. (3) Its coordinate axis is only set to reflect the distance relationship between samples after downscaling.

In addition, from node 7, the education node divides the sample into two terminals: terminal 8 is "below high school" and "bachelor degree or above"; node 9 is "technical secondary school and higher vocational school" group. It can be seen from the figure that the sample size of node 8 is larger than that of node 9, indicating that this group of people has a greater probability of making positive evaluation of the environment. For one thing, more educated people may have better knowledge and ability to manage personal health and access to healthcare, higher incomes, better jobs, and stronger social connections and then improve health. Educational attainment may also be associated with differences in occupational exposure, living conditions, or baseline health status [23]. However, lower socioeconomic groups are at increased risk of mortality and morbidity after exposure to environmental pollution. George [19] also found a higher susceptibility to environmental pollution in the least-educated population, as well as higher risk factors that affect health when exposed to air pollution. At the same time, because of the realistic environmental pressure caused by economic, unemployment, and even security problems faced by undereducated people, attention to environmental protection issues is reduced, so it is easier to give better environmental evaluation [24].

There is a general recognition that higher education is often associated with a broader awareness of environmental pollution. Thus, we have to admit that, with the improvement of social education level (especially in developing countries), more and more people will start to notice the change of environmental quality. Therefore, strengthening basic education and environmental awareness education are effective tools to improve the awareness of environmental quality.

3.4. Regional Heterogeneity Analysis. Samples in this study cover 56 cities in China, so whether these driving factors have similar rules in each city (or the region where they are located) is the question to be explored in this section. Consistent with the above method, we first applied the random forest algorithm to the samples of China's six major geographical regions to calculate the main influencing factors of each region (see Figure S1*). Figure 9 shows the conditional inference trees of the six regions in China. In general, it can be found that the main factors influencing the subjective and objective evaluation differences are urban factors in east China, north China, and northeast China. The three most important factors are population density, foreign direct investment, and urban road area. In the northwest, southwest, and south, the main factors are individual factors, such as education, household registration, income, and expenditure. In the six districts, the main* *environmental problems faced by each district are basically similar. The economic and cultural environment of its residents is relatively consistent. Here, we can assume that the characteristics of residents of "adjacent cities" have more commonality. We use the nonmetric multidimensional scale (NMDS) to visualize the relationship between cities and predictors as accurately as possible in low-dimensional space.*

In addition, we assume that the characteristics of the residents of the "same area" have more commonality. We use the nonmetric multidimensional scaling (NMDS) to visualize the relationship between cities and factors in low-dimensional space more accurately. We should consider nine factors due to the multidimensional nature of our data. Based on that, it is necessary to do NMDS sequencing and multivariate techniques.

It is not difficult to find that there is no centralized distribution of the influencing factors, which is conducive to the observation of urban distribution in Figure 10. Obviously, around each of the main factors, we cannot see a concentration of cities in the same region, and all the cities are scattered in the ordering space. Although the results are contrary to our hypothesis that the consistency of the influencing factors with the regional environment is not obvious, the heterogeneity of the key influencing factors in each city to the environmental assessment indicates that each city has its own relatively unique set of correlations. For example, there are many samples clustered around ave_cost, occupation, edu, and sex, and some samples are clustered around household and ave_income to varying degrees. Thus, the policy formulation of promoting residents' environmental awareness and environmental relevance should be adjusted according to the special situation of each region.

Taking cities in northeast and southern China clustered around educational factors as examples, the CTREE analysis of these two origins also shows that educational factors have a greater impact on them. Therefore, policy makers can focus on analyzing the deeper relationship between educational factors and environmental quality and environmental assessment, so as to guide policy formulation.

4. Conclusion

First of all, it should be affirmed that the environmental evaluation of cities is driven by different factors. The empirical results of this paper make us better understand the importance of these factors and how they work together. From a national perspective, the situation of lower population density and better transportation infrastructure in cities can bring about more perceptive environmental optimization. In particular, it should be pointed out that the importance of population density is always important in the analysis of the whole sample. The increase of population density will increase the demand for housing and automobiles, which will lead to the increase in the emission of construction dust, automobile exhaust, and other pollutants. It will affect the environmental quality [22]. Hence, the appropriate increase of urban road investment matching the growth rate of car ownership should pay special attention to the growth of road area, so as to improve the smoothness of urban traffic, reduce the emission of air pollutants, and achieve the balance and all-round development of urban traffic.

On the other hand, from the perspective of cities, we found that educational factors frequently appeared. The results of conditional inference tree also proved the above basic hypothesis: the influence of education on environmental evaluation is not linear. Residents with high and low education levels are more likely to make better environmental assessment choices on the basis of their respective factors. Although the results showed that people with lower education also tended to give higher environmental quality ratings, this "positive feedback" was irrelevant to environmental improvements. Consequently, it is a better choice to strengthen basic education and environmental protection education, enhance residents' awareness of environmental protection, and promote the improvement of environmental quality.

Meanwhile, the consistency of major factors among regions is not obvious and the situation that different cities share the same factors is also not significant. Since there is no significant consistency between the major influencing factors in different regions and cities, we should not ignore the influence of subsidiary factors, although we pay close attention to the analysis of the major factors and these factors with the highest evaluation rate. Consequently, according to the main driving factors, the city can adjust its political focus under the guidance of the unified national environmental policy.

Data Availability

The data are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Supplementary Materials

The supplementary file shows the random forest results of the six regions in China representing the ranking of important drivers for each region. (*Supplementary Materials*)

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Research Article

Pre-Evaluation of Industrialization Project of Local Science and Technology Achievements Based on FAHP

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In order to build a scientific pre-evaluation system for the industrialization of local science and technology (sci-tech) achievements, based on the analysis of the characteristics and laws of the industrialization projects of sci-tech achievements, the pre-evaluation of the industrialization projects of sci-tech achievements at home and abroad, the importance of the pre-evaluation of the industrialization projects of local sci-tech achievements and the research methods, the pre-evaluation index system of industrialization projects of local sci-tech achievements has been established from six aspects: policy environment, technical performance, economic benefits, resource guarantee, organizational guarantee, and social benefits. The research took the smart manufacturing project in Xiqing District of Tianjin as the object of empirical analysis and applied the fuzzy analytic hierarchy process (FAHP) to comprehensively evaluate the project. The overall score of the smart manufacturing project was 87.639, and the evaluation result was good and in accordance with the actual situation. The feasibility and validity of the evaluation index system and the evaluation model are verified, the risks of economy and policy in the industrialization of sci-tech achievements are reduced, and the optimization rate of the industrialization project is improved, which provide a reliable basis for local governments to realize the industrialization of sci-tech achievements.

1. Introduction

The development of science and technology is the internal driving force of economic growth, and the industrialization of sci-tech achievements can greatly promote economic development [1, 2]. At present, all countries in the world are actively adjusting their strategies to seize the commanding heights [3] of industrialization of sci-tech achievements. There are many scientific discoveries and technological breakthroughs around the world every year, and very few of them have been successful in industrialization. China has ranked first in the number of global patent applications for many years, but the level of industrialization is significantly behind that of developed countries. One of the very important reasons is that the current pre-evaluation work for the industrialization of sci-tech achievements in my country is not in place.

Pre-evaluation is the prerequisite and basic work for the industrialization of sci-tech achievements [4, 5]. The implementation of effective pre-evaluation can not only distinguish the promising projects, promote project establishment, and optimize resource allocation but also propose improvement directions and measures for unsatisfactory projects, laying the foundation for later project establishment [6].

The pre-evaluation of the industrialization of local sci-tech achievements refers to the scientific and technological management activities in which the competent department of sci-tech employs peer experts to review and evaluate the sci-tech achievements in accordance with the prescribed forms and procedures and make corresponding appraisal conclusions. It is suitable for China's national conditions at this stage, the government's macromanagement of sci-tech work means. The main functions of the pre-evaluation of the industrialization of local sci-tech achievements are as follows: it can distinguish the authenticity of sci-tech achievements and provide credible appraisal opinions for the market; review the sci-tech achievements and evaluate the advanced nature, innovation, novelty, and practicability of sci-tech achievements; affirmation and encouragement of scientific research achievements of sci-tech personnel; to provide the necessary basis for sci-tech awards, enjoying relevant policies and scientific research projects; to evaluate the scientific research and development strength of scientific research institutes; and it marks the end of a scientific research project cycle and provides appraisal conclusions for the end. It is of great significance to correctly judge the quality and level of sci-tech achievements through pre-evaluation, promote the improvement of sci-tech achievements, encourage sci-tech personnel to actively carry out sci-tech innovation activities, accelerate the transformation of sci-tech achievements, and promote economic and social development.

2. Characteristics and Study Method of Pre-Evaluation of Industrialization Project of Sci-Tech Achievements

Grasping the basic laws of the industrialization project of sci-tech achievements is a prerequisite for building a pre-evaluation index system and promoting the industrialization level.

2.1. Characteristics and Laws of Industrialization Projects. The transformation of science and technology into actual productivity is a common concern in the world today. The industrialization of sci-tech achievements has both scientific and economic nature and has certain regularities in itself. The industrialization process of sci-tech achievements can be roughly divided into four stages, namely, the market forecasting stage, the achievement generation stage, the achievement transfer stage, and the achievement use stage [7–9]. The connotation of the stages and the relationship between them are shown in Figure 1.

The industrialization project of sci-tech achievements has the following basic characteristics: First, the direct purpose of the industrialization project of sci-tech achievements is to obtain economic benefits. Second, sci-tech achievements are the results of innovation and are differentiated, but they are inseparable from technological development paradigm, so it has its own regularity [10, 11]. Third, it requires continuous advancement, which may lead to the failure of the whole project if one link is interrupted. Fourth, it contains multiple links and various elements, and it is bound to be promoted in a combined way. Lastly, the whole process is faced with a variety of high risks, such as technical risks, market risks, and business risks, and at the same time, it should be of high profitability.

Summarizing the experience of industrialization at home and abroad, the key conditions for the industrialization of sci-tech achievements are as follows: to ensure the allocation of high-quality talents, sufficient funds, and other key elements; to meet the market demand so that the achievements can be transformed into economic benefits; and the government should issue the necessary policies to support and protect them and create a good environment for industrialization [12–14].

2.2. The Pre-Evaluation of the Industrialization Projects. The pre-evaluation of sci-tech industrialization project is a complicated and systematic work. The comprehensive evaluation of sci-tech achievements can be obtained from the evaluation process, evaluation indicators, evaluation criteria of evaluation indicators, and evaluation results of various content (indices). On the whole, the pre-evaluation methods, processes, standards, and priorities for technological industrialization projects are different for different institutions at home and abroad [15, 16].

2.2.1. Pre-Evaluation Features of Foreign Achievement Industrialization. The main subjects of pre-evaluation of sci-tech achievement industrialization projects abroad are large-scale technology companies, venture capital companies, and bank credit institutions. Different subjects have different pre-evaluation processes and evaluation focuses [17, 18]. The details are as follows: as the large technology companies, its first step is feasibility assessment, focusing on the assessment of technical and economic feasibility, operational feasibility, and compatibility with future enterprise production and operation activities. The second step is the technical evaluation, which is a complete and reasonable inspection of the process design and technical scheme of the transformation results from a microscopic point of view. The third step is economic evaluation, forecast economic costs, and expenditures and to see whether the project or technology has a good application prospect, to ensure that the benefits can cover the costs and expenditures. The fourth step is risk assessment to identify the probability and degree of impact of the risk.

The Venture Capital Company. There are basically four stages for the venture capital company: the first stage is mainly to understand whether the project is in line with the company's investment policy and strategy; the second stage is mainly to inspect the project management and core personnel and to initially verify the authenticity of the main indicators considered and to find out what needs to be improved; the third stage is mainly based on the indicators for a more comprehensive and detailed evaluation; the fourth stage is the decision-making stage, which comprehensively evaluates the results of the detailed investigation. The key factors to be considered in decision-making are the quality of leaders, market demand, innovation of products and technologies, and the return on investment. Regarding the key points and indicators of the investigation, several sets of index values and weights will be given for projects in different industries and at different stages of development in combination with their operational experience and theoretical analysis.

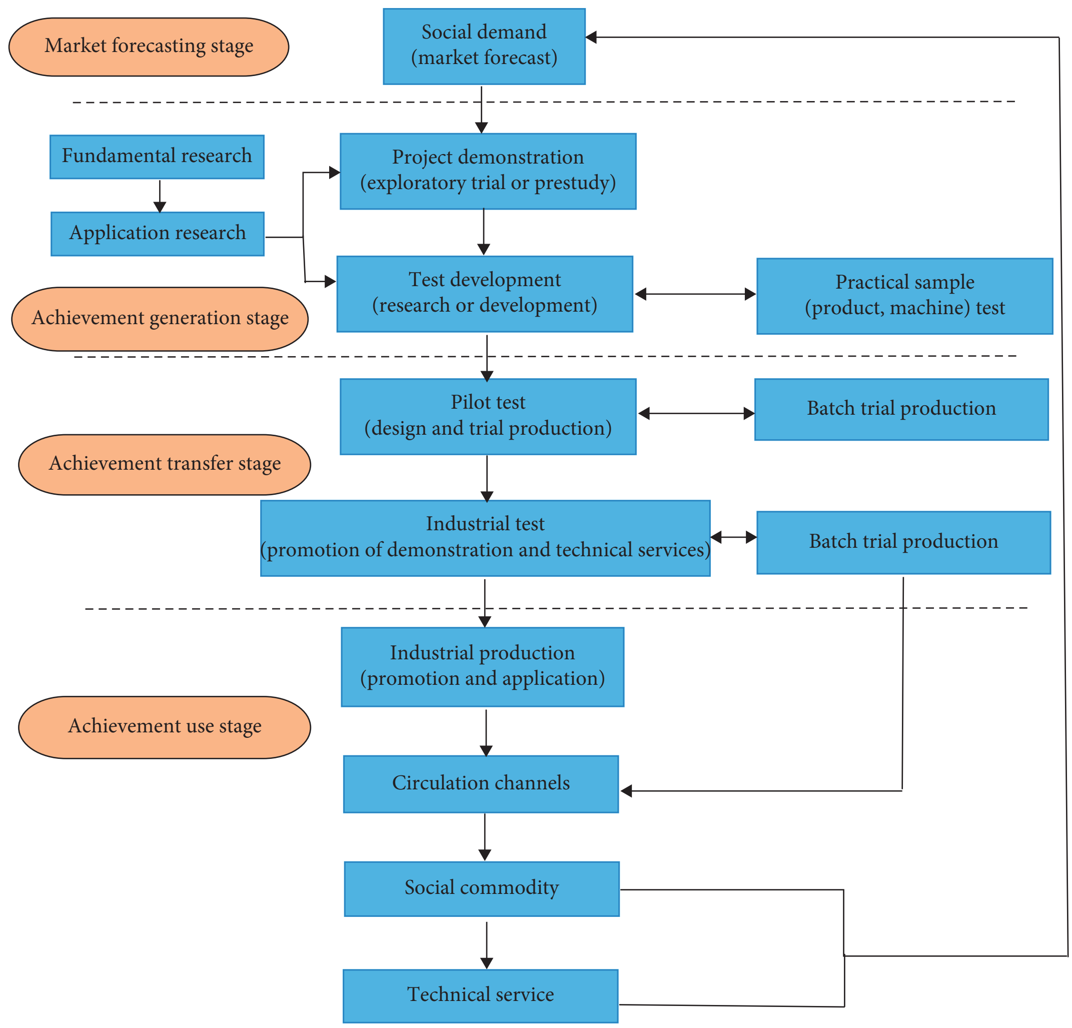

Figure 1: Chart of the basic process of industrialization of science and technology achievements.

Concerning the bank credit institutions, banks and other institutions have not yet formed a unified index system. Although there are different views, the five aspects of morality, ability, capital, mortgage, and environment are generally recognized (see Table 1).

2.2.2. Pre-Evaluation Features of Domestic Achievement Industrialization. The pre-evaluation of the industrialization projects of sci-tech achievements in China is mainly based on the pre-evaluation of commercial bank loans and the project evaluation of the industrialization of sci-tech achievements in various regions.

As for the commercial bank, at present, China's state-owned commercial banks mainly focus on the credit status and financial strength of the enterprises applying for loans. They have paid insufficient attention to the market prospects and development potential of the project itself. As a result, some high-quality projects have lost their industrialization opportunities due to the lack of corporate financial resources, and they cannot effectively promote the industrialization of sci-tech achievements [19–22].

As for the local provinces, some provinces and cities in China have explored and established pre-evaluation standards and related systems for the industrialization of sci-tech achievements, taking Qinghai Province and Yunnan Province as examples. Qinghai Province adopts a comprehensive evaluation method combining peer review with analytic hierarchy process. The evaluation index system for project establishment mainly includes five aspects: enterprise development capabilities, the feasibility of project technical scheme, product markets, business models, and economic benefit evaluation. In Kunming of Yunnan Province, the evaluation index system of the major science and technology projects mainly includes two parts: technology and management evaluation and economic and financial evaluation. In the evaluation, due to the different development stages of the project application enterprises, the indicator system is slightly different.

2.2.3. Deficiency in China. Although more comprehensive evaluation and selection methods and procedures have been formed in many places of China, and good results have been

Table 1: The main indexes of the pre-evaluation of foreign bank credit institutions.

Index category	Purpose and focus of the investigation
Moral character	Mainly to evaluate the borrower's ethical code of conduct.
Ability	Mainly the ability to make profits and repay borrowings.
Capital	The company's overall financial strength is usually measured by its net worth (total capital–total liabilities).
Mortgage	Refers to the collateral that the borrower should provide as a guarantee for repayment. Mainly to evaluate the feasibility of the borrower to provide collateral. The collateral provided by the borrower must be able to guarantee the creditor's rights.
Environment	Evaluate the internal and external business environment in order to make prejudgment in advance and take measures when necessary to ensure the security of loans.

achieved, there are still a series of problems and deficiencies, which are prominently shown as follows:

(i) The evaluation index system is not comprehensive enough. Judging from the research results in the field of index system, the pre-evaluation in China still focuses on the evaluation of science and technology itself and economic benefits, and the nontechnical factors that have a significant impact on the success or failure of the project, such as the project implementing team, are insufficiently reflected.

(ii) The design of the evaluation system is not strongly pertinent. Most of the existing evaluation systems do not fully involve relevant indicators of economic benefits, social benefits, and industrialization levels and do not distinguish well between national-level technology industrialization projects and local technology industrialization projects.

(iii) There is a lack of targeted research on evaluation methods and models. There are many evaluation methods in the existing research, and evaluation methods and models emerge in an endless stream, but there is a lack of targeted research and methodology research.

(iv) The utilization of pre-evaluation value is insufficient. Most of the pre-evaluation results are still used in project selection and elimination, and deep-level value mining is not sufficient.

(v) The legal protection mechanism is not sound enough. Most regions mainly inherit legal protection mechanism of national overall pre-evaluation. Due to the particularity of the pre-evaluation of technological industrialization projects, the existing relevant legal system cannot form a targeted legal protection for pre-evaluation.

(vi) The overall research level lags behind that of foreign countries. The domestic research obviously lags behind the foreign research progress, and the domestic research literature mainly focuses on tracking research and the application of ready-made methods, lacking the evaluation theory and method research for the industrialization project of scientific and technological achievements and the operation characteristics of scientific and technological system in China, and the evaluation for the local scientific and technological industrialization project is also less.

Due to the differences between the industrialization project of local sci-tech achievements and the industrialization project of general sci-tech achievements, the local government pays more attention to the economic value and social value brought by the industrialization project of sci-tech achievements, the contribution to the optimization of the local industrial structure and the promotion of the competitiveness of the core industry, and the impact on the tax revenue and employment of the local industry. Therefore, in view of the fact that the existing pre-evaluation index of the industrialization project of local sci-tech achievements is not accurate and easy to realize the evaluation operation, this paper constructs an objective and standard evaluation index system, makes the ideal index system realistic, and can carry out quantitative processing, to ensure the rationality, objectivity, and fairness of the index comparison results. At the same time, in view of the lack of organic combination of qualitative or quantitative research methods used in the pre-evaluation of the industrialization project of sci-tech achievements, this paper adopts more effective quantitative statistical methods to conduct more detailed and in-depth evaluation and analysis of the industrialization project of sci-tech achievements and establish a normalized monitoring system covering comprehensive data and statistical basis.

2.3. Pre-Evaluation Method of Industrialization Project of Local Sci-Tech Achievements. There are many comprehensive evaluation methods with its own advantages and limitations, and each method has its own scope of application. The conventional comprehensive evaluation methods mainly include index method, efficiency coefficient method, optimal distance method, and queuing method; modern comprehensive evaluation methods include multiple statistical evaluation methods, operations research evaluation methods, systems engineering evaluation methods, intelligent evaluation methods, etc., which have developed rapidly in recent years. Principal component analysis (PCA) and factor analysis (FA) are multisystem evaluation methods, which are objective methods that do not rely on expert judgment. Therefore, the interference and influence of human factors in the evaluation can be eliminated, and they are more suitable for evaluating each other. The comprehensive evaluation of the target system with a greater degree of relevance ignores the actual importance of the indicators and overemphasizes the objectivity of the indicator data, and the evaluation conclusions are relative. Usually, PCA and FA emphasize that the information contained in the evaluation index is independent and uncorrelated. If there is a certain correlation between the evaluation indexes (neither completely independent nor completely related), it will bring great inconvenience to the research. If too many indicators are selected, it will increase the difficulty and complexity of the analysis. If too few indicators are selected, the indicators that have a greater impact on the sample may be missed, which will affect the reliability of the results.

In this study, when establishing the pre-evaluation index system of the industrialization project of local sci-tech achievements, there are certain restrictions on the requirements of the correlation among the indexes, and considering that there are many uncertain concepts which cannot be measured objectively, so the use of principal component analysis and factor analysis are abandoned. Both the efficacy coefficient method and the comprehensive index method are applicable to target systems with clear goals or reference systems. The industrialization projects of local sci-tech achievements cannot be measured by a unified standard because of the differences in the scale, nature, and characteristics of the evaluation objects; therefore, it is impossible to get the ideal evaluation results through these two evaluation methods. It is difficult for the queuing method to precisely quantify the evaluation content and can only distinguish the superior and inferior order. The evaluation value of the optimal value distance method is based on the optimal value of a single index, when the optimal value deviates far from the general level, the evaluation result is easily influenced by the extreme value (the optimal value), making the gap between the evaluation results of most units not obvious. TOPSIS evaluation method is a common method used in multi-objective decision analysis of limited schemes in systems engineering. It finds the optimal scheme and the worst scheme among the limited alternatives and obtains the relative closeness of each evaluation object to the optimal scheme, which is used as the basis of pros and cons of evaluation. While the scope of application of data envelopment analysis is limited to multi-input and multioutput object systems, the gray relational analysis law requires the sample data to have the characteristics of time series.

The pre-evaluation of the local sci-tech achievement industrialization project in this article cannot meet this condition, and the gray relational analysis method only distinguishes the pros and cons of the project evaluation and cannot reflect the absolute level. Rough set theory is a mathematical method to deal with ambiguity and uncertainty. It does not require any prior information besides processing data. It cannot provide the weight distribution of system attributes based on objective information. Fuzzy comprehensive evaluation is also a mathematical method, which can effectively analyze and process all kinds of inaccurate, incomplete, and uncertain information. In the evaluation process, some fuzzy factors can be considered, and various factors can be used to evaluate things. On the basis of determining the degree of membership, the analytic hierarchy process is used to determine the index weight. This method has both strict quantitative description and qualitative description of fuzzy phenomena that are difficult to quantitatively analyze. It is a very effective multifactor decision-making method that closely combines qualitative description and quantitative analysis.

The pre-evaluation of industrialization projects of local sci-tech achievements studied in this paper is affected by many factors, including both quantitative and qualitative indexes. It is necessary to combine various influencing factors to make a comprehensive evaluation of local sci-tech achievement industrialization projects, and multilevel fuzzy comprehensive evaluation method has good applicability on this issue. There is no strict requirement for data, and the method is simple and easy to operate. Therefore, this paper will use this method to pre-evaluate the industrialization project of local sci-tech achievements.

3. Construction of Pre-Evaluation Index System

3.1. Construction Process. There is no uniform procedure and steps for the pre-evaluation process of the industrialization of sci-tech achievements, but generally speaking, it roughly includes the following seven stages:

(i) Making sure the evaluation objective and scope: according to the main objectives and functions of the industrialization of sci-tech achievements, national (regional) sci-tech development objectives, social development objectives, etc., the evaluators will analyze and study the main influencing factors listed in this method and find the most influential factors as the evaluation objectives.

(ii) Selection of evaluation indicators: according to the types and characteristics of the project itself, scientific and reasonable evaluation indicators are selected, including qualitative indicators and quantitative indicators.

(iii) Preliminary evaluation of the project: based on the survey and forecast data, conduct a preliminary evaluation of the project to see whether the various indicators of the project meet the minimum requirements for evaluation, especially whether they meet the national and industrial policies, environmental protection requirements, consumer safety, and other screening indicators.

(iv) Evaluation of the selected projects in detail: for the projects qualified in the preliminary evaluation, the projects will be evaluated in detail according to the indicators of the evaluation system and comprehensive evaluation will be carried out.

(v) Comprehensive evaluation of the project: the detailed evaluation results of the project are synthesized to obtain a comprehensive evaluation value, and then the comprehensive evaluation value is made to select the best project with the highest evaluation value.

(vi) Organizing expert seminars: for valuable projects, expert seminars are organized to modify and improve the project plan based on expert opinions with a summary report.

(vii) Evaluation summary: summarize the whole evaluation work, put forward the evaluation conclusion, and write the summary report.

According to the above basic steps, the basic process of pre-evaluation industrialization projects of local sci-tech achievements is preliminarily designed, as shown in Figure 2.

3.2. Principles of Constructing. The design of pre-evaluation index system is the key content of the whole pre-evaluation system design. The selection of index determines the focus of future evaluation, and the design of index system will affect the rationality of pre-evaluation results to a great extent. The design of the index system should be scientific, standardized, and reasonable. On the basis of the following, the law of sci-tech achievements and drawing lessons from the new evaluation system at home and abroad, especially the pre-evaluation index design experience of venture capital industrialization project of sci-tech achievements, and combining with the development conditions and characteristics of China's current industry, this paper discusses and designs a set of scientific, normative, and comprehensive index system suitable for China a pre-evaluation index system integrating operability. The construction principle of pre-evaluation index system is reflected in the following aspects:

(i) Scientific principles: scientificity is reflected in the correctness and maturity of scientific theory, the maturity and feasibility of the technology line, and the standardization and advanced degree of research methods.

(ii) The principle of usability: the usability of technology describes the difficulty and universality of technology. If the technology is used under harsh conditions, the risk will increase. The investigation of technology applicability includes the following: the number of technology applicable industries; whether technology is restricted by national conditions, geographical conditions, and natural resources; whether the technology is compatible with the existing standards and products in the market; and whether the technology can be flexibly applied or improved to meet the needs of the market.

(iii) The principle of feasibility: feasibility refers to the probability that the product (or technical service) formed by the industrialization of sci-tech achievements can play its specific function without failure under the specified conditions and within the specified time. It requires the improvement of engineering technology and product technology. High-tech production is to seek its supporting and perfect engineering technology and product technology, and product performance needs to reach the feasibility standard.

(iv) The principle of cost-effectiveness: the products formed by the projects based on the industrialization of sci-tech achievements belong to high-tech products with high added value. The success of the industrialization project largely depends on the profitability of products and services. It is necessary to analyze the excess returns that can be obtained by the investment of capital, the return on equity investment, the return on equity investment, and the return on equity investment. This paper analyzes the factors such as the gross profit rate of products and services that reflect the profit margin of the project, and the relevant indicators established according to the criteria directly reflect the profitability of the venture capital the industrialization project of sci-tech achievements.

In addition, in the pre-evaluation of the industrialization of local government sci-tech achievements, it is necessary to discuss one matter for special situation.

3.3. Establishment of Pre-Evaluation Index System. When establishing the index system, this article refers to relevant research materials, according to the characteristics of industrialization projects of local sci-technological achievements, combined with the influencing factors of general sci-tech evaluation, comprehensively using expert investigation methods, correlation analysis, and discriminative analysis based on the principles of comparability and operability, comprehensiveness and representativeness, hierarchy and system, scientificity, and accuracy. Six first-level indicators and twenty-five second-level indicators were selected, and the evaluation index system of local sci-tech achievements is completed in Table 2.

4. Principle of Fuzzy Analytic Hierarchy Process

In 1965, Zaden [23] proposed fuzzy set theory, which laid the foundation for fuzzy set theory and application research, marking the birth of fuzzy mathematics. In the 1980s, Saaty [24] first proposed the analytic hierarchy process (AHP) to solve some complex and difficult problems. Fuzzy analytic hierarchy process (FAHP) is a multifactor and multilevel composite method based on AHP. It can be divided into two categories: based on fuzzy number and based on consistent judgment matrix. The basic idea and steps of FAHP are consistent with the AHP proposed by Saaty, but the difference is that it considers the fuzziness of human judgment. Firstly, the research objectives are dealt with hierarchically; then, the fuzzy number or fuzzy function is used to describe the judgment, and the fuzzy judgment matrix is constructed to obtain the relative weight of each factor; secondly, defuzzification and normalization are carried out; and finally, the weight of the index is obtained to solve the decision of complex problems. Compared with the traditional weight determination method, FAHP can improve the objectivity of the weight. In addition, because the pre-evaluation of industrialization project of local sci-tech achievements involves many interrelated elements, many elements cannot be explained quantitatively by simple data. FAHP's advantages not only can systematically combine qualitative analysis with quantitative analysis to solve complex problems but also can

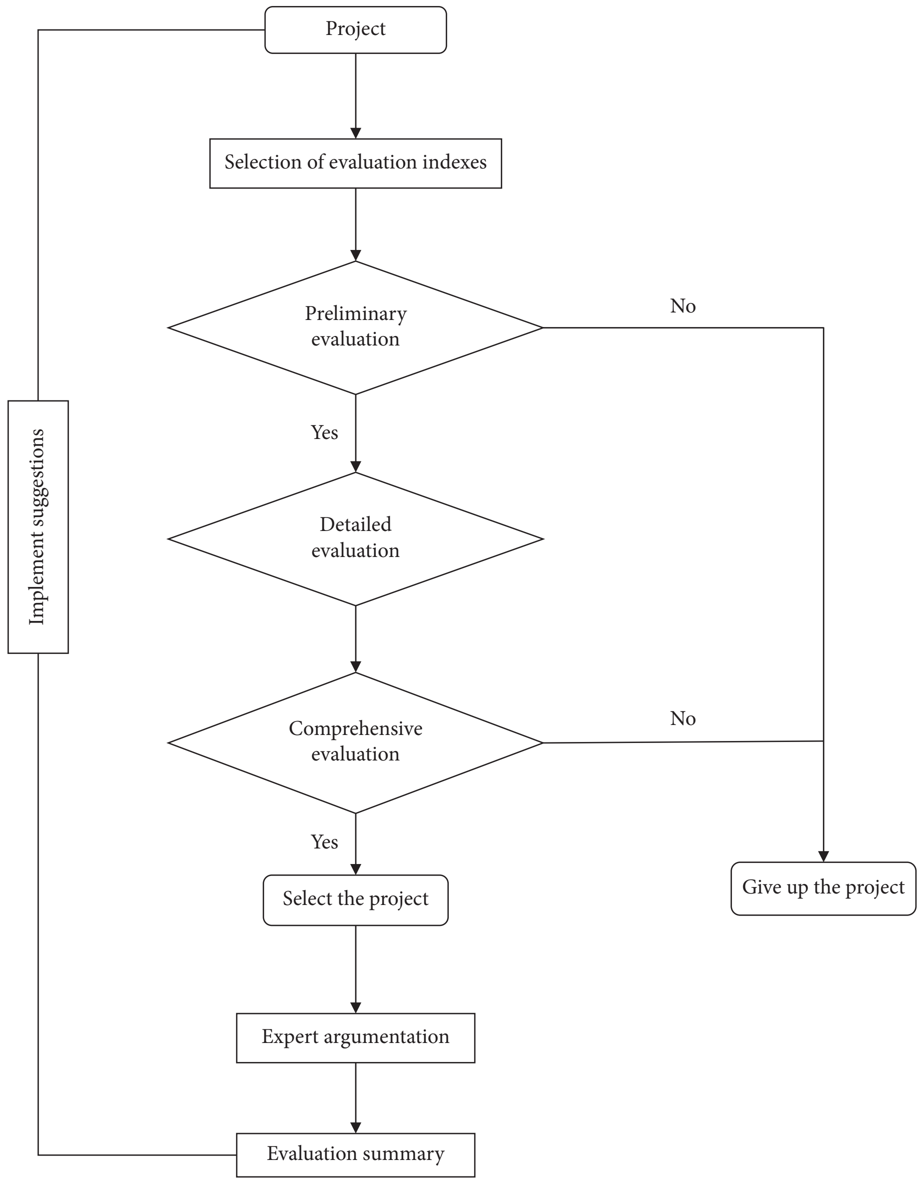

Figure 2: Flowchart of pre-evaluation of industrialization of sci-tech achievements.

directly and effectively combine the objective judgment results of decision-makers and decision analysts, and it is easy to calculate, simple and clear, and easy to be accepted by people to systematize, mathematicise, and model the decision-maker's thinking change process. Therefore, this study uses FAHP to study the pre-evaluation of industrialization project of local sci-tech achievements, which is scientific and applicable. The specific steps are as follows.

4.1. Construction of Evaluation Factor Set. The factor set of the evaluation system is established. The evaluation system is set as U, $U = \{u_1, u_2, \ldots, u_n\}$. It is the factor set. Among them, u_i refers to the i^{th} research object that has an influence on the system.

4.2. Determination of the Set of Weights. AHP analyzes the factors and the related relationships that are contained in the complex system, organizes and hierarchizes the problem, constructs a hierarchical analysis structure model, compares the elements of each level in pairs, and obtains the relative importance according to a certain scale theory. Comparing the scale and establishing a judgment matrix, calculating the maximum eigenvalue of the judgment matrix and its eigenvector, and obtaining the order of importance of each level element to an element of the upper level, thereby a weight vector was established.

After the establishment of the evaluation index system, the membership relationship between the indicators at the lower and lower levels is determined. Pairwise comparison is made for the importance of the indicators at the same level to

Table 2: Pre-evaluation index system of local sci-tech achievement industrialization project.

Total index	First-level index	Second-level index
The evaluation system for the industrialization of local scientific and technological achievements	Policy environment X_1(0.1038)	Industrial policy compliance X_{11} (0.3406) Environmental policy X_{12} (0.2088) Industrial policy conformity X_{13} (0.4506)
	Technical performance X_2 (0.2008)	Technical economy X_{21} (0.1268) Technical innovation X_{22} (0.5321) Technical feasibility X_{23} (0.1718) Technical risk X_{24} (0.1693)
	Economic benefits X_3 (0.4216)	Direct economic benefit X_{31} (0.3054) Indirect economic benefit X_{32} (0.2851) Rationality of economic structure X_{33} (0.0871) Improve product quality X_{34} (0.2251) Improve labor productivity X_{35} (0.0973)
	Resource guarantee X_4 (0.1668)	Human resources X_{41} (0.3302) Fund protection X_{42} (0.3101) Facilities and equipment conditions X_{43} (0.0803) Industrialization conditions X_{44} (0.1846) Research basis X_{45} (0.0948)
	Organizational guarantee X_5(0.0661)	Entrepreneurship X_{51} (0.0784) Corporate governance structure X_{52} (0.2013) Market operation ability X_{53} (0.2013) Management capability X_{54} (0.5190)
	Social benefits X_6 (0.0409)	Promotion of regional industries X_{61} (0.5324) Impact on tax revenue X_{62} (0.1688) Impact on ecology and resources X_{63} (0.1269) Impact on employment opportunities X_{64} (0.1719)

obtain the pairwise comparison coefficient to form a judgment matrix. Set n second-level indicators $s_{1,} s_{2,} \ldots, s_n$,and the constructed judgment matrix R is given by

$$R = \left(s_{ij}\right)\left(s_{ij}\right)_{n\times n} = \begin{bmatrix} s_{11} & s_{12} & \cdots & s_{1n} \\ s_{21} & \ddots & \vdots & \vdots \\ \vdots & \cdots & \ddots & \vdots \\ s_{n1} & s_{n2} & \cdots & s_{nn} \end{bmatrix}. \tag{1}$$

Among them, s_{ij} represents the importance of s_i relative to s_j, which is represented by numbers from 1 to 9 in pair-to-pair comparison. This scale is adopted in matrices to determine the weights of relative criteria and to compare the alternatives linked to every criterion. Table 3 summarizes the basic ratio scale. All final weighted coefficients are shown in matrices. Alternatives and criteria can be ranked based on the overall aggregated weights in the matrices. The alternative with the highest overall weight would be the most preferable.

Table 3: Saaty's scale for AHP pairwise comparisons [25, 26].

Weight	Description
1	Equal importance
3	Moderately more important
5	Strongly more important
7	Very strongly more important
9	Dominant importance
2, 4, 6, 8	Reciprocals

Based on this first index's judgment matrix, the weights of every first grade index can be calculated by the geometric calculation method of mean.

$$\overline{w_i} = \sqrt[n]{\prod_{j=1}^{n} s_{ij}}, \quad (i = 1, 2, \ldots, n). \tag{2}$$

Then make the normalized processing, using the following equation:

$$w_i = \frac{\overline{w_i}}{\sum_{i=1}^{n} \overline{w_i}}, \quad (i = 1, 2, \ldots, n). \tag{3}$$

The weight vector of first index is obtained as follows: $w = (w_1, w_2, \ldots, w_n)^T$.

The largest characteristic roots $\lambda_{\max}$ can be calculated by the following equation:

$$\lambda_{\max} = \frac{1}{n}\sum_{i=1}^{n} \frac{(AW)_i}{W_i}, \quad (i = 1, 2, \ldots, n). \tag{4}$$

However, due to the extreme complexity of objective things, the influencing factors of subjective understanding occasionally cannot entirely meet the requirement of consistency. Thus, checking the matrix for consistency is necessary, and the process is as follows.

The consistency ratio requirements are as follows: $\mathrm{CR} = (\mathrm{CI}/\mathrm{RI}) < 0.1$. $\mathrm{CI} = \lambda_{\max}/n - 1$. The mean random consistency index (RI) is shown in Table 4.

4.3. Establishment of Evaluation Set. Several evaluation sets were selected to form an evaluation set $V = \{v_1, v_{2,} \ldots, v_m\}$, and the evaluation criteria were divided into m grades.

4.4. Comprehensive Evaluation. First, the membership R set is calculated according to the opinions and scores of experts. According to equation (5), the comprehensive evaluation value of each level can be obtained. Finally, the evaluation of the project can be obtained through the maximum membership degree method or the weighted average method.

$$B = wR = (w_1, w_2, \ldots, w_n)\begin{bmatrix} s_{11} & s_{12} & \cdots & s_{1n} \\ s_{21} & \ddots & \vdots & \vdots \\ \vdots & \cdots & \ddots & \vdots \\ s_{n1} & s_{n2} & \cdots & s_{nn} \end{bmatrix}. \tag{5}$$

According to equation (5), the comprehensive evaluation value of each level can be obtained, and then the final evaluation can be obtained according to equation $G = B \cdot C$.

5. Empirical Analysis

5.1. Case Overview. In recent years, Xiqing District has deeply implemented the Beijing-Tianjin-Hebei Coordinated Development Plan. The economic structure has been continuously optimized, and its comprehensive strength has been at the forefront of Tianjin. For the past few years, Xiqing District has firmly grasped the opportunity of building a national advanced manufacturing research and development base, closely focusing on the Made in China 2025 plan and vigorously upgrading the level of industrial intelligence, and achieved positive results. Research on artificial intelligence and intelligent networked automobile industry has been carried out. The state-level vehicle network pilot area was approved to build a pilot application scenario and a three-level test system, opening 24.5 km of test road. The six top-end industries, such as electronic information, automobile, and equipment manufacturing, accounted for 74.7 percent of the region's large-scale industries. In 2020, Xiqing District's high-tech manufacturing sector accounted for 26.9 percent of the total value added of large-scale industries.

In order to verify the application of the evaluation model for the industrialization of local sci-tech achievements, this article applies the Internet + smart manufacturing support direction in the first batch of smart manufacturing special fund projects in Tianjin in 2019, and an industrialization project in Xiqing District, research and development of driving scene data management platform for intelligent network vehicle simulation test, was evaluated as an example, and the actual situation of the project is completed to verify the effectiveness of the evaluation results.

5.2. Fuzzy Comprehensive Evaluation. A fuzzy evaluation model is established for this example, which is the total evaluation index and is divided into six first-level indexes: policy environment, technical performance, economic benefits, resource guarantee, organizational guarantee, and social benefits, which are denoted as x_1, x_2, x_3, x_4, x_5, and x_6

According to the cascade theory, the results of the pre-evaluation are divided into five levels, and the corresponding fractionation section is $C = (0, 65, 75, 85, 95)$. The classification standard is shown in Table 5.

After constructing the completed index system, the weight of the index is determined by the analytic hierarchy process (AHP), the relative importance of the index is assigned by experts, and then the weight of the index after each expert's assignment is obtained according to the calculation method in this paper and to the final weight table with its arithmetic mean as an indicator (Table 2).

According to the classification of the evaluation set, 10 experts and representatives of enterprises in the industry were invited to pre-evaluate the project, and the quantitative scores of each secondary index were given. The score result is sorted out, and the score table is shown in Table 6. The numbers in the table represent the number of experts selected for the indicator, and the membership of the indicator is obtained by dividing the number of experts at different levels of each indicator by the total number of experts.

According to Table 6, the set of membership degree R is obtained as follows:

Table 4: The mean random consistency index.

Order	2	3	4	5	6	7	8	9	10	11	12	13	14
RI	0	0.52	0.86	1.10	1.26	1.34	1.40	1.43	1.49	1.51	1.54	1.56	1.58

Note. Reproduced from Chang et al. (2016) [25].

$$R_1 = \begin{bmatrix} 0 & 0 & 0.1 & 0.6 & 0.3 \\ 0 & 0 & 0.1 & 0.6 & 0.3 \\ 0 & 0 & 0 & 0.5 & 0.5 \end{bmatrix},$$
$$R_2 = \begin{bmatrix} 0 & 0 & 0.1 & 0.4 & 0.5 \\ 0 & 0 & 0.1 & 0.5 & 0.4 \\ 0 & 0 & 0.1 & 0.6 & 0.3 \\ 0 & 0.1 & 0.2 & 0.5 & 0.2 \end{bmatrix},$$
$$R_3 = \begin{bmatrix} 0 & 0 & 0 & 0.6 & 0.4 \\ 0 & 0 & 0.2 & 0.5 & 0.3 \\ 0 & 0 & 0 & 0.7 & 0.3 \\ 0 & 0 & 0.1 & 0.5 & 0.4 \\ 0 & 0.1 & 0.2 & 0.5 & 0.2 \end{bmatrix},$$
$$R_4 = \begin{bmatrix} 0 & 0 & 0 & 0.5 & 0.5 \\ 0 & 0.1 & 0.1 & 0.6 & 0.2 \\ 0 & 0 & 0.1 & 0.7 & 0.2 \\ 0 & 0 & 0.1 & 0.6 & 0.3 \\ 0 & 0 & 0 & 0.6 & 0.4 \end{bmatrix}, \tag{6}$$
$$R_5 = \begin{bmatrix} 0 & 0 & 0 & 0.7 & 0.3 \\ 0 & 0 & 0.1 & 0.6 & 0.3 \\ 0 & 0 & 0.1 & 0.6 & 0.3 \\ 0 & 0 & 0 & 0.4 & 0.6 \end{bmatrix},$$
$$R_6 = \begin{bmatrix} 0 & 0 & 0 & 0.5 & 0.5 \\ 0 & 0.1 & 0.1 & 0.6 & 0.2 \\ 0 & 0 & 0 & 0.7 & 0.3 \\ 0 & 0 & 0.1 & 0.5 & 0.4 \end{bmatrix}.$$

Combined with the weight values of the second-level indicators in Table 3, the weighted average model $M(\bullet, +)$ and equation (5) are used to calculate the following: $B_1 = w_1 \cdot R_1 = (0,\ 0,\ 0.0550,\ 0.5549,\ 0.3901)$

It is worth noting here that the model chosen in this paper is the weighted average model because the result of the main factor determining model is determined by the maximum index, the remaining indexes change within a certain range and do not affect the evaluation results, which is suitable for the single optimal case. Although the evaluation results of the main factor prominent model are more detailed than that of the main factor decisive model, they partly reflect the nonmain indexes. In order to make an accurate assessment of the results of the industrialization of sci-tech achievements in this paper, all the indicators in the evaluation index system have different effects on the assessment results, so the research gives up the other models and chooses the weighted average model [27–29].

Table 5: Classification standard.

Rank	Unideal (R_1)	Poor (R_2)	Normal (R_3)	Good (R_4)	Excellent (R_5)
Score	< 60	60–69	70–79	80–94	95–100

Similarly, we can get $B_2 = w_2 \bullet R_2 = (0, 0.0169, 0.1169, 0.5046, 0.3616)$, $B_3 = w_3 \bullet R_3 = (0, 0.0097, 0.0990, 0.5480, 0.3433)$, $B_4 = w_4 \bullet R_4 = (0, 0.0310, 0.0575, 0.5750, 0.3365)$,$B_5 = w_5 \bullet R_5 = (0, 0, 0.0403, 0.5040, 0.4557)$, and$B_6 = w_6 \bullet R_6 = (0, 0.0169, 0.0340, 0.5423, 0.4068)$.

Finally, the membership matrix of the pre-evaluation of the industrialization project of the scientific and technological achievements is as follows:

$$R = \begin{bmatrix} B_2 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \\ B_6 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0.0550 & 0.5549 & 0.3901 \\ 0 & 0.0169 & 0.1169 & 0.5406 & 0.3616 \\ 0 & 0.0097 & 0.0990 & 0.5480 & 0.3433 \\ 0 & 0.0310 & 0.0575 & 0.5750 & 0.3365 \\ 0 & 0 & 0.0403 & 0.5040 & 0.4557 \\ 0 & 0.0169 & 0.0340 & 0.5423 & 0.4068 \end{bmatrix}. \tag{7}$$

It can be seen from Table 3 that the weight of first-level indicators is$w = (0.1038, 0.2008, 0.4216, 0.1668, 0.0661, 0.0409)$. According to the weighted average model, $B = w \times R = (0, 0.0061, 0.0846, 0.5486, 0.3607)$ is calculated.

Then the pre-evaluation results of the industrialization of the scientific and technological achievements are as follows: $G = B \times C = 87.639$.

5.3. Analysis of Evaluation Results. According to the final evaluation result of the fuzzy and the comprehensive evaluation method, the pre-evaluation result of the industrialization project of the sci-tech achievements is good. In order to evaluate the industrialization project of sci-tech achievements from a comprehensive point of view, so as to facilitate the comparison between similar projects, this paper adopts the grading parameter evaluation method to pre-evaluate the industrialization project of sci-tech achievements. Excellent scores are between 95 and 100, and for this kind of evaluation results of science and technology projects, the key guidance and support should be given, as the driving force of local economic development, to promote the development of industrialization. Good is 80 to 94 points, and for this kind of evaluation results of science and technology projects, local governments and science and technology management should focus on support, but the fund support

Table 6: Local sci-tech achievement industrialization project pre-evaluation evaluation table.

First-level index	Second-level index	Unideal	Poor	Normal	Good	Excellent
Policy environment X_1	x_{11}	0	0	1	6	3
	x_{12}	0	0	1	6	3
	x_{13}	0	0	0	5	5
Technical performance X_2	x_{21}	0	0	1	4	5
	x_{22}	0	0	1	5	4
	x_{23}	0	0	1	6	3
	x_{24}	0	1	2	5	2
Economic benefits X_3	x_{31}	0	0	0	6	4
	x_{32}	0	0	2	5	3
	x_{33}	0	0	0	7	3
	x_{34}	0	0	1	5	4
	x_{35}	0	1	2	5	2
Resource guarantee X_4	x_{41}	0	0	0	5	5
	x_{42}	0	1	1	6	2
	x_{43}	0	0	1	7	2
	x_{44}	0	0	1	6	3
	x_{45}	0	0	0	6	4
Organizational guarantee X_5	x_{51}	0	0	0	7	3
	x_{52}	0	0	1	6	3
	x_{53}	0	0	1	6	3
	x_{54}	0	0	0	4	6
Social benefits X_6	x_{61}	0	0	0	5	5
	x_{62}	0	1	1	6	2
	x_{63}	0	0	0	7	3
	x_{64}	0	0	1	5	4

should be different from the former type of projects, which can promote the development of project industrialization. Generally, the score is 70 to 79 points, and for this kind of evaluation results of the project, the inspection should be focused. Industrialization support can still be given when the project time is ripe and conditions are met. Projects with a pre-evaluation result of less than 70 points, in principle, do not obtain support. At the same time, based on the evaluation results, local governments and science and technology management departments can provide targeted guidance and assistance, environment and security-independent innovation for the majority of small- and medium-sized enterprises for independent innovation. In this paper, the comprehensive evaluation of the industrialization project of sci-tech achievements selected in this paper is good. When the project was approved, the experts unanimously agreed that the technical route of the project was reasonable, the budget of the industrialization project was scientific, and the economic and social benefits were obvious.

The evaluation results of the case analysis in this article are consistent with the actual situation, verifying the effectiveness of the evaluation method. By pre-evaluating the industrialization projects of local sci-tech achievements by local governments and science and technology management departments, on the one hand, the study can greatly reduce the risk of sci-tech project management, allow qualified sci-tech industrialization projects to be implemented, and optimize the allocation of sci-tech funds. On the other hand, according to the evaluation results, the research puts forward guidance, suggestions, and improvement directions for sci-tech industrialization projects with unsatisfactory evaluation results, so as to lay the foundation for future projects.

6. Conclusions

(i) This research is based on the analysis of the characteristics and laws of the industrialization of sci-tech achievements, the pre-evaluation of the importance of the industrialization of local sci-tech achievements, and the analysis of research methods. The evaluation index system has been established from six aspects: policy environment, technical performance, economic benefits, resource guarantee, organization guarantee, and social benefit. Comprehensive evaluation was carried out by using FAHP, which reduced the economic and policy risks in the industrialization of sci-tech achievements, increased the selection rate of industrialization projects, and provided a reliable basis for local governments to realize the industrialization of sci-tech achievements.

(ii) FAHP is used to determine the weights of the factors affecting the pre-evaluation of the industrialization of local sci-tech achievements, which has strong objectivity and operability. This method effectively combines the objective judgment of the decision-maker and the decision analyst and realizes the systematization, mathematization, and modeling of the decision-maker's thinking change process.

(iii) Through the pre-evaluation of the industrialization of the smart manufacturing project in Xiqing District of Tianjin, the overall evaluation of the project is good and consistent with the actual evaluation results. The local government and technology management should guide and support as a driving force for local economic development and industrialization development. At the same time, verifying the reliability of the model has a certain guiding role in the industrialization of local scientific and technological achievements.

(iv) The pre-evaluation research of industrialization projects of local sci-tech achievements has important practical significance. While reducing the project management risks of local sci-tech management departments, local sci-tech achievements can be managed according to the evaluation results, and the sci-tech achievements can be managed accordingly. Industrialization projects have a certain guiding role. However, the establishment of the pre-evaluation index system for the industrialization of local sci-tech achievements cannot be accomplished overnight. It will change with the evaluation environment and the objectives of the project establishment unit. This requires continuous improvement in future research and practice to make the pre-evaluation system more targeted and the evaluation results more effective, so as to provide a reference for the industrialization of local sci-tech projects.

(v) Sci-tech innovation has become the first driving force to lead the development. Sci-tech progress and sci-tech achievements will play a core role in the modern economic system and social development. In the transformation of sci-tech achievements, the role positioning of governments, universities, institutions, enterprises and intermediaries, multi-party games, and cooperation mechanisms in the pre-evaluation system still needs to be further studied.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Optimal Operation and Financing Decisions in Green Supply Chain with a Capital-Constrained Manufacturer

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Capital constraint, immensely existing in practice, became major stressors for manufacturers during the green research and development (R & D) triggered by managers integrating green concept into their business models. Considering the initial capital of a capital-constrained manufacturer, this paper formulates a Stackelberg game model comprising a manufacturer and a retailer, to discuss the optimal operation and financing decisions under the bank financing channel and trade credit financing channel, to detect the relationship between the manufacturer's initial capital and green R & D investment, and to find which financing channel is better by comparing the two financing channels when the same initial capital is set. According to the above analysis, the results find that the capital-constrained manufacturer prefers financing only when meeting certain conditions. Furthermore, financing might be detrimental to the manufacturer but always beneficial to the retailer. Especially, under trade credit financing channel, the profit improvement of the retailer is higher than the manufacturer in the same financing channel, which suggests that the retailer has strong internal motivation to cooperate with the manufacturer from the perspective of financing.

1. Introduction

Nowadays, it is already accepted that the green R & D has become an important way for enterprises to meet market access standards and attain market competitive advantages [1–3]. Over the years, some manufacturers have adopted the green concept in their supply chain management and effectively improved their economic and environmental performances [4]. However, some manufacturers limited by capital constraints, especially small and medium-sized enterprises (SMEs), are still struggling to implement green R & D [5]. Financing is an efficient way to solve the capital-constrained problem; for the capital-constrained manufacturer, bank financing and credit financing are the two main financing channels. More specifically, bank financing refers to the manufacturer obtaining loans from banks [6], while trade credit financing refers to a supply chain's internal financing in which enterprises provide financial support for capital-constrained supply chain members in the form of early or delayed payment [7, 8]. Considering manufacturer initial capital, how does the initial capital effect the green R & D investment and profits of the manufacturer? Comparing bank financing with trade credit financing, which is better for the capital-constrained manufacturer? All the above-mentioned issues inspired us to detect the optimal operation and financing decisions of the capital-constrained manufacturer under two available financing channels that are widely applied in practice, and then to explore the financing preference of manufacturers in different situations.

Once these questions are answered, we can provide managers with financing decision-making reference. Financing decision is one of the important management aspects of managers; if solved, it can guide managers to choose the appropriate financing channel and improve their profits. Although many literatures on financing provided relevant evidences, and revealed the benefits of financing to capital-constrained enterprises [9–11], only a few scholars have concentrated on the capital-constrained manufacturer in the green supply chain. For example, Cao et al. [12] studied the ordering problem of capital-constrained manufacturers under supplier financing and bank financing. Nowadays, the green R & D financing problem has not been solved. To further enrich the existing research, we adopt the Stackelberg game model, which can correctly describe the decision-making process of supply chain members, to analyze the operation and financing decisions of manufacturers facing green R & D capital-constrained, and endeavor to remedy the limitation of existing researches in the green supply chain.

To answer the abovementioned research questions, this paper takes the green supply chain composed of a single capital-constrained manufacturer and a single capital ample retailer as the research objects. To generalize our result insights, our paper mainly focuses on two common financing channels, bank and trade credit, in the green supply chain. By constructing the Stackelberg game model under no financing, bank financing, and trade credit financing, we explore the optimal products' green degree, wholesale price, and retail price under the three situations. In addition, this paper further considers the initial capital, analyzes manufacturer financing preference, and assesses the impact of different financing strategies on profits of the manufacturer and retailer.

Given the growth of the green supply chain and capital constraints in practice, it is a significant reference for supply chain management to understand how the initial capital affects the green supply chain decisions. According to this, we investigate the operation and financing problems when a manufacturer's initial capital is insufficient to invest in the demanded green R & D. Our main contributions are as follows. (1) Considering that many previous researches on green supply chain management assumed that manufacturers have sufficient capital, we extend research to the scenario of capital constraint where the capital-constrained manufacturer is faced with the challenge of integrating green concept into its business. (2) This paper particularly concentrates on the initial capital because more related researches on supply chain financing pay less attention to the initial capital. Hence, we creatively incorporate the initial capital into the Stackelberg model and study the problem of capital-constrained green R & D. (3) By comparing the financing strategies of the manufacturer, we explore the manufacturer's relative financing preference when the initial capital is constrained. Although some studies have explored the choice of supply chain financing channel, the majority of them focused on the capital-constrained retailer or inventory decision; financing related to manufacturers need to be further detected.

The remainder of the paper is organized as follows. Section 2 reviews the related work. Section 3 provides problem description and basic assumptions. Section 4 establishes a Stackelberg game model and analyzes the optimal operation and financing decisions. Section 5 conducts the numerical analysis. Finally, the conclusion is provided in Section 6.

2. Related Work

This paper belongs to the interface between green supply chain and financing. According to the previous researches, the literature review of this paper can be divided into following aspects: "green R & D of supply chain" and "financing decision of supply chain." The latter could be further divided into "bank financing" and "trade credit financing."

Green supply chain management has been an active area of research in operations management, such as Beamon [13], Murali et al. [14], Wang et al. [15], and Zhang et al. [16]. Despite the high additional cost of green R & D, many literatures are unfolded under the assumption of sufficient capital. For example, Zhu and He [17] compared two green R & D strategies under sufficient capital; one is the development-intensive green product, the other is the marginal-cost-intensive green product. Yenipazarli [18] confirmed that green R&D exhibits diminishing returns for R & D efforts. To optimize returns, Jiang and Chen [19], considering consumer preference and green investment, discussed the optimal green R & D strategy. In fact, the capital of enterprises is not always sufficient to support enterprises to invest in R & D. To alleviate the R & D cost pressure, Gao et al. [20] and Wong et al. [15] explored the methods that can not only protect the ecological environment but also limit production cost rise. Similarly, Taleizadeh et al. [21] found that the green-cost-sharing contract between supply chain members can control the cost. The above research provides a way to solve the capital constraints from the perspective of contract. Different from the above research, this paper cancels the assumption of sufficient capital and solves the capital-constrained problem through financing.

Considering previous financing studies, the main studies related to our work are bank financing and trade credit financing. Bank financing is the main channel of supply chain members financing [6]. In this area, Cao and Yu [22] studied the problem that capital-constrained manufacturers obtain pledge loans by utilizing carbon emission permits. Wu et al. [23] constructed a mathematical model, and found that bank financing can solve the problem of capital constraints to a certain extent. Tao et al. [11] conformed that SMEs and banks can achieve a win-win situation as more good SMEs choose bank financing. Conversely, Yu and Rehman Khan [24] pointed out that bank financing is not the best way because SMEs cannot afford the high interest rate of banks. For other available financing channels, some scholars pay attention to trade credit financing in operation management: for example, Haley and Higgins [25], Seifertet et al. [26], etc. These literatures proved that trade credit is an effective financing channel, especially for SMEs. Similarly, Wang et al. [27] and Ma et al. [28] also proved that enterprises cooperate with each other in supply chain financing, which can improve interests of both parties at the same time. In summary, existing studies have extensively confirmed that supply chain financing plays an important role in supply chain management [29]. The above research mainly focuses on a single financing channel. When considering some available financing channels, the financing decision of enterprises is more worthy of attention.

This paper is closely related to the choice of financing channels when enterprises are facing multiple available financing channels. Some works compared bank financing and trade credit financing when retailers are under capital constraints [4, 30]. In the green supply chain, Wu et al. [31] discussed the impact of manufacturer carbon emission reduction on the optimal ordering of capital-constrained retailer under bank financing and trade credit financing. The literatures mentioned above pay more attention to retailers' financing. As for manufacturers' financing, Huang et al. [32] explored green credit, manufacturer subsidy, and sales subsidy, and proved that green credit (GC) can bring the highest benefits of social welfare and environmental protection. Cao and Yu [7] studied the financing equilibrium of green credit financing and mixed financing. Considering the uncertainty of market demand and consumers' low-carbon preference, Cao et al. [12] further studied the optimal procurement issues of capital-constrained manufacturer under two financing channels.

In the aforementioned literature, besides subsidy research [32], a common assumption is that green R & D capital of manufacturers is sufficient. Moreover, the researches on financing mainly study the ordering and inventory problems of capital-constrained supply chain. While the insights gained from these works are valuable, they do not address green R & D financing of manufacturers commonly observed in practice. Therefore, we inject more realism by considering a manufacturer whose green R & D capital is capital-constrained, and answer the practical question as to how manufacturer initial capital affects operational and financing decisions. In summary, this paper analyzes three scenarios of green supply chain: no financing, bank financing, and trade credit financing, by the proposed game model.

3. Problem Description and Basic Assumptions

This paper takes a typical supply chain with a manufacturer M and a retailer R as the research objects. Among them, the manufacturer is the leader, and the retailer is the follower. Facing an increasing environmental awareness of consumers, manufacturers enhance the product green degree by green R & D to meet consumers' green demand. Taking automobile industry as example, products' green degree can refer to the emission reduction level or energy saving level of automobiles. In the process of the Stackelberg game, the manufacturer first decides the wholesale price w and products' green degree g, then the retailer follows by setting the retailer price p. Due to the increasing marginal cost, the R & D cost of manufacturers will increase rapidly with the improvement of product green degree. Hence, referring to Zhu and He [17], Jiang and Chen [19], this paper assumes that the green R & D cost of manufacturers is a function of products' green degree g: $kg^2/2$, where $k\,(k > 0)$ is the green R & D cost coefficient. Furthermore, since the green R & D cost of manufacturers belongs to one-time capital investment, the green R & D of manufacturers will not affect products' unit cost $c\,(c > 0)$, and $c < w < p$.

When the manufacturer's initial capital $F\,(F \geq 0)$ cannot support the optimal green R & D, the decision of the manufacturer is constrained by the initial capital, while the retailer's decision is only indirectly affected by the game process. The manufacturer obtains the remaining capital $L = kg^2/2 - F$ through two available financing channels: bank and trade credit. This paper assumes that the output of R & D is certain, that is, there is no risk of R & D failure. To simplify the explanation, the superscripts B, T, N are used to indicate bank financing, trade credit financing, and no financing, and the subscripts M, R are used to indicate the manufacturer and retailer.

In this paper, the demand of the manufacturer is consistent with that of the retailer. According to the description of green product demand in Zhu and He [17], the products' demand is set as $D = \alpha - \beta p + \gamma g$. Among them, $\alpha\,(\alpha > 0)$ is the total market demand potential, $\beta\,(\beta > 0)$ is the consumer price sensitivity, and $\gamma\,(\gamma > 0)$ is the consumers' preference for green products . That is, the market demand for green products is negatively correlated with price p, and positively correlated with products' green degree g.

4. Model

4.1. Basic Model. This subsection constructs the green supply chain operation decision-making model when no financing channel is viable and it is taken as the basic model for subsequent analysis.

We suppose that the manufacturers' capital is not enough to invest in the optimal R & D investment. According to Zhu and He [17], the optimal R & D investment of the manufacturer with sufficient capital is $F^N = (k\gamma^2(\alpha - \beta c)^2/2(4\beta k - \gamma^2)^2)$. When no viable financing channels are available, the manufacturer can only determine the produce green degree and wholesale price under its initial capital. Sequentially, the retailer decides the optimal retail price according to the wholesale price and the produce green degree. In this scenario, both the manufacturer and retailer are rational and take profit maximization as decision-making objectives:

$$\begin{cases} \text{Max} \quad \pi_M^N = (w - c)(\alpha - \beta p + \gamma g) - \dfrac{1}{2}kg^2 \\ \\ \text{s.t.} \quad \dfrac{1}{2}kg^2 \leq F, \end{cases} \tag{1}$$

$$\text{Max}\, \pi_R^N = (p - w)(\alpha - \beta p + \gamma g), \tag{2}$$

Proposition 1. *When no financing channels are available, the optimal products green degree g^{N*}, wholesale price w^{N*}, and retail price p^{N*} are, respectively*

$$g^{N*} = \begin{cases} \dfrac{\gamma(\alpha-\beta c)}{4\beta k-\gamma^2}, & F \geq F^N, \\ \sqrt{\dfrac{2F}{k}}, & F < F^N, \end{cases}$$

$$w^{N*} = \begin{cases} \dfrac{2k(\alpha+\beta c)-c\gamma^2}{4\beta k-\gamma^2}, & F \geq F^N, \\ \dfrac{\alpha+\beta c}{2\beta}+\dfrac{\gamma}{2\beta}\sqrt{\dfrac{2F}{k}}, & F < F^N, \end{cases} \tag{3}$$

$$p^{N*} = \begin{cases} \dfrac{3\alpha k+\beta c k-c\gamma^2}{4\beta k-\gamma^2}, & F \geq F^N, \\ \dfrac{3\alpha+\beta c}{4\beta}+\dfrac{3\gamma}{4\beta}\sqrt{\dfrac{2F}{k}}, & F < F^N, \end{cases}$$

where $F^N = (k\gamma^2(\alpha-\beta c)^2/2(4\beta k-\gamma^2)^2)$.

All proofs are presented in Appendix.

Proposition 2. *When no financing channels are available, the products demand D^{N*}, manufacturer's optimal profit π_M^{N*}, and retailer's optimal profit π_R^{N*} are, respectively,*

$$D^{N*} = \begin{cases} \dfrac{\beta k(\alpha-\beta c)}{4\beta k-\gamma^2}, & F \geq F^N, \\ \dfrac{\alpha-\beta c+\gamma\sqrt{2F/k}}{4}, & F < F^N, \end{cases}$$

$$\pi_M^{N*} = \begin{cases} \dfrac{k(\alpha-\beta c)^2}{2\left(4\beta k-\gamma^2\right)}, & F \geq F^N, \\ \dfrac{\left(\alpha-\beta c+\gamma\sqrt{2F/k}\right)^2}{8\beta}-F, & F < F^N, \end{cases} \tag{4}$$

$$\pi_R^{N*} = \begin{cases} \dfrac{\beta k^2(\alpha-\beta c)^2}{\left(4\beta k-\gamma^2\right)^2}, & F \geq F^N, \\ \dfrac{1}{16\beta}\left(\alpha-\beta c+\gamma\sqrt{\dfrac{2F}{k}}\right)^2, & F < F^N. \end{cases}$$

4.2. Bank Financing Channel. When the manufacturer's initial capital is $F < F^N$, the manufacturer chooses bank financing to obtain the required financial support. As shown in Figure 1, the bank acts as the capital provider. At the beginning, based on manufacturer's fixed assets, the bank provides the manufacturer the needed capital at the interest rate r. Then, the capital-constrained manufacturer determines the product green degree g, wholesale price w, and the financing scale L^B ($L^B = (1/2)kg^2 - F$). Finally, the retailer provides green products to consumers at retail price p and the manufacturer repays the loan and interest $(1+r)L^B$ to the bank. Both the manufacturer and retailer make decisions to maximize profits π_M^B and π_R^B:

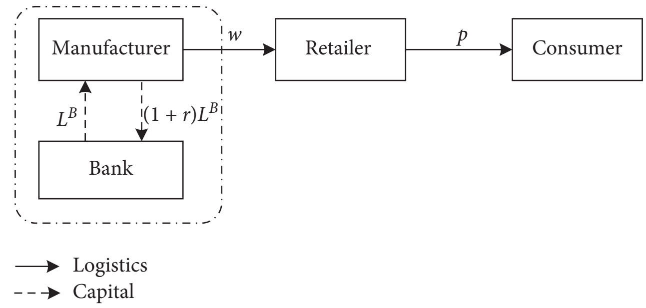

Figure 1: Supply chain operation and financing process under bank financing channel.

$$\begin{cases} \text{Max} \quad \pi_M^B = (w-c)D-(1+r)L^B-F = (w-c)D-rL^B-\dfrac{1}{2}kg^2 \\ \text{s.t.} \quad F < F^N, \end{cases}$$
$$\text{Max}\, \pi_R^B = (p-w)(\alpha-\beta p+\gamma g). \tag{5}$$

Proposition 3. *Under the bank financing channel, the products' optimal green degree g^{B*}, wholesale price w^{B*}, and retail price p^{B*} are, respectively,*

$$g^{B*} = \begin{cases} \sqrt{\dfrac{2F}{k}}, & F \geq F^B, \\ \dfrac{(\alpha-\beta c)\gamma}{4\beta k(1+r)-\gamma^2}, & F < F^B, \end{cases}$$

$$w^{B*} = \begin{cases} \dfrac{\alpha+\beta c}{2\beta}+\dfrac{\gamma}{2\beta}\sqrt{\dfrac{2F}{k}}, & F \geq F^B, \\ \dfrac{2k(\alpha+\beta c)(1+r)-c\gamma^2}{4\beta k(1+r)-\gamma^2}, & F < F^B, \end{cases} \tag{6}$$

$$p^{B*} = \begin{cases} \dfrac{3\alpha+\beta c}{4\beta}+\dfrac{3\gamma}{4\beta}\sqrt{\dfrac{2F}{k}}, & F \geq F^B, \\ \dfrac{k(3\alpha+\beta c)(1+r)-c\gamma^2}{4\beta k(1+r)-\gamma^2}, & F < F^B, \end{cases}$$

where $F^B = (k\gamma^2(\alpha-\beta c)^2/2[4\beta k(1+r)-\gamma^2]^2)$.

Corollary 1. *When $0 < F < F^B$, the products' optimal green degree g^{B*}, wholesale price w^{B*}, and retail price p^{B*} are positively correlated with the consumers' green sensitivity γ,* *and negatively correlated with the green cost coefficient k and bank interest rate r.*

Consumers with higher green preference pay more attention to the products' green degree and tend to pay higher prices. However, the higher R & D cost coefficient and financing cost restrain the manufacturer's willingness to invest in R & D. Hence, faced with the higher green preference, the lower R & D cost, and bank loan interest rate, the manufacturer can benefit from increasing green R & D investment. Meanwhile, with the increase in R & D costs, manufacturers transfer part R & D costs to retailers by increasing the wholesale price, which sequentially leads to the rise of retail prices.

Proposition 4. *Under the bank financing channel, the product demand D^{B*}, manufacturer's financing scale L^{B*}, retailer's optimal profit π_R^{B*}, and manufacturer's optimal profit π_M^{B*} are, respectively,*

$$
\begin{aligned}
D^{B*} &= \begin{cases} \dfrac{\alpha - \beta c + \gamma\sqrt{2F/k}}{4}, & F^B \le F < F^N, \\[2ex] \dfrac{\beta k(1+r)(\alpha - \beta c)}{4\beta k + 4bkr - \gamma^2}, & 0 \le F < F^B, \end{cases} \\
L^{B*} &= \begin{cases} 0, & F^B \le F < F^N, \\[2ex] \dfrac{k\gamma^2 (\alpha - \beta c)^2}{2\left[4\beta k(1+r) - \gamma^2\right]^2} - F, & 0 \le F < F^B, \end{cases} \\
\pi_R^{B*} &= \begin{cases} \dfrac{1}{16\beta}\left(\alpha - \beta c + \gamma\sqrt{\dfrac{2F}{k}}\right)^2, & F^B \le F < F^N, \\[2ex] \dfrac{\beta k^2 (\alpha - \beta c)^2 (1+r)^2}{4\beta kr + 4\beta k - \gamma^2}, & 0 \le F < F^B, \end{cases} \\
\pi_M^{B*} &= \begin{cases} \dfrac{(\alpha - \beta c + \gamma\sqrt{2F/k})^2}{8\beta} - F, & F^B \le F < F^N, \\[2ex] \dfrac{k(\alpha - \beta c)^2 (1+r) + 2Fr\left[4k\beta(1+r) - \gamma^2\right]}{2\left[4k\beta(1+r) - \gamma^2\right]}, & 0 \le F < F^B. \end{cases}
\end{aligned}
\tag{7}
$$

To ensure that the results are meaningful, manufacturer's financing scale should be nonnegative. From the above equilibrium decisions, we can obtain that manufacturer will choose bank financing when $F \le F^B = (k\gamma^2(\alpha - \beta c)^2 / 2[4\beta k(1+r) - \gamma^2]^2)$, which indicates that manufacturer's initial capital is a crucial factor affecting manufacturer financing strategy.

Corollary 2. *When $0 < F < F^B$, the optimal financing scale L^{B*} of the manufacturer is positively correlated with consumers' green preference γ, and negatively correlated with green cost coefficient k and bank interest rate r.*

Corollary 2 shows that when manufacturer's initial capital is fixed, the manufacturer's optimal financing scale increases as consumers' green preference increases but decreases as the green cost coefficient and bank loan interest rate increase. This is because the higher consumers' green preference urges manufacturers to improve the products' green degree to meet consumers' preference. Similarly, lower R & D cost and bank interest rate enable manufacturers to obtain greater benefits from expanding green R & D. Hence, with the increase of consumer preference, and the decrease of R & D cost and interest rate, the manufacturer will expand the financing scale to implement greener R & D investment, and then achieve greater profit.

Corollary 3. *When $0 < F < F^B$, the manufacturer's optimal profit π_M^{B*} is positively correlated with its initial capital F, while the retailer's optimal profit π_R^{B*} is irrelevant to the initial capital F.*

From the above corollary, it is worth noting that the profitability of the manufacturer is closely related to its initial capital level and the retailer's profit is not affected. Obviously, the higher the manufacturer's initial capital, the smaller the required financing scale and the lower the financing cost under the same green R & D investment. Hence, manufacturer's profit increases accordingly. However, the result about the retailer seems counter-intuitive. In fact, it is the result of the game between the manufacturer and retailer. Because in the Stackelberg game, the manufacturer is the leader and has the decision-making advantage. The manufacturer can transfer the corresponding financing costs by increasing the wholesale price to maximize profit. Similarly, the retailer is also not willing to bear the extra cost. Hence, the result of the game between the manufacturer and the retailer is that the retailer cannot get extra profit. For this reason, retailer's profit change is determined, and it has no direct relationship with manufacturer's initial capital under bank financing.

4.3. Trade Credit Financing Channel. When manufacturer's initial capital is $F < F^N$, the manufacturer will finance from the trade credit channel. As shown in Figure 2, the retailer acts as capital provider, and gains early payment discounts $\theta (0 < \theta < 1)$ as a return on cooperation. The manufacturer determines the products' green degree g and wholesale price w. The retailer provides the manufacturer the required capital $L^T = kg^2/2 - F$ in the form of advance payment. After production, the manufacturer needs to deliver products $L^T/[(1-\theta)w]$ to the retailer because of the retailer's advance payment. Then, the remaining products are offered to the retailer at the wholesale price w. Ultimately, the retailer provides all green products to consumers at retail price p. Both the manufacturer and the retailer make decisions to maximize profits π_M^T and π_R^T.

$$\begin{cases} \text{Max} \quad \pi_M^T = (w-c)\left[D - \dfrac{L^T}{(1-\theta)w}\right] + \left[\left(\dfrac{1}{2}kg^2 - F\right) - c\dfrac{L^T}{(1-\theta)w}\right] - \dfrac{1}{2}kg^2 \\ \text{s.t.} \quad F < F^N, \end{cases} \tag{8}$$

$$\text{Max}\, \pi_R^T = (p-w)\left[D - \frac{L^T}{(1-\theta)w}\right] + \left[-p\frac{L^T}{(1-\theta)w}\right] - \left(\frac{1}{2}kg^2 - F\right).$$

Proposition 5. *Under the trade credit financing channel, the optimal products' green degree g^{T*}, wholesale price w^{T*}, and retail price p^{T*}, respectively, are*

$$\begin{aligned} g^{T*} &= \begin{cases} \sqrt{\dfrac{2F}{k}}, & F \geq F^T, \\ \dfrac{(1-\theta)(\alpha-\beta c)\gamma}{4\beta k - (1-\theta)\gamma^2}, & F < F^T, \end{cases} \\ w^{T*} &= \begin{cases} \dfrac{\alpha+\beta c}{2\beta} + \dfrac{\gamma}{2\beta}\sqrt{\dfrac{2F}{k}}, & F \geq F^T, \\ \dfrac{2k(\alpha+\beta c) - (1-\theta)c\gamma^2}{4\beta k - (1-\theta)\gamma^2}, & F < F^T, \end{cases} \\ p^{T*} &= \begin{cases} \dfrac{3\alpha+\beta c}{4\beta} + \dfrac{3\gamma}{4\beta}\sqrt{\dfrac{2F}{k}}, & F \geq F^T, \\ \dfrac{k(3\alpha+\beta c) - (1-\theta)c\gamma^2}{4\beta k - (1-\theta)\gamma^2}, & F < F^T, \end{cases} \end{aligned} \tag{9}$$

where $F^T = (k\gamma^2(1-\theta)^2(\alpha-\beta c)^2/2[4\beta k - (1-\theta)\gamma^2]^2)$.

Corollary 4. *When $0 < F < F^T$, the optimal green degree g^{T*}, wholesale price w^{T*}, and retail price p^{T*} are positively correlated with consumers' green preference coefficient γ, and negatively correlated with green cost coefficient k and early payment discounts rate θ.*

Corollary 4 is consistent with Corollary 1; the optimal green degree, wholesale price, and retail price of products increase with the increase of green preference of consumers but decrease with the increase of R & D cost coefficient and early payment discounts rate. The result indicates that the relationship between the optimal decision of supply chain and the green preference of consumers and the cost of R & D is not affected by the financing channel.

Proposition 6. *Under the trade credit financing channel, the product's demand D^{T*}, manufacturer's financing scale L^{T*}, and optimal profit π_M^{T*}, as well as retailer's optimal profit π_R^{T*}, respectively, are*

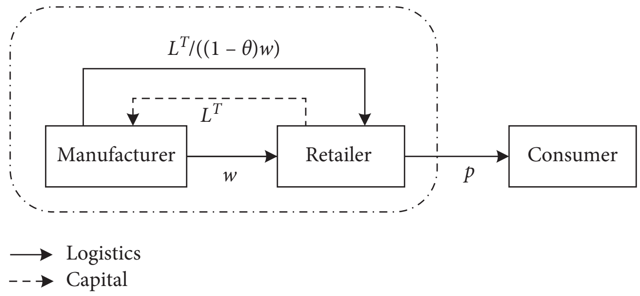

FIGURE 2: Supply chain operation and financing process under trade credit financing channel.

$$D^{T*}=\begin{cases}\dfrac{\alpha-\beta c+\gamma\sqrt{2F/k}}{4}, & F^T\le F<F^N,\\[2ex] \dfrac{k\beta(\alpha-\beta c)}{4\beta k-(1-\theta)\gamma^2}, & 0\le F<F^T,\end{cases}$$

$$L^{T*}=\begin{cases}0, & F^T\le F<F^N,\\[2ex] \dfrac{k\gamma^2(1-\theta)^2(\alpha-\beta c)^2}{2\left[4\beta k-(1-\theta)\gamma^2\right]^2}-F, & 0\le F<F^T,\end{cases}$$

$$\pi_M^{T*}=\begin{cases}\dfrac{(\alpha-\beta c+\gamma\sqrt{2F/k})^2}{8\beta}-F, & F^T\le F<F^N,\\[2ex] \dfrac{k(1-\theta)(\alpha-\beta c)^2+2F\theta\left[4k\beta-(1-\theta)\gamma^2\right]}{2(1-\theta)\left[4\beta k-(1-\theta)\gamma^2\right]}, & 0\le F<F^T,\end{cases} \tag{10}$$

$$\pi_R^{T*}=\begin{cases}\dfrac{1}{16\beta}\left(\alpha-\beta c+\gamma\sqrt{\dfrac{2F}{k}}\right)^2, & F^T\le F<F^N,\\[2ex] \dfrac{2Fk^2(1-\theta)(\alpha-\beta c)^2+\theta k\gamma^2(1-\theta)^2(\alpha-\beta c)^2-2\theta F\left[4\beta k-(1-\theta)\gamma^2\right]^2}{2(1-\theta)\left[4k\beta-(1-\theta)\gamma^2\right]^2}, & 0\le F<F^T.\end{cases}$$

As the financing scale is nonnegative, the initial capital of manufacturers should meet the condition $F<F^T=(k\gamma^2(1-\theta)^2(\alpha-\beta c)^2/2[4\beta k-(1-\theta)\gamma^2]^2)$. *The result is consistent with bank financing, this is, trade credit financing is not always dominant for the capital-constrained manufacturer. When manufacturer's initial capital meets certain conditions, advance payment by retailer is a better decision, which proves that the initial capital is a key factor that cannot be ignored, no matter which financing channel.*

Corollary 5. *When* $0<F<F^T$, *the optimal financing scale* L^{T*} *of manufacturers is positively correlated with consumers' green preference* γ, *and negatively correlated with green cost coefficient* k *and early payment discounts rate* θ.

Corollary 5 indicates that manufacturer's financing scale is affected by consumers' green preference, green cost coefficient, and early payment discounts rate. The results are reasonable. Smaller financing scale should be adopted if consumers' green preference is low or green cost coefficient and early payment discounts rate are high. Thus, for manufacturer financing, consumers' green preference is an incentive factor, while cost is a restraining factor, and no matter which financing channels are employed, the conclusion is always valid.

Corollary 6. *When* $0<F<F^T$, *manufacturer's optimal profit* π_M^{T*} *is positively correlated with its initial capital* F, *while the retailer's optimal profit* π_R^{T*} *is negatively correlated with the initial capital* F.

Corollary 6 demonstrates the effect of manufacturer's initial capital on the optimal profit of the manufacturer and retailer under the credit trade financing channel. Note that if the manufacturer possesses more initial capital, the smaller is the financing scale required under the same green R & D investment, and thereby the lower is the financing cost paid. Accordingly, the manufacturer's profit is improved. As for the retailer, the revenue from selling greener products is roughly balanced with the increased wholesale prices. However, with the increase of the initial capital, the manufacturer pays the retailer less financing cost, which leads to the increase of purchasing cost that the retailer needs to pay. Hence, retailer's profit decreases.

4.4. Comparative Analysis. As in the above analysis, when $F < F^N$, the manufacturer can obtain financial support through the bank or trade credit. However, faced with the two financing channels simultaneously, which financing channel is better, and how different financing channels affect supply chain operation decisions? These questions inspire us to detect; this subsection will further compare and analyze the supply chain operation decision and manufacturer profit under different financing channels, and search for the dominant financing channel of the manufacturer.

Corollary 7. *When $\theta > r/(1+r)$, there is $F^T < F^B$; otherwise, $\theta \leq r/(1+r)$, $F^T \geq F^B$.*

Corollary 7 demonstrates the influence of the financing cost on the financing preference of the manufacturer. Compared with the trade credit financing channel, the manufacturer's financing willingness under the bank channel is higher when $\theta > r/(1+r)$; On the contrary, when $\theta \leq r/(1+r)$, the manufacturer prefers to choose trade credit financing channels. The implication of the result is interesting. Manufacturers whose capital is insufficient may be tempted to seek viable financing channels to increase R & D investment. Besides, the financing willingness of manufacturers is closely related to the cost of different financing channels. That is, the lower financing cost not only reduces the cost but also promotes the manufacturer's financing willingness, which enlightens us that adjusting the financing environment can also effectively affect the greening process in the case of insufficient capital.

Corollary 8. *$F < \min(F^T, F^B)$, when $\theta > r/(1+r)$, there are $g^{B*} > g^{T*}, w^{B*} > w^{T*}$, $p^{B*} > p^{T*}$. Conversely, $\theta \leq r/(1+r)$, there are $g^{B*} \leq g^{T*}, w^{B*} \leq w^{T*}, p^{B*} \leq p^{T*}$.*

From the result, we know that the optimal decision of the green supply chain operation is closely related to r and θ under the two financing channels. When $\theta > r/(1+r)$, compared with the trade credit, the manufacturer needs to pay lower financing costs under bank financing channels. According to Corollaries 1 and 4, we document that the product green degree is always negatively correlated with the R & D cost coefficient and financing cost. Hence, under the bank financing channel, the financing willingness of the manufacturer can be released more, and thereby the financing scale will be expanded to increase R & D investment, and the corresponding product green degree will be improved. Simultaneously, with the increase of the R & D cost, the manufacturer transfers part of the R & D cost to the retailer by increasing the wholesale price, which makes retail price rise accordingly. On the contrary, when $\theta \leq r/(1+r)$, the financing cost of the manufacturer under trade credit financing is smaller than bank financing, and then the financing willingness of the manufacturer is enhanced. Thus, under the trade credit financing channel, manufacturers will increase green R & D investment, and the green degree of products will be improved. Ultimately, wholesale and retail prices also rise.

Corollary 9. *$F < \min(F^T, F^B)$, when $\theta > r/(1+r)$, there are $D^{B*} > D^{T*}, L^{B*} > L^{T*}$, $\pi_M^{B*} > \pi_M^{T*}$. Conversely $\theta \leq r/(1+r)$, there are $D^{B*} \leq D^{T*}, L^{B*} \leq L^{T*}, \pi_M^{B*} \leq \pi_M^{T*}$.*

Corollary 9 shows that the relationship of the manufacturer's financing scale, market demand, and profit is closely related to bank interest rate and early payment discounts rate. From Corollary 8, we know that the green degree of products under the bank financing channel is higher than that of trade credit financing when $\theta > r/(1+r)$. Therefore, under the bank financing channel, manufacturers demand larger financing to support the increased R & D investment when the initial capital is fixed, because the improvement of product green degree can better meet the green preference of consumers and stimulate greener consumption; then, the demand is increased. Hence, the improvement effect of manufacturer's profit under the bank financing channel is more significant in the case of $\theta > r/(1+r)$. On the contrary, $\theta \leq r/(1+r)$, compared with the bank financing channel, the financing cost under trade credit financing is more suitable for capital-constrained manufacturer. In other words, the same financing cost makes the manufacturer benefit more from financing under the trade credit channel. Consequently, under the same level of initial capital, the manufacturer prefers trade credit financing to improve revenue.

5. Numerical Analysis

In order to further clarify the manufacturer's financing decision with capital constraints$F < F^N$, this section analyzes the impact of manufacturer's initial capital on manufacturer's and retailer's profits through numerical examples under different financing channels. Here, we refer to the numerical analysis method and parameter setting of existing research, such as Zhu and He [17], Su and Li [33], to verify the above conclusions. The optimal solution without capital constraint as a benchmark is denoted by superscript S, and the parameters are set as $\alpha = 2000$; $\beta = 10$; $\gamma = 7$; $c = 2$; $k = 500$; $r = 0.1$, then $F^N = 120$. Accordingly, the manufacturer's capital value range is less than 120 in the numerical analysis.

Figures 3(a) and 3(b) describe the change of the manufacturer's profit with initial capital under different financing strategies when $\theta = 0.3$ and $\theta = 0.03$ (i.e., $\theta > r/(1+r)$ and $\theta \leq r/(1+r)$). Figure 3 shows that when $F < \min(F^T, F^B)$, the manufacturer's profits are positively correlated with manufacturer's initial capital no matter which financing strategy, and with the increase of manufacturer's initial capital, financing is not always the dominant decision. This is, when $F < \max(F^B, F^T)$, manufacturers can improve their profits by financing through bank or trade credit; however, with the increase of initial capital

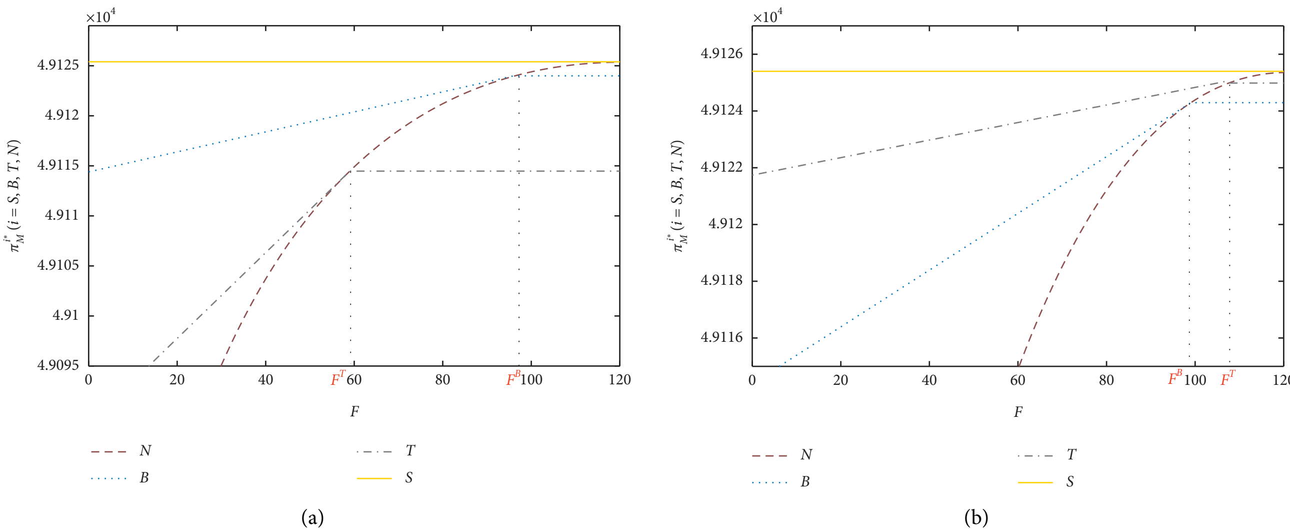

Figure 3: The influence of the initial capital on manufacturer's profit. (a) $\theta = 0.3$. (b) $\theta = 0.03$.

$\max(F^B, F^T) < F$, the profit without financing is better than the two financing channels. These results are consistent with Propositions 3 and 5, which indicate that the financing performance of manufacturers is closely related to initial capital, only under conditions $F < \max(F^B, F^T)$ can the manufacturer choose financing and improve profits.

In addition, comparing the manufacturer's optimal profit in four scenarios, we can get the optimal financing decision of the manufacturer with capital constraints. In Figure 3(a), $F^T < F^B$, the manufacturer chooses the bank financing first when the initial capital is lower than the financing threshold (i.e., $0 < F < F^B$); with the improvement of initial capital, the manufacturer will not finance (i.e., $F^B < F < F^N$). However, in Figure 3(b), $F^B < F^T$, manufacturers merely prefer trade credit (i.e., $0 < F < F^T$) or no financing (i.e., $F^T < F < F^N$). On the one hand, the higher initial capital reduces the financing cost; on the other hand, the lower financing cost encourages manufacturers to expand financing scale, which enables the manufacturer to further optimize R & D investment and improve profits.

Figures 4(a) and 4(b) show the change of the retailer's profit with F under different financing strategies when $\theta = 0.3$ and $\theta = 0.03$ (i.e., $\theta > r/(1+r)$ and $\theta \le r/(1+r)$). It can be seen from Figure 4 that the retailer profit under the bank financing channel is independent of the manufacturer's capital level, which proves the conclusion of Corollary 3. Under the trade credit financing channel, the retailer's profit is always negatively correlated with manufacturer's initial capital which is consistent with Corollary 6; the reason is that the higher initial capital reduces the financing scale of the manufacturer, which leads to the increase of the retailer' s purchasing costs, and accordingly, the retailers profit decrease.

Recalling the financing decision analyzed in Figure 3, we compare the profit, respectively, of the manufacturer and retailer in four situations. The results are interesting; the optimal profit of the retailer is roughly consistent with the manufacturer's financing preference in four cases. That is, when the manufacturer chooses the bank (i.e., $0 < F < F^B$) or trade credit (i.e., $0 < F < F^T$), the retailer's profit is better under the corresponding financing channel (see Figure 4); however, when manufacturers merely prefer no financing (i.e., $\max\{F^B, F^T\} < F < F^N$), retailer profits are not always optimal (see Figure 4(b)). Obviously, the profit of the retailer is higher when the retailer funds the manufacturer at a lower cost. The result indicates that the manufacturer and the retailer are a community of interests. In other words, the retailer has an intrinsic motivation to encourage the capital-constrained manufacturer to expand the scale of trade credit with lower financing cost, which can achieve a win-win situation.

Compared with no financing, Figure 5 ($\theta = 0.3$ and $\theta = 0.03$) presents the impact of the initial capital on the profit change of the manufacturer and retailer when the manufacturer chooses bank financing or trade credit financing. Obviously, both financing channels can improve the manufacturer's income when the manufacturer's initial capital meets the condition $0 < F < \min(F^T, F^B)$. However, no matter which financing channel is chosen, the retailer's profit improvement is more significant than that of the manufacturer under the corresponding financing channel. The profit growth of the retailer is the largest, especially under the trade credit financing channel. The manufacturer seeks financial support, but the retailer gains more. The lower financing cost can further release the manufacturer's R & D willingness and produce products with higher green degree. Accordingly, retailers prefer making profits by selling products with higher green degree to meet the needs of consumers. Furthermore, under the trade credit financing channel, retailers can save part of the purchase cost. Here, the study further verifies again that the retailer has a strong internal motivation to support the manufacturer who is facing capital constraints. Hence, the retailer actively cooperates with the manufacturer on financing issues.

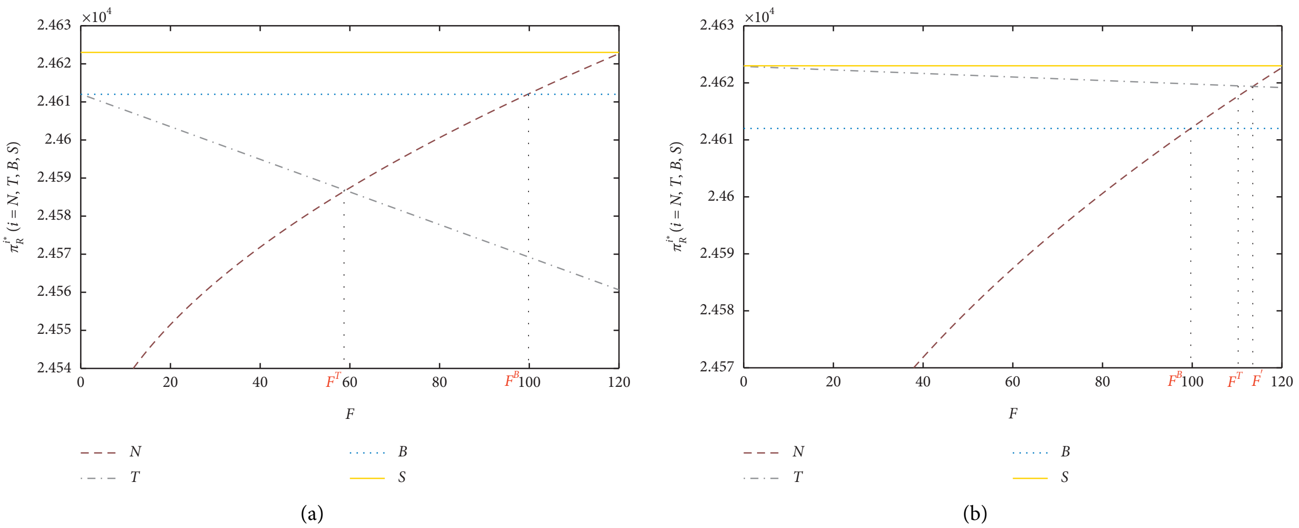

FIGURE 4: The influence of initial capital on the retailer's profit. (a) $\theta = 0.3$. (b) $\theta = 0.03$.

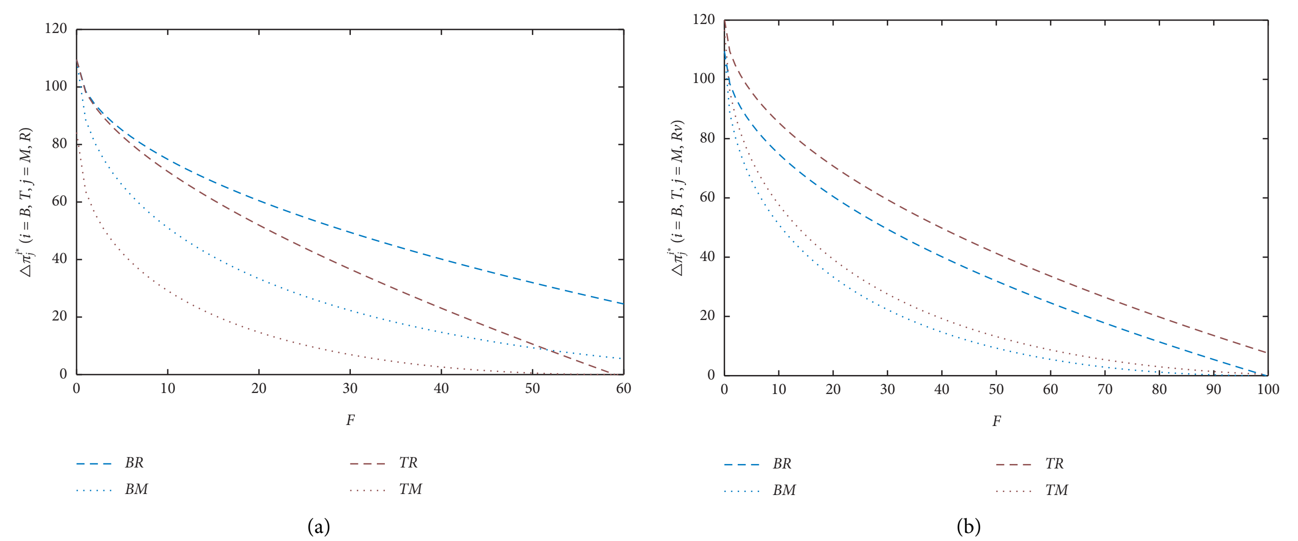

FIGURE 5: The influence of initial capital on the profit improvement of the manufacturer and retailer. (a) $\theta = 0.3$. (b) $\theta = 0.03$.

6. Conclusion and Future Work

To provide a reference for the green R & D decision of manufacturers who face initial capital constraint, this paper investigates the issue of the retailer and manufacturer's operating and financing decisions under capital constraints. Considering the manufacturer's initial capital, this paper constructs the Stackelberg game models in three scenarios: no financing, bank financing, and trade credit financing, and discusses the relationship between financing strategy and initial capital. Finally,, this paper further analyzes the manufacturer's financing preference and the impact of different financing strategies on profits of the manufacturer and retailer, and then proves the importance of supply chain internal coordination from the perspective of supply chain financing. The main conclusions of the research are as follows:

Firstly, no matter which financing channel, financing is the optimal decision when manufacturer's initial capital is severely constrained. However, financing is not always dominant for the manufacturer with the increasing of the initial capital. That is, when the manufacturer's initial capital meets certain conditions, the manufacturer will no longer choose financing, which indicates that the financing decision is closely related to its initial capital.

Secondly, faced with the two financing channels of bank and trade credit, the manufacturer chooses bank's financing or trade credit financing entirely depending on the relationship of the bank interest rate and early payment discounts rate. What's more, the manufacturer has higher financing willingness under the preferred financing channel. From this, we can know that besides the green preference of consumers, financing factors can also affect the financing willingness of manufacturers.

Thirdly, no matter which financing strategy is adopted, the financing scale of manufacturers is positively correlated with consumers' green preference, and negatively correlated with green cost coefficient and financing cost. All these factors have a significant impact on the manufacturer's decision. Based on this, it provides a reference for controlling relevant variables and influencing the decisions of manufacturers with capital constraints

Finally, the retailer's optimal profit is roughly consistent with the manufacturer's preference in three scenarios. Moreover, the profit improvement of the retailer is always higher than that of the manufacturer, especially under the trade credit financing channel. In other words, compared with bank financing, when the retailer provides financing for the manufacturer in a dominant way, the win-win strategy of the manufacturer's profit and the retailer's profit can be realized at the same time.

The conclusions of this paper can be widely used in the manufacturing industry, such as automobile and household appliances, to provide support for the financing decisions of management. Based on our research, more general demand distribution functions can be studied in the future. Meanwhile, we just consider the situation of one manufacturer and one retailer, the competition among multiple supply chain members is worth considering. Besides, the influence of supply chain members' behavior on financing strategy of capital-constrained enterprises is also worth studying, such as fairness concerns.

Appendix

Proof of Proposition 1. This paper uses Backward Induction method to solve. Firstly, from equation (1), the second-order partial derivatives of π_R^N with respect to p can be obtained as $(\partial^2\pi_R^N/\partial p^2) = -2\beta < 0$. Thus, the retailer profit function π_R^N has maximum value, and the optimal retailer price is given by $(\partial\pi_R^N/\partial p) = \alpha + g\gamma - 2\beta p + \beta w = 0$.

To prove the joint concavity of π_M^N on w and g, we need to show that the Hessian matrix of $\pi_M^N(w,g)$ is negative (semi) definite, i.e., $(\partial^2\pi_M^N/\partial w^2) = -\beta < 0$, $(\partial^2\pi_M^N/\partial g^2) = -k < 0$, and the determinant of the Hessian matrix is nonnegative. The Hessian matrix of $\pi_M^N(w,g)$ is

$$H = \begin{bmatrix} \dfrac{\partial^2\pi_M^N}{\partial w^2} & \dfrac{\partial^2\pi_M^N}{\partial w\,\partial g} \\ \dfrac{\partial^2\pi_M^N}{\partial g\,\partial w} & \dfrac{\partial^2\pi_M^N}{\partial g^2} \end{bmatrix} = \begin{bmatrix} -\beta & \dfrac{\gamma}{2} \\ \dfrac{\gamma}{2} & -k \end{bmatrix}. \tag{A.1}$$

Hence, $\det[H(w,g)] = \beta k - (\gamma^2/4)$, if $\beta k - (\gamma^2/4) > 0$ are satisfied, $\det[H(w,g)] \geq 0$. Therefore, we take the first-order derivative of π_M^{T*} with respect to g and w, then set them to be equal to zero $(\partial\pi_M^N/\partial g) = ((w-c)\gamma/2) - kg = 0$ and $(\partial\pi_M^N/\partial w) = ((\alpha + \beta c + \gamma g)/2) - \beta w = 0$ can be obtained. Solving two equations can provide the equilibrium result $g^{N*} = (\gamma(\alpha - \beta c)/(4\beta k - \gamma^2))$ and $w^{N*} = (2k(\alpha + \beta c) - c\gamma^2)/(4\beta k - \gamma^2)$. Substituting g and w into p, $p^{N*} = (3\alpha k + \beta ck - c\gamma^2)/(4\beta k - \gamma^2)$ is proved. The optimal operation decisions without capital constraint have been proved.

When $F < F^N$, the manufacturer only invests in R&D at their initial level, $g^{N*} = \sqrt{2F/k}$, we prove that π_M^N can get the maximum on w for π_M^N satisfy condition $(\partial^2\pi_M^N/\partial w^2) = -\beta < 0$. Hence, $w^{N*} = ((\alpha + \beta c)/2\beta) + (\gamma/2\beta)\sqrt{2F/k}$, $p^{N*} = ((3\alpha + \beta c)/4\beta) + (3\gamma/4\beta)\sqrt{2F/k}$.

Proof of Proposition 2. By substituting the equilibrium result of Proposition 1 into the equations (1) and (2), Proposition 2 can be obtained. Similarly, Propositions 4 and 6 can be proved.

Proof of Propositions 3 and 5. The proof is similar to that of Proposition 1, so we will not repeat it here.

Proof of Corollary 1. According to hypothesis 1 $\alpha - \beta p > 0$, $c < w < p$, hence $\alpha - \beta c > 0$.

$$\frac{\partial g^{B*}}{\partial \gamma}=\frac{(\alpha-\beta c)\left[\gamma^2+4\beta k(1+r)\right]}{\left[4\beta k(1+r)-\gamma^2\right]^2}>0,$$

$$\frac{\partial w^{B*}}{\partial \gamma}=\frac{4\gamma k(1+r)(\alpha-\beta c)}{\left[4\beta k(1+r)-\gamma^2\right]^2}>0,$$

$$\frac{\partial p^{B*}}{\partial \gamma}=\frac{6\gamma k(1+r)(\alpha-\beta c)}{\left[4\beta k(1+r)-\gamma^2\right]^2}>0,$$

$$\frac{\partial g^{B*}}{\partial k}=\frac{-4\beta\gamma(1+r)(\alpha-\beta c)}{\left[4\beta k(1+r)-\gamma^2\right]^2}<0,$$

$$\frac{\partial w^{B*}}{\partial k}=\frac{-2\beta\gamma^2(1+r)(\alpha-\beta c)}{\left[4\beta k(1+r)-\gamma^2\right]^2}<0, \qquad \text{(A.2)}$$

$$\frac{\partial p^{B*}}{\partial k}=\frac{-3\gamma^2(1+r)(\alpha-\beta c)}{\left[4\beta k(1+r)-\gamma^2\right]^2}<0,$$

$$\frac{\partial g^{B*}}{\partial r}=\frac{-2\beta\gamma k(\alpha-\beta c)}{\left[4\beta k(1+r)-\gamma^2\right]^2}<0,$$

$$\frac{\partial w^{B*}}{\partial r}=\frac{-2\gamma^2 k(\alpha-\beta c)}{\left[4\beta k(1+r)-\gamma^2\right]^2}<0,$$

$$\frac{\partial p^{B*}}{\partial r}=\frac{-3\gamma^2 k(\alpha-\beta c)}{\left[4\beta k(1+r)-\gamma^2\right]^2}<0.$$

The proof of Corollary 4 is similar to that of Corollary 1, so here we will not repeat it.

Proof of Corollary 2. According to hypothesis 1 $\alpha-\beta p>0$, $c<w<p$, hence $\alpha-\beta c>0$. Based on Proposition 4, when $F<F^B$, taking the first-order of L^{B*} with respect to γ, k and r can be obtained as follows:

$$\frac{\partial L^{B*}}{\partial \gamma}=\frac{\gamma k(\alpha-\beta c)^2\left[\gamma^2+4\beta k(1+r)\right]}{\left[4\beta k(1+r)-\gamma^2\right]^3}>0,$$

$$\frac{\partial L^{B*}}{\partial k}=\frac{-k\gamma^2(\alpha-\beta c)^2\left[\gamma^2+4\beta k(1+r)\right]}{\left[4\beta k(1+r)-\gamma^2\right]^3}<0, \qquad \text{(A.3)}$$

$$\frac{\partial L^{B*}}{\partial r}=\frac{-4\beta\gamma^2 k^2(\alpha-\beta c)^2}{\left[4\beta k(1+r)-\gamma^2\right]^3}<0.$$

Because of $\beta k-(\gamma^2/4)>0$, therefore $(\partial L^{B*}/\partial\gamma)>0$, $(\partial L^{B*}/\partial k)<0$, and $(\partial L^{B*}/\partial r)<0$ hold. Corollary 2 is proved.

Proof of Corollary 3. Under the bank financing channel, based on the optimal profit of manufacturer and retailer of Proposition 4, we can obtain that $(\partial\pi_M^{B*}/\partial F)=r>0$ and $(\partial\pi_R^{B*}/\partial F)=0$ hold. Thus, Corollary 3 holds.

Proof of Corollary 5. Based on Proposition 6, we take the first-order derivative of L^{T*} and then obtain that

$$\frac{\partial L^{T*}}{\partial \gamma}=\frac{\gamma k(1-\theta)^2(\alpha-\beta c)^2\left[4\beta k+(1-\theta)\gamma^2\right]}{\left[4\beta k-(1-\theta)\gamma^2\right]^3}>0,$$

$$\frac{\partial L^{T*}}{\partial k}=\frac{-\gamma^2(1-\theta)^2(\alpha-\beta c)^2\left[4\beta k+(1-\theta)\gamma^2\right]}{2\left[4\beta k-(1-\theta)\gamma^2\right]^3}<0, \qquad \text{(A.4)}$$

$$\frac{\partial L^{T*}}{\partial \theta}=\frac{4(\theta-1)\beta\gamma^2 k^2(\alpha-\beta c)^2}{\left[4\beta k-(1-\theta)\gamma^2\right]^3}<0.$$

Hence, the relation between L^{T*} and γ,k,θ can be obtained.

Proof of Corollary 6. Based on Proposition 6, we take the first-order derivative of π_M^{T*} and π_R^{T*}, the result is that both $(\partial\pi_M^{T*}/\partial F)=\theta/(1-\theta)>0$ and $(\partial\pi_R^{T*}/\partial F)=\theta/(\theta-1)<0$ hold.

Proof of Corollary 7. When $F<\min(F^T,F^B)$, the threshold value of manufacturers in the bank financing channel and trade credit financing channel is,

$$F^T=\frac{k\gamma^2(1-\theta)^2(\alpha-\beta c)^2}{2\left[4\beta k-(1-\theta)\gamma^2\right]^2}=\frac{k\gamma^2(\alpha-\beta c)^2}{2\left[(4\beta k/(1-\theta))-\gamma^2\right]^2},$$

$$F^B=\frac{k\gamma^2(\alpha-\beta c)^2}{2\left[4\beta k(1+r)-\gamma^2\right]^2}. \qquad \text{(A.5)}$$

Building function $f(x)=(k\gamma^2(\alpha-\beta c)^2/2[4\beta kx-\gamma^2]^2)$, and $f'(x)=-(4\beta k^2\gamma^2(\alpha-\beta c)^2/[4\beta kx-\gamma^2]^3)<0$; hence $f(x)$ is negatively correlated with x. When $1/(1-\theta)>1+r$, Substitute into the function $f(x)$, we can obtain $f(1/(1-\theta))<f(1+r)$. That is, $\theta>r/(1+r)$, $F^T<F^B$, $F<F^T$. Conversely $\theta\le r/(1+r)$, $F^T\ge F^B$, then $F<F^B$. Hence Corollary 7 is proved.

Proof of Corollary 8. From Propositions 3 and 5, the optimal wholesale prices under bank and trade credit are

$$w^{B*}=\frac{2k(\alpha+\beta c)(1+r)-c\gamma^2}{4\beta k(1+r)-\gamma^2}=\frac{2k(\alpha+\beta c)-\left(c\gamma^2/(1+r)\right)}{4\beta k-\left(\gamma^2/(1+r)\right)}, \qquad \text{(A.6)}$$

$$w^{T*}=\frac{2k(\alpha+\beta c)-(1-\theta)c\gamma^2}{4\beta k-(1-\theta)\gamma^2},$$

respectively. Set the function $f(x)=((2k(\alpha+\beta c)-c\gamma^2x)/(4\beta k-\gamma^2x))(0<x<1)$, and then take the first-order derivative $f'(x) = (2k\gamma^2(\alpha - \beta c)/(4\beta k - \gamma^2 x)^2) > 0$; therefore, $f(x)$ is positively correlated with x.

When $1/(1+r) > 1-\theta$, in other words $\theta > r/(1+r)$, substituting them into function $f(x)$, we can obtain

$$\frac{2k(\alpha+\beta c)(1+r) - c\gamma^2}{4\beta k(1+r) - \gamma^2} > \frac{2k(\alpha+\beta c) - (1-\theta)c\gamma^2}{4\beta k - (1-\theta)\gamma^2}, \quad (A.7)$$

that is, $w^{B*} > w^{T*}$. Using the same method $g^{B*} > g^{T*}, p^{B*} > p^{T*}$ can be proved. On the contrary, $\theta \le r/(1+r)$, $g^{B*} \le g^{T*}, w^{B*} \le w^{T*}, p^{B*} \le p^{T*}$ still holds. Corollary 8 is proved.

Proof of Corollary 9. From Propositions 4 and 6, the optimal profit of the manufacturer under bank financing and trade credit financing is

$$\begin{aligned}\pi_M^{B*} &= \frac{k(\alpha-\beta c)^2(1+r) + 2Fr\left(4k\beta(1+r) - \gamma^2\right)}{2\left[4k\beta(1+r) - \gamma^2\right]},\\ \pi_M^{T*} &= \frac{k(1-\theta)(\alpha-\beta c)^2 + 2F\theta\left[4k\beta - (1-\theta)\gamma^2\right]}{2(1-\theta)\left[4\beta k - (1-\theta)\gamma^2\right]},\end{aligned} \quad (A.8)$$

respectively. We set function

$$\begin{aligned}v(\theta) &= \pi_M^{B*} - \pi_M^{T*}\\ &= \frac{k(\alpha-\beta c)^2}{2}\left(\frac{1}{4k\beta - \left(\gamma^2/(1+r)\right)} - \frac{1}{4k\beta - (1-\theta)\gamma^2}\right)\\ &\quad + F\left(r - \frac{\theta}{1-\theta}\right),\end{aligned} \quad (A.9)$$

and when $\theta = r/(1+r)$, substitute into function $v(\theta)$, $v(r/(1+r)) = 0$ holds. The first-order derivative $v'(\theta) = (k\gamma^2(\alpha-\beta c)^2/2[4\beta k - (1-\theta)\gamma^2]^2) - (F/(1-\theta)^2)$. From Proof of Corollary 7, we know when $\theta > r/(1+r)$, $F < F^T$, and $(k\gamma^2(\alpha-\beta c)^2/2[4\beta k - (1-\theta)\gamma^2]^2) - (F^T/(1-\theta)^2) = 0$.

Therefore, we get

$$\begin{aligned}v'(\theta) &= \frac{k\gamma^2(\alpha-\beta c)^2}{2\left[4\beta k - (1-\theta)\gamma^2\right]^2} - \frac{F}{(1-\theta)^2}\\ &> \frac{k\gamma^2(\alpha-\beta c)^2}{2\left[4\beta k - (1-\theta)\gamma^2\right]^2} - \frac{F^T}{(1-\theta)^2} = 0,\end{aligned} \quad (A.10)$$

v is positively correlated with θ. Hence, when $\theta \le r/(1+r)$, we get $v(\theta) \le 0$, here $\pi_M^{B*} \le \pi_M^{T*}$. With the increase of θ, when $\theta > r/(1+r)$, $v(\theta) > 0$; that is $\pi_M^{B*} > \pi_M^{T*}$. The proof of $D^{B*} \le D^{T*}, L^{B*} \le L^{T*}$ and $D^{B*} > D^{T*}, L^{B*} > L^{T*}$ is similar to Corollaries 8 and 9 is proved.

Data Availability

All the data come from simulation analysis and no real data are adopted in this paper.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Study on Promoting Intelligent Manufacturing Path Choice of Manufacturing Enterprises Based on Coevolution Strategy

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The basic guarantee of promoting intelligent manufacturing ability of manufacturing enterprises is to enhance the comprehensive strength of the country and realize industrialization. Based on the coevolution strategy, considering the time and space structure, this paper determines that the path of manufacturing enterprises to promote intelligent manufacturing is adaptive, visionary, planned, and emerging. According to the factors influencing the promotion of intelligent manufacturing by manufacturing enterprises, the paper proposes the following steps: adaptive strategy path, vision strategic path, planned strategic path, and emerging strategy path. The paper constructs an evaluation system for manufacturing enterprises to promote the selection of intelligent manufacturing path with 25 evaluation indexes and establishes the three-dimensional model of promoting intelligent manufacturing path selection by using the combination of Choquet fuzzy integral method and SPACE method. Through the empirical analysis of ARR, it is found that the planned strategic path is the most suitable path to promote intelligent manufacturing, and the scientificity and objectivity of the three-dimensional path selection model are shown. It is of great theoretical innovation and practical significance to develop a new perspective for manufacturing enterprises to promote the research and selection of intelligent manufacturing path.

1. Introduction

With the development of information and Internet technology, there have been profound changes in manufacturing. These changes have brought new products, modes, and technologies and also promoted the development of manufacturing enterprises in intelligence and individuation. Recently, the development of manufacturing has been in a key stage. An important issue, which is how to stimulate manufacturing enterprises' vitality and innovation and how to overcome the bottleneck during intelligence promotion, has attracted a great attention recently.

Intelligent manufacturing and its promoting path have been studied intensively in the literature. From the perspective of research, Humphrey et al. [1] developed the path "OEM-ODM-OBM," which was based on gradually improving the value chain, to help the enterprise realize intelligent manufacturing. Stanescuet al. [2] proposed three paths, that is, from top to bottom, form bottom to top, and jump-over service, for promoting intelligent manufacturing based on the viewpoint of discrete time, intelligent information, synergic production, and advanced business information control. From the perspective of open innovation, Laursen and Salter [3] proposed four paths for manufacturing enterprises to promote intelligent manufacturing: promoting industrial innovation resource agglomeration, acquiring innovative teams, building open innovation multiparty support, and participating in global technological innovation alliance. Tanaka et al. [4] proposed the path for small- and medium-sized manufacturing enterprises to realize intelligent manufacturing from the perspective of global value chain, including the process and product upgrading, value chain reconstruction, and the upgrading path of integrating their own resources and capabilities. Zhou et al. [5] proposed the path of "parallel promotion of integrated development" to promote the development of intelligent manufacturing in manufacturing enterprises according to the basic paradigm of enterprise intelligent manufacturing. Based on the theory of service ecosystem, Sklyar et al. [6] emphasized that enterprises should regard service as the center and make full use of digitalization in the process of promoting intelligent manufacturing, rather than purely pursuing technological progress.

From the aspect of research contents, some researchers take the development of intelligent manufacturing as the starting point to explore the path of intelligent manufacturing: Pang [7] proposed two paths to realize intelligent manufacturing: the high-end embedding of low value chain and upstream and downstream embedding of manufacturing service integration. Xu et al. [8] considered that the enterprises are the main of implementing intelligent manufacturing and proposed three spiral development paths of intelligent manufacturing: the top-down oriented to the overall situation, bottom-up based on the actual situation of enterprises, and snowball oriented to customers. Felderer et al. [9] analyzed the typical centralized mode of intelligent transformation of manufacturing enterprises and summarized the upgrading path of information resource sharing, "hierarchical" ladder type, step-by-step, and "breakthrough intermediately, power at both ends" enterprise intelligent transformation. Li et al. [10] considered that the intelligent manufacturing is a new driving force for the transformation and upgrading of manufacturing enterprises and proposed the "two-step" path of "smart manufacturing" and "energy conversion of manufacturing industry." Oliff et al. [11] proposed the path for manufacturing enterprises with "human-computer interaction and two-way cooperation" to promote intelligent manufacturing. Bittencourt et al. [12] emphasized the important role of the subjectivity of manufacturing enterprises and proposed three ways to realize intelligent manufacturing in manufacturing enterprises, namely, market type, network transportation type, and vertical chain type.

Some researchers explored the path of intelligent manufacturing based on the change of external macro environment: Brassaia and Iantovicsb [13] proposed that the enterprises can realize intelligent manufacturing through the path of "supply side," "demand side," and "pilot before investment" according to the new situation and policy requirements of China's intelligent manufacturing development. Qiu [14] constructed the industrial cluster upgrading model of "butterfly effect-path dependence-butterfly effect-path transformation and new path dependence," so as to better promote the realization of intelligent manufacturing. Qian et al. [15] summed up three nonlinear upgrading paths of manufacturing enterprises, bidirectional embedded/reconstructed value chain innovation drive, technology capital cross industry innovation drive, and integrated intelligent innovation drive, in the environment of big data and Internet. Simeone et al. [16] proposed an intelligent cloud manufacturing platform according to the characteristics of large fluctuations in the demand of modern manufacturing industry. Enterprises can use the intelligent module of the platform to realize the transformation and upgrading of intelligent manufacturing.

In conclusion, many researchers have realized the importance and urgency of intelligent manufacturing for manufacturing enterprises and have achieved some enlightening research results, but most of the research work focuses on the construction of intelligent manufacturing path, without considering the selection of intelligent manufacturing path, and the quantitative analysis is mainly based on a single method. At the same time, there are few studies on the use of strategic thinking to analyze manufacturing enterprises to promote intelligent manufacturing. As a result, the intelligent manufacturing theory is lack of practical application value in current stage. This paper constructs the path selection of manufacturing enterprises to promote intelligent manufacturing based on the coevolution strategy and considering the time factor and spatial structure. According to the influencing factors of manufacturing enterprises to promote intelligent manufacturing, we construct the evaluation system of manufacturing enterprises to promote intelligent manufacturing path selection and establish the three-dimensional model of manufacturing enterprises to promote intelligent manufacturing path selection by using the combination method of Choquet fuzzy integral and SPACE, which provides a scientific method for manufacturing enterprises to promote intelligent manufacturing path selection.

2. Theoretical Background

The coevolution strategy is the common evolution strategy, which emphasizes systematic thinking. The essence of enterprise development is the process of coevolution among various elements of the enterprise. The theoretical framework of coevolution strategy includes three parts: the four elements of coevolution strategy, the four stages of coevolution strategy, and the four paths of coevolution strategy. Analyzing enterprises strategy from strategic elements, strategic stages, and strategic paths can solve basic strategic issues closely related to the survival and development of enterprises.

2.1. Four Elements of Coevolution Strategy. Due to the complexity of the enterprise environment, the future development direction of the enterprise is uncertain, and the future development path is discontinuous. The coevolution strategy starts from the two dimensions of the object of enterprise management and the boundary of the enterprise and proposes four strategic elements of product, organization, user, and market. The four elements of coevolution strategy reflect the essence of strategy. Among them, products and organizations are the internal elements of an enterprise, and users and markets are the external elements of an enterprise. At the same time, organizational elements and user elements are related to "people," while product elements and market elements are related to "things." In general, user factors analyze people outside the company, organizational factors analyze people inside the company, market factors analyze things outside the company, and product factors analyze things inside the company. Therefore, the coevolution strategy is based on the two dimensions of "people and things" and "inside and outside" and follows the principles of "people first, things second" and "first outside, second inside" [17].

2.2. Four Stages of Coevolution Strategy. The coevolution strategy theory divides the enterprise life cycle into four stages: lean startup stage, specialized growth stage, gain expansion stage, and boost transformation stage. At the same time, it also analyzes the development characteristics of the enterprise at each stage, as shown in Table 1.

2.3. Four Paths of Coevolution Strategy. Following the principles of continuity, accuracy, systemicity, and criticality, the coevolution strategy considers that manufacturing companies are facing two major problems of uncertain development direction and discontinuous development path in a complex and changeable business environment. According to the level of the two major problems, it analyzes the corresponding environmental characteristics in different situations. Different situations match different driving forces and finally get manufacturing companies to promote smart manufacturing paths. Smart manufacturing paths include adaptive strategic path, visionary strategic path, planned strategic path, and emergent strategic path. The adaptive strategic path means that manufacturing companies adjust their smart manufacturing policies in a timely manner as the environment changes. The visionary strategic path refers to the use of ambitious missions and visions by business leaders to guide manufacturing companies to promote smart manufacturing. The planned strategic path means that the leaders of manufacturing enterprises plan ahead of time the strategic direction and path for the promotion of smart manufacturing in the next few years based on the existing foundation and development goals. The emergent strategic path refers to stimulating the vitality of the enterprise through emergence and self-organization, allowing grass-roots employees to participate in decision-making and promoting smart manufacturing.

3. Research Methodology

3.1. Analysis on the Factors Influencing the Promotion of Intelligent Manufacturing by Manufacturing Enterprises Based on Coevolution Strategy. Researchers have made active explorations of the factors that influence the promotion of intelligent manufacturing by manufacturing enterprises, with substantial findings.

Lin et al. [18] demonstrate the positive correlation between the informationalized level and the realization of intelligent manufacturing by manufacturing enterprises. Elena and Orietta [19] believe that technology system integration ability, technology learning ability, technology detection ability, and organizational system integration ability are the core foundation for manufacturing enterprises to promote intelligent manufacturing. Cichocki et al. [20] believe that the processing cost, labor cost, inventory cost, and other factors constrain the collaborative allocation of resources in the job shop and affect the transformation to intelligent manufacturing. Dennis and Detlef [21] indicate that the intelligent manufacturing level of an enterprise is influenced by the ability of operators to perceive production problems and errors, data collection of products and production lines, and production planning and scheduling. Stephan et al. [22] believe that the key for enterprises to realize the transformation of intelligent manufacturing lies in technological innovation, comprehensive integration of systems, and application of digital technology. Ivanov et al. [23] put forward that organization, personnel, and other factors are the basic guarantee for an enterprise to realize intelligent manufacturing, while the degree of information fusion and system integration and other factors determine the degree of manufacturing intelligence improvement. Esmaeilian et al. [24] propose that the level of production technology, the degree of sustainable manufacturing, and the integration degree between manufacturing and operation are the factors that affect the intelligent manufacturing level of enterprises. Yew et al. [25] believe that the information perception ability of different types of workers and the degree of collaboration between workers and equipment are the key factors affecting the flexibility of intelligent manufacturing system. Thomaset al. [26] find that acquiring user knowledge is beneficial to guiding the development direction of enterprise intelligent manufacturing. In the research, Adriana et al. [27] find that the speed of information transmission and processing, the complexity of the environment, and user requirements are the keys to realize service-oriented intelligent manufacturing system. Pan [28] believes that the degree of product innovation, the level of technology, and the advanced degree of industrial chain are the keys for manufacturing enterprises to realize intelligent manufacturing. Goncalves et al. [29] put forward that enterprises' innovation ability, business performance, and informatization level are important factors affecting enterprises intelligent transformation. Han et al. [30] find that the flexibility of information technology is the critical factor affecting the development of enterprise intelligence. Burger et al. [31] point out that the technology level of information system and Internet of Things is the key factor affecting the flexibility of manufacturing system. Bürger et al. [32] regarded the number of researchers and research and development institutions as endogenous determinants and industrial research and development willingness as exogenous influencing factors to jointly promote the transformation of enterprises to intelligence. Jay et al. [33] analyze the influence of internal core factors such as enterprise technological innovation ability and digital informatization level and external factors such as national policy and industry competition on the development of intelligent manufacturing. Stadnicka et al. [34] believe that the reserve of high-end talents is a key factor in creating and improving intelligent manufacturing systems.

In conclusion, the influencing factors of intelligent manufacturing enterprises can be summarized as external and internal factors. However, this paper argues that, in addition to the external and internal factors, the development stage of manufacturing enterprises should also be considered. Therefore, based on the coevolution strategy, it is considered that the influencing factors of manufacturing enterprises to promote intelligent manufacturing are external influencing factors, internal influencing factors, and the development stage of enterprises. The external

Table 1: Four stage characteristics of coevolution strategy.

Four stages of coevolution strategy	Characteristics
Lean startup stage	The short establishment of the company, the small overall scale, the fact that entrepreneurs are still groping, the internal and external environment of the company is in an unstable state, the overall strength of the company is weak, and the development direction of the company is not clear. Thus, there are more choices.
Specialized growth stage	The gradual occupation of a certain share in the market, the continuous expansion of the scale of the enterprise, the internal and external environment of the enterprise is relatively stable, and the overall strength of the enterprise is significantly improved compared with the lean startup stage.
Gain expansion stage	They already have a certain overall strength, their scale is rapidly expanding, their resources are abundant, and they have a strong ability to adapt to environmental changes.
Boost transformation stage	The overall strength of the company still exists, but the original strategy and products of the company may be out of touch with the market, and the phenomenon of being unable to adapt to the rapid changes in the environment appears. The company needs to grasp the future development trend. The enterprise should give full play to the original resources; otherwise, it will face the risk of bankruptcy.

influencing factors include user factors and market factors, and the internal influencing factors include organization factors and product factors. Measure the matching degree between the development stage of manufacturing enterprises and a certain path to promote intelligent manufacturing [35].

3.2. Design Principles for Manufacturing Enterprises to Promote the Intelligent Manufacturing Path Selection System. The design of the evaluation index system directly affects the accuracy of the evaluation results of the manufacturing enterprises path selection to promote intelligent manufacturing and then affects the manufacturing enterprises to choose the correct path of intelligent manufacturing. Therefore, the following principles should be followed when designing the evaluation index system:

(1) *Systematic Principle*. It is a complex decision-making process for manufacturing enterprises to promote intelligent manufacturing, and it is the final decision-making based on the full understanding and evaluation of the external and internal influencing factors of manufacturing enterprises and the development stage of enterprises. Therefore, the selected indicators should include the influencing factors of manufacturing enterprises to promote intelligent manufacturing as far as possible, make it meet the requirements of integrity and coordination, and form a complete evaluation system according to the logical relationship between the indicators.

(2) *Scientific Principle*. The construction of path selection evaluation index system should be based on the influencing factors of manufacturing enterprises to promote intelligent manufacturing. According to the internal logic between the indexes, the evaluation index system should be designed, and the data should be processed with scientific methods, so that the results of manufacturing enterprises to promote intelligent manufacturing path selection can reflect the actual situation of the evaluated object scientifically and accurately.

(3) *Feasibility Principle*. The evaluation indexes for manufacturing enterprises to promote intelligent manufacturing path selection include qualitative indexes and quantitative indexes. When designing the index system, we should fully consider the reliability of data sources, ensure the reliability and accuracy of index measurement, and guarantee the objective and fair evaluation results.

(4) *Pertinence Principle*. The evaluation index system should be designed for the influencing factors of intelligent manufacturing in manufacturing enterprises. At the same time, the design and evaluation of the index system are to guide the selection of paths. Therefore, the index system should also reflect the commonness and difference among the paths, which is conducive to improving the rationality and accuracy of the path selection.

3.3. Manufacturing Enterprises Promoting the Construction of the Evaluation Index System for Intelligent Manufacturing Path Selection. On this basis, according to the principles of systematization, scientificity, feasibility, and pertinence, and based on the influencing factors of coevolution strategic manufacturing enterprises to promote intelligent manufacturing, 25 evaluation indexes are selected from five aspects of users, market, organization, products, and the development stage of enterprises to form the evaluation index system, as shown in Table 2.

4. Promoting Intelligent Manufacturing Path Choice of Manufacturing Enterprises Based on Coevolution Strategy

4.1. Indicator Quantitative Analysis—Choquet Fuzzy Integral Method. Choquet fuzzy integral method is a comprehensive evaluation method for fuzzy objects using fuzzy measure. This method can analyze indicators with correlation and is suitable for evaluation and processing of subjective value judgment [8]. Some indicators of intelligent manufacturing path choice are fuzzy and difficult to be quantified, and some

Table 2: Evaluation index system of promoting the choice of intelligent manufacturing path for manufacturing enterprises.

Primary index	Secondary index	Tertiary index	Four-level index	Index description
The path choice of promoting intelligent manufacturing for manufacturing enterprises (A)	External factors (B_1)	User factors (C_{11})	Degree of demand for personalized products (D_{111})	It reflects the degree of user's demand for product customization.
			The user to the enterprise product approval and the trust degree (D_{112})	It reflects the user's preference for the original products of the manufacturing enterprise.
			Speed of change in user requirements (D_{113})	It reflects whether the iterative speed of products can keep up with the change of users' demands.
			The purchasing power of the user (D_{114})	It reflects the consumption ability of users.
			Degree of demand for extensional products (D_{115})	It reflects the extent of customers' demand for epitaxial products.
			The urgency of the shift from one-way consumption to participatory consumption (D_{116})	It reflects the change from one-way consumption to participatory consumption.
		Market factors (C_{12})	The trend of industry intelligence transformation (D_{121})	It reflects the general trend of intelligent transformation of manufacturing industry.
			The adequacy of resources such as intelligent equipment and service agencies (D_{122})	It reflects that the resources of intelligent equipment and service organization are critical to the promotion of intelligent manufacturing in manufacturing enterprises.
			The extent to which national or local governments encourage smart manufacturing policies (D_{123})	It reflects the degree of encouragement and support of the national or local government to the manufacturing enterprises to promote the intelligent manufacturing.
			Intensity of competition among enterprises in the same industry (D_{124})	It reflects the competitive pressure faced by manufacturing enterprises.
			The penetration of the new generation of information technology (D_{125})	It reflects that the new generation of information technology is the basis of intelligent manufacturing.
			Degree of cooperation with users, suppliers, complementarities, and competitors (D_{126})	It reflects the relationship between manufacturing enterprises and stakeholders such as users, suppliers, completers, and competitors.
	Internal factors (B_2)	Organization factors (C_{21})	Awareness of leadership and decision-making, planning, policy implementation (D_{211})	It reflects the importance of leaders to the direction of the industry.
			Investment ability of high-tech talents (D_{212})	It reflects the investment degree of manufacturing enterprises in high-tech talents.
			The advantage of organizational structure to advance intelligent manufacturing (D_{213})	It reflects the influence of the current organization structure of manufacturing enterprises on the promotion of intelligent manufacturing.
			The popularization of intelligent management (D_{214})	It reflects the popularity of intelligent management.
			Development consciousness and will of enterprise intelligent manufacturing (D_{215})	It reflects the importance of the manufacturing enterprise itself to the development of intelligent manufacturing.
			Employee recognition for advancing smart manufacturing (D_{216})	It reflects the employee to the manufacturing enterprise to promote the intelligent system the degree of approval.
		Product factors (C_{22})	Enterprise digital integration capability (D_{221})	It reflects the consummation degree of data integration system in manufacturing enterprises.
			The intelligent level of manufacturing process (D_{222})	It reflects the intelligent technology of manufacturing enterprise and its application level in production line.
			Degree of data connectivity in intelligent manufacturing (D_{223})	It reflects the degree of intelligent manufacturing promoted by intelligent manufacturing of manufacturing enterprises.
			Management level of intelligent manufacturing system (D_{224})	It reflects the current application of intelligent manufacturing system in manufacturing enterprises.
			Accuracy of product market positioning (D_{225})	It reflects the accuracy of manufacturing enterprises to grasp and determine their own product competitive advantage.
			Product function and quality level (D_{226})	It reflects the current product competitive strength of manufacturing enterprises.
	The stage of development of an enterprise (B_3)	The advantages of the stage of development in which an enterprise is located (C_{31})	Advantages of the development stage of manufacturing enterprises (D_{311})	It reflects the matching between the development stage of manufacturing enterprises and a certain advance path of intelligent manufacturing.

indicators are related to each other but not completely independent.

Therefore, the Choquet fuzzy integral method is used in this paper to quantitatively analyze the evaluation indexes for the path choice of intelligent manufacturing in manufacturing enterprises. The steps are as follows:

Step 1: determine the target path of evaluation; based on the coevolution strategy, there are adaptive strategic path, vision strategic path, planned strategic path, and emergent strategic path for manufacturing enterprises to promote intelligent manufacturing.

Step 2: determine the total evaluation value of external indicators. The specific calculation steps are as follows:

(1) Determine the fuzzy evaluation value of each index
Invite senior managers and related employees of manufacturing enterprises to score each index in the index system and determine the evaluation value of each index. For quantitative indicators, the corresponding numerical range of each grade was determined according to the relevant statistical yearbook and relevant statistical bulletin, and then the values of each index were obtained through questionnaire. As for the qualitative index, the specific evaluation value is directly given by the senior management and related employees of the manufacturing enterprise according to the actual situation and their own knowledge and experience of the manufacturing enterprise. Because of the fuzziness of description, the semantic variable represented by trapezoidal fuzzy number is used to represent the subjective evaluation value in the scoring process of the index value. Experts are invited to give the semantic value of each indicator according to the semantic change scale, and the semantic value set $\tilde{f}$ of the indicator is constituted.

$$\tilde{f} = \left\{\tilde{f}_j\left(X_i^k\right) | k = 1, \ldots, n, i = 1, \ldots, dn_k, j = 1, \ldots, m\right\}, \tag{1}$$

where $\tilde{f}_j(X_i^k)$ is a trapezoidal fuzzy number, representing the semantic value given by the jth expert to the i evaluation indexes X_i^k in the evaluation layer X_k, represented by $(a_i^k, b_i^k, c_i^k, d_i^k)$, $\in[0, 1]$, $b_i^k \in [0, 1]$, $c_i^k \in [0, 1]$, $d_i^k \in [0, 1]$. n represents the number of evaluation layers. dn_k represents the number of evaluation indicators of X_k in the evaluation level; m is the number of specialists.

(2) Determine the fuzzy weight value of each index
Relevant experts were invited to score each evaluation index according to semantic variables, and the semantic value of trapezoidal fuzzy number was also used to score at different layers, and the semantic value was obtained as follows:

$$\tilde{g}_1 = \left\{\tilde{g}_j\left(X_i^k\right) | k = 1, \ldots, n, i = 1, \cdots, n_k, j = 1, \ldots, m\right\}, \tag{2}$$

where $\tilde{g}_j(X_i^k)$ is a trapezoidal fuzzy number, representing the semantic value given by the jth expert to the $i$evaluation indexes in the evaluation layer X_k, represented by $(a_i^k, b_i^k, c_i^k, d_i^k)$, $\in[0, 1]$, $b_i^k \in [0, 1]$, $c_i^k \in [0, 1]$, $d_i^k \in [0, 1]$. n represents the number of evaluation layers. n_k represents the number of evaluation indicators of X_k in the evaluation level; m is the number of specialists.

(3) Calculate the fuzzy value of each index
According to the opinions of experts, the fuzzy operation is carried out on the semantic value of the index, and the fuzzy value set $\tilde{f}$ of the index is obtained.

$$\tilde{f}\left(X_i^k\right) = \frac{1}{m} \otimes \left\{\tilde{f}_1\left(X_i^k\right) \oplus \tilde{f}_2\left(X_i^k\right) \oplus \cdots \oplus \widetilde{f_m}\left(X_i^k\right)\right\}, \tag{3}$$

where $\tilde{f}(X_i^k)$ is the fuzzy value of the i index X_k in the evaluation layer X_i^k after integrating the opinions of m experts. + and × are fuzzy operators. The same method is applied to the semantic value set of fuzzy weight.

(4) The explicit values of fuzzy evaluation and fuzzy weight are obtained by defuzzification operation
Relative distance formula (M_1), center value method (M_2), and center of gravity value method (M_3) are used to transform fuzzy number into explicit value. The calculation method for converting the fuzzy value $\tilde{f}(X_i^k)$ of the i qualitative index X_i^k in the evaluation level X_k into the explicit index value $f(X_i^k)$ is as follows:

$$f\left(X_i^k\right) = \frac{M_1\left(\tilde{f}\left(X_i^k\right)\right) + M_2\left(\tilde{f}\left(X_i^k\right)\right) + M_3\left(\tilde{f}\left(X_i^k\right)\right)}{3}, \tag{4}$$

where

$$M_1\left(\tilde{f}\left(X_i^k\right)\right) = \frac{d_i^{k-}}{d_i^{k-} + d_i^{k+}}, \quad \left(i = 1, \ldots, d_{n_k}\right), \tag{5}$$

$$d_i^{k-} = \sqrt{\frac{1}{4}\left(\left(a_i^k\right)^2 + \left(b_i^k\right)^2 + \left(c_i^k\right)^2 + \left(d_i^k\right)^2\right)}, \tag{6}$$

$$d_i^{k+} = \sqrt{\frac{1}{4}\left[\left(1-a_i^k\right)^2 + \left(1-b_i^k\right)^2 + \left(1-c_i^k\right)^2 + \left(1-d_i^k\right)^2\right]}, \tag{7}$$

$$M_2\left(\tilde{f}\left(X_i^k\right)\right) = \frac{\left(b_i^k + c_i^k\right)}{2} + \frac{\left[\left(d_i^k - c_i^k\right) - \left(b_i^k - a_i^k\right)\right]}{6} = \frac{2b_i^k + 2c_i^k + d_i^k + a_i^k}{6}, \tag{8}$$

$$M_3\left(f\left(X_i^k\right)\right) = \begin{cases} a_i^k, & a_i^k = b_i^k = c_i^k = d_i^k, \\ \dfrac{\left(d_i^k\right)^2 + \left(c_i^k\right)^2 - \left(b_i^k\right)^2 - \left(a_i^k\right)^2 + c_i^k d_i^k - a_i^k b_i^k}{3\left(d_i^k + c_i^k - b_i^k - a_i^k\right)}, & \text{else.} \end{cases} \tag{9}$$

Through the calculation of the above formula, the fuzzy values of each index can be, respectively, defuzzified and converted into explicit values, and the explicit values of fuzzy evaluation can be obtained. The calculation method of explicit value of fuzzy weight is the same, which will not be described here.

(5) Determine the λ value
The value of parameter λ is uniquely determined by the following equation:

$$\lambda + 1 = \prod_{i=1}^{n} \left[1 + \lambda \cdot G\left(x_i\right)\right]. \tag{10}$$

(6) Calculate the λ fuzzy measure
According to equation (11), the λ value and the fuzzy weight value g(x_i) of each index are substituted to obtain the λ fuzzy measure of each evaluation layer, and the following is obtained: $g_\lambda(\{X_1^k, X_2^k\})$, $g_\lambda(\{X_2^k, X_3^k\})$, …, $g_\lambda(\{X_1^k, X_2^k, X_3^k\})$, $\cdots g_\lambda(\{X_1^k, X_2^k, \ldots, X_{n-1}^k\})$, …, $g_\lambda(\{X_1^k, X_2^k, \ldots, X_n^k\})$.

$$\begin{aligned} g_\lambda\left(\{x_1, \ldots, x_n\}\right) &= \sum_{i=1}^{n} g\left(x_i\right) + \lambda \sum_{i_1=1}^{n-1} \sum_{i_2=i_1+1}^{n} g\left(x_{i_1}\right) g\left(x_{i_2}\right) \\ &\quad + \cdots + \lambda^{n-1} g\left(x_1\right) g\left(x_2\right) \cdots g\left(x_n\right) \\ &= \frac{1}{\lambda} \left| \prod_{i=1}^{n} \left(1 + \lambda g\left(x_i\right)\right) - 1 \right| \lambda \in [-1, \infty) \lambda \neq 0. \end{aligned} \tag{11}$$

(7) Calculate the fuzzy integral evaluation value of each evaluation layer
The calculation steps of fuzzy integral evaluation value of each evaluation layer are as follows:

$$\begin{gathered} f\left(X_{i_1}^k\right) \geq \cdots \geq f\left(X_{i_j}^k\right) \geq \cdots \geq f\left(X_{i_{n_k}}^k\right) \\ \left(\left\{i_j \mid j = 1, \ldots, n_k\right\} = \left\{i \mid i = 1, \ldots, n_k\right\}\right). \end{gathered} \tag{12}$$

Firstly, the index value $f\left(X_i^k\right)\left(i = 1, \ldots, n_k\right)$ under the evaluation layer X_k is reordered according to its size.

Secondly, the fuzzy integral formulas (5)–(8) are used to obtain the evaluation layer of the evaluation layer.

$$\begin{aligned} f\left(X_k\right) = f\left(X_{i_{n_k}}^k\right) g_\lambda\left(\left\{X_{i_1}^k, X_{i_2}^k, \ldots, X_{i_{n_k}}^k\right\}\right) \\ + \cdots + \left(f\left(X_{i_2}^k\right) - f\left(X_{i_3}^k\right)\right) g_\lambda\left(\left\{X_{i_1}^k, X_{i_2}^k\right\}\right) \\ + \left(f\left(X_{i_1}^k\right) - f\left(X_{i_2}^k\right)\right) g_\lambda\left(X_{i_1}^k\right). \end{aligned} \tag{13}$$

(8) Calculate the total evaluation value
Combined with the evaluation value of fuzzy integral at all layers, the fuzzy integral total evaluation value can be obtained by adopting the fuzzy integral method.

Step 3: determine the total evaluation value of internal indicators, using the same method as Step 2.

Step 4: determine the total evaluation value of the development stage of the enterprise. The method is the same as Step 2.

4.2. Construction of the Path Selection Evaluation Model Based on the SPACE Method. SPACE method is the strategic position and action evaluation method. It can accurately judge the strength of manufacturing enterprises, seek advantages and opportunities, weaken disadvantages, and reduce external threats. It uses space coordinate diagram to build a path selection model for manufacturing enterprises to promote intelligent manufacturing. The obtained overall evaluation value of external indicators for manufacturing enterprises to promote intelligent manufacturing path selection is placed on the Y-axis, the total evaluation value of internal indicators is placed on the X-axis, and the development stage of the enterprise is placed on the Z-axis, thus forming a spatial point $I(X_i, Y_i, Z_i)$, as shown in Figure 1. Then, the comprehensive index method is used to calculate the degree of proximity between point I and the ideal solution, and each path is sorted according to the degree of proximity. The path with the largest degree of proximity indicates the best, that is, the most appropriate path for manufacturing enterprises to promote intelligent manufacturing.

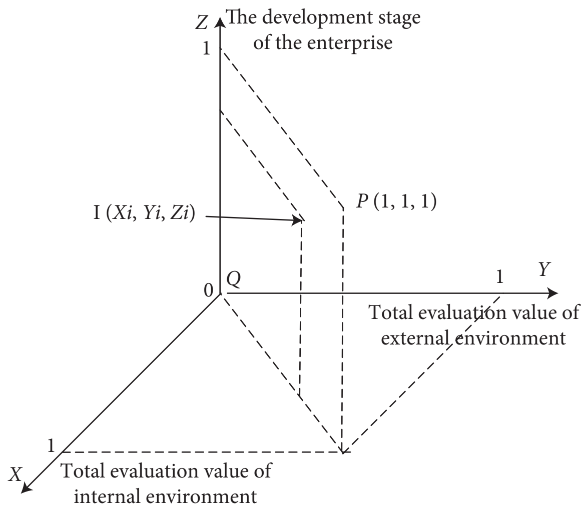

FIGURE 1: Path selection model of intelligent manufacturing promoted by manufacturing enterprises.

4.2.1. Determining the Ideal Solution. As we can see from Figure 2, there are two extreme points, $P(1, 1, 1)$ and $Q(0, 0, 0)$. If the manufacturing enterprises are located at point P, it means that the internal and external environments of the manufacturing enterprises at this time are very conducive to the promotion of intelligent manufacturing, and the development stage of the manufacturing enterprises matches a certain path to promote intelligent manufacturing very well. However, few manufacturing enterprises can achieve this state. Therefore, $P(1, 1, 1)$ is defined as the ideal solution. On the contrary, if the manufacturing enterprises are at point Q, it means that the internal and external environments of the manufacturing enterprises at this time are not conducive to the promotion of intelligent manufacturing, and the development stage of the manufacturing enterprises does not match a certain path to promote intelligent manufacturing. Of course, such cases are rare. So we define $Q(0, 0, 0)$ as a negative ideal solution.

4.2.2. Selecting the Appropriate Path to Promote Intelligent Manufacturing. According to the external indicators, internal indicators, and the total evaluation value of the development stage of the manufacturing enterprises obtained above, the four states of the manufacturing enterprises under the four paths can be obtained: I_1X_i, I_2,I_3, and I_4. We need to calculate the distance from $I_i(X_i, Y_i, Z_i)$ ($i = 1$ represents the adaptive strategic path. $i = 2$ represents the vision strategic path. $i = 3$ represents the planned strategic path. $i = 4$ represents emergent strategic path) to the ideal solution P, S_{1i}, and the distance from the negative ideal solution Q, S_{2i}, As shown in Figure 2, the formulas are as follows:

$$S_{1i} = \sqrt{(1 - X_i)^2 + (1 - Y_i)^2 + (1 - Z_i)^2}, \tag{14}$$

$$S_{2i} = \sqrt{(X_i - 0)^2 + (Y_i - 0)^2 + (Z_i - 0)^2} = \sqrt{X_i^2 + Y_i^2 + Z_i^2}. \tag{15}$$

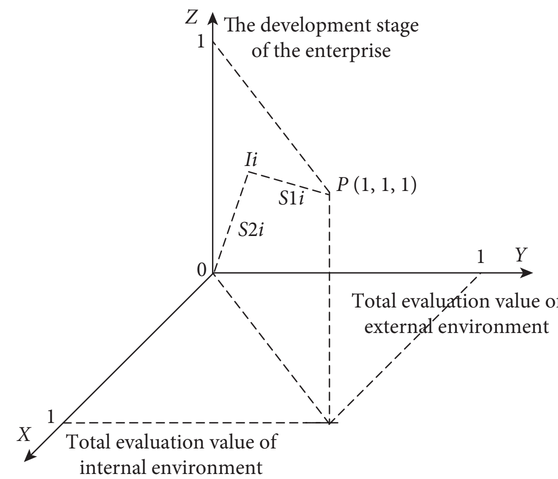

FIGURE 2: Schematic diagram of S_{1i} andS_{2i}.

At this point, the degree to which point I is close to the ideal solution can be positioned as C_i and its formula is

$$C_i = \frac{S_{1i}}{S_{1i} + S_{2i}}, \quad (0 < C_i < 1; i = 1, 2, 3, 4). \tag{16}$$

According to the four points known above, the approximate degree C_i of I_1, I_2, I_3, and I_4 to the ideal solution is calculated and compared, respectively. The smaller C_i is, the more suitable the corresponding path is, that is, the appropriate path for manufacturing enterprises to promote intelligent manufacturing.

5. Empirical Analysis

ARR is a manufacturer of crystal materials and equipment. The company has strong capital and large scale of production. Some technologies are in a leading position in the industry. Its products have a high market share and stable customer relationships. Under the guidance of market demand and based on the judgment of future market development trends, the company has done a lot of work in equipment research and development. At present, under the background of the rapid development of the industry, the company will continue to build smart manufacturing industry ecosphere. The self-developed advanced equipment is gradually turning to smart innovative design, accumulating resources in the field of smart manufacturing, and developing one-stop integrated production line solution business, resulting in the loss of some traditional superior products or part of the original product advantages. Therefore, this paper analyzes the path selection of ARR to promote intelligent manufacturing. In order to further clarify the objectives and measures of ARR to promote intelligent manufacturing, according to the analysis of the reality of ARR, it is in the boost transformation stage.

According to the steps of manufacturing companies to promote intelligent manufacturing path selection, first, obtain the fuzzy integral value of the four-level indicators for the four paths of ARR enterprises to promote smart manufacturing, that is, adaptive strategic paths (Table 3),

Table 3: ARR advance intelligent manufacturing-adaptive strategic path four-level index and fuzzy technique integral value.

External factor evaluation index									
Index		Fuzzy technique evaluation value	Fuzzy technique evaluation value	Fuzzy technique integral value	Index		Fuzzy technique evaluation value	Fuzzy technique evaluation value	Fuzzy technique integral value
f_{11}	f_{111}	0.6095	0.5200	0.5230	f_{12}	f_{121}	0.6840	0.5498	0.5673
	f_{112}	0.7140	0.6497			f_{122}	0.6662	0.5898	
	f_{113}	0.5994	0.6392			f_{123}	0.5250	0.7498	
	f_{114}	0.6014	0.6817			f_{124}	0.6318	0.6694	
	f_{115}	0.5944	0.6799			f_{125}	0.5148	0.6322	
	f_{116}	0.3070	0.6799			f_{126}	0.6312	0.5799	
Internal factor evaluation index									
Index		Fuzzy technique evaluation value	Fuzzy technique evaluation value	Fuzzy technique integral value	Index		Fuzzy technique evaluation value	Fuzzy technique evaluation value	Fuzzy technique integral value
f_{21}	f_{211}	0.5994	0.7783	0.5281	f_{22}	f_{221}	0.5993	0.5199	0.5210
	f_{212}	0.6289	0.8713			f_{222}	0.5793	0.6497	
	f_{213}	0.5297	0.6493			f_{223}	0.6736	0.8197	
	f_{214}	0.6140	0.5299			f_{224}	0.7284	0.6822	
	f_{215}	0.7134	0.6293			f_{225}	0.6541	0.6722	
	f_{216}	0.6116	0.6690			f_{226}	0.5446	0.5699	
Evaluation index system of enterprise's development stage									
Index				Fuzzy technique evaluation value	Fuzzy technique evaluation value	Fuzzy technique integral value			
f_3	f_{31}			0.1621	0.2125	0.3682			

visionary strategic paths (Table 4), planned strategic paths (Table 5), and emergent strategic paths (Table 6).

Second, obtain the fuzzy integral value table of the three-level indicators of ARR to promote the smart manufacturing path selection, as shown in Table 7.

Finally, the total evaluation value table for ARR to promote smart manufacturing path selection is obtained, as shown in Table 8.

It can be concluded from Table 7 that the total evaluation value of ARR is $I_1(0.3759, 0.3552, 0.3682)$ under the adaptive strategic path, $I_2(0.4939, 0.3957, 0.4642)$ under the visionary strategic path, $I_3(0.4053, 0.3878, 0.4895)$ under the planned strategic path, and $I_4(0.4493, 0.6984, 0.3659)$ under the emerging strategic path.

Then, the approximation degree of I_1, I_2, I_3, and I_4 to ideal solution is calculated and compared; thus the appropriate path for ARR to promote intelligent manufacturing is selected. According to equations (11)–(14), the approximate degree of each path to the ideal solution can be obtained as follows:

Adaptive strategic path: $S_{11} = 1.0974$, $S_{21} = 0.6349$, and $C_1 = 0.6335$

Visionary strategic path: $S_{12} = 0.9531$, $S_{22} = 0.7849$, and $C_2 = 0.5484$

Planned strategic path: $S_{13} = 0.8779$, $S_{23} = 0.8839$, and $C_3 = 0.4958$

Emerging strategic path: $S_{14} = 0.8924$, $S_{24} = 0.9075$, and $C_4 = 0.4983$

Obviously, $C_3 < C_4 < C_2 < C_1$, indicating that the planned strategic path is the most suitable path for ARR enterprises to promote intelligent manufacturing.

According to the planned strategic path, ARR leaders plan the strategic direction and path of intelligent manufacturing in the next 5 years in advance according to the existing foundation and development goals. In the specific implementation process, do the following: ① Pay attention to the incremental market and the stock users. The market share of ARR in the early stage is the basis for the later research and development of enterprises. For the better development of ARR, it is necessary to plan the technical R&D arrangement, constantly meet the needs of users, and establish a perfect user feedback information management and transmission mechanism, so as to ensure the effective implementation and promotion of intelligent manufacturing. ② Apply advanced technology in the whole value chain of product design, production, and management, while advanced technology can be realized through enterprises-independent innovation supplemented by technology integration innovation and cooperative innovation with universities and research institutions. Build information exchange platform. Building an information exchange platform is the quickest way to realize the efficient allocation of enterprise resources. With the help of the platform, building an information platform will integrate multiple resources into the operation decision-making, capital flow, cost accounting, and warehousing logistics of ARR enterprises, so as to speed up the level of enterprise intelligent manufacturing. ③ Strengthen the core competitiveness of enterprises, provide technical support for the realization of intelligent manufacturing, and avoid the inertia of enterprise development. Talent is the source of intelligence, and the knowledge reserve and innovation ability of talent are the cornerstone of ARR to promote intelligent manufacturing. Therefore, while recruiting high-tech talents from the outside, ARR should also encourage the existing talents of the enterprise, so as to ensure the long-term vitality of the enterprise and support the implementation of the intelligent

Table 4: ARR advance intelligent manufacturing-vision strategic path four-level index and fuzzy technique integral value.

External factor evaluation index									
Index		Fuzzy technique evaluation value	Fuzzy technique evaluation value	Fuzzy technique integral value	Index		Fuzzy technique evaluation value	Fuzzy technique evaluation value	Fuzzy technique integral value
	f_{111}	0.6687	0.5696			f_{121}	0.6535	0.5796	
	f_{112}	0.5891	0.7783			f_{122}	0.6167	0.6797	
f_{11}	f_{113}	0.5445	0.7486	0.6538	f_{12}	f_{123}	0.7009	0.7798	0.4839
	f_{114}	0.7953	0.8592			f_{124}	0.7361	0.7395	
	f_{115}	0.7284	0.7397			f_{125}	0.6637	0.6690	
	f_{116}	0.5891	0.6392			f_{126}	0.6959	0.5896	
Internal factor evaluation index									
Index		Fuzzy technique evaluation value	Fuzzy technique evaluation value	Fuzzy technique integral value	Index		Fuzzy technique evaluation value	Fuzzy technique evaluation value	Fuzzy technique integral value
	f_{211}	0.6608	0.7688			f_{221}	0.5696	0.5399	
	f_{212}	0.6337	0.7596			f_{222}	0.6786	0.7895	
f_{21}	f_{213}	0.6337	0.7083	0.4852	f_{22}	f_{223}	0.5696	0.6395	0.5237
	f_{214}	0.5297	0.8172			f_{224}	0.7327	0.7089	
	f_{215}	0.6860	0.6596			f_{225}	0.7400	0.6395	
	f_{216}	0.6441	0.7092			f_{226}	0.7842	0.7189	

Evaluation index system of enterprise's development stage				
	Index	Fuzzy technique evaluation value	Fuzzy technique evaluation value	Fuzzy technique integral value
f_3	f_{31}	0.8319	0.7868	0.4642

Table 5: ARR advance intelligent manufacturing-planned strategic path four-level index and fuzzy technique integral value.

External factor evaluation index									
Index		Fuzzy technique evaluation value	Fuzzy technique evaluation value	Fuzzy technique integral value	Index		Fuzzy technique evaluation value	Fuzzy technique evaluation value	Fuzzy technique integral value
	f_{111}	0.6490	0.6797			f_{121}	0.5571	0.7293	
	f_{112}	0.7379	0.6493			f_{122}	0.6439	0.4801	
f_{11}	f_{113}	0.5446	0.6791	0.5592	f_{12}	f_{123}	0.6437	0.6791	0.3969
	f_{114}	0.6039	0.6196			f_{124}	0.7079	0.5597	
	f_{115}	0.5595	0.6395			f_{125}	0.6142	0.6793	
	f_{116}	0.5569	0.5597			f_{126}	0.7057	0.7783	
Internal factor evaluation index									
Index		Fuzzy technique evaluation value	Fuzzy technique evaluation value	Fuzzy technique integral value	Index		Fuzzy technique evaluation value	Fuzzy technique evaluation value	Fuzzy technique integral value
	f_{211}	0.6464	0.7285		f_{22}	f_{221}	0.6588	0.6094	
	f_{212}	0.7109	0.8079			f_{222}	0.5993	0.7688	
f_{21}	f_{213}	0.6608	0.6891	0.5200		f_{223}	0.7529	0.6295	0.5262
	f_{214}	0.6140	0.6690			f_{224}	0.7451	0.7890	
	f_{215}	0.7287	0.7694			f_{225}	0.6515	0.6392	
	f_{216}	0.6069	0.4900			f_{226}	0.6163	0.6690	

Evaluation index system of enterprise's development stage				
	Index	Fuzzy technique evaluation value	Fuzzy technique evaluation value	Fuzzy technique integral value
f_3	f_{31}	0.2060	0.2683	0.4895

Table 6: ARR advance intelligent manufacturing-emerging strategic path four-level index and fuzzy technique integral value.

External factor evaluation index									
Index		Fuzzy technique evaluation value	Fuzzy technique evaluation value	Fuzzy technique integral value	Index		Fuzzy technique evaluation value	Fuzzy technique evaluation value	Fuzzy technique integral value
	f_{111}	0.6815	0.7398			f_{121}	0.6687	0.7398	
	f_{112}	0.6315	0.7783			f_{122}	0.5891	0.7783	
f_{11}	f_{113}	0.5824	0.7696	0.5444	f_{12}	f_{123}	0.5445	0.7696	0.5933
	f_{114}	0.6768	0.6997			f_{124}	0.7953	0.6997	
	f_{115}	0.6590	0.6896			f_{125}	0.7284	0.6896	
	f_{116}	0.7255	0.8298			f_{126}	0.5891	0.8298	

Table 6: Continued.

Internal factor evaluation index									
Index		Fuzzy technique evaluation value	Fuzzy technique evaluation value	Fuzzy technique integral value	Index		Fuzzy technique evaluation value	Fuzzy technique evaluation value	Fuzzy technique integral value
f_{21}	f_{211}	0.7657	0.8092	0.8350	f_{22}	f_{221}	0.6091	0.8484	0.5821
	f_{212}	0.5915	0.7096			f_{222}	0.7191	0.6797	
	f_{213}	0.6240	0.9592			f_{223}	0.7906	0.6195	
	f_{214}	0.6715	0.8598			f_{224}	0.6295	0.7194	
	f_{215}	0.6316	0.6395			f_{225}	0.7797	0.7194	
	f_{216}	0.6439	0.7194			f_{226}	0.7057	0.8997	

Evaluation index system of enterprise's development stage				
Index		Fuzzy technique evaluation value	Fuzzy technique evaluation value	Fuzzy technique integral value
f_3	f_{31}	0.9076	0.8088	0.3659

Table 7: ARR advanced intelligent manufacturing path selection three-level index and fuzzy technique integral value.

Index		Adaptive strategic path			Strategic path of vision		
		Fuzzy technique evaluation value	Fuzzy technique evaluation value	Fuzzy technique integral value	Fuzzy technique evaluation value	Fuzzy technique evaluation value	Fuzzy technique integral value
f_1	f_{11}	0.6341	0.5230	0.3759	0.7391	0.6538	0.4939
	f_{12}	0.6423	0.5673		0.6695	0.4839	
f_2	f_{21}	0.6699	0.5281	0.3552	0.7362	0.4852	0.3957
	f_{22}	0.6681	0.5210		0.6774	0.5237	
f_3	f_{31}	0.1621	0.2125	0.3682	0.8319	0.7868	0.4642
Index		Adaptive strategic path			Strategic path of vision		
		Fuzzy technique evaluation value	Fuzzy technique evaluation value	Fuzzy technique integral value	Fuzzy technique evaluation value	Fuzzy technique evaluation value	Fuzzy technique integral value
f_1	f_{11}	0.6534	0.5592	0.4053	0.7354	0.5444	0.4493
	f_{12}	0.6121	0.3969		0.8270	0.5933	
f_2	f_{21}	0.7338	0.5200	0.3878	0.6845	0.8350	0.6984
	f_{22}	0.6573	0.5262		0.7654	0.5821	
f_3	f_{31}	0.2060	0.2683	0.4895	0.9076	0.8088	0.3659

Table 8: Total evaluation value table of path selection for ARR to promote intelligent manufacturing.

Overall value	Adaptive strategic path	Vision strategic path	Planned strategic path	Emergent strategic path
External evaluation indicator	0.3759	0.4939	0.4053	0.4493
Internal evaluation indicators	0.3552	0.3957	0.3878	0.6984
The stage of development of an enterprise	0.3682	0.4642	0.4895	0.3659

manufacturing path. We can start from the material, spiritual, and institutional aspects to encourage high-tech talents and stimulate the potential and power of talents.

6. Conclusions

With the rapid development of the Internet and information technology, intelligent manufacturing has become the trend of the development of manufacturing industries all over the world. The promotion of intelligent manufacturing by Chinese manufacturing enterprises can not only solve the development problems of enterprises but also will enable our country to extricate itself from the predicament of being big but not strong. Based on the coevolution strategy, based on the coevolution strategy, this paper analyzes the influencing factors of manufacturing enterprises to promote the intelligent manufacturing and constructs an evaluation index system for manufacturing enterprises to choose the way to promote the intelligent manufacturing; the Choquet (fuzzy technique integral value)-SPACE combination method is used to establish a three-dimensional model for the path selection of the manufacturing enterprise to promote the intelligent manufacturing. At the same time, this model is used for empirical analysis of ARR. Firstly, Choquet fuzzy integral method is used to quantify the evaluation index, which fully considers that some indexes of ARR promoting intelligent manufacturing path selection are difficult to quantify and fuzzy, and there is a certain correlation between some indexes, so as to ensure that the constructed evaluation index system can significantly affect its evaluation results. Then improve the space coordinate diagram, accurately judge the strength of ARR, seek advantages and opportunities, weaken disadvantages and reduce external threats, ensure the comprehensiveness and reliability of the final evaluation results, and finally get that the planned strategic path is the most suitable path for ARR enterprises to promote intelligent manufacturing, and put forward the measures for ARR to promote intelligent manufacturing. It can effectively solve the problem of promoting intelligent manufacturing path selection.

Choquet fuzzy integral-SPACE combination method is used to establish a three-dimensional model of manufacturing enterprises to promote intelligent manufacturing path selection, which can comprehensively analyze the current situation of manufacturing enterprises to promote intelligent manufacturing, and provide strategic guidance for future development; it is of great practical significance for manufacturing enterprises to speed up intelligent manufacturing, realize industrial supply-side reform, form strategic emerging industrial clusters, break the lock-in of traditional industrial structure, and cultivate new economic growth drivers.

However, due to its own limited level, it will continue to deepen its research in this area, focusing on the two following points:

(1) The selection of evaluation indicators. In this paper, the influence factors of promoting intelligent manufacturing by manufacturing enterprises are used to construct their evaluation index system, but the influence factors are a complex system; it needs to be more perfect in the selection of evaluation index of promoting the intelligent manufacturing path choice of manufacturing enterprises.

(2) Path construction and selection. In the next stage of research, in the future research, the advance of intelligent manufacturing path constructed in this paper is based on the theory of coevolution strategy; we can design various ways to promote smart manufacturing according to the internal strength of manufacturing enterprises, as well as technology trends, market changes, and national policies, so as to improve the diversity and practical application of promoting the path choice of intelligent manufacturing in manufacturing enterprises.

Data Availability

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

Conflicts of Interest

The authors declare no conflicts of interest.

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Research Article

Path and Mechanism of Blockchain Embedded in Innovation Management of Cultural and Creative Industrial Park

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As a new business form of Cultural and Creative Industrial Cluster, the management of Cultural and Creative Industrial Park is faced with many difficulties, such as imperfect credit mechanism, lagging efficiency of intellectual property management, difficulties in industrial chain integration and upgrading, and imperfect development evaluation system. The "decentralization" concept of blockchain 3.0 technology can provide guidance value for the management concept innovation of Cultural and Creative Industry Park, and the embedding of technologies such as "smart contract", "distributed ledger", and "digital currency" can promote the construction of "programmable management system of Cultural and Creative Industry Park". According to the analysis path of architecture, function system, and application scenario of park management, this paper constructs the architecture from consensus layer, network layer, and data layer, constructs the function system from the public chain, alliance chain, and private chain, and locates the application scenario from the dimensions such as industrial chain management and government supervision and management; thus, the direction and focus of management innovation of blockchain 3.0 technology embedded in Cultural and Creative Industry Park are clarified. The research results of this paper have good theoretical guidance for the management subjects of Cultural and Creative Industry Park (local government, park management committee, industry organizations, etc.) to determine the path of implementing management innovation by using blockchain 3.0 and to build a scientific park management mechanism.

1. Introduction

In 2020, blockchain has been included in the outline of the 14th five-year plan for China's national economic and social development, listed as an important part of the digital economy industry, and a new engine to promote the deep integration of digital technology and the real economy. As a new technological innovation, the main value of blockchain is to provide data management technology, credit mechanism solutions, and a "decentralized" management philosophy. On the one hand, blockchain can provide underlying technical support for emerging technologies such as AI, Big Data, and IOT and promote their collaborative innovation and application. On the other hand, with the advent of the era of Blockchain 3.0 "programmable society", the application of blockchain in the financial industry, copyright industry, energy industry, education industry, social welfare, and other fields is deepening, and its wide application has strategic guiding significance.

Cultural and Creative Industrial Park is the gathering of culture, innovation, art, design, and other industries in a specific area of the city, which is composed of various enterprises such as creativity, manufacturing, communication, and consumption. It is also an important symbol of the city's cultural image which is characterized by spatial agglomeration, functional diversification, and a low-carbon economic model. The planning and construction of the Cultural and Creative Industrial Park is an important link and key task to boost the cultural industry to become a pillar of the national economy. The "fourteenth five-year development plan of the national economy" proposes implementing the digital strategy of cultural industry, which points out a new direction for the management innovation of Cultural and Creative Industry. Cultural and Creative Industry Park is a complex self-organization system, its management is a complex system engineering, and the management object includes the park strategy, resources, marketing, and operation. Blockchain 3.0 provides ideological guidance and technical support for the construction of the digital management platform of Cultural and Creative Industry Park. It can not only provide ideas and paths for the management innovation of Cultural and Creative Industry Park on the technical level but also promote the coupling effect and innovate the management mechanism of Cultural and Creative Industry Park.

Exploring the path and mechanism of blockchain 3.0 embedded in the management innovation of Cultural and Creative Industry Park will not only help to find a new way to solve the dilemma of traditional park management through expanding the application value of blockchain technology in the field of real economy but also help to achieve the strategic goal of cultural industry digitization through innovating the management mode of Cultural and Creative Industry Park.

2. Literature Review

2.1. Management System and Technical Innovation of Blockchain 3.0. Blockchain 3.0 has two meanings: one is the progress and breakthrough from "decentralization" to "smart contract" and then to "intelligent IOT" on the technical level; the other is the breakthrough extension from "programmable currency" represented by Bitcoin to "programmable finance" represented by Ethereum and then to "programmable society" [1]. The management system and technological innovation of blockchain 3.0 can be understood from three levels: "decentralization", "smart contract", and "distributed data". The relationship between them is shown in Figure 1.

2.1.1. Decentralized Management System. At the beginning of the birth of blockchain, "decentralization" has become its core, which realizes the weakening of the center and the construction of the programming self-organization operation system on the technical level. According to the design of Satoshi Nakamoto, the core economic operation system of the blockchain is "competition-bookkeeping-reward" [2], and they are interrelated based on data technology to form a self-organization management system containing each other. Compared with the traditional human-centered management system, this system has two major advantages: first, "decentralization" can weaken the subjective, bias, and deviation errors in management and avoid the risks and losses; the second is to give full play to the advantages of technical rationality and carry out system operation management based on network programming technology.

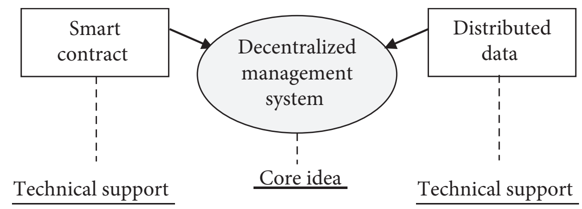

Figure 1: Management system and technical support of Blockchain 3.0.

The management system of "decentralization" of blockchain depends on the technical support of "functional contract" and "distributed data".

2.1.2. Smart Contract Technology Innovation. The smart contract is a concept put forward by Nick Szabo in the 1990s, which was born at the same time as the Internet [3]. The characteristic of the smart contract is that once it is set up, it can be executed automatically without the participation of an intermediary, and no one can stop it from running. Taking Ethereum's smart contract as an example, it is the code on the blockchain composed of a series of programming languages, such as Solidity, Serpent, Lisp-Like Language, and Mutan. The user writes the designed business logic into a smart contract and deploys it in Ethereum, which is automatically executed by Ethereum Virtual Machine (EVM) [4].

The functional contract management system is a collection of a series of underlying technologies, which together support the formation of smart contracts and solve the credit mechanism problem in the blockchain. Specifically, technologies to solve consensus and credit problems based on pluggable consensus templates mainly include PoW, PoS, DpoS, Pbft, Raft, Casper, and PoET. The intelligent IOT is the evolution of intelligent contract technology. Combined with the IOT, it can broaden the application of blockchain in the field of the real economy and promote the continuous development of blockchain technology.

2.1.3. Data Management Technology Innovation. Data management technology of blockchain originated from "encrypted distributed ledger", whose breakthrough innovation is to break the trust problem and information storage security problem of traditional central bookkeeping. The data management of blockchain solves the problem of information security through the mechanism of cryptography and the use of data programming means, distributed to each node to record data, in order to ensure that data records are not tampered with.

The technical elements of distributed data management include block data, digital signature, chain structure, hash algorithm, Merkle tree, and asymmetric encryption. Digital currency is a unique distributed database. Its purpose is to realize the point-to-point payment of virtual currency and avoid the problem of double spending in finance.

2.2. Feasibility Analysis of Blockchain 3.0 Embedded in Cultural and Creative Industrial Park Management Innovation. The extensive exploration of blockchain in the management and operation of other industries provides a reference for its practical application in the management of Cultural and Creative Industry Park. At present, there are some urgent difficulties in the management of Cultural and Creative Industry Park, such as financing difficulties, high cost of industrial value chain operation and data management, credit mechanism among member enterprises, technical support weakness, and intellectual property protection and development. These dilemmas lead to the low efficiency of the management of Cultural and Creative Industry Park and the difficult evaluation of the park.

There are few researches and explorations on the application of blockchain technology in the management of cultural and creative industries. At present, it only involves copyright confirmation and transaction, product traceability and authentication, trust fund, and digital finance. Zhang and Luo [5] discussed the possibility of blockchain application in the art trust fund and digital finance; Yu et al. [6], based on the blockchain technology, designed the function modules of copyright registration, online preview, copyright trading, user rights protection, etc., and reconstructed the ceramic art design copyright trading platform; Wang [7] explored the application of blockchain technology in art identification; Ding discussed the application mode of "blockchain + art education".

In the meantime, blockchain technology has attracted extensive attention in theoretical and related industrial fields; it has been widely used in financial services, supply chain management, copyright management, intelligent manufacturing, social welfare, education, energy industry, file management, performance appraisal, sharing economy, etc. The exploration of blockchain in the field of the real economy has achieved certain progress, which has been tested by practice. The typical representative of its application in the field of commodity traceability is the "Jingdong blockchain anti-counterfeiting traceability platform", which realizes the traceability and anti-counterfeiting of online and offline retail commodities in the form of alliance chain. In the field of copyright protection and trading, Xiamen Annie Co. Ltd. is connected with the official copyright institutions through an alliance chain, which improves the efficiency of confirmation and trading of copyright digital. In the field of precision marketing, the "marketing data link" platform jointly built by LEO Digital Network and MI has distributed records of Internet advertising monitoring, bidding, exposure, click, and follow-up behavior logs. Through marketing data cooperation, the data efficiency and value are maximized. In addition, the application of blockchain in the field of IOT, digital identity, and E-government has also made some achievements [8].

To sum up, blockchain technology has made some achievements in the application of the real economy. Although these application modes and paths cannot be directly applied to the management innovation of Cultural and Creative Industrial Park, they provide a certain reference value for blockchain to boost the programmable management of Cultural and Creative Industrial Park. The management system of blockchain is coupled with the management system of Cultural and Creative Industry Park. Blockchain can provide technical support for management innovation of Cultural and Creative Industry Park. It has a solid theoretical and practical foundation to explore the path and mechanism of blockchain promoting the management innovation of Cultural and Creative Industry Park.

3. Methodology

3.1. Method Explanation. In order to express the relationship of factor sets more directly, this study sets the elements of Blockchain 3.0 as X, the management function of Cultural and Creative Industry Park as Y, and the functional elements of the park as A. Next, this study uses the Likert scale to score the correlation between X and Y, Y, and A, respectively, through expert interviews.

$$X = \{X_1, X_2, X_3\}, \tag{1}$$

$$Y = \{Y_1, Y_2, Y_3, Y_4\}, \tag{2}$$

$$A = \{A_1, A_2, A_n, \ldots, A_{11}\}. \tag{3}$$

Among them, X_1, X_2, and X_3 represent distributed data, smart contract, and digital currency of Blockchain 3.0, respectively; Y_1, Y_2, Y_3, and Y_4 represent planning, organization, leadership, and control of management means of Cultural and Creative Industry Park, respectively; A_1, A_2, A_{n} ... and A_{11} represent public relations management, intermediary service, IP copyright management, personnel management, enterprise/institution management, financial management, industrial chain management, IOT management, equipment and technology management, government supervision, customer management, public relations management, and intermediary service management, respectively. Two groups of factors that need to be scored are "X–Y" and "Y–A"; they express "the relevance between Blockchain 3.0 and the management functions of Cultural and Creative Industry Park" and "the relevance between Blockchain 3.0 and the management functions and elements of Cultural and Creative Industry Park", respectively. The score of {5, 4, 3, 2, 1} in Likert's scales represents the degree of correlation. Two survey scales are shown in Tables 1 and 2.

The correlation degree is R and the expert score is C. The function expression of the two factors is as follows:

$$R_n = \{R_1, R_2, \ldots, R_n, \ldots R_{12}\}, \tag{4}$$

$$C_n = \{Cn_1, Cn_2, Cn_3, Cn_4, Cn_5\}, \tag{5}$$

$$Rn = \frac{Cn_1 + Cn_2 + \ldots + Cn_5}{5} = \frac{\sum_{i=1}^{5} Cn_i}{5}. \tag{6}$$

3.2. Data Sources. In this study, five experts were invited to participate in the study to determine the relevance between Blockchain 3.0 and the management means and

Table 1: Research on the correlation between Blockchain 3.0 and the management means of Cultural and Creative Industry Park.

	X_1	X_2	X_3
Y_1	(5, 4, 3, 2, 1)	(5, 4, 3, 2, 1)	(5, 4, 3, 2, 1)
Y_2	(5, 4, 3, 2, 1)	(5, 4, 3, 2, 1)	(5, 4, 3, 2, 1)
Y_3	(5, 4, 3, 2, 1)	(5, 4, 3, 2, 1)	(5, 4, 3, 2, 1)
Y_4	(5, 4, 3, 2, 1)	(5, 4, 3, 2, 1)	(5, 4, 3, 2, 1)

Table 2: Research on the correlation between management functions and elements of Blockchain 3.0 embedded in Cultural and Creative Industry Park.

	A_1	A_2	...	A_{11}
Y_1	(5, 4, 3, 2, 1)	(5, 4, 3, 2, 1)	...	(5, 4, 3, 2, 1)
Y_2	(5, 4, 3, 2, 1)	(5, 4, 3, 2, 1)	...	(5, 4, 3, 2, 1)
Y_3	(5, 4, 3, 2, 1)	(5, 4, 3, 2, 1)	...	(5, 4, 3, 2, 1)
Y_4	(5, 4, 3, 2, 1)	(5, 4, 3, 2, 1)	...	(5, 4, 3, 2, 1)

management elements of Cultural and Creative Industry Park, respectively. They completed all the Likert scales in Tables 1 and 2.

3.3. Data Validation. Kurtosis and skewness were used to test the data.

The calculation formula of kurtosis is as follows:

$$K = \frac{(1/n-1)\sum_{i=1}^{n}\left(x_i - \overline{x}\right)^4}{\mathrm{SD}^4} - 3. \tag{7}$$

In the formula, K is kurtosis; i is serial number; $\overline{x}$ represents the average value; n is the number of samples; SD represents standard deviation.

The calculation formula of skewness is as follows:

$$S = \frac{(1/n-1)\sum_{i=1}^{n}\left(x_i - \overline{x}\right)^3}{\mathrm{SD}^3}. \tag{8}$$

In the formula, S is skewness, i is serial number, $\overline{x}$ represents the average value, n is the number of samples, and SD represents standard deviation.

4. Results and Findings

4.1. Association Mapping Model of Blockchain 3.0 and Cultural and Creative Industry Park Management. From the perspective of the management system, Blockchain 3.0 and Cultural and Creative Industrial Park are both complex operation systems, showing complex scientific management philosophy, creative management philosophy, and game theory management philosophy.

4.1.1. Complex Scientific Management Thinking Mode. It is a new management thinking mode formed and developed in the 21st century. Its core is system thinking mode, and the management object is a complex system with self-organization, self-adaptability, and dynamic. The "decentralized" management system of Blockchain 3.0 realized by software programming technology is essentially a self-organizing and adaptive dynamic operation process realized by script programming and hardware facilities. Although there are three types of management modes of Cultural and Creative Industry Park: government-led, market-led, and mixed-led [9], the operation is also a complex adaptive system, which has the characteristics of self-organization, self-adaptation, and dynamic. The main performance is that the constituent elements of Cultural and Creative Industry Park are complex and diverse, they constitute a complex system, and their evolution process shows the self-organization characteristics of industrial organization evolution.

4.1.2. Creative Management Thinking Mode. It is also the common management thinking mode in the management of Blockchain 3.0 and Cultural and Creative Industrial Park which runs through the whole management process. The management activities of both are essentially continuous creation and innovation. The creativity of Blockchain 3.0 is mainly reflected in the development and innovation of new technologies such as consensus mechanism, encryption algorithm, data storage mode, data dissemination mechanism, and data verification mechanism. The creativity in the management of Cultural and Creative Industrial Park is mainly reflected in the innovation of the subject's management thinking model and management technology.

4.1.3. The Game Theory Management Mode. It is also a common feature in the management of blockchain and Cultural and Creative Industrial Park. The consensus mechanism and equal trading rights in the blockchain are all based on the core of game theory; The competition relations among enterprises in the Cultural and Creative Industrial Park, such as "zero-sum game", "positive-sum game", and "negative-sum game", also reflect the idea of game theory.

In summary, the technical development and maturity of Blockchain 3.0 can provide technical support for the renewal of management means of Cultural and Creative Industrial Park. According to the research methods in 3.1, this paper collates the data of the management relevance between Blockchain 3.0 and Cultural and Creative Industrial Park Management; the results are shown in Table 3.

At the same time, the formulas (7) and (8) calculate the kurtosis $K = -1.16$ and skewness $S = -0.39$. The schematic diagram is as shown in Figure 2, and the data as a whole presents a flat right-skewed distribution.

In order to better describe the significance and value of Blockchain 3.0 for the management of Cultural and Creative Industrial Park, this paper calculated the correlation degree of the above 12 groups of factors according to formula (5), and the association mapping analysis model is made from the two levels of the management system and technical means, as shown in Figure 3.

4.1.4. Technical Support Association Mapping. The correlation degree of "distributed data" (X_1) and Y is 4.8, 4.8, 3.2, and 4.6, respectively, which can provide technical support for the data storage of enterprise/institution management,

Table 3: Research data on the correlation between Blockchain 3.0 and the management means of Cultural and Creative Industry Park.

	X_1Y_1	X_1Y_2	X_1Y_3	X_1Y_4	X_2Y_1	X_2Y_2	X_2Y_3	X_2Y_4	X_3Y_1	X_3Y_2	X_3Y_3	X_3Y_4
C_1	5	5	3	5	5	5	4	5	4	4	4	4
C_2	5	4	3	4	5	5	4	5	3	4	3	3
C_3	4	5	4	5	4	5	3	4	4	4	3	3
C_4	5	5	3	5	5	5	4	5	4	3	4	4
C_5	5	5	3	4	5	5	4	5	5	4	3	4

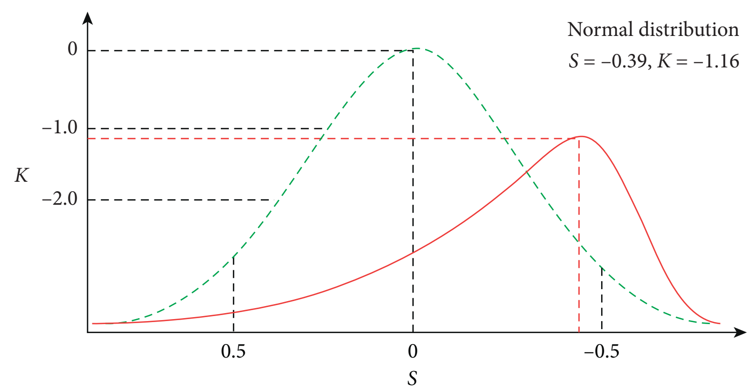

Figure 2: Kurtosis and skewness of data.

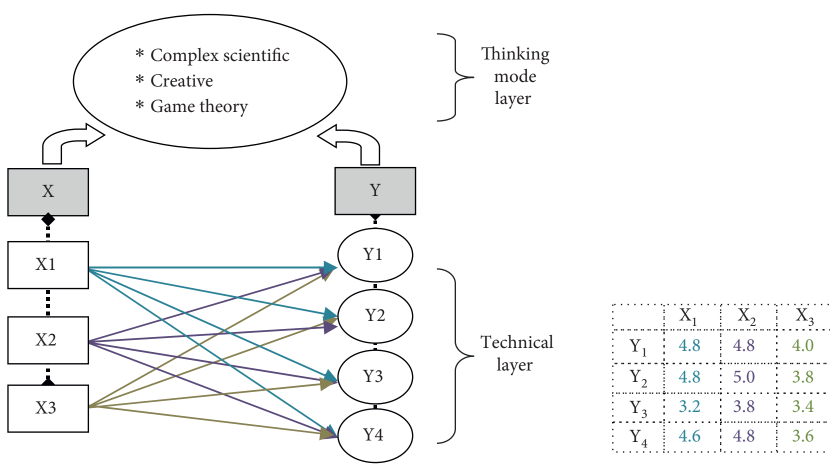

Figure 3: Association mapping model between Blockchain 3.0 and the management system of Cultural and Creative Industry Park.

policy management, resource management, and infrastructure management in the planning, organization, leadership, and control of Cultural and Creative Industrial Park Management and constantly update the data to form a block data chain to provide traceability and unchangeable data. The correlation degree of "smart contract" (X_2) and Y is 4.8, 5.0, 3.8, and 4.8, respectively, which can solve the consensus and rule problems in management activities. The electronic contract automatic execution program is compiled in the form of a smart contract, which can alleviate the cumbersome problems in traditional management. The correlation degree between "digital currency" (X_3) and Y is 4.0, 3.8, 3.4, and 3.6, respectively. It can reduce the intermediate cost of legal currency circulation in value transmission activities, improve management efficiency and save management expenses, and avoid double spending.

4.2. Path of Blockchain 3.0 Technology Embedded in the Management Innovation of Cultural and Creative Industrial Park. By analyzing and processing the expert survey data of the relationship between programmable management objectives and framework elements of the Cultural and Creative Industry Park, this paper get the correlation degree data of the management functions and elements of the Cultural and Creative Industry Park embedded in Blockchain 3.0, as shown in Table 4.

At the same time, formulas (7) and (8) calculate the kurtosis $K = -1.22$ and skewness $S = 0.66$. The schematic diagram is as shown in Figure 4, and the data as a whole presents a flat left-skewed distribution.

The results show that the average correlation degree of $A_1, A_2, A_3, A_4, A_5, A_6, A_7, A_8$, and A_9 is higher than 4.0, while the average correlation degree of A_{10} and A_{11} is lower than

Table 4: Correlation degree of management functions and elements of Blockchain 3.0 embedded in Cultural and Creative Industry Park.

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	A_{11}
Y_1	4.60	4.40	4.60	4.60	4.60	4.20	4.20	4.40	4.20	2.40	2.20
Y_2	4.40	4.80	4.40	5.00	4.80	4.60	4.20	4.20	4.40	3.00	2.40
Y_3	4.60	4.60	4.80	4.80	5.00	4.20	4.20	5.00	4.20	2.00	2.20
Y_4	4.80	4.60	4.60	4.60	4.80	4.40	4.80	4.40	4.80	2.40	2.20
$\overline{X}$	4.60	4.60	4.60	4.75	4.80	4.35	4.35	4.50	4.40	2.45	2.25

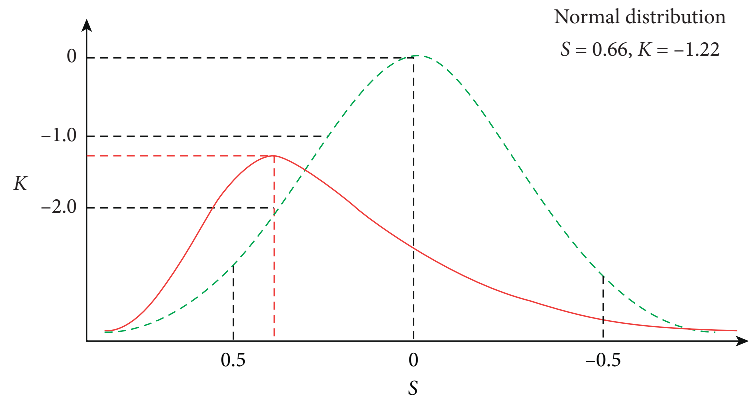

Figure 4: Kurtosis and skewness of data.

3.0. Therefore, this paper omits the two modules of public relations management module and intermediary service management module of Cultural and Creative Industry Park and constructs a "DAPP, Decentralized Application" composed of the data layer, technology layer, and application layer, as shown in Figure 5.

The data layer is located in the core position, which is composed of {1, 2, ..., n} blocks, building a decentralized cloud storage system. The technology layer is located in the middle, which is composed of link mechanism, propagation mechanism, verification mechanism, consensus mechanism, intelligent contract, asymmetric encryption, and other technologies. The application layer is located in the periphery and consists of nine application modules, which are IP copyright management module, government department supervision module, equipment and technology management module, customer management module, Internet of things management module, industrial chain management module, financial management module, enterprise/institution management module, and personnel management module.

In addition, according to the mode of participation, blockchain can be divided into a public chain, alliance chain, and private chain. Their characteristics and applicable scenarios are different. According to the principle of "Mundellian Trilemma" in economics, blockchain can only meet two goals at most among "decentralization", "security" and "efficiency". Public chain mainly realizes "decentralization" and "security", while alliance chain and private chain focus more on "efficiency" and "security". The architecture, categories, and application scenarios of Blockchain 3.0 in the programmable management system of Cultural and Creative Industry Park are shown in Figure 6.

The characteristic of the Permissionless/public chain is that there is no official organization and management organization; participating nodes have free access to the network and work based on consensus. Bitcoin and Ethereum are the most representative public chain applications. The main function of the public chain construction of Cultural and Creative Industry Park is to boost the construction of Digital Sharing Economy and Smart Park, realize the programmable management system construction of the park, and complete the strategic management innovation of the park.

The consortium blockchain is a limited blockchain and is only limited to the participation of alliance members. Alliance chain plays an important role in the operation and management innovation of Cultural and Creative Industry Park, which can promote the realization of "enterprise cooperation informatization" among alliance enterprises in the park, reach consensus through the mutual trust of multicenters, and realize the informatization business model of multiparty and peer-to-peer cooperation.

Private blockchain has a smaller scope of participation and generally exists in enterprises or project groups. Its main function is to provide a secure, traceable, and automatic computing platform for teamwork.

4.2.1. IP Rights Management Module. In terms of IP copyright management activities, technologies such as timestamp, encryption algorithm, and smart contract of Blockchain 3.0 provide technical support for efficient right confirmation, rights protection, and copyright transaction and solve problems such as right confirmation, use, transaction, license, and transfer of intellectual property, as

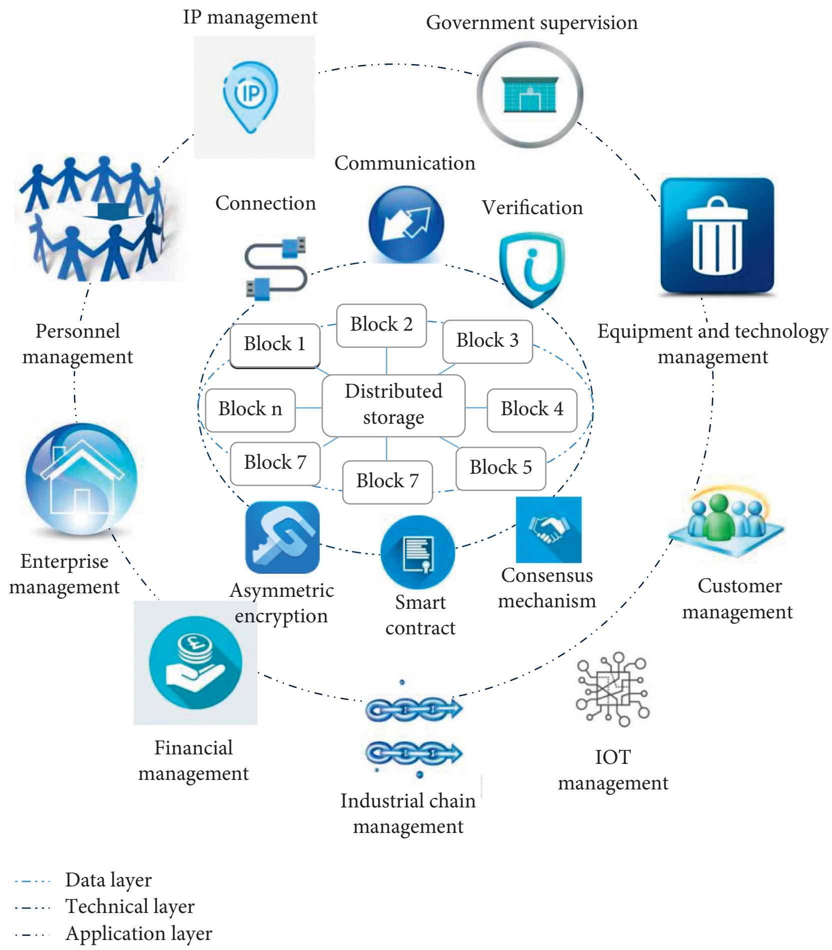

FIGURE 5: Programmable management system of Cultural and Creative Industry Park based on Blockchain 3.0.

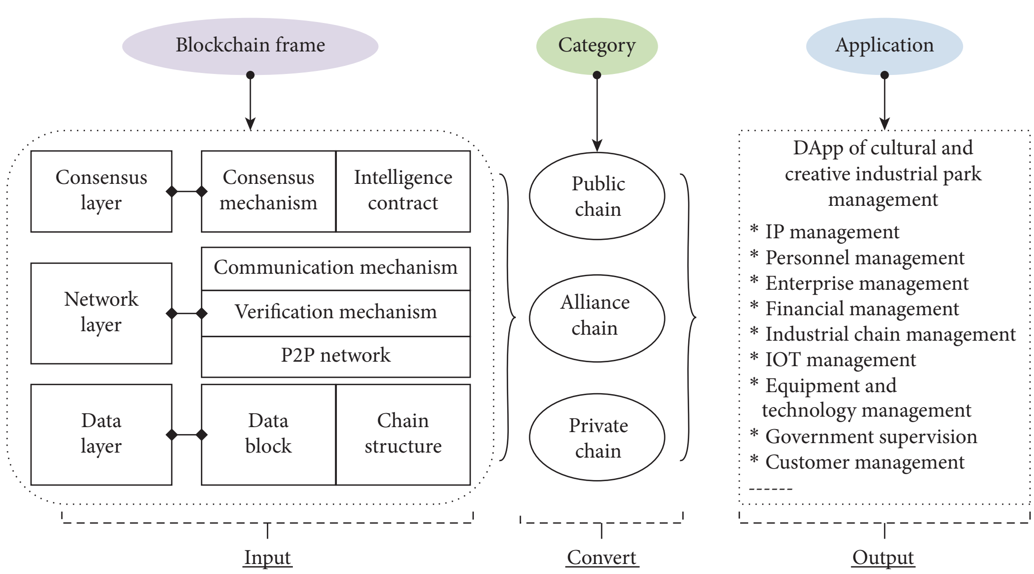

FIGURE 6: Architecture, category, and application scenario of blockchain in the management of Cultural and Creative Industrial Park.

shown in Figure 7. For example, we optimize the distribution mode of digital rights transaction income, user payment mechanism [10], reduce cross-regional infringement [11], balance the interests between copyright owners and the public, between platform intermediaries and copyright owners, and between the public and platform intermediaries

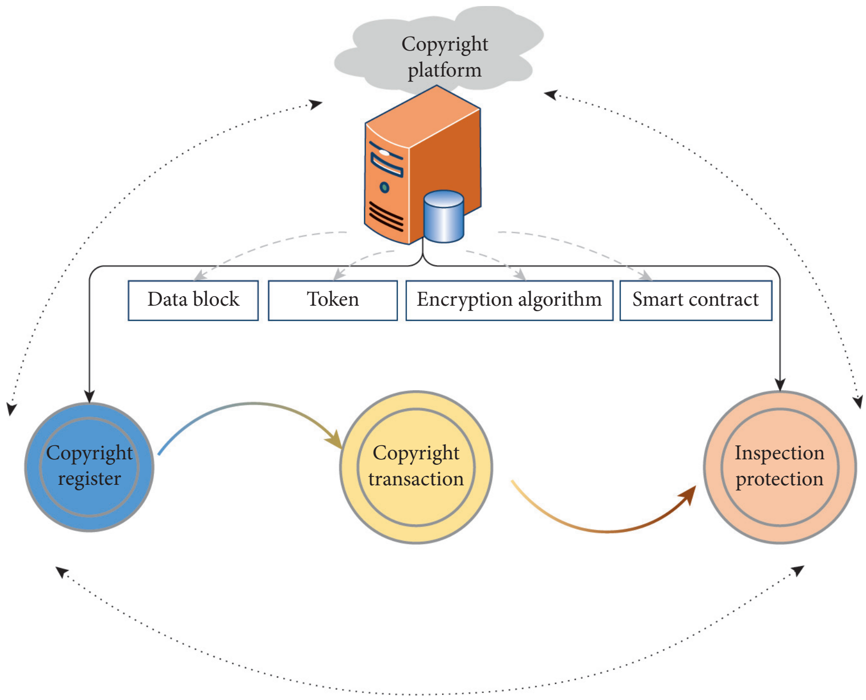

Figure 7: Operation mechanism and content of IP copyright management module.

[12], and automatically allocate license fees to platform intermediaries and copyright owners. At present, the more successful cases of using blockchain for intellectual property management include Annie shares, Ascribe [13], Edition Family [14], Minelabs [15], and China Copyright Protection Center.

4.2.2. Personnel Management Module. The traditional personnel file management is faced with the disadvantages of low efficiency of personnel information updating, insufficient utilization of human resources in the park, and high risk of personnel information leakage. Establishing a personnel information system in the park can record the personnel information of each enterprise and form a personnel information blockchain in the park, realize the real-time synchronous update of personnel information data [16], ensure the credibility of personnel information, protect the confidentiality of data, and improve the efficiency of human resources.

4.2.3. Enterprise/Institution Management Module. First of all, blockchain plays an important role in enterprise credit governance, which can promote transaction subjects to participate in credit governance activities [17]. Based on distributed data storage, point-to-point transmission, and other computer technologies, different nodes and platforms can share data in the system. At the same time, it can also use hash function and RSA asymmetric encryption digital signature and other technologies generate a public key and special key to protect the privacy of data information [18]. Secondly, blockchain can also participate in the life cycle management of enterprises/institutions. Establishing alliance chains at provincial and municipal levels can record the registration, change, and other information of market members, synchronize to the blockchain information network, and support business activities in the life cycle of market subject registration, major information change, major event publicity, and delisting [19]. Third, blockchain can also innovate enterprise performance management. Blockchain can solve the problems of authenticity, openness, and security in enterprise performance data management. According to the social consensus mechanism of the blockchain, the project information and data recorded on the chain will be transferred in turn to all nodes of the chain. Any change of information between nodes will cause information conflict between nodes. If you want to modify the data, you must modify more than 51% of the nodes on the blockchain at the same time to succeed [20].

4.2.4. Financial Management Module. In Ethereum, the deployment and transfer of smart contracts need to pay digital currency. Asymmetric encryption and distributed storage of blockchain technology can ensure the security of equity delivery of digital assets. With authorization, financial institutions have a clear understanding of the current accounts and historical credit records of enterprises, which fundamentally solves the biggest problem that SMEs are difficult to obtain credit loans [21]. The “blockchain + supply chain” financial service platform can also provide financing services for small and microenterprises in Cultural and Creative Industry Park and solve their financing difficulties [22].

4.2.5. Industrial Chain Management Module. The tamper-proof property of the blockchain provides an effective solution for the anti-counterfeiting and traceability of goods [23], thus improving the trust mechanism among enterprises in the supply chain and realizing the automatic management of the supply chain transaction system [24].

4.2.6. IOT Management Module. The Internet of things (IOT) is a kind of network that connects any item with the Internet according to the agreed protocol through radio frequency identification, infrared sensors, global positioning system, laser scanner, and other information sensing devices to exchange and communicate information, so as to realize the intelligent identification, positioning, tracking, monitoring, and management of items [25]. The "blockchain + IOT" in the Cultural and Creative Industry Park can solve the pain points such as the leakage of personal privacy and the lack of trust of operators in the IOT. The organic combination of the two can make people, machines, and everything fully interconnected, and the deep integration of information technology, human, and industrial technology, so as to build a comprehensive and reliable digital industrial Internet.

4.2.7. Customer Management Module. In terms of customer management activities, the distributed data recording and sharing function of the blockchain is used to store the consumption information of customers in the park, the convenience of DAPP is used to collect customers' opinions, and the evaluation information of customers on the overall facilities and artistic atmosphere of the park in the "Art + Tourism" website is used. The art institutions in the park can more scientifically analyze consumers' behaviors, attitudes, and suggestions so as to do a better job in customer management activities.

4.2.8. Equipment and Technology Management Platform. As the technical support of the programmable management system of the Cultural and Creative Industry Park, the technical maintenance department of the blockchain is an important link to ensure the normal operation of the whole management system. Therefore, there must be professional departments and technical teams to maintain and update the cloud server, virtual host, storage service, network service, operation, and maintenance service management system related to the operation of the blockchain. At the same time, the encryption technology and smart contract of blockchain are facing the risk of being attacked by hackers. Therefore, the maintenance of blockchain network security is also an important functional module and link.

4.2.9. Government Department Supervision Module. As one of the nodes of the blockchain, the government can share the data and information of the development of the park, supervise the data of the park, evaluate the development of the park, and supervise and manage the park according to the development plan of the park.

4.3. Mechanism of Blockchain 3.0 Technology Embedded in Management Innovation of Cultural and Creative Industrial Park. Mechanism refers to the structure, function, and interrelationship of the organism. The connotation of sociology can be expressed as "the specific operation mode of coordinating the relationship between different parts in order to play a better role under the premise of facing up to the existence of each part of things". There are three mechanisms for the existence and sustainable development of any system: incentive mechanism, renewal mechanism, and supervision mechanism [26]. As a system, the programmable management system of Cultural and Creative Industrial Park has no exception.

4.3.1. Incentive Mechanism. The incentive mechanism of programmable management of Cultural and Creative Industrial Park includes internal and external dynamic mechanisms. In terms of internal dynamic mechanism, the internal demand of Cultural and Creative Industrial Park Management for the upgrading of efficient industrial chain and industrial value chain, as well as the strategic alliance formed by the intermediary organization structure of enterprises/institutions, finance, government regulatory departments, and blockchain technology departments, its power and direction goal is to continuously improve the collaborative innovation ability and obtain the competitive advantage of the alliance.

In terms of external dynamic mechanism, first of all, blockchain technology has promoted the innovation of management means in some related industries and encouraged Cultural and Creative Industrial Park to change management means; secondly, in response to the call of national planning and development, the development scope and strength of "blockchain + substantial economy" are expanded. In the white paper on the development of China's blockchain industry in 2018, MIIT proposed that blockchain is expected to promote technological, organizational, and efficiency changes in China's economic system and make important contributions to the construction of a modern economic system [8]. In January 2019, general secretary Xi Jinping stressed that "we must promote the deep integration of blockchains and real economies, use blockchain technology to promote greater interconnection among the city, and further open up the innovation chain, application chain, and value chain".

4.3.2. Update Mechanism. The operation of any system needs to be continuously developed through the updating of elements, and the dynamic organization of the management system of the programmable Cultural and Creative Industry Park also meets this requirement. The system operation of the Cultural and Creative Industry Park involves many factors, but the five factors that play a major role in the system operation are consensus mechanism, communication mechanism, confidentiality mechanism, decision-making mechanism, and evaluation mechanism.

The consensus mechanism is the basis of value exchange activities among node enterprises in Cultural and Creative Industry Park, which involves enterprise credit, contract formulation, and implementation. The traditional consensus mechanism is based on offline contracts and credit verification by third-party organizations, but there are some problems, such as low efficiency and complex costs. Blockchain technology provides distributed data storage, digital encryption technology, intelligent contract, script code, and other means, which makes the nodes of blockchain reach a consensus and mutual dependence, forming a credible cooperation environment. At the same time, smart contracts, electronic signatures, and other technologies can help to complete the contract verification and performance and realize an efficient and secure online consensus working mechanism. At present, consensus mechanisms for blockchain creation mainly include PoW, PoS, Dpos, and distributed consistency algorithm.

The communication mechanism is a way for enterprises/institutions in the Cultural and Creative Industry Park to carry out information exchange. The information-sharing convenience brought by the distributed storage of the blockchain and the information security guarantee brought by digital encryption enable the information communication and exchange between and within the Cultural and Creative Industry Park to realize the P2P (peer-to-peer) communication mode. The relevant information of enterprises can be directly obtained from the blockchain, and there is no need to repeatedly query and confirm with relevant institutions, which is of great value and significance for efficient information dissemination and exchange.

The traditional information security work is in the charge of the people-centered organization department, which has objective risk. There are three types of blockchain, namely public chain, alliance chain, and private chain, which can provide data security support from different areas. Asymmetric encryption technology, hash function, and digital signature can support limited access rights, control the access rights of some stored data between limited nodes, and achieve decentralized, safe, and efficient security work.

In addition, blockchain has also changed the subjective errors such as perceptual errors and data fraud hidden in the traditional people-centered decision-making mechanism and evaluation mechanism in the Cultural and Creative Industry Park. The storage of distributed data greatly improves the authenticity and nontamperability of data, making the decision-making in the Cultural and Creative Industry Park more scientific and objective and the evaluation more authentic.

4.3.3. Supervision Mechanism. The supervision department in the operation of the management system of Cultural and Creative Industrial Park is essential, whether it is the internal supervision organization of the enterprise or the external supervision organization of the government or the social supervision organization. The internal decision-making mechanism refers to the supervision and governance mechanism for the internal development of enterprises or parks to monitor and manage the personnel, financial data, revenue, and expenditure data, while the external supervision mechanism refers to the mechanism for the government and social organizations to evaluate and supervise the development data of Cultural and Creative Industrial Park. The distributed data storage of blockchain provides convenient, reliable, and tamperable basic data for supervision information, which can change the inefficiency and information asymmetry of traditional supervision mechanisms.

5. Conclusion

(1) The "decentralization" concept of blockchain can provide guidance value for the management concept innovation of Cultural and Creative Industry Park, and the embedding of technologies such as smart contract, distributed ledger, and digital currency can promote the construction of "programmable Cultural and Creative Industry Park management system."

(2) The Cultural and Creative Industry Park introduces Blockchain 3.0 technology to carry out management innovation along the path of structure, function, and application. The architecture of the consensus layer, network layer, and data layer of the blockchain is not only the hierarchical structure of the blockchain of the park but also provides a support platform for the management informatization of the park. The functional system construction of public chain, alliance chain, and private chain provides support conditions for the lean management of the park. IP copyright management, enterprise/institution management, industrial chain management, government supervision management, and other activities provide clear application scenarios and management innovation direction for blockchain being applied in the park.

(3) The blockchain in Cultural and Creative Industry Park constructs the system architecture through consensus layer, network layer, and data layer. The consensus layer of the blockchain in the park enables the main bodies of the park to establish a consensus on the operation of the park through joint efforts, and the management and technical means such as "consensus mechanism" and "intelligent contract"

are used to guarantee the management activities. The network layer constitutes the basic carrier of the blockchain of the park and becomes the technical means to realize the management activities of the park. The role of the data layer is to provide data basis for the realization of the digital sharing economy in the park by establishing decentralized cloud storage.

(4) Different levels of blockchain in Cultural and Creative Industry Park can promote different levels of management innovation. The public chain can solve the problem of information asymmetry in the park from the strategic level, cultivate an efficient self-organization management system, and promote the integration and upgrading of the industrial value chain in the park. Alliance chain can provide a mature and reliable data sharing system for organization operation, eliminate the credit barriers between enterprise nodes, and build an efficient value exchange system and evaluation system. Private chain mainly provides data sharing, credit guarantee mechanism, and technical services for enterprises and teams at the microlevel.

(5) Cultural and Creative Industry Park can implement management innovation through blockchain construction and its combination with the park management system. The blockchain of the park is constructed and operated based on consensus mechanism, intelligent contract mechanism, connection mechanism, communication mechanism, verification mechanism, and other mechanisms. Through the mutual embedding and collaboration between the blockchain information platform and the park management system, it supports the park to implement management innovation.

Data Availability

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

Conflicts of Interest

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

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Research Article

Investigating the Complex Relationship between Financial Performance and Company's Green Behavior: A Comparative Analysis

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Under the new normal of economy, the relationship between economic benefits and company's environmental behavior (green behavior) has long been the focus of scholars' research, but less attention has been paid to the effect of financial performance on company's green behavior in China as a developing country. Thus, by adopting a mixed methodology, we conduct a quantitative study by selecting 228 companies as samples with good and poor green behavior for comparative analysis, followed by a qualitative study of 20 specific cases, to analyse the complex relationship mechanism of how financial performance in terms of business solvency, profitability, and development ability affect company's green behavior. The results indicate that business solvency, profitability, and development ability are strongly associated with company's green behavior, respectively. This study contributes to the green behavior literature.

1. Introduction

In recent years, green development has become an important issue of companies given the growing public concern for environmental protection issues [1, 2]. As the most important participants in economic activities, companies tend to ignore environmental pollution while actively pursuing economic benefits. They will be alert to environmental protection only when problems arise. So, is economic benefit necessarily contradictory to company's green behavior? In fact, there has been no answer given to this issue.

Extant studies try to elaborate the relationship between corporate financial and environmental performance and its nature in mature market economies from various theoretical perspectives [3]. For instance, drawing on the resource-based theory, Wu et al. evidenced that a firm's sustainable efficiency and competitive advantage rely on its capabilities and diverse resources which cannot be replicated by its competitors [4]. Utilizing the stakeholder theory, El Ghoul et al. believed that a firm who has better corporate environmental performance is provided with a lower cost of capital since it decreases business risk by forming stakeholder satisfaction and goodwill [5]. In addition, most other studies concentrate on unidirectional causality of measuring the impact of corporate environmental performance on financial performance [3, 6]. However, slack resource theory suggests that business organisations can opt for better environmental performance if their resources available are abundant. That is because improving environmental practices is costly, so some companies have to ensure first their financial situation before inputting resources in efficient environmental practices. Consequently, causation in such a situation suggests improved financial performance results in better corporate environmental behavior [3].

Furthermore, more attention has been paid to the studies of corporate environmental behavior and green behavior. Yu and Zhu [7] analyzed the influence of policy mechanisms, public preferences, and profit motives on the implementation of positive environmental behavior by companies. Zhou [8] constructed a functional system inclusive of corporate environmental behavior, its driving force, and its performance, in a way to quantitatively illustrate the path and effect of different factors that affect corporate environmental behavior, and pointed out the fact that this behavior is beneficial to improving corporate performance. Meanwhile, corporate green behavior refers to an activity or a series of positive plans conducted by companies in terms of resources and environmental protection, which is equivalent to environmental behavior in connotation. Different scholars have explained that stakeholder pressure promotes corporate's green behavior by affecting the implementation of corporate forward-looking strategies. For example, Greenley and Foxall [9] first proposed the concept of stakeholder orientation and perfected the stakeholder orientation model with Europe as the background on the basis of market orientation and argued that stakeholder orientation is an important choice for companies to promote environmental protection. Schaltegger et al. [10] examined that the effective participation of stakeholders in monitoring corporate environmental behavior can prompt companies to respond positively to environmental issues.

In spite of the above academic achievements, there is no consistent conclusion that clearly answers the questions raised above, with little attention paid to the impact of financial performance on corporate's green behavior. Given that financial performance determines the arteries and veins of economic development, it will inevitably promote or restrict the development of corporate green behavior, so this study reveals the internal complex mechanism of how financial performance affects company's green behavior. Specifically, this study employs the support vector machine (SVM) as the mathematical measurement model as it has been generally used in researches dealing with financial indicators due to its good judgment confirmed on the performance of financial indicators [11, 12]. By adopting this mathematical measurement model, taking companies with good and bad green behavior as samples for a comparative analysis, this article selects three financial indicators of business solvency, profitability, and development ability as they are key measures to represent companies' economic level and operating status, thereby revealing their complex relationship with company's green behavior because environmental management in developing counties is less mature than in developed countries [13].

This article is organized as follows. The following section discusses theoretical hypotheses and a mathematical measurement model, followed by research methodology and data analysis and results. Further, this article provides the discussion and conclusion in terms of key findings and implications for theory and practice.

2. Theoretical Hypotheses

In this section, we develop arguments for hypotheses about the complex relationships that tap into environment, economy, and society aspects among variables.

2.1. Business Solvency and Green Behavior. Business solvency is a company's ability to repay short-term and long-term debts with its assets and is an important symbol to reflect the company's stable financial conditions and operating ability. Moreover, the strength of business solvency is taken as an important yardstick to measure financial status and economic power [13]. The company with strong business solvency will be more favoured by insurance companies and other financial companies if it effectively implements environmental management behavior [14]. From the angle of economic and environmental benefits, Khanna [15] pointed out that many current assessment agencies incorporate environmental protection policies and company's environmental behavior into the scope of risk assessment. Then, company's environmental expenditure behavior makes for attracting external investors to expand the size and strength of the economy and thus generate positive effect to their development. In other words, the company with strong solvency engaged in green behavior can help reduce financing cost and broaden its chance of development [16].

In other words, economic ability is increased; then, it will naturally enhance the company's business solvency, so that the company is more willing to engage in different environmental practices to establish favourable relationship with stakeholders (e.g., suppliers, distributors, and customers) by addressing their environmental concerns. From the angle of social and environmental benefits, the company with strong business solvency usually has stable operation ability and can timely repay the loans owed when funds are returned. It has prestige and credibility in stakeholders. Such a company has a sense of social ethics and pays attention to maintaining a positive corporate image. Therefore, it will actively implement green practices to safeguard the welfare of the society where people live.

With the deepening of environmental protection behavior, such companies will gain more and more social recognition, including a variety of financial institutions and partners, which is conducive to improving the company's financial indicators and improving its solvency. Following that, we believe the company with strong business solvency can gain stronger competitive advantage in environmentally friendly protection with a result of financial and social performance improved. Therefore, we propose the following hypothesis:

> H1: business solvency is strongly associated with company's green behavior.

2.2. Profitability and Green Behavior. Profitability is understood as the capital or capital appreciation ability manifested usually as the level and amount of company's earnings in some period, so it is defined as a company's ability to gain profits [17]. The company with strong profitability usually produces products or provides services that are loved by consumers and win broad market recognition and wins consumers' increasing recognition of green products. Nowadays, as citizens' awareness of social responsibility and safety improves, consumers are increasingly advocating green consumption; thereby, they would like to pay environmental protection premium for products that have fulfilled their environmental responsibilities [18].

In order to further gain more market share, the company's profitability can impact the investment of environmental initiatives with better financial status as such companies enable better environmental initiatives than that with poor status [19]. The company with high profitability will pay more attention to reducing environmental pollution and thus will increase investment in equipment and technology and strategies, shifting attention to pollution prevention and control in the production process; doing such can realize energy conservation and emission reduction and reduced costs and facilitates effective improvement in green productivity; in this sense, the company is more willing to nurture green behavior and also improve the company's profitability by more tangible economic returns acquired.

Additionally, the company with strong profitability is a large-scale company with certain scale, whose organizational atmosphere is created to promote employees' green behavior. Specifically, the company invests in environmental protection budget to launch employee training programs and research and development activities with regard to environmental issues and forward the company's green behavior. Such a company takes the initiative to assume environmental responsibility and sets up a good reputation on the society, in a way to reduce the possibility of pollution incidents and decreasing additional expenditures incurred therefrom [20]. As the company with strong profitability inputs more energy in environmental protection actions, it will gain more environmental and social benefits and competitive advantage. Therefore, we propose the following hypothesis:

> H2: profitability is strongly associated with company's green behavior.

2.3. Development Ability and Green Behavior. Development ability is a company's potential ability to extend its strength and scale, known as growth ability. It is also called the company's growth, referring to the development potential created by continuous accumulation and expansion of the company's operation and production activities [21]. While the company with development ability pursues economic profits, it will focus on building the company's social image and thus have a sense of social responsibility to comply with social ethics and order, from which the company can be more trusted by its partners and remembered by the mainstream market, thus leading to willingness to protect environment. Under such conditions, it will receive peers' social valuable resources and will increase efforts to energize environment-oriented production and process, which assists the company to save energy, reduce emissions, improve efficiency, decrease environmental costs, and achieve sustainable development; thereby, it will continuously enhance its competitive advantage in the long run and promote its more willingness to engage in green behavior in turn.

Furthermore, the company with development ability pays more attention to team building within the organization and form an environment-oriented cultural atmosphere. Environmental orientation is deemed as a critical respect of environmentalism [20] that presents the extent to which the company gets involved in overcoming environmental degradation [22]. In such a cultural atmosphere, the idea of environmental protection is embedded in daily routines of employees, and to promote employees to assume environmental responsibility with positive attitude, encourage employees' full participation in environmental protection activities where their environmental behavior is fostered [23]. Moreover, such a behavior will contribute to shaping an environmentally friendly image for the company on the society, expanding market share to increase sales, and giving rise to better profits eventually; thereby, it is beneficial to enhance the company's development ability. Thus, we propose the following hypothesis:

> H3: development ability is strongly associated with company's green behavior.

2.4. Mathematical Measurement Model. According to statistical learning theory, support vector machine (SVM) is a method to optimize learning performance by adopting the idea of structural risk minimization. Its basic idea is to nonlinearly transform input data by means of kernel function, map input space to a space of high-dimension, and then receive optimal classification hyperplane in a space of high dimension. In fact, samples in classification problems are more easily separated in an accurate manner in high-dimensional space than in low-dimensional space, which explains why support vector machine is easier to solve classification problems. Since data of financial indicators is spatially distributed in a very complex way, support vector machine is good at processing such data distributed spatially and complexly and is often used in the studies related to financial data [11, 12]. Therefore, this article uses support vector machine as a judgment model to process financial index data and judge whether a company has green behavior. Support vector machine is a generalized linear classifier to carry out binary classification of data by means of supervised learning. Its classification form for a given dataset is

$$f(x) = \langle w, \phi(x) \rangle. \tag{1}$$

By adopting the regularized risk generalization principle, it can be obtained that

$$R(w) = \frac{1}{2}\|w\|^2 + C\sum_{i=1}^{m} L\left(f(xi), y_i\right), \tag{2}$$

where C is the penalty coefficient, L is the loss function, and its expression is

$$L(f(x), y) = \max\{|f(x) - y| - \varepsilon, 0\}. \tag{3}$$

By minimizing $R(w)$, we can get

$$w = \sum_{i=1}^{m} \left(\alpha_i - \alpha_i'\right) \cdot \phi(x_i), \tag{4}$$

where α_i, α_i' are Lagrangian multipliers.

By substituting w into equation (1), the following equation can be obtained:

$$f(x) = \sum_{i=1}^{m} (\alpha_i - \alpha_i') \cdot \langle \phi(x_i) \cdot \phi(x) \rangle = \sum_{i=1}^{m} (\alpha_i - \alpha_i') \cdot k(x_i, x) + b, \tag{5}$$

where σ is the kernel function. In this article, the Gaussian kernel function is employed, and its expression is

$$K(x_i, x) = \exp\left(\frac{-\|x_i - x\|^2}{2\sigma^2}\right), \tag{6}$$

where σ is an adjustable parameter of Gaussian kernel function and $\|x_i - x\|$ represents the distance between two sample points.

2.5. Research Methodology. A mixed methodology is preferable in this study to clarify our understanding of the complex relationship mechanism of constructs. Quantitative and qualitative methods combined are ideal to generate clearer understanding of the mechanism that underlie quantitative outcomes in at least new territory partially [24]. Moreover, this approach is expected to help corroborate the results of both quantitative and qualitative analyses [25], in a way to provide better findings and improve reliability and validity [26]. The quantitative Study 1 is applied first to confirm the hypotheses and then followed by the qualitative Study 2 to explore selected cases.

3. Quantitative Study 1

3.1. Sample and Data Collection. Taking the concept of green behavior into account, this study selected samples according to the "List of Leading Central Enterprises in the Field of Energy Conservation and Environmental Protection" published by China Enterprise News. It considered companies which have achieved good green behavior effect in environmental protection by employing low-carbon and green production processes and transportation as green samples, involving high-tech companies in energy-saving and environmental protection, new energy, aerospace transportation equipment, and communication and electronic equipment industries, and then, 114 companies were selected from companies listed on Shanghai and Shenzhen stock markets.

In view of the range of samples selected, this study chose 114 manufacturing companies listed on Shanghai and Shenzhen stock markets in a ratio of 1 : 1 in areas of petroleum processing, coal mining, and chemical products as control samples, which were on the blacklist issued by the Ministry of Environmental Protection as a result of their poor green behavior in energy conservation and environmental protection. The data came from CSMAR database of Guo Tai'an and the CCER economic and financial database of Xenophon. By using the data of 14 financial indicators of business solvency, profitability, and development ability released from the 2019 annual report, we constructed a preliminary sample indicator system. The financial indicators are specifically reported in Table 1.

The prerequisite for judging financial indicators a company should have for good green behavior is that there must be significant differences in financial data. This study employed the t-test to perform significance testing for initial financial indicator system of all samples, with test results shown in Table 2. It was found that debt-to-tangible assets ratio (X_4) failed the test at the level of 5%, so that this variable was deleted. Additionally, other 13 financial indicators have all passed the test. To this end, this study selected 13 financial indicators as the final sample indicator system.

3.2. Experimental Design. This study aims at analyzing the complex relationship between financial performance and company's green behavior. Relying on the hypotheses proposed, financial indicators of business solvency, profitability, and development ability were gradually brought into the model to verify their accuracy and distinguish company's behavior. That is to say, first, one financial indicator of business solvency, profitability, and development ability was selected and put into the model, respectively, to calculate its judgment accuracy. Second, any two financial indicators out of business solvency, profitability, and development ability were selected to build a dataset, and then the dataset was put into the model to calculate the accuracy of its judgment. Finally, the data of all financial indicators was brought into the model to calculate the accuracy of its judgment. The results were compared and analyzed to determine the validity of financial indicators in judging if the company has green behavior.

For binary classification, it is easier to obtain optimal separating plane in the higher-dimensional feature space, while the core idea of SVM is to build an optimal separating hyperplane to enhance classification accuracy without complex mapping rules. Hence, we ultimately adopted Gaussian RBF Kernel as a kernel function after a series of experiments because of its best prediction results. Regularization parameter C and kernel parameter G are two important parameters set as 1. SVM model is described in detail in Table 3. In addition, by using a ten-fold cross-validation method for model training and verification, this study compared the optimal judgment results with MATLAB2015b as a tool for modeling analysis.

3.3. Evaluation Indicator Design. Three evaluation indicators referring to recall, precision, and accuracy were applied to compare the pros and cons of models. It was assumed that the company with good green behavior was marked positive value while the company with poor green behavior marked negative value. Specifically, the expressions of those three indicators were presented as follows:

Table 1: Initial financial indicator system.

Type	Financial indicators
Business solvency	Current ratio (X_1); quick ratio (X_2); equity ratio (X_3); debt-to-tangible assets ratio (X_4); cash coverage ratio (X_5)
Profitability	Net profit rate of total assets (X_6); return on equity (X_7); cost and expense ratio (X_8); return on total assets ratio (X_9); operating profit ratio (X_{10})
Development ability	Growth rate of main income (X_{11}); growth rate of total assets (X_{12}); growth rate of net profit (X_{13}); sustainable growth rate (X_{14})

Table 2: t-test of financial indicators.

Financial indicator	X_1	X_2	X_3	X_4	X_5	X_6	X_7
t value	14.831	13.437	9.672	1.022	10.310	20.883	20.113
P value	0.000	0.000	0.000	0.308*	0.000	0.000	0.000
Financial indicator	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}
t value	17.579	16.814	14.748	5.822	2.921	7.130	14.347
P value	0.000	0.000	0.000	0.000	0.004	0.000	0.000

Note: *significance at the level of 5%.

Table 3: The parameter settings of SVM.

Kernel function type	Regularization parameter C	Kernel parameter G
Gaussian RBF kernel	1	1

$$
\begin{aligned}
\text{recall} &= \frac{\text{TP}}{\text{TP} + \text{FN}},\\
\text{precision} &= \frac{\text{TP}}{\text{TP} + \text{FP}},\\
\text{accuracy} &= \frac{\text{TP} + \text{TN}}{\text{TP} + \text{FN} + \text{FP} + \text{TN}},
\end{aligned}
\tag{7}
$$

where true positive (TP) stands for the number of positive samples that were classified as positive correctly, false negative (FN) for the number of positive samples that were misclassified as negative, false positive (FP) for the number of negative samples that were misclassified as positive, and true negative (TN) for the number of negative samples that were classified as negative correctly. All variables are reported in Table 4.

3.4. Quantitative Analysis and Results. As described in experimental design, we first divided the data of financial indicators into 7 datasets, named Datasets 1 to 7. Among them, Datasets 1 to 3 contain one of three financial indicators out of business solvency, profitability, and development ability in sequence, respectively, wherein Dataset 4 involves the data of business solvency and profitability, Dataset 5 consists of the data of business solvency and development ability, Dataset 6 includes the data of profitability and development ability, and Dataset 7 covers the data of 13 financial indicators in terms of all indicators. After conducting many experiments, the SVM model with radial basis kernel function was capable of obtaining optimal judgment results. Thus, this study adopted it as the judgment model, and then 7 datasets were taken into the SVM model.

Table 4: Meaning of four variables.

	Classified positive	Classified negative
Actually positive	TP	FN
Actually negative	FP	TN

The results of Datasets 1 to 3 are presented in Table 5; results of Datasets 4 to 6 are presented in Table 6. Table 7 reports the mean values of Dataset 7 and the first two groups.

Comparing the results in Table 5, three types of financial indicators were put into the model, respectively, and the results obtained were very similar. Three indicators of Dataset 2 were similar, of which accuracy was the best, with a value of 67.35%. The results of these comparisons are shown in Figure 1. The mean values of three financial indicators were calculated to be 69.44%, 62.75%, and 64.63%, respectively. Then, comparing the results in Table 6, the results of Datasets 4 to 6 were very similar, but they were all better than the results of the first three datasets.

Among the results of Datasets 4 to 6, the best one is Dataset 4, whose accuracy was 81.63%. These comparative results are shown in Figure 2. The mean values of these three datasets were 79.17%, 76.25%, and 77.55%, respectively. Last, we compared the mean values of the first two kinds of data with the results of Dataset 7 (all data of financial indicators), as shown in Table 7, the prediction result was the best regardless of which indicator, namely, 95.83%, 82.14%, and 87.76%, respectively. This is also shown in Figure 3 that the column of each indicator is the highest. From these judgment results, we can make it clear that each type of financial indicator can be used to judge whether the company has green behavior; it will achieve better result if the company's green behavior is rated through combining these three types of financial indicators.

3.5. Brief Discussion. In the quantitative Study 1, the experimental results are consistent with the hypotheses proposed, but to further explore why, this study conducted a number of follow-up interviews with typical enterprises with

Table 5: Results of SVM model for Datasets 1–3.

Dataset	Recall	Precision	Accuracy
Dataset 1	70.83	62.96	65.31
Dataset 2	66.67	66.67	67.35
Dataset 3	70.83	58.62	61.22
Mean 1	69.44	62.75	64.63

Table 6: Results of SVM model for Datasets 4–6.

Dataset	Recall	Precision	Accuracy
Dataset 4	79.17	82.61	81.63
Dataset 5	75.00	69.23	71.43
Dataset 6	83.33	76.92	79.59
Mean 2	79.17	76.25	77.55

Table 7: Results of SVM model for Dataset 7 and mean values.

Dataset	Recall	Precision	Accuracy
Dataset 7	95.83	82.14	87.76
Mean 1	69.44	62.75	64.63
Mean 2	79.17	76.25	77.55

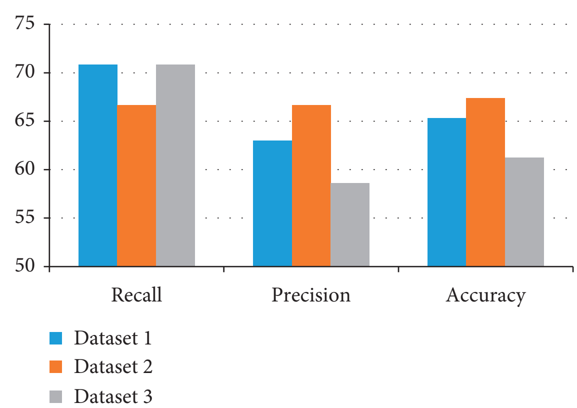

Figure 1: Comparison of judgment results among Datasets 1–3.

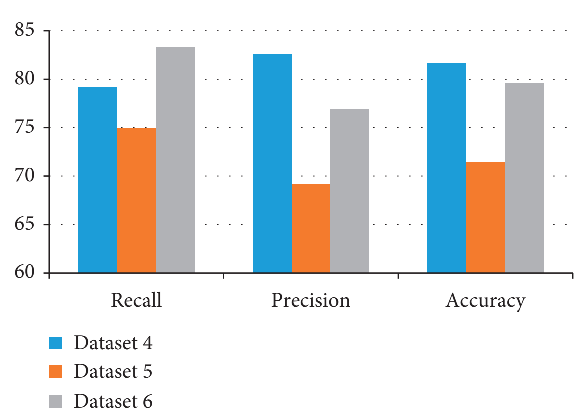

Figure 2: Comparison of judgment results among Datasets 4–6.

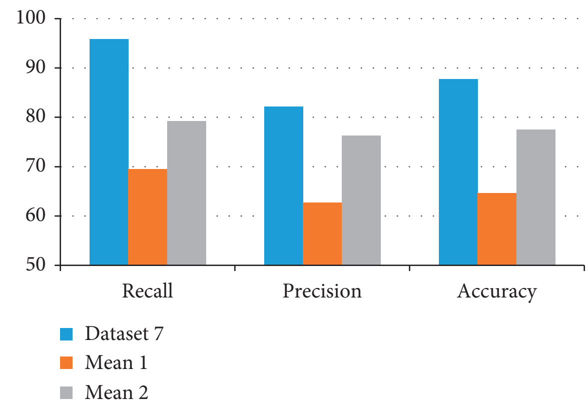

Figure 3: Comparison of judgment results among Dataset 7 and mean values.

good or bad green behaviors in different industries to investigate the underlying mechanism of the above relationships.

4. Qualitative Study 2

4.1. Sample and Data Collection. In the qualitative Study 2, this article adopts a case study approach to reveal the relationship mechanism linking financial indicators and company's green behavior. In order to conduct in-depth comparative analysis, this study selected 64 employees of ten enterprises (A^+–J^+) with good green behavior on the "List of Leading Central Enterprises in the Field of Energy Conservation and Environmental Protection" and 61 employees of ten enterprises (A^{-}–J^{-}) with bad green behavior on the blacklist as final interviewees. We chose senior executives, managers, and employees primarily involved in environmental practices, with an assistance of documentation of those cases. By applying nonstandardized interviews (semistructured and in-depth), we gathered better replies to "why" issues in case study. The departments involved referred to finance, strategic planning, intelligence and standardization, and general management. Each interview lasted 1.5 to 2 hours.

4.2. Data Analysis. Following data analysis of Miles et al., we began our study with a specific thematic analysis of interview transcripts, from which we identified common categories compared to those constructs included in our theoretical model. Followed by a second-cycle coding for identifying patterns, our initial coding was conducted with analysis of every case, so as to capture all expressions of phenomena and explain them in view of extant concepts, i.e., financial indicators and green behavior. Codes regarding the impact of financial indicators on green behavior emerged via a continuous comparison between data newly gathered and that collected previously and their coding. Then, coding deductively began with reviewing extant literatures on financial indicators and green behavior and then extended into inductive interpretation according to additional information given data of interviews and display of all findings [27]. Categories were formed and refined after the association between text coded previously, and codes created newly were checked. Emergent codes and connections among all categories give rise to variables identified, such as three dimensions of financial indicators, and their interpretation of data of interviews caused reoccurring patterns identified, resulting in green behavior process. Data collection, data analysis, and conceptualization process were constantly overlapped [28] until the relationship between concepts emerged and reached theoretical saturation. Further, to avoid potential bias of respondents, our study put emphasis on both narrative openness and guarantee of problems to be accurately presented.

4.3. Qualitative Analysis and Results. The findings indicated that respondents from companies with good green behaviors agreed that all three financial indicators were associated with their respective corporate green behaviors, as shown in Table 8. Otherwise, for companies with bad green behaviors, these three financial indicators had relatively weak effects on the development of their green behaviors. From the interviews, it was also learned that three financial indicators promoted the development of companies and their environmental protection behaviors, for the reason that when a company's financial situation was good, it would pay more attention to corporate social responsibility and social image and would further develop environmental protection behaviors; second, a company's good financial status signified that it could win profits only if its products were sold well on the market, so that the company would like to develop environmentally friendly products and take active green measures, thereby being more willing to perform environmental protection behaviors.

In business solvency, companies with strong business solvency were more likely to be favored by financial institutions due to their stable operation, economic power, good reputation, and financial status and hence, they were more motivated to foster green behaviors. In companies with good green behaviors, respondents all believed business solvency has an impact on company's green behavior, because it is to manifest a company's economic strength so that the company is confident to mobilize long-term and short-term funds to ensure sound business development. It is understood the stronger the solvency is, the enhanced ability the company has to operate steadily. For instance, interviewees in Company E^+ pointed out that their company quickly received financial support from partners for an aim of launching a large technology development project, which is beneficial to the production of new green products. Interviewees in Company B^+ explained that their company emphasized social reputation and corporate image, so it is often a foregoer in environmental protection. Otherwise, in companies with bad green behaviors, interviewees believed to fail to get loans or receive any other investments, or their company was not operated well with low business volume and capital flow, so it did expose disadvantages in business solvency. Hence, they had no money to engage in environmentally friendly product development, and even there would be no time for green behavior.

In profitability, respondents thought that their company had strong profitability, good financial status, and good reputation in society and catered to consumers' demand for green products, so they had initiative to invest in green productivity. In companies with good green behaviors, interviewees were unanimous that the more profitable the businesses were, the more they would strengthen green behavior to give back to the society. Interviewees in Company C^+ argued that the increase in profitability led to investing more in environmental protection and optimizing green behavior. For example, increasing utilization rate of green resources is to indirectly decrease corporate pollution control costs and potential fines. Interviewees in Company F^+ put forward that all companies underlined the development of green products. The greener the products, the higher the sales, then the more increased the revenue, so that their company would be more willing to invest in practices for green behavior.

In companies with bad green behaviors, interviewees made a point that their company had no instant abilities to carry out green behavior due to low profits available and wage coefficient turned down. Interviewees in Company B^- indicated that environmental cost accounts for higher proportion in total manufacturing cost, which decreased their profit margins and ultimately led to competitive disadvantage. In this sense, their company would not like to increase environmental input as it was considered an additional cost. Interviewees in Company I^- described that if they increased the investment in human, material, and financial resources in environmental protection, this would inevitably affect their company's operations and distribution of revenue.

In development ability, respondents mentioned that they laid emphasis on cultivating their own long-term development potential and social and environmental responsibilities, on delivering green development concept to employees within the organization, and thus indoctrinating them with environmental ideas. In companies with good green behaviors, interviewees explained that green development was required by an objective of current social and economic development. Sometimes, companies that had long-term and promising development insisted on facing up to environmental protection issues, so they would be willing to perform green behaviors voluntarily. Interviewees in Company I^+ believed that their company with strong development ability was willing to give back to the society and consumers, so they had a sense of social responsibility, including environmental protection and social ethics. Accordingly, they would like to have green behaviors. In companies with bad green behaviors, interviewees suggested that their companies had less development ability, sometimes in lack of money or resources to develop green behaviors, so it caused less benefits obtained. Interviewees in Company J^- mentioned that their company was criticized by name and received a fine because of their improper waste disposal a while ago. Interviewees in Company C^- emphasized that their company's development ability was not

Table 8: Evidence from data illustrating major relationships between financial indicators and company's green behavior.

Typical quotes from interviews			Insight
Business solvency	Companies with good green behaviors	"Business solvency is often a key factor in measuring a company's reputation in society, standing for credibility in society. The company with strong business solvency tends to take good care of their reputation, so they will actively participate in green practices." (Company E^{+}) "The company has strong business solvency, implying that it has the ability to repay debt, has economic development potential, and will also establish green behaviors to enhance trust between partners." (Company C^{+}) "Our company has no debts in arrears, but has stable and good operating efficiency, and has a high reputation in the industry. It is well known that our company is a role model in green behavior area, and is the first to apply many environmental protection measures." (Company G^{+})	Business solvency is strongly associated with company's green behavior in terms of its favor by financial institutions, stable operation, economic power and financial status, and good reputation.
	Companies with bad green behaviors	"The company that has long-term debts must be the one in poor financial condition. Such a company often has poor prospects, so that it will think more about their own interests rather than their contributions to environmental causes." (Company B^{-}) "Our company has been good in green practices before, and has invested a lot in the development of green innovative products, but recently some problems have occurred in capital chain, causing debts not to be repaid in time, so green products developed have to be terminated, which hinders our green behavior." (Company D^{-}) "Our company has been busy with product development in large-scale heavy industry, so we have debts not repaid as there has been no return of funds before we sell our products out, I am afraid we have no power to care about green behavior. (Company C^{-})	

Table 8: Continued.

Typical quotes from interviews			Insight
Profitability	Companies with good green behaviors	"Our products have a high reputation in society and are sold profitably. Only by internally digesting environmental protection costs can we ensure the orderly development of our market share, so we have the ability to perform green behaviors." (Company A^+) "Profitability represents a company's financial status and is positively related to environmental performance, and economically supported, we have incentives to reduce environmental damages." (Company I^+) "With good profits, we have the energy to focus on green behaviors, such as adjusting green product structure and upgrading industrial structure, because environmental protection activities can increase corporate revenue, such as converting waste into reuse, or even turning it into products for sales. These green products bring additional benefits to our company." (Company B^+) "Profitability is of course an issue that affects the company's environmental responsibilities. The company with strong profitability usually has large-scale, wide market coverage, and great impact, so it should be most aware of environmental impact of their operations and should actively take actions to bear corresponding environmental responsibilities." (Company D^+)	Profitability is strongly associated with company's green behavior in terms of its good reputation, financial status, initiative to invest in green productivity, and social and environmental responsibilities.
	Companies with bad green behaviors	"In order to solve external environmental problems, the company will inevitably have capital investment, which can reduce its operating profits. Thus, we have not carried out green behaviors." (Company F^-) "Because of limited profitability, we have not paid too much attention to technological innovation to produce green products and meet the growing green demand of consumers, resulting in a decrease in market share." (Company H^-) "Our company's profits are not good enough. Survival is our top priority. We have the willingness to perform green behaviors but our real strength does not allow us to do so. We are more concerned about expanding market and improving business development, so we rarely take into account green behavior." (Company E^-)	

Table 8: Continued.

Typical quotes from interviews			Insight
Development ability	Companies with good green behaviors	"Our development prospects are very optimistic, we have always had a sense of social and environmental responsibilities. We have a good image in society and are willing to set an example in environmental protection decisions and behaviors." (Company H^+) "From a long-term development perspective, it is an inescapable responsibility for our company to participate in environmental protection practices. Therefore, we decompose the performance of green behaviors within the company and distribute it to every employee, so that everyone is responsible for green behavior." (Company I^+)	Development ability is strongly associated with company's green behavior in terms of its social and environmental responsibilities, long-term development potential, and providing environmental ideas to employees.
	Companies with bad green behaviors	"Our company has relatively weak development ability, for those with strong abilities, they are obliged to return to the market and to the society with healthier and green products, but we have not done enough at this point." (Company D^-) "The development prospects we face and our existing development ability limit our vision for future development in every respect. For us, following the original supply chain activities will bring us the same benefits as before, but we are also trying to change to cater to environmental protection. but it is impossible to achieve rapid change of concept in a short period." (Company A^-) "Our development ability has not yet made it possible for us to immediately focus on the development of green behavior, because this requires a transformation from the inside to the outside. First, our company has not set off such a green atmosphere to employees. Second, we have no suppliers to provide environmentally friendly resources. These may be determined by our original heavy industry development route." (Company G^-)	

prominent, they were weakly aware of obligation and responsibilities for future development, and thus, that was the reason that they were unable to actively perform green behaviors.

4.4. Brief Discussion. In Study 2, the results are consistent with those in Study 1, verifying H1, H2, and H3. More importantly, the longitudinal case studies revealed new findings of the underlying relationship mechanism between variables, as depicted in Figure 4. The frame reports that three financial indicators have different influences on company's green behaviors through diverse channels and also, to adapt to the development trend of the times, companies actively start green activities to implement green behaviors and meet green needs of stakeholders so as to win their support, this is conducive to companies' long-term construction of competitive advantage as their green strategic objectives will provide them with a large number of business opportunities. For example, in this case, some profitable companies that embarked money in pollution-reducing processing equipment achieve competitive advantages; by means of brand recognition and customer loyalty, they can perfect their products towards higher quality of environmental protection, decreased pollution to the environment, and balance of the relationship between corporate economic benefits and the environment. Hence, these companies will keep sustainable competitive advantages in the long run.

In a similar way, when companies undertake a series of environmental management measures to upgrade the quality of environmental assets for production in supply chain, all moves satisfy market value conditions with unique, irreplaceable, and nonimitable green products, thus

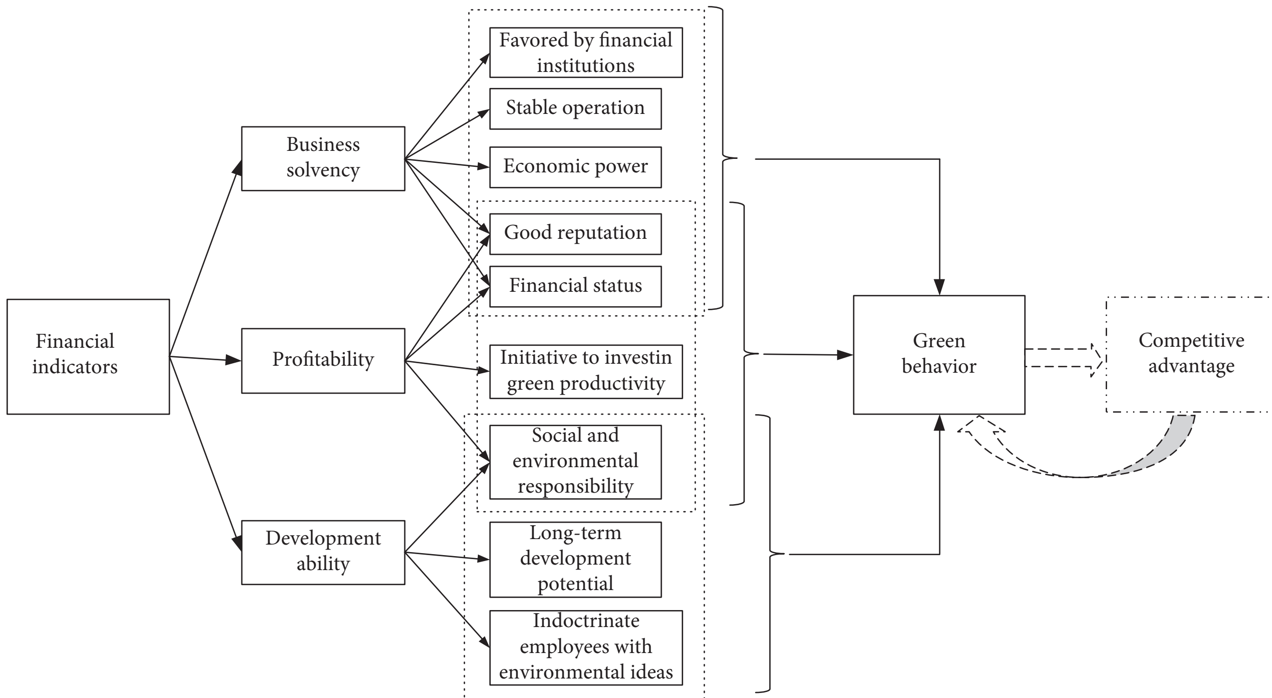

Figure 4: The relationship mechanism between variables.

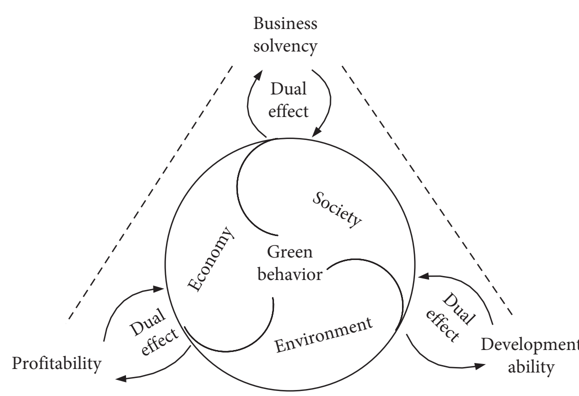

Figure 5: Dual effect among variables.

improving companies' three financial indicators in diverse ways in turn. Finally, it secures green behavior quality and elevates it to a higher level.

5. Discussion and Conclusion

This article adopts the mixed methodology to investigate the complex relationships mechanism between key financial indicators and company's green behavior with a sample of companies with good or bad green behaviors for a comparative analysis. The results show that business solvency, profitability, and development ability are strongly associated with company's green behavior, respectively.

The three financial indicators selected in this article are all key indicators of corporate financial status, reflecting enterprise development and operational stability. This study analyses their impact on company's green behavior from different perspectives. The findings of this study are in line with the existing research trend that a company's financial status affects whether it is engaged in environmental protection and development [23], implying that companies will be committed to engaging in environmentally responsible and economical operations while acknowledging stakeholders' interests and will, and also, to improve company's reputation; companies will take efficient advantage of resources to lower raw material costs and reduce possible pollution costs and fines. This confirms to the result that when companies consider environmental protection incidents in the long run, they will deliver environmentally friendly products to customers, so that they can increase market share and/or charge higher price for their products [15]. From this, companies' environmental protection or green behavior will become a potential source of corporate competitive advantage [29, 30].

Combined with the findings of this study, it can be found that our results show a dual-effect relationship between financial performance and corporate green behavior. Specifically, when companies are in pursuit of better environmental practices, their brand profile and social image will be raised up to let them be trusted by more stakeholders in the society and further, they will take more social responsibilities and realize higher work efficiency for consumers and for their economic benefits. As a result, our findings also demonstrate the bidirectional and cyclical relationship effect among environment, society, and economy, as shown in Figure 5. This is in line with existing researches. For example, Walter [31] and Woolman and Veshagh [32] believed that environmental and economic benefits can be effectively integrated. Our findings also broaden the dimensions of their relationship among environment, economy, and society rather than the prior two.

In summary, through the circular effect depicted in Figure 5, as corporate competitive advantage or financial performance can be improved sustainably, it will inevitably intensify the driving force of green behavior and improve its quality. In this way, our findings corroborate the studies of Abdul and Mohammad [19] who argued that financial development stimulates environmental quality and environmental development in different countries.

5.1. Theoretical Implications. Our study has several theoretical implications to the extant literature; in particular, it makes up for deficiency of most studies that are only conducted in developed countries [13]. As environmental problems become global in scope and environmental management in companies is getting more attention in developing countries, our results first contribute to the green behavior literature by applying a mixed methodology to investigate the complex relationship mechanism between financial performance and company's green behavior with a comparative study, wherein support vector machine which has good performance to process financial indicators is used as a mathematical model method in the quantitative study.

Second, this study extends the green behavior literature by examining the impact of financial performance on corporate green behavior/environmental behavior as currently many scholars have investigated how firms are financially rewarded for improving environmental behavior [33]. Specifically, our study differentiates how business solvency, profitability, and development ability affect company's green behavior based on environment, economy, and society perspectives. Hence, our findings complement the sustainability literature that has been discussed recently as a cross-sectional character, following the socioeconomic trend of sustainable development [34].

Third, this study contributes to the green behavior literature by extending the researches regarding financial development-environmental quality [19] and by providing an additional proof to debate on the effect on financial development on environmental quality [34]. More specifically, our findings reveal environmental quality can be improved ultimately after the driving force of green behavior is intensified by financial indicators or by competitive advantage resulting therefrom. Our findings confirm the conclusions that believe financial development is able to promote environmental development and quality [35, 36], but are contradictory to the studies insisting on no effect between them [37, 38].

5.2. Practical Implications. The findings of this study have several practical implications for managers in companies that pursue green behaviors. First, our results show that business solvency, profitability, and business ability are major drivers of company's green behavior, leading to environmental quality improved in dual ways. Companies can emphasize the complex two-way relationship to improve environmental development while pursuing economic interests. Second, our study takes into account the integration perspectives of environment, economy, and society, so companies can make more effort in assuming responsibility for environmental protection with an increase of investment in green practices, because they can prevent from suffering negative exposure by media, penalties fined by government, and shareholder boycotts, but also achieve both social reputation and better economic benefits in the long run.

5.3. Limitations and Future Research Directions. While this study provides valuable insights for research and practice, it suffers from several limitations. First, our study only selects three key variables of financial performance to investigate how they influence company's green behavior. Further research is encouraged to analyse other specific variables that may explain company's green behavior as well in the same context, i.e., long-term or short-term solvency and operational capacity. Second, this study applies the mathematical measurement model to verify the hypotheses proposed. Further research can strive for using other empirical methods to test hypotheses in this study as well as its credibility and extend scope of its application. Third, this study adopts the method of comparative analysis to explore the complex relationships, so that further researches can carry out similar analysis in certain category of enterprises from different perspectives and thus to form systematic and complete longitudinal studies.

Data Availability

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

Conflicts of Interest

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

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Research Article

Dual-Source Procurement and Supplier Pricing Decision under Supply Interruption

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The occurrence of major public health events usually leads to interruptions in the supply chain. This article studies the supply chain consisting of two suppliers and one manufacturer. In the case of supply interruptions, the manufacturer adopts two models of unit cost subsidies and proportional subsidies. The reliability of the supplier's supply is incentivized and ensured. A Stackelberg game model is established in which the manufacturer is the leader and the supplier is the follower. The research results show that the optimal order quantity of the supplier manufacturer and the optimal wholesale price of the supplier will be affected by the reliability level, and the optimal supply chain profits of the two models under different parameters are compared.

1. Introduction

With the development of supply chain management towards lean performance and globalization, the supply chain has been extended in time and space, but its complexity has also increased, and the risk of supply interruption has also increased. Since the spread of the new crown pneumonia epidemic, it has had a huge impact on the economy, especially the supply chain. At present, the supply chain is in a critical period of transition from fragmentation to systemization and from node to network as a whole, with a large total scale and rapid development speed. As an emergency, the new crown pneumonia epidemic has caused a short-term interruption of the supply chain, which has a huge impact on both ends of supply and demand. The impact of the epidemic on the supply chain through up and down transmission and repeated pulses will cause a series of chain reactions. In order to prevent and control the spread of the epidemic, various places have adopted phased "city closures" and strict traffic control measures. Traditional logistics have been interrupted and offline supply chains have suffered severe setbacks. On the upstream production side, suppliers cannot transport raw materials to other places, and purchasers from other places cannot go to the place of production to purchase. On the downstream sales side, consumers cannot make normal purchases. At the same time, due to the epidemic prevention measures of various countries, international logistics have been blocked, and the import and export trade of products has also been severely set back. [1].

The mismatch between supply and demand has become a challenge and difficulty in the supply chain field [2, 3]. In the face of disruption, suppliers and manufacturers will take some measures to improve the reliability of the supply chain. Dual-source supply is an important means to improve the reliability of the supply chain [4]. Another way to mitigate the risk of supply interruption that cannot be ignored is to improve the reliability of the supply process [5–7]. However, suppliers themselves must face the problem of balancing the improvement of reliability and input costs. Moreover, in order to maintain the autonomy of operation, supply chain member companies often aim to maximize their own interests [8]. Therefore, whether the supplier's reliability cost investment is necessary and how much the investment is determine the stability and profit level of the overall supply chain.

In order to maintain the stability of supply, downstream manufacturers will adopt some strategies, such as revenue sharing contracts and quantity discount contracts, to encourage upstream suppliers to maintain a certain degree of supply reliability. Most of the existing studies on supply chain interruption have established that the level of supply reliability is endogenous [4, 9] and when there is a supply interruption in the supply chain, the literature on retailers adopting different incentive strategies to promote supplier investment in supply reliability construction is relatively lacking.

Through the above content, it can be found that the failure of supply nodes in the supply chain due to accidents will have an adverse impact on the entire supply chain [10, 11]. In order to effectively respond to accidents, supply chain member companies have adopted relevant coping methods and measures. Therefore, this article intends to solve the following questions: (1) In the face of supply interruption, how do manufacturers make purchasing decisions? (2) What incentives should the manufacturer take to maintain supply stability when it is impacted by supply disruptions? (3) Under the manufacturer's subsidy policy, whether it is necessary for the supplier to invest in reliability costs.

This article studies the supply chain interruption problem by means of dual-source supply. In particular, it takes the two-tier supply chain, including dual suppliers, and single manufacturer, such as the research object, and constructs a dynamic game model between suppliers and manufacturers to discuss the purchase and supply of manufacturers considering cost subsidies and supply reliability cost inputs and pricing issues. Finally, it was verified by numerical simulation.

Compared with the existing research, in the dual-source supply chain, the manufacturer's subsidy is also considered to improve the reliability of supply, and the research on the pricing decision-making of the dual-source procurement based on the manufacturer's subsidy and the supplier's reliability cost input has not been seen yet. Second, most of the literature considers supply reliability issues from the perspective of manufacturers and purchasers. However, suppliers can also avoid supply interruption risks by affecting the reliability of the supply process. Therefore, discussing the response mechanism of supply interruption from the perspective of suppliers also has important research value. Finally, innovative suggestions and conclusions are put forward for the optimal decision-making of supply chain members.

In the past related literature in the field of supply chain management, many scholars have conducted extensive research on the Stackelberg game, Cournot game, and Bertrand game in the supply chain system. However, in the related research on dual-source procurement strategy, there are still few considerations of vertical game behaviour between upstream and downstream companies or horizontal game behaviour between homogenized product companies, and there are only a handful of studies that combine the above-mentioned games. In response to this problem, in several chapters, this article considers the influence of different competitive behaviours between companies on the supply chain decision-making according to the characteristics of the decision-making environment in which the member companies are located and fully considers the decision-making research considering mixed competition. Each member company faces relevant decision-making and optimization problems in horizontal and vertical competition, which have not yet appeared in previous studies.

2. Literature Review

2.1. Supply Chain Coordination under Supply Disruption. The literature on supply disruptions includes qualitative and quantitative studies. Most of the research methods used are mathematical programming and game models. Baghersad has found through empirical research that companies of different sizes and different industry sectors have announced the interruption, not only in the short term, but also in the long term; after the interruption occurred, different losses were shown [12]. Ma developed a three-layer supply chain network equilibrium model using probability of risk occurrence and risk loss function to express the characteristics of risk management in the supply chain network [13]. Ivanov proposed a new supply chain interruption risk management method, in which supply chain behaviour is less dependent on the certainty of our knowledge of the environment and its changes, that is, the low certainty demand (LCN) supply chain. By combining lean elements with elastic elements, three key characteristics of the LCN supply chain are determined, namely, the reduction of structural complexity, the flexible use of processes and resources, and efficient parameter redundancy [14].

2.2. Supply Chain Coordination of Different Procurement Modes. In order to better solve the problem of manufacturer procurement and supplier supply under supply interruption, many scholars have carried out research on this. Hou believed that issues such as the dual-source supply model decision and supplier pricing are important measures to mitigate interruption risks and reduce supply network losses and are worthy of in-depth analysis [15]. Konishi believed that only when the purchaser cannot obtain diversified benefits through other channels and the supplier's supply capacity is greater than the demand for market products, single-source procurement will be the manufacturer's optimal procurement strategy; otherwise, dual-source procurement will be the best optimal procurement strategy [16]. Ji and Gong constructed a CLSC model with two competitive dominant upstream suppliers and one following a downstream (re-)manufacturer and then coordinated supply chain through a cost-sharing contract [17]. Liu et al. compared the supply chain coordination issues when supplier groups and buyers adopt revenue sharing + second-penalty contracts and option contracts [18]. Ping studied the optimal decision-making problem when a manufacturer purchases parts from two suppliers with random output and the possibility of supply interruption under the conditions of demand and supply uncertainty [19]. Wan and Chen studied the multiperiod dual-source procurement and supply problem using options and spot markets. The study found that the option strategy is better than the procurement strategy without options [20].

2.3. Establishing a Contract or Coordination Mechanism Supply Chain. Feng et al. considered the reliability factor, reviewed the profit distribution mechanism of supply chain members in a multilevel supply chain, and discussed how to optimize the operating efficiency of the supply chain under different reliability conditions [21]. Liu et al. studied how companies make investment decisions and adopt new technologies to improve supply reliability [22]. Gurnani showed that the degree of input from suppliers to improve reliability depends on their ability to negotiate prices with downstream manufacturers [23]. For example, Walmart uses radio frequency identification technology to track products in real-time, eliminating manual errors in factories, distribution centres, warehouses, and shopping malls, greatly improving the level of supply reliability [24]. On the other hand, retailers provide incentive strategies to encourage suppliers to improve the stability of supply. Giri and Roy constructed a profit model for decentralized and centralized decision-making underprice disturbances and believed that appropriate modification of the revenue sharing contract parameters will increase the profit of the supply chain [25]. Huang and Yang analyzed the impact of asymmetric cost disturbance information on the performance of the supply chain, introduced the principal-agent theory to build a decision-making model with the goal of maximizing supply chain profits, and believed that an effective contract menu was designed, and the manufacturer's production quantity was affected according to the actual situation. The decision-making combination of retail prices is an effective means to deal with asymmetric information disturbances [26]. Different supply chain entities cope with different types of disturbances, and there are more effective coordination methods such as linear quantity discount contracts, two-part fee system contracts, promotion subsidy contracts, and reward and punishment contracts [27–29]. Tan studied the reward and punishment contract under the supply chain contract model, focusing on the problem of how to coordinate the closed-loop supply chain when facing emergencies. The research results show that the coordination problem of the closed-loop supply chain caused by emergencies can be achieved through contract mediation [30].

Most of the above-mentioned documents are related studies on the methods used by supply chain members to maintain supply stability when responding to supply interruptions, from the purchasing mode chosen by the manufacturer to ensuring the stability of the supply process. There are few literatures that analyze the impact of manufacturers' subsidy policies on supply chain members under dual-source supply and the necessity of suppliers to maintain stable supply. This article is mainly based on predecessors' research on supply chain risk and emergency management, starting from the supply chain procurement field, through the use of manufacturer cost subsidies to coordinate the interests within the supply chain. At the same time, consider the impact of two different subsidy methods on the supplier's supply stability and its own profits. On this basis, is it necessary for the supplier to invest in costs based on the probability of supply interruption in order to obtain the optimal order quantity and supply in the supply chain when the benefits of the supply chain member companies are also balanced while the overall benefits of the supply chain are maximized? The wholesale price of raw materials from suppliers can solve the problem of income distribution between manufacturers and suppliers in the supply chain.

3. Model Symbols and Assumptions

This article considers that two suppliers provide buyers with products with no difference in quality to meet random market demand. The main purpose of buyers choosing two suppliers is to ensure the reliability of long-term supply and maintain certain bargaining power. The two suppliers have differences in supply costs and supply reliability. Affected by factors such as production technology and logistics distribution, the suppliers may not be able to deliver on time, causing supply interruptions. Purchasers and suppliers will adopt a unit cost subsidy policy in order to improve their production and transportation processes to reduce supply costs and improve supply reliability; that is, purchasers will provide appropriate subsidies for supplier losses to achieve supply chain coordination.

In this supply chain, suppliers and buyers form a Stackelberg game of decision-making. Figure 1 is a conceptual model when a buyer purchases raw materials from a supplier, and the market is disrupted by supply disruptions and market demand caused by supply disruptions.

Assumption 1. Information is symmetrical between manufacturers and retailers; that is, they are fully aware of each other's cost and demand information.

Assumption 2. Assuming that the purchaser's order quantity to each supplier is Q_1 and Q_2 respectively, similar to the literature [31–33], the actual supply quantity is 0 when the supplier has an emergency that causes the supply to be interrupted; otherwise, the actual supply quantity is equal to the order quantity; that is, "all-or-noting" [34] supply is completely interrupted mode. Assume that two strategic suppliers are exactly the same, and the unit production cost is c. When the supply is interrupted, the supplier's early input unit loss is λc [35], $\lambda \geq 0$. The sales price changes with the supply volume and satisfies $s = a - b(Q_1 + Q_2)$ [7]; a and b are constants greater than 0; based on the actual supply volume of the supplier, the retailer pays the unit wholesale price ω.

Assumption 3. The probability that the supplier does not have the risk of interruption is θ_i; then, the probability of the risk of interruption is $(1 - \theta_i)$. The probability of occurrence of interruption risk between two suppliers is independent and irrelevant, while the market's demand for manufacturers' products is price-sensitive and changes with changes

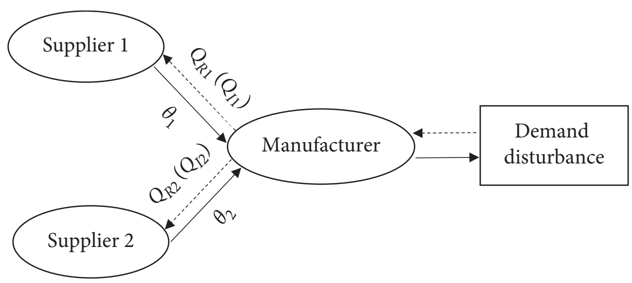

Figure 1: Conceptual model of dual-source procurement.

in sales prices [36]. The first letter I and R of the subscript in the model represent model 1 and model 2, respectively; the subscripts s and m represent supplier and manufacturer, respectively. When the supplier is unable to supply due to supply interruption because of an emergency, the retailer will give the supplier subsidy δc for every unit of the product ordered by the retailer.

Table 1 is a parameter table obtained by summarizing the above assumptions.

4. Model

4.1. Manufacturer's Unit Wholesale Price Subsidy Policy Model. Model 1 is to provide a fixed cost subsidy to the supplier when the manufacturer considers the supplier's supply interruption, that is, to add an additional subsidy to the original wholesale price. In the supply chain, the manufacturer, as the leader of the Stackelberg game, first decides the order quantity and unit wholesale price subsidy; the supplier, as a follower, decides its product production volume and wholesale according to the order quantity and unit wholesale price subsidy set by the retailer price. Using the reverse induction method to solve, first solve the manufacturer's optimal order quantity and then solve the supplier's optimal wholesale price. Under the decentralized decision-making, based on the above assumptions and symbol descriptions, considering the possibility of supply interruption, there are four possible scenarios for the final supply:

The first situation is that supplier 1 supplies successfully and supplier 2 supplies interruption. The probability of occurrence is $\theta_{I1}(1-\theta_{I2})$. The manufacturer's expected profit is as follows:

$$\Pi_{I,m1} = \theta_{I1}(1-\theta_{I2})(a-bQ_{I1})Q_{I1} - \omega_{I1}Q_{I1} - \delta c Q_{I2}. \quad (1)$$

Table 1: Main parameters and parameter description.

Parameters	Definition
θ_i	Supplier reliability level
ω_i	Supplier's wholesale price $(i = 1, 2, 3, 4)$
Q_i	Manufacturer's order quantity at supplier $(i = 1, 2, 3, 4)$
δc	Manufacturer's subsidies to suppliers
λc	Supplier's early input unit loss when supply is interrupted
c	Supplier's unit production cost
s	Manufacturer's sales price $s = a - b(Q_1 + Q_2)$
α_1	Manufacturer/supplier1 input cost ratio
α_1	Manufacturer/supplier2 input cost ratio

The second scenario is that supplier 2's supply is successful and supplier 1's supply is interrupted. The probability of occurrence is $\theta_{I2}(1-\theta_{I1})$. The manufacturer's expected profit is as follows:

$$\Pi_{I,m2} = \theta_{I2}(1-\theta_{I1})(a-bQ_{I2})Q_{I2} - \omega_{I2}Q_{I2} - \delta c Q_{I1}. \quad (2)$$

The third situation is that both suppliers 1 and 2 have supply interruption, and the probability of occurrence is $(1-\theta_{I1})(1-\theta_{I2})$. The manufacturer's expected profit is as follows:

$$\Pi_{I,m3} = (1-\theta_{I1})(1-\theta_{I2})[-\delta c(Q_{I1}+Q_{I2})]. \quad (3)$$

The fourth situation is that both suppliers 1 and 2 supply successfully, and the probability of occurrence is $\theta_{I1}\theta_{I2}$. The manufacturer's expected profit is as follows:

$$\begin{aligned}\Pi_{I,m4} = {} & \theta_{I1}\theta_{I2}[a-b(Q_{I1}+Q_{I2})](Q_{I1}+Q_{I2}) \\ & - \omega_{I1}Q_{I1} - \omega_{I2}Q_{I2}.\end{aligned} \quad (4)$$

Establish the overall expected profit function model of the manufacturer in four situations, where Q_{I1} and Q_{I2} are the main variables that affect the expected profit, and other values are related parameters; then, the expected profit function is as follows:

$$\text{Max}\Pi_{I,m} = \Pi_{I,m1} + \Pi_{I,m2} + \Pi_{I,m3} + \Pi_{I,m4}. \quad (5)$$

Based on the manufacturer's total profit function, the optimal purchase quantity of the manufacturer is then solved. First, find the first-order partial derivative and the second-order partial derivative of the total expected profit function to Q_{I1} and Q_{I2}, and get the following:

$$\frac{\partial \Pi_{I,m}}{\partial Q_{I1}} = \theta_{I1}\theta_{I2}[a - 2b(Q_{I1} + Q_{I2})] - 2\omega_{I1} + (\theta_{I2} - 1)[-\theta_{I1}(a - bQ_1) + b\theta_{I1}Q_{I1} - \delta c\theta_{I1}], \tag{6}$$

$$\begin{aligned} \frac{\partial \Pi_{I,m}}{\partial Q_{I2}} &= \theta_{I1}\theta_{I2}(a - 2b(Q_{I1} + Q_{I2})) - 2\omega_{I2} + (\theta_{I1} - 1)[-\theta_{I2}(a - bQ_{I2}) - \delta c\theta_{I2} + bQ_{I2}\theta_{I2}], \\ \frac{\partial^2 \Pi_{I,m}}{\partial Q_1^2} &= -2b\theta_{I1}, \\ \frac{\partial^2 \Pi_{I,m}}{\partial Q_2^2} &= -2b\theta_{I2}, \\ \frac{\partial^2 \Pi_{I,m}}{\partial Q_1 Q_2} &= \frac{\partial^2 \Pi_{I,m}}{\partial Q_2 Q_1} = -2b\theta_{I1}\theta_{I2}. \end{aligned} \tag{7}$$

Secondly, verify whether there is an optimal solution for the profit function and perform the Hessian matrix operation. Therefore, the Hessian matrix is as follows:

$$H(Q_{I1}, Q_{I2}) = \begin{bmatrix} -2b\theta_{I1} & -2b\theta_{I1}\theta_{I2} \\ -2b\theta_{I1}\theta_{I2} & -2b\theta_{I2} \end{bmatrix}. \tag{8}$$

Calculate the Hessian matrix; get $|H_1(Q_{I1}, Q_{I2})| = \partial^2\Pi_{I,m}/\partial Q_{I1}^2 = -2b\theta_{I1} < 0$, $|H_2(Q_{I1}, Q_{I2})| = \partial^2\Pi_{I,m}/\partial Q_{I1}^2 \partial^2\Pi_{I,m}/\partial Q_{I2}^2 - (\partial^2\Pi_{I,m}/\partial Q_{I2} Q_{I1})^2 = 4b^2\theta_{I1}\theta_{I2}(1 - \theta_{I1}\theta_{I2}) > 0$. It can be seen from $H1$ and $H2$ that the Hessian matrix is negative definite, indicating that the objective function has a maximum value. Currently, Q_{I1} and Q_{I2} exist and are unique.

Let $\partial\Pi_{I,m}/\partial Q_{I1}$, $\partial\Pi_{I,m}/\partial Q_{I2}$ be equal to zero; then, the optimal solution is the solution of the $\partial\Pi_{I,m}/\partial Q_{I1} = 0$, $\partial\Pi_{I,m}/\partial Q_{I2} = 0$ equations. Solve the two formulas $\partial\Pi_{I,m}/\partial Q_{I1} = 0$ and $\partial\Pi_{I,m}/\partial Q_{I2} = 0$ together and calculate the manufacturer's optimal purchase quantity from suppliers 1 and 2.

$$\begin{aligned} Q_{I1}^* &= \frac{2\omega_{I1} - \theta_{I1}(a + 2\omega_{I2} - a\theta_{I2}) + 2\delta c - \delta c\theta_{I2} + \delta c\theta_{I1}(\theta_{I1} - 3 + 2\theta_{I2} - \theta_{I1}\theta_{I2})}{2b\theta_{I1}(\theta_{I1}\theta_{I2} - 1)}, \\ Q_{I2}^* &= \frac{2\omega_{I2} - \theta_{I2}(a + 2\omega_{I1} - a\theta_{I1}) + 2\delta c - \delta c\theta_{I1} + \delta c\theta_{I2}(\theta_{I2} - 3 + 2\theta_{I1} - \theta_{I1}\theta_{I2})}{2b\theta_{I2}(1 - \theta_{I1}\theta_{I2})}. \end{aligned} \tag{9}$$

At this time, the expected profit objective function of supplier 1 is as follows:

$$\Pi_{I,s1} = [\theta_{I1}(\omega_{I1} - c) + (1 - \theta_{I1})(\delta c - \lambda c)]Q_{I1}^*. \tag{10}$$

The expected profit objective function of supplier 2 is as follows:

$$\Pi_{I,s2} = [\theta_{I2}(\omega_{I2} - c) + (1 - \theta_{I2})(\delta c - \lambda c)]Q_{I2}^*. \tag{11}$$

Same as the method of solving the optimal purchase quantity, by processing the supplier's profit function, the supplier's optimal wholesale price is obtained:

$$\begin{aligned} \frac{\partial \Pi_{I,s}}{\partial \omega_{I1}} &= -\frac{\theta_{I1}(c - \omega_{I1}) - (\theta_{I1} - 1)(\lambda c - \delta c)}{b\theta_{I1}(\theta_{I1}\theta_{I2} - 1)} \frac{2\omega_{I1} + \theta_{I1}(-a + a\theta_{I2} - 2\omega_{I2}) - \delta c(\theta_{I2} - 2) + \delta c\theta_{I1}(\theta_{I1} - 3 + 2\theta_{I2} - \theta_{I1}\theta_{I2})}{2b(\theta_{I1}\theta_{I2} - 1)}, \\ \frac{\partial \Pi_{I,s}}{\partial \omega_{I2}} &= -\frac{c\lambda + c - \delta c - \lambda cb\theta_{I2} + \omega_{I1}\theta_{I2}}{b\theta_{I2}(\theta_{I1}\theta_{I2} - 1)} - \frac{(-4\omega_{I2} + a\theta_{I2} - a\theta_{I1}\theta_{I2}) + \delta c\theta_{I2}(3 - \theta_{I2} - 2\theta_{I1} + \theta_{I1}\theta_{I2}) + \delta c\theta_{I1}}{2b(\theta_{I1}\theta_{I2} - 1)} \end{aligned} \tag{12}$$

The suppliers' best wholesale prices are as follows:

$$\omega_{I1}^{*}=\frac{c\left(-2-\theta_{I1}+2\lambda+\lambda\theta_{I1}\right)-a\theta_{I1}}{\theta_{I1}\theta_{I2}-4}+\frac{2\delta c\theta_{I2}-2\lambda c\theta_{I2}-\lambda c\theta_{I1}^{2}+\delta c\theta_{I1}^{2}}{\theta_{I1}\theta_{I2}\left(\theta_{I1}\theta_{I2}-4\right)}\frac{\theta_{I1}\theta_{I2}\left(a+a\theta_{I1}+\delta c+\delta c\theta_{I2}-\delta c\theta_{I1}\theta_{I2}\right)+\delta c\left(-2\theta_{I2}-6\theta_{I1}+\theta_{I1}^{2}\right)}{2\left(\theta_{I1}\theta_{I2}-4\right)},$$

$$\omega_{I2}^{*}=\frac{c\theta_{I2}\left(-\lambda+\delta\right)}{\theta_{I1}\left(\theta_{I1}\theta_{I2}-4\right)}+\frac{\theta_{I1}\theta_{I2}\delta c\left(1+\theta_{I1}-\theta_{I1}\theta_{I2}\right)+\theta_{I1}\theta_{I2}a\left(1+\theta_{I2}\right)+\delta c\theta_{I2}^{2}}{2\left(\theta_{I1}\theta_{I2}-4\right)}+\frac{\left(-2c-a\theta_{I2}-c\theta_{I2}+2\lambda c+\lambda c\theta_{I2}-3\delta c\theta_{I2}-\delta c\theta_{I1}\right)}{\theta_{I1}\theta_{I2}-4}+\frac{c\left(2\delta-2\lambda c\right)}{\theta_{I2}\left(\theta_{I1}\theta_{I2}-4\right)}. \quad (13)$$

Bring Q_{I1}^{*}, Q_{I2}^{*}, ω_{I1}^{*}, ω_{I2}^{*} into the function of manufacturer's profit and supplier's target profit, respectively, to obtain the optimal profit of manufacturer, supplier, and the entire supply chain.

$$\Pi_{I}^{*}=\Pi_{I,m}^{*}+\Pi_{I,s1}^{*}+\Pi_{I,s2}^{*}. \quad (14)$$

4.2. Manufacturer's Cost Proportional Subsidy Model. The manufacturer first issues an order to the supplier and adopts a cost subsidy policy for the upstream supplier. Unlike Model 1, in Model 2, the manufacturer subsidizes the supplier according to a certain proportion. At the same time, the supplier depends on the manufacturer, the subsidy ratio of the company, and the cost input to the level of its own supply reliability, thus improving the production process and optimizing the logistics system, so as to improve supply reliability, prevent supply interruption, and send the produced products to the retailer; finally, the manufacturer sends the product to the retailer. Sell to the customer market and get profit. Suppose that the supplier's supply reliability cost input $(1-\alpha)k\theta_{R1}^{2}/2$ is a quadratic function of the supply reliability level, k is the reliability cost sensitivity coefficient, and $k>0$ [37, 38].

The supplier invests in the cost of supply reliability, and the manufacturer subsidizes it in proportion to α. Similar to the situation in Model 1, therefore, the manufacturer's profit function is as follows:

$$\Pi_{R,m1}=\theta_{R1}\left(1-\theta_{R2}\right)\left(a-bQ_{R1}\right)Q_{R1}-\omega_{R1}Q_{R1}-\frac{\alpha_{2}k\theta_{R2}^{2}}{2}, \quad (15)$$

$$\Pi_{R,m2}=\theta_{R2}\left(1-\theta_{R1}\right)\left(a-bQ_{R2}\right)Q_{R2}-\omega_{R2}Q_{R2}-\frac{\alpha_{1}k\theta_{R1}^{2}}{2}, \quad (16)$$

$$\Pi_{R,m3}=-\frac{\alpha_{1}k\theta_{R1}^{2}}{2}-\frac{\alpha_{2}k\theta_{R2}^{2}}{2}, \quad (17)$$

$$\begin{aligned}\Pi_{R,m4}=&\ \theta_{R1}\theta_{R2}\left[a-b\left(Q_{R1}+Q_{R2}\right)\right]\left(Q_{R1}+Q_{R2}\right)\\&-\omega_{R1}Q_{R1}-\omega_{R2}Q_{R2}.\end{aligned} \quad (18)$$

Establish the overall expected profit function model of the manufacturer in four situations, where Q_{R1} and Q_{R2} are the main variables that affect the expected profit, and other values are related parameters; then, the expected profit function is as follows:

$$\mathrm{Max}\Pi_{R,m}=\Pi_{R,m1}+\Pi_{R,m2}+\Pi_{R,m3}+\Pi_{R,m4}. \quad (19)$$

The calculation process is the same as that in Model 1. Find the first-order partial derivative and the second-order partial derivative of formula (19), and by calculating the Hessian matrix, it is determined that the manufacturer's profit function has a unique solution. The derivative analysis of (19) shows that the manufacturer's optimal purchase quantity is as follows:

$$Q_{R1}^{*}=\frac{\left(2\omega_{R1}-a\theta_{R1}-2\theta_{R1}\omega_{R2}+a\theta_{R1}\theta_{R2}\right)}{2b\theta_{R1}\left(\theta_{R1}\theta_{R2}-1\right)}, \quad (20)$$

$$Q_{R2}^{*}=\frac{\left(2\omega_{R2}-a\theta_{R2}-2\theta_{R2}\omega_{R1}+a\theta_{R1}\theta_{R2}\right)}{2\theta_{R2}\left(-b\theta_{R1}\theta_{R2}+b\right)}. \quad (21)$$

The manufacturer's optimal purchase quantity and its subsidy policy are determined, and the supplier responds accordingly. Then, the profit functions of supplier 1 and supplier 2 are, respectively:

$$\Pi_{R,s1}=\left[\theta_{R1}\left(\omega_{R1}-c\right)-\frac{(1-\alpha)k\theta_{R1}^{2}}{2}\left(1-\theta_{R1}\right)\right]Q_{R1}^{*}, \quad (22)$$

$$\Pi_{R,s1}=\left[\theta_{R2}\left(\omega_{R2}-c\right)-\frac{(1-\alpha)k\theta_{R2}^{2}}{2}\left(1-\theta_{R2}\right)\right]Q_{R2}^{*}, \quad (23)$$

$$\begin{aligned}\frac{\partial\Pi_{R,s}}{\partial\omega_{R1}}&=\frac{2\omega_{R1}-2\theta_{R1}\omega_{R2}-a\theta_{R1}\left(1-\theta_{R2}\right)}{2b\left(\theta_{R1}\theta_{R2}-1\right)}-\frac{\theta_{R1}\left(c-\omega_{R1}\right)+\theta_{R1}^{2}k\left(\theta_{R1}-1\right)\left(\alpha_{1}-1\right)}{b\theta_{R1}\left(\theta_{R1}\theta_{R2}-1\right)},\\\frac{\partial\Pi_{R,s}}{\partial\omega_{R2}}&=\frac{2\left(c-\omega_{R2}\right)+\theta_{R2}k\left(\theta_{R2}-1\right)\left(\alpha_{2}-1\right)}{-2b\theta_{R1}\theta_{R2}+2b}-\frac{2\omega_{R2}-2\theta_{R2}\omega_{R1}-a\theta_{R2}+a\theta_{R1}\theta_{R2}}{-2b\theta_{R1}\theta_{R2}+2b}.\end{aligned} \quad (24)$$

Calculate the partial derivative of the supplier's profit function, and then use $\partial\Pi_{R,s}/\partial\omega_{R1} = 0$ $\partial\Pi_{R,s}/\partial\omega_{R2} = 0$, to find the optimal solution of ω_{R1} and ω_{R2}; then,

$$\begin{aligned}\omega_{R1}^{*} &= -\frac{4c + 2\theta_{R1}\left(a + c + k - k\alpha_1\right) - 2k\theta_{R1}^{2}\left(1 - \alpha_1\right) + \theta_{R1}\theta_{R2}\left(-a + k - a\theta_{R1} - k\theta_{R2} - k\alpha_2 + k\alpha_2\theta_{R2}\right)}{2\left(\theta_{R1}\theta_{R2} - 4\right)},\\ \omega_{R2}^{*} &= -\frac{4c + 2\theta_{R2}\left(a + c + k - k\theta_{R2} + k\alpha_2\theta_{R2} - k\alpha_2\right) + \theta_{R1}\theta_{R2}\left(-a + k - a\theta_{R2} - k\theta_{R1} - k\alpha_1 - k\alpha_1\theta_{R1}\right)}{2\left(\theta_{R1}\theta_{R2} - 4\right)}.\end{aligned} \tag{25}$$

Bring Q_{R1}^{*}, Q_{R2}^{*}, ω_{R1}^{*}, ω_{R2}^{*} into the function of manufacturer's profit and supplier's target profit, respectively, to obtain the optimal profit of manufacturer, supplier, and the entire supply chain:

$$\Pi_{R}^{*} = \Pi_{R,m}^{*} + \Pi_{R,s1}^{*} + \Pi_{R,s2}^{*}. \tag{26}$$

5. Numerical Analysis

Assume that there are two suppliers and one manufacturer in the secondary supply chain. The manufacturer is a medium-sized industrial enterprise that needs to purchase raw materials and process them into finished products for sale. Suppliers 1 and 2 are upstream suppliers of the manufacturer. Two suppliers of the same products are produced on different scales, so the probability of supply interruption when subjected to shocks is different. Their main business is to provide manufacturers with raw materials, and their production volume is affected by the manufacturer's purchase volume, while being affected by uncertain factors will produce different interruption probabilities. The manufacturer purchases raw materials from two suppliers. In order to maintain the continuity and stability of the supply, the supplier will adopt incentives and the supplier will also invest in reliability costs. Moreover, the information among business members in the supply chain is completely symmetrical. That is, the revenue function of each participant and the supplier's improvement function, cost, and supply stability information are common information among all participants. Therefore, the specific parameters are set to $\theta_2 = 0.4$, $\delta = 0.7$, $a = 1000$, $b = 10$, $\lambda = 0.4$, $c = 20$, $k = 80$, $\alpha_1 = \theta_{R1}$, $\alpha_2 = \theta_{R2}$. The loss cost of the supplier's early input caused by the supply interruption is $\lambda c = 8$.

5.1. Sensitivity Analysis. The following analyzes the impact of the change of supplier 1's supply reliability level on the supplier's supply price and the manufacturer's purchase volume when supplier 2's supply reliability level is 0.4. The result is shown in the figures.

Figure 2 shows the impact of supplier 1's supply reliability changes on the manufacturer's purchase volume. It can be seen that under the condition that the supply reliability level of supplier 2 remains unchanged, as the supply reliability level of supplier 1 changes, the manufacturer's purchasing decision is also different. In Model 1, when $0 < \theta_1 < 0.3$, the manufacturer's purchase at supplier 1 shows a downward trend. Later, as the supply reliability level of supplier 1 increases, the manufacturer's optimal order quantity for raw material supplier 1 will gradually increase, while the optimal order quantity for raw material supplier 2 will gradually decrease. $\theta_1 = 0.2$ and $\theta_1 = 0.4$ are the key points. When $0.2 < \theta_1 < 0.4$, the manufacturer chooses supplier 2 for more raw materials, and supplier 2 has a competitive advantage. When $0.4 < \theta_1 < 1$, manufacturers purchase more raw materials from supplier 1, and supplier 1 has a greater competitive advantage.

In Model 2, the manufacturer's purchase changes are roughly the same as in Model 1. The key point is $\theta_1 = 0.4$; at this point, the two suppliers get the same optimal order quantity from the manufacturer, which means that under this probability combination, supplier 1 has no competitive advantage over supplier 2. The number of orders obtained by supplier 1 is equal to that of supplier 2. This is because the two suppliers have the same other conditions except for the probability of interruption, which does not affect the optimal order quantity.

As shown in Figure 3, for model 1, the total optimal order quantity first shows a downward trend, and then it flattens out. When the supplier 1's supply reliability level is greater than 90%, the total order quantity will gradually decrease, mainly because of the maintenance of high supply stability. The cost for manufacturers and suppliers to invest is higher, which in turn leads to higher prices for suppliers, which will cause manufacturers to hesitate, and the gains are not worth the loss. In Model 2, the total amount of optimal orders shows a trend of first increasing and then decreasing.

Figure 4 reflects the two models in the stable state of supplier 2's supply. As supplier 1's supply reliability level increases, supplier 1's supply price gradually increases, while supplier 2's supply price gradually decreases. When the reliability levels of supplier 1 and supplier 2 are the same, their supply prices are the same. At this time, the level of competition between the two is the same. When $0.4 < \theta_1 < 1$, the supply price of supplier 1 is greater than that of supplier 2 because at this time, the supply reliability level of supplier 1 is greater than the supply reliability level of supplier 2. The same is true, when $0 < \theta_1 < 0.4$, The supply price of supplier 1 is lower than the price of supplier 2.

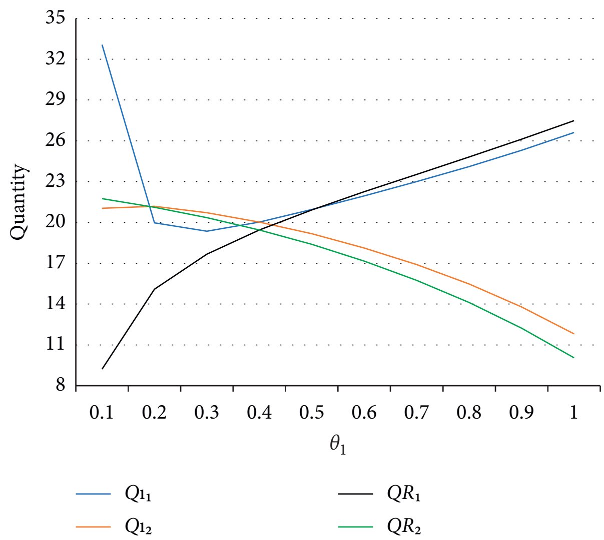

Figure 2: The impact of θ_1 changes on manufacturers' purchase.

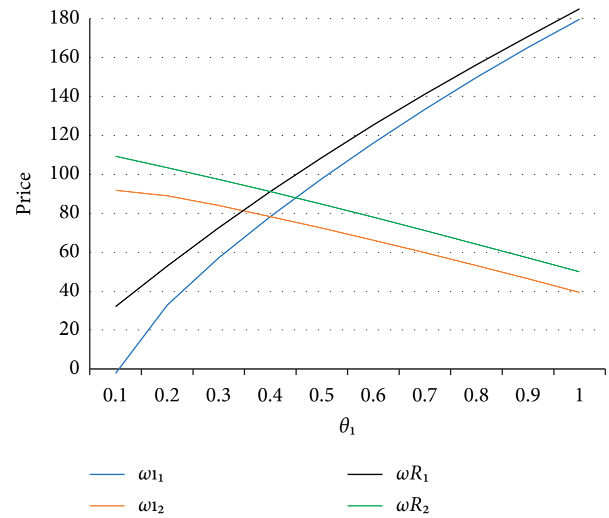

Figure 4: The impact of θ_1 changes on supplier wholesale prices.

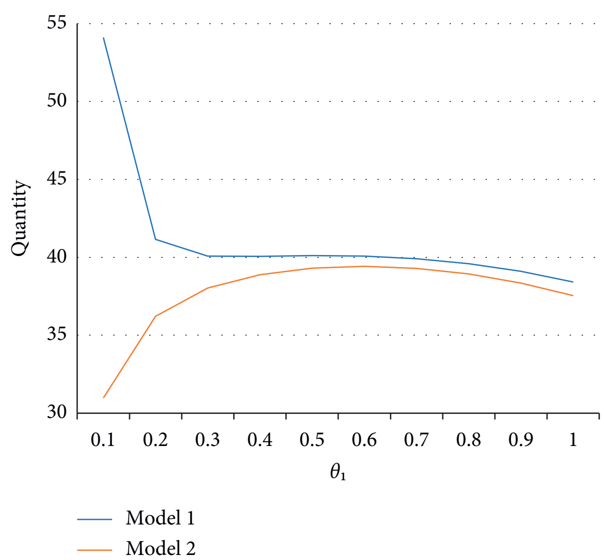

Figure 3: The impact of θ_1 changes on manufacturers' total purchase.

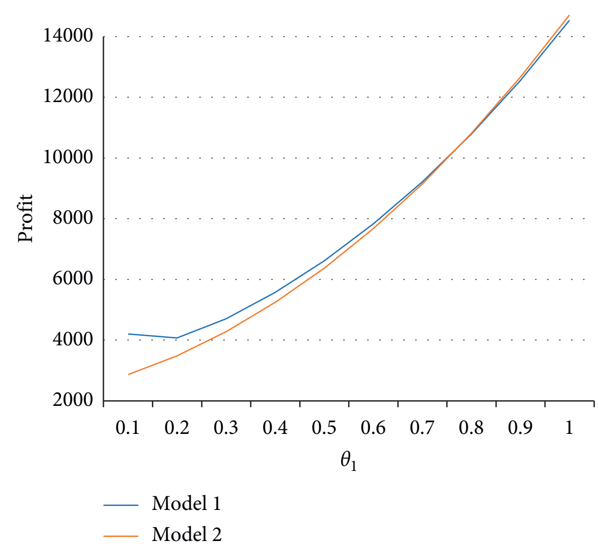

Figure 5: The impact of θ_1 changes on total profit.

In our perception, the higher the supplier's price is, the less the manufacturer purchases, but what is interesting is that in the model, the higher the supplier's price is, the more the manufacturer purchases. This proves that supply stability plays an important role in the supply and purchase process. A high supply price represents a stable supply level, so manufacturers are willing to pay for the high price. Of course, the supplier's pricing is also affected by the manufacturer's incentives. The following is a comparative analysis of the two models.

5.2. Profit Analysis of Model 1 and Model 2. Figure 5 describes the relationship between the total profit of the supply chain and the supply reliability level of supplier 1 when the probability of occurrence of interruption risk of supplier 2 is 0.6. It can be seen from the figure that when the supply reliability level of supplier 1 is less than 0.75, the profit of model 1 is greater than that of model 2, and when the supply reliability level is greater than 0.75, the profit of model 2 gradually exceeds the profit of model 1. Therefore, when the supply reliability level of supplier 2 is stable, when $0 < \theta_1 < 0.75$, choose model 1 and the overall supply chain will obtain greater profits; when $0.75 < \theta_1 < 1$, choose model 2, the overall supply chain will obtain greater profits.

Figure 6 is a comparison of the profits of the two suppliers in Model 1 when the profits of the two suppliers are affected by the level of supply reliability. It can be observed from the figure that supplier 1 is greatly affected by its own supply reliability level, and as the reliability of the supply chain increases, supplier 1's profit rises rapidly. Supplier 2 is less affected by the reliability of supplier 1's supply. It can be seen from the figure that the profit of supplier 2 changes smoothly, indicating that when the supplier itself is stable, it is less affected by other external conditions.

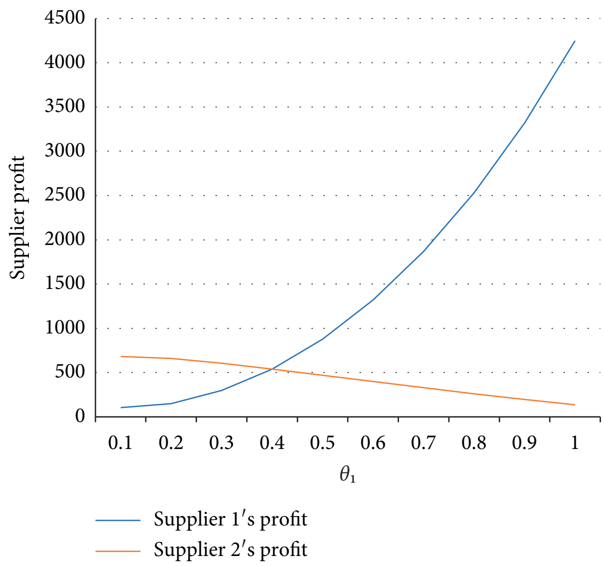

Figure 6: The impact of θ_1 changes on suppliers' profit.

6. Conclusions

Modern procurement management is an important part of supply chain management. The quality of procurement activities and material supply determines to a large extent whether a company's production, business management, and other tasks can be effectively carried out. Various uncertain factors are widely present in the current globalized market environment, which makes the benign operation of the supply chain system more and more susceptible to influence. The dual-source procurement strategy can greatly reduce the probability of supply risk and its possible losses. At the same time, the manufacturer's incentives to suppliers can also encourage suppliers to improve supply reliability. Therefore, this article mainly studies the dual-source procurement supply chain game problem based on the risk of supply interruption in a single cycle and analyzes the following two situations: the use of subsidy policy optimization supply chain model in the case of decentralized decision-making and the use of cost proportional subsidy policy optimization in the case of decentralized decision-making and, at the same time, considers the supply chain game model of supplier reliability cost input in two situations. Based on two raw material providers with different interruption probabilities, and considering the possible interruption probability, the expected profit function model of the core enterprise and the raw material provider is constructed, and the optimal order quantity and the optimal order quantity when the entire supply chain and the members obtain the expected profit are obtained. The value range of the correlation coefficient is obtained. The advantages and disadvantages of the two models are analyzed, and finally, the corresponding management enlightenment is obtained. The main research conclusions and results obtained in this article are as follows:

(1) When the supplier's reliability level is low, the total profit of the supply chain optimized based on the unit price subsidy is higher than the total profit of the proportionally subsidized supply chain; but when the supplier's supply reliability level is high, the total profit of the supply chain optimized by the unit price subsidy is higher than the total profit of the supply chain with the proportional subsidy.

(2) When a manufacturer chooses to adopt a dual-source supply strategy to prevent possible supply interruption risks, the first thing to pay attention to is the impact of supplier interruption probability. For two homogeneous suppliers, in order to prevent the possibility of supply interruption risk, the manufacturer should order more products from the supplier with the lower interruption probability and the one with the higher interruption probability should order fewer products to ensure maximum profit.

(3) In the face of supply interruption, under the premise that the manufacturer adopts the subsidy policy, it is necessary for the supplier to invest in the reliability cost, but an appropriate amount of investment must be made to ensure the stability of the supply while maintaining the optimal cost and own profit.

(4) Aiming at the procurement problem with the risk of supply interruption, this article considers that the manufacturer adopts the strategic mode of backup procurement to ensure the stability of its supply quantity. On this basis, comparing the supply stability and pricing and profit changes of the two suppliers, it is found that when the suppliers themselves are stable, they are less affected by homogeneous suppliers.

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 article.

Acknowledgments

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Research Article

Distribution Service Competition with the Consideration of Different Consumer Behaviors

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Logistics distribution plays an important role in the operation of e-commerce firms. This paper considers two logistics distribution modes with service competition: the e-commerce platform self-distribution (SDL) mode and third-party logistics (TPL) mode. By introducing consumer behavior into the model, we examine the competition between two firms with the same functionalities in the context of e-commerce. According to the real scene, we build the corresponding mathematical optimization model. Each firm needs to decide a logistics distribution mode and a corresponding price for the selected logistics mode. We first analyze the two firms chosen logistics modes and prices simultaneously and then extend it to Stackelberg game situation. We find out the optimal strategy for two firms. Finally, we propose numerical analysis to identify our models and provide a series of managerial insights.

1. Introduction

With the rapid development of information technology and electricity economy, the proliferations of economic globalization have created enormous e-commerce marketplaces. Numerous e-commerce platforms like JD.com and Amazon.com have emerged in recent years.

A crucial part coinciding with e-commerce operation is logistics distribution. Shu and Sun [1] considered an integrated distribution network design problem for an integrated supply chain. There are two major types of logistics distribution modes: the e-commerce platform SDL mode and TPL mode. To reduce the burden of e-commerce enterprises in a degree, those companies outsource their logistics functions to TPL providers. As indicated by Ellinger et al. [2], TPL service providers have been increasing the investments in expanding their capacities and major e-commerce players. A large number of practices have been carried out in the e-commerce logistics [3]. However, logistics outsourcing may fail to meet the customers' high level of logistics requirements. Some e-commerce platforms must establish SDL system. Lee and Whang [4] proved that many platforms choose to build their own logistics service network, because the logistics service quality, especially the last-mile service, is one of the most important factors for successful e-commerce business. Ellinger et al. [2] said that JD.com has invested heavily in creating their own logistics facilities like distribution centers. JD.com had 7 major logistics centers nationwide and operated 166 large warehouses in 44 cities by the end of 2015.

For e-commerce firms, it is important to decide on choosing a better distribution mode and set the corresponding price strategy. We can find that the same goods on the same e-commerce platform may set different prices due to different distribution modes. Chen et al. [5] considered the pricing and inventory decision-making under an online retailer and an offline retailer with cooperative situation. For consumers, logistics service is also an important basis for their choice of e-commerce firms. For e-commerce firms, if they choose the e-commerce platform SDL mode, it means that e-commerce firms can better manage logistics services and shape their own service brands, making them one of their core competitiveness areas. But it is inevitable that they must invest a lot of money, and it is difficult to get a large logistics coverage in a short time. On the contrary, if they choose TPL, they can reduce the funds invested in logistics services and rapidly access to a wide range of logistics coverage. But the level of logistics services of TPL service providers is mixed, and e-commerce firms are difficult to form effective constraints and management for the hired TPL companies.

There are two important factors to consider when making pricing and logistics decisions. One concern is competition among homogeneous firms. E-commerce firms are in a constantly changing environment. To survive and develop, e-commerce firms need to cope with the price and logistics policies pressure of competitors. From game theory, the utility of the firms is not only depending on its own choices but also depending on the choice of its competitors. E-commerce firms need to consider how to adopt the right pricing and logistics strategies to make them in a favorable position in the market competition. The other concern is consumer behavior, consumers have service and price sensitivity, as well as channel preference, which could be measured by consumer utility. Consumer utility refers to the degree of satisfaction that a commodity brings to consumers. The utility function is the relationship between the utility acquired by consumers and the quantity of goods purchased. To realize the win-win situation between the customer and the logistics service vender, as well as maximize the value of the customer, Wang and Sang [6] analyzed the relationships between the TPL and supply chain members under an e-commerce environment. Choudhary et al. [7] assumed that consumers have different preferences in two distribution modes.

During the past decades, research on logistics distribution modes in the e-commerce context is increasingly important. Researchers have deep research on e-commerce logistics. E-commerce logistics can be analyzed in various ways, including a case study approach, multiple discriminate analysis, interpretive structural modeling, and an investment model [8–11]. Although there have been many studies on e-commerce logistics, there is still limited analysis that focuses on the competitive firm's pricing and logistics decisions, especially those taking potential factors into account such as consumer behavior.

To fill this gap, this paper aims to investigate the competitive e-commerce firms' pricing and logistics policies. By introducing consumer behavior into the model, we examine the competition between two firms with the same functionalities in the context of e-commerce. We first analyze the two firms chosen logistics modes and prices simultaneously and then extend it to Stackelberg game situation. E-commerce firms need to solve three problems while determining the optimal price and logistics strategy. First, how can competitive e-commerce firms make their own decisions based on the strategies of their competitors? Second, how does consumer behavior affect e-commerce firms' pricing and logistics decisions? Third, under different decision-making situations, how to establish the optimal model of e-commerce firms?

The class of literature relevant to the work in this paper falls into pricing and logistics decisions. With the development of e-commerce and the fierce competition in logistics industry, studies on the firms' pricing and logistics decisions have been increasing since the last decade. Mu et al. [12] developed a congestion pricing model for achieving efficient e-commerce logistics. Chen et al. [13] derived two different pricing strategies and three game theoretic models to address the reverse logistics of a green supply chain with environmentally conscious customers. These studies highlight the problem of price strategy in logistics. Chu et al. [14] investigated the logistics service innovation by TPL mode providers in China. We can find that, in the previous studies, there was little attention paid to SDL mode, and few considered the choice of the SDL mode and TPL, as well as the price strategy at the same time.

Our work is related to previous research on consumer behavior. It is obvious that consumer behavior can influence the consumer's purchase decision. Veena and Gopinath [15] revealed that the strategic customers play an important role in service providers' decisions. In this paper, we mainly consider the price and service sensitivity and their preferences for different logistics modes. There are some researches in overlapping areas but is not exhaustive on our problem. Tong et al. [16] considered the consumers' preferences on environmental in a retailer-led supply chain, to investigate the stability of the equilibrium solutions of the evolutionary game. Qu et al. [17] proposed a robust decision model in uncertain environment. Consumers exhibit altruistic environmental and "egoistic" brand preferences. These literatures mainly focus on the characteristics of consumer preferences.

Shin et al. [18] used conjoint analysis to estimated consumer preference for mobile telecommunication service, and the results indicated that consumer preferences for price and service quality are the most valuable attributes. Cai et al. [19] established the dynamic game relationship to coordinate a vendor-managed inventory supply chain with service-level sensitive customers, and related customer demand with retailer's service level. Zheng et al. [20] investigated the effect of customer value and power structure on retail supply chain product choice and pricing decisions. They defined the customer value with price sensitive. Hu and Su [21] developed an algorithm to study a news vendor's joint procurement and pricing under the price-sensitive stochastic demand. These literatures take consumer sensitivity as the research factor. Based on previous studies, it is found that scholars mainly consider one or two of the factors of consumer behavior, but seldom consider the sensitivity and preference of consumers together.

Another importance issue is competition among firms. In this study, we focus on price competition and Stackelberg game. Many scholars have also conducted certain research on price competition and game theory. Kogan and El-Ouardighi [22] addressed quality improvement in a competitive duopoly market for partially substitutable products and derived Nash equilibrium pricing and induced learning effort dynamic policies. Hua et al. [23] examined the prices and optimal decisions of delivery lead time in centralized and decentralized dual-channel supply chain using the two-stage optimization technique and Stackelberg game. Eltoukhy et al. [24] developed a Stackelberg–Nash game model and considered the price competition among maintenance providers. Qu et al. [25] studied a government's optimal subsidies for energy-efficient products in a market with two competing firms. They derived the subgame Nash equilibrium of the product prices and product efficiency strategies. Feng et al. [26] considered a dual-recycling reverse supply chain with price competition, where the recyclable dealer acts as a Stackelberg game leader, and the recycler acts as a follower. In this paper, we consider not only the Stackelberg game, but also the simultaneous game of two firms, which is also our innovation.

The rest of this article is summarized as follows. Section 2 describes the basic problems and related assumptions and constructs the corresponding model. In Section 3, according to the model, the optimal strategies of two enterprises under two scenarios of simultaneous decision-making and Stackelberg game are analyzed. In Section 4, the sensitivity of the parameters is analyzed numerically to verify the effectiveness of the model. In Section 5, the main conclusions of this paper are summarized.

2. Problem Description and Basic Assumptions

2.1. Problem Description. Introducing consumer price and service sensitivity and preferences for different logistics modes into the model, we examine the competition between two firms with the same functionalities in the context of e-commerce. We study the pricing and logistics strategies of e-commerce firms under different game scenarios. The influence of each parameter on firms' decisions is also analyzed.

We consider two decision scenarios: one is the simultaneous decision-making scenario, and the other is the Stackelberg game scenario. Without loss of generality, we believe that, under the situation of simultaneous decision-making like Figures 1 and 2, two firms choose the same logistics distribution mode. Currently, there is only price competition between them. To occupy a favorable market share, each firm makes decisions according to its competitor. Under this situation, the consumer demand in the market is a linear relationship between the price of the two firms. Consider the price decisions and profits of two firms when they choose two logistics modes, respectively, in the context of simultaneous decision-making.

Under the Stackelberg game scenario, one of the two firms, as the leader, makes the price and logistics decisions first. And the other one, as the follower, makes the corresponding strategies according to the decisions of the leading firm. The two firms choose different logistics modes like Figures 3 and 4. Meanwhile, in addition to the price competition between the two firms, there is also competition in the level of logistics services. Consumers have different preferences for the two logistics distribution modes and are sensitive to the level of logistics services. In this scenario, the consumer's purchase decision depends on the consumer's utility. According to the consumer utility, we can establish the consumer demand model related to firms' pricing and logistics decisions. We first consider the situation that the leader chooses the e-commerce platform SDL mode, and the follower chooses the TPL, and then consider the situation that the leader chooses the TPL, and the follower chooses the e-commerce platform SDL mode. Analyze and compare the price strategies and profits of the two firms in the two cases. The notations used in this paper are listed in Table 1.

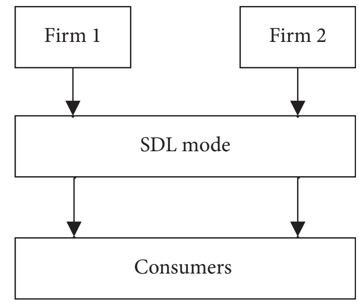

Figure 1: Logistics mode with SDL.

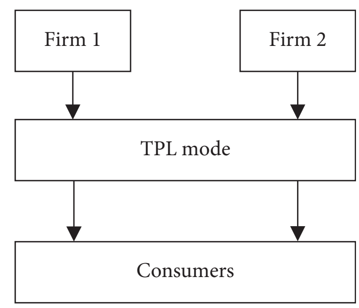

Figure 2: Logistics mode with TPL.

2.2. Basic Assumptions. Combined with the feasibility analysis of the modeling of real-world scene, the following basic assumptions are proposed in this paper.

(i) We assume an e-commerce firm who delivers to consumers through the e-commerce platform SDL mode or TPL mode.

(ii) We assume that consumers are rational persons, and consumer behavior can be expressed as price and service sensitivity and preference for different logistics modes. Consumers' preference for two modes of logistics is different, in which customers' acceptance of TPL is less than SDL, because the service level provided by SDL is often better than that of TPL, and consumers tend to accept SDL. They would choose the logistics mode based on the utility that consumers get. When consumer utility is greater than zero, consumers prefer the logistics mode, which makes them more efficient.

(iii) We assume that logistics service level can be expressed by delivery time. The delivery time of the two modes is different; that is, the level of logistics service is different. We assume that the service level of SDL is higher than that of TPL, $T_s < T_t$.

3. Basic Model

Assume that there are two firms with the same functionalities, indexed 1 and 2, competing on price and logistics distribution model decisions in the context of e-commerce.

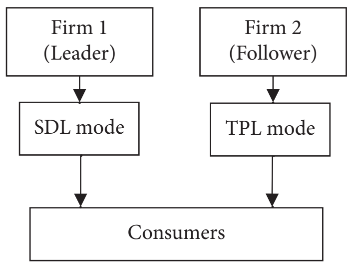

Figure 3: Logistics mode followers use TPL.

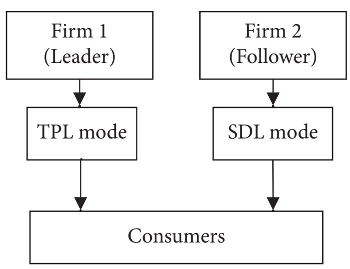

Figure 4: Logistics mode leaders use TPL.

Table 1: Notations for the model.

Symbol	Descriptions
α	Consumers' price sensitivity
β	Consumers' service sensitivity
θ	The customers' acceptance of TPL
N	Consumer valuation
W	Cost price shall be paid to the TPL supplier
H	Firm's demand sensitivities to its cross price
p_i	A price set of firms (decision variable)
T_a	Logistics service level
Π	Firm's profits
U_a	Consumer utility
D	Demand of consumers
d	Basic market demand

Each firm faces two major types of logistics distribution modes: the e-commerce platform SDL and TPL. A firm i ($i = 1,\ 2$) can choose either SDL or TPL and sets a corresponding price p_i. The service level of the two logistics distribution modes can be expressed as expected delivery time T_a. To facilitate the calculation, we set the marginal cost of the logistics service to zero when the firm chooses the e-commerce platform SDL mode. When choosing the TPL mode, the cost price that shall be paid to the TPL supplier is w. There is a continuum of consumers, who make purchase decisions from one of the two firms based on their evaluation. In this paper, we introduce strategic consumer and assume that consumers have price sensitivity α; service sensitivity β; and acceptance of the TPL mode is $\theta\theta \in (0, 1)$, and the acceptance of the e-commerce platform SDL mode is 1. The consumer's value of assessment for logistics service is v, and it is a uniform distribution from 0 to 1, with the submergence of consumers in the market being 1. At the time of requesting a service, the consumer chooses the service from the firm in a manner that maximizes his utility. The consumer's utility is $U_s = \theta v - \alpha p_{si} - \beta T_s$ (SDL mode) and $U_t = v - \alpha p_{ti} - \beta T_t$ (TPL mode). For all consumers, when $U_s > 0$, all consumers would consider accept SDL. The marginal consumer, whose value of assessment v_s equals $(\alpha p_{si} + \beta T_s)/\theta$, is indifferent to accepting SDL or not at all. Similarly, only when $U_t > 0$, the consumers would accept TPL. The marginal consumer, whose value of assessment v_t equals $\alpha p_{ti} + \beta T_t$, is indifferent to accepting SDL or not at all. If $U_t \geq U_s$, all consumers prefer TPL. The consumer's valuation v_{st} that equals $\alpha(p_{ti} - p_{si}) + \beta(T_t - T_s)/1 - \theta$ is indifferent between the two ways. And if the valuation is larger than v_{st}, they prefer TPL.

3.1. Price Competition with Simultaneous Choices. In this section, we analyze the situation that two enterprises choose the same logistics distribution mode. In detail, it analyzes which parameters will affect the logistics decision-making of enterprises and how to determine the price accordingly. Since both firms choose the same logistics distribution mode, each firm faces price-sensitive demand, which are assumed as

$$D_i = d - \alpha p_i + \eta p_j,$$
$$D_j = d - \alpha p_j + \eta p_i, \tag{1}$$

where $i \in \{1, 2, \ldots, n\}$, $j = n + 1 - i$, d represents the basic market demands, and η denotes the demand sensitivities to its cross price. The demand function is widely used in previous studies. When both firms choose the e-commerce platform SDL mode, the profit function of the firm is

$$\Pi_{si} = p_{si} D_{si} = p_{si}\left(d - \alpha p_{si} + \eta p_{sj}\right). \tag{2}$$

We can solve the above functions to obtain the optimal decision.

Lemma 1. *When both firms choose the e-commerce platform SDL mode, the optimal price is given by*

$$p_{si}^{*} = \frac{d}{2\alpha - \eta};\ \Pi_{si}^{*} = \frac{\alpha d^2}{(2\alpha - \eta)^2}. \tag{3}$$

Proof. Let $\partial\Pi_{si}/\partial p_{si} = d - \alpha p_{si} + \eta p_{sj} - \alpha p_{si} = 0$, so that $p_{si} = d + \eta p_{sj}/2\alpha$, in the same way $p_{sj} = d + \eta p_{si}/2\alpha$ set up two equations, and we can know that $p_{si}^{*} = p_{sj}^{*} = d/2\alpha$ $-\eta D_{si} = d - \alpha p_{si} + \eta\ p_{sj} = \alpha\, d/2\alpha - \eta \Pi_{si} = p_{si} D_i = p_{si}\ (d - \alpha\ p_{si} + \eta p_{sj}) = \alpha d^2/(2\alpha - \eta)^2$.

Lemma 1 implies that, without logistics distribution differentiation, competitive firms will set the same price, and it is mainly affected by the price-sensitive parameters of consumers. We can know that, with the increase of consumer price sensitivity, firms choose to lower their prices to attract more consumers. Besides, the firm's price is affected by its cross price, as the crossed price sensitivity increases, the firm must increase the price to occupy a certain market share. It is also interesting to note that only when $\alpha > \eta/2$, firms make positive profits. Without loss of generality, we can get function (4) of the firm's profit when choosing the TPL mode:

$$\Pi_{ti} = (p_{ti} - w)D_{ti} = (p_{ti} - w)\left(d - \alpha p_{ti} + \eta p_{tj}\right). \tag{4}$$

□

Lemma 2. *When both firms choose the TPL mode, we can know the optimal decisions:*

$$p_{ti}^* = \frac{(2\alpha+\eta)d + (\eta+1)\alpha w}{4\alpha^2 - \eta^2},$$
$$\Pi_{ti}^* = \left[\frac{(2\alpha+\eta)d + (\eta+1)\alpha w}{4\alpha^2 - \eta^2} - w\right] \cdot \frac{(2\alpha+\eta)\alpha d + (\eta-\alpha)(\eta+1)\alpha w}{4\alpha^2 - \eta^2}. \tag{5}$$

Proof. Similarly, let the first derivative of Π_{ti} with respect to p_{ti} equal zero. $\partial\Pi_{ti}/\partial p_{ti} = d - 2\alpha p_{ti} + \eta p_{tj} + \alpha w = 0$, $p_{ti} = d + \eta p_{tj} + \alpha w/2\alpha$ in the same way,

$$\begin{aligned} p_{tj} &= \frac{d + \eta p_{ti} + \alpha w}{2\alpha}; p_{ti}^* = \frac{(2\alpha+\eta)d + (\eta+1)\alpha w}{4\alpha^2 - \eta^2}, \\ D_{ti}^* &= \frac{(2\alpha+\eta)\alpha d + (\eta-\alpha)(\eta+1)\alpha w}{4\alpha^2 - \eta^2}, \\ \Pi_{ti}^* &= (p_{ti} - w)D_{ti} = \left[\frac{(2\alpha+\eta)d + (\eta+1)\alpha w}{4\alpha^2 - \eta^2} - w\right] \\ &\quad \cdot \frac{(2\alpha+\eta)\alpha d + (\eta-\alpha)(\eta+1)\alpha w}{4\alpha^2 - \eta^2}. \end{aligned} \tag{6}$$

When both firms choose TPL, their price strategy is also affected by the cost factor. Interestingly, despite the increase in costs, the market demand also increased, which is due to the monopoly of TPL providers. Firms can get more profit by setting higher prices. □

Lemma 3. *We have $p_{ti}^* > p_{si}^*$; $D_{ti}^* > D_{si}^*$; when $\alpha < (\eta+1)/4$, $\Pi_{ti}^* > \Pi_{si}^*$.*

Proof. We compare firms' decisions in two cases. We have $p_{ti} - p_{si} = (\eta+1)\alpha w/4\alpha^2 - \eta^2 > 0$, so $p_{ti}^* > p_{si}^*$. The same as before, $D_{ti} - D_{si} = (\eta-\alpha)(\eta+1)\alpha w/4\alpha^2 - \eta^2 > 0$, we get

$$\begin{aligned} D_{ti}^* > D_{si}^*, \Pi_{ti} - \Pi_{si} &= \frac{\alpha d}{2\alpha - \eta} \cdot \frac{(\eta-\alpha)(\eta+1)\alpha w}{4\alpha^2 - \eta^2} \\ &\quad + \frac{\left[(\eta+1)\alpha - 4\alpha^2 + \eta^2\right]w}{4\alpha^2 - \eta^2} \\ &\quad \cdot \frac{(2\alpha+\eta)\alpha d + (\eta-\alpha)(\eta+1)\alpha w}{4\alpha^2 - \eta^2}. \end{aligned} \tag{7}$$

It is obvious that $\alpha d/2\alpha - \eta \cdot (\eta-\alpha)\ (\eta+1)\alpha w/4\alpha^2 - \eta^2 > 0$ only when $[(\eta+1)\alpha - 4\alpha^2 + \eta^2]w/4\alpha^2 - \eta^2 \cdot (2\alpha+\eta)\alpha d + (\eta-\alpha)(\eta+1)\alpha w/4\alpha^2 - \eta^2 > 0$, $\Pi_{ti} > \Pi_{si}$. However, we can know $D_{ti} = (2\alpha+\eta)\alpha d + (\eta-\alpha)(\eta+1)\alpha w/4\alpha^2 - \eta^2 > 0$, so only if $\alpha < \eta + 1/4$, $\Pi_{ti} > \Pi_{si}$.

We usually believe that firms choose the e-commerce platform SDL mode that can save costs and obtain greater benefits. However, this is not the case. We can see from Lemma 3 that when firms choose the TPL mode, they set a higher price to cover the cost. And currently, consumer demand in the market is greater than that of consumers who choose the e-commerce platform SDL mode. When the price sensitivity of consumers and the cross-price sensitivity of enterprises meet a certain relationship, firms will get more benefits if they choose the TPL mode. □

Corollary 1. *In the case that two competitive firms choose the same logistics distribution mode, it is more advantageous for the two firms to choose the TPL mode.*

Proof. Through the comparison in Lemma 3, we find that when two competitive firms choose the same logistics mode, they can get higher returns when they choose TPL than when they choose the e-commerce platform SDL mode.

3.2. Competition with Differentiated Choices. We consider Stackelberg game, when the two firms make decisions independently, and each aims to maximize their profit. The Stackelberg game decision structure is assumed as follows: one firm (the leader) decides upon its logistics distribution mode T_a^L and price p^L first; and then the other firm (the follower) chooses its logistics distribution mode T_a^F and the corresponding price p^F. We assume that, in the Stackelberg game, two firms will not choose the same logistics distribution mode. There can be only one unique solution to maximize each firm's profit if the follower chooses the same logistics distribution mode. It is given in Section 3.1. If the leader chooses the e-commerce platform SDL mode, and the follower chooses the TPL mode, we can estimate the expected demand for each firm. All consumers whose valuation satisfies $U_s^L = v - \alpha p^L - \beta T_s^L \geq 0$ would buy from the leader. And if they valuation satisfies $U_t^F = \theta v - \alpha p^F - \beta T_t^F \geq 0$, they would consider buying from the follower. From the consumer's utility maximization principle, we can characterize the demand functions (8), as follows:

$$\begin{aligned} D_s^L &= 1 - \frac{\alpha\left(p^L - p^F\right) + \beta\left(T_s^L - T_t^F\right)}{1 - \theta}, \\ D_t^F &= \frac{\alpha\left(\theta p^L - p^F\right) + \beta\left(\theta T_s^L - T_t^F\right)}{\theta(1 - \theta)}. \end{aligned} \tag{8}$$

Based on the demand functions, we can establish the profit function (9) of two firms. The leader's priority is to maximize profit Π_t^L by optimally deciding the price p^L:

$$\Pi_s^L = p^L D_s^L = p^L\left[1 - \frac{\alpha\left(p^L - p^F\right) + \beta\left(T_s^L - T_t^F\right)}{1-\theta}\right]. \quad (9)$$

Similarly, the follower will try to maximize profit Π_s^F by deciding the price as

$$\Pi_t^F = \left(p^F - w\right)D_t^F = \left(p^F - w\right)\left[\frac{\alpha\left(\theta p^L - p^F\right) + \beta\left(\theta T_s^L - T_t^F\right)}{\theta(1-\theta)}\right]. \quad (10)$$

We derive the equilibrium condition through backward induction.

Lemma 4. *If the leader chooses the e-commerce platform SDL mode T_s^L and the follower chooses the TPL mode T_t^F, for a given p^L, the follower would react by choosing a price $p^F = \theta/2p^L + \beta(\theta T_s^L - T_t^F) + \alpha w/2\alpha$; and the leader chooses price $p^L = 1-\theta+\alpha p^F - \beta(T_s^L - T_t^F)/2\alpha$ to maximize his profit.*

Proof. According to the demand and profit function established above, we can get $\Pi_s^L = p^L D_s^L = p^L[1-\alpha(p^L - p^F) + \beta(T_s^L - T_t^F)/1-\theta]$ taking the first derivative with respect to p^L and setting it equal to 0; then, $\partial\Pi_s^L/\partial p^L = 1-\theta-2\alpha p^L + \alpha p^F - \beta(T_s^L - T_t^F)/1-\theta = 0$, and we get $p^L = 1-\theta+\alpha p^F - \beta(T_s^L - T_t^F)/2\alpha$.

Similarly, $\Pi_t^F = (p^F - w)D_t^F = (p^F - w)[\alpha(\theta p^L - p^F) + \beta(\theta T_s^L - T_t^F)/\theta(1-\theta)]$, taking the first derivative with respect to p^F, and then, $\partial\Pi_t^F/\partial p^F = 0$, $p^F = \theta/2\, p^L + \beta(\theta T_s^L - T_t^F) + \alpha w/2\alpha$.

Lemma 5. *Based on Lemma 4, if the leader chooses the e-commerce platform SDL mode, and the follower chooses the TPL mode, the optimal prices are given by*

$$p^{L*} = \frac{2(1-\theta) + \beta\left[(\theta-2)T_s^L + T_t^F\right] + \alpha w}{(4-\theta)\alpha},$$
$$p^{F*} = \frac{\theta(1-\theta) + \beta\theta\left(T_s^L + T_t^F\right) + 2\left(\alpha w - \beta T_t^F\right)}{(4-\theta)\alpha}. \quad (11)$$

We can obtain the demands as

$$D_s^L = \frac{2(1-\theta) + \beta\left[(\theta-2)T_t^F + T_s^L\right] + \alpha w}{(4-\theta)(1-\theta)},$$
$$D_t^F = \frac{\theta(1-\theta) + \beta\left[(\theta-2)T_t^F + \theta T_s^L\right] + (\theta-2)\alpha w}{(4-\theta)(1-\theta)\theta}. \quad (12)$$

The profits are given by

$$\Pi_s^{L*} = p^L D_t^L = \frac{\left[A + \beta\left((\theta-2)T_s^L + T_t^F\right)\right]\cdot\left[A + \beta\left((\theta-2)T_t^F + T_s^L\right)\right]}{B},$$
$$\Pi_t^{F*} = \left(p^F - w\right)D_t^F = \frac{\left[C + \beta\left((\theta-2)T_t^F + \theta T_s^L\right)\right]^2}{\theta B}, \quad (13)$$

where $A = 2(1-\theta) + \alpha w$, $B = (4-\theta)^2(1-\theta)\alpha$, $C = \theta(1-\theta) + (\theta-2)\alpha w$

Proof. By backward recursion, p^F is substituted into p^L:

$$p^L = \frac{1-\theta+\alpha p^F - \beta\left(T_s^L - T_t^F\right)}{2\alpha} = \frac{2(1-\theta) + \beta\left[(\theta-2)T_s^L + T_t^F\right] + \alpha w + \alpha\theta p^L}{4\alpha}. \quad (14)$$

So,

$$p^L = \frac{2(1-\theta) + \beta\left[(\theta-2)T_s^L + T_t^F\right] + \alpha w}{(4-\theta)\alpha},$$
$$p^F = \frac{\theta(1-\theta) + \beta\left[(\theta-2)T_t^F + \theta T_s^L\right] + 2\alpha w}{(4-\theta)\alpha}. \quad (15)$$

Based on the price function $D_s^L = 2(1-\theta) + \beta[(\theta-2)T_t^F + T_s^L] + \alpha w/(4-\theta)(1-\theta)$, and, $D_t^F = \theta(1-\theta) + \beta[(\theta-2)T_t^F + \theta T_s^L] + (\theta-2)\alpha w/(4-\theta)((1-\theta)\theta)$. By substituting the price function and demand function back into the profit function, two profit models of firms can be obtained.

Lemma 6. *Firms' decisions are influenced by consumer behavior. (i) As consumer price sensitivity increases, the two firms choose to lower their prices. (ii) The higher the consumer's acceptance of the TPL mode, the greater the demand to the follower.*

Proof. For

$$\frac{\partial p^L}{\partial\alpha} = -\frac{2(1-\theta) + \beta\left[(\theta-2)T_s^L + T_t^F\right]}{(4-\theta)\alpha^2} < 0, \frac{\partial p^F}{\partial\alpha} = -\frac{\theta(1-\theta) + \beta\left[(\theta-2)T_t^F + \theta T_s^L\right]}{(4-\theta)\alpha^2} < 0 \quad (16)$$

it is obvious that as consumer price sensitivity increases, the two firms choose to lower their prices. As the consumer's acceptance of the TPL mode increases, consumers prefer to the TPL mode, and the demand to the follower is higher. The leader needs to take certain measures to ensure his own benefits. □

Lemma 7. *When $\beta/\alpha > w/(3-\theta)T_t^F - 2T_s^L$, we have $p^L > p^F$; $D_s^L > D_t^F$; $\Pi_s^L < \Pi_t^F$.*

Proof. We have $p^L - p^F = (\theta-2)(1-\theta) + \beta[(\theta-3)T_s^L + 2T_t^F] + \alpha w/(4-\theta)\alpha$, only when $\beta[(\theta-3)T_s^L + 2T_t^F] + \alpha w > (2-\theta)(1-\theta) > 0$, which means that $\beta/\alpha > w/(3-\theta)T_t^F - 2T_s^L p^L > p^F; D_s^L - D_t^F = \theta(1-\theta) + \beta(\theta-1)(\theta-2)T_t^F + 2\alpha w/(4-\theta)(1-\theta)\theta > 0$,. So, $D_s^L > D_t^F$; Clearly, $\Pi_s^L < \Pi_t^F$.

Lemma 7 has several important managerial implications. Firms need to consider consumer behavior when making their pricing and logistics decisions. When $\beta/\alpha > w/[(3-\theta)T_t^F - 2T_s^L]$, to occupy more market shares and obtain higher profits, the leader chooses to set higher prices. The leaders have certain decision-making advantages, and they can take the lead in choosing favorable pricing and logistics strategies. Without loss of generality, we can characterize the demand functions the same as before. If the leader chooses the TPL mode, and the follower chooses the SDL mode, the consumer's utility is $U_t^L = \theta v - \alpha p^L - \beta T_t^L$, $U_s^F = v - \alpha p^F - \beta T_s^F$. The demand functions are as follows: $D_t^L = \alpha(\theta p^F - p^L) + \beta(\theta T_s^F - T_t^L)/\theta(1-\theta), D_s^F = 1 - \alpha \quad (p^F - p^L) + \beta(T_s^F - T_t^L)/1-\theta$.

Similarly, the leader's profit is $\Pi_t^L = (p^L - w) \alpha(\theta p^F - p^L) + \beta(\theta T_s^F - T_t^L)/\theta(1-\theta)$, and the follower's profit is $\Pi_s^F = p^F[1 - \alpha(p^F - p^L) + \beta(T_s^F - T_t^L)/1-\theta]$. □

Lemma 8. *If the leader chooses the TPL mode T_t^L, and the follower chooses the e-commerce platform SDL mode T_s^F, the leader sets his price as $p^L = \theta/2p^F + \beta(\theta T_s^F - T_t^L) + \alpha w/2\alpha$, and the follower would react by choosing a price as $p^F = 1 - \theta + \alpha p^L - \beta(T_s^F - T_t^L)/2\alpha$*

Proof. Same to the Proofs above, we get $\Pi_t^L = (p^L - w)[\alpha(\theta p^F - p^L) + \beta(\theta T_s^F - T_t^L)/\theta(1-\theta)]$, taking the first derivative with respect to p^L and setting it equal to 0; then, $\partial \Pi_t^L/\partial p^L = 0$

$\alpha\theta p^F - 2\alpha p^L + \beta(\theta T_s^F - T_t^L) + \alpha w/\theta(1-\theta) = 0$, $p^L = \theta/2 \, p^F + \beta(\theta T_s^F - T_t^L) + \alpha w/2\alpha$; similarly, $\Pi_s^F = p^F D_s^F = p^F [1 - \alpha(p^F - p^L) + \beta(T_s^F - T_t^L)/1-\theta]$, taking the first derivative with respect to p^F and setting it equal to 0; then, $\partial \Pi_s^F/\partial p^F = 1 - \theta - 2\alpha p^F + \alpha p^L - \beta(T_s^F - T_t^L)/1-\theta = 0$, $p^F = 1 - \theta + \alpha p^L - \beta(T_s^F - T_t^L)/2\alpha$. □

Lemma 9. *If the leader chooses the TPL mode T_t^L, and the follower chooses the e-commerce platform SDL mode T_s^F, the optimal prices are given by*

$$p^{L*} = \frac{\theta(1-\theta) + \beta\left[(\theta-2)T_t^L + \theta T_s^F\right] + 2\alpha w}{(4-\theta)\alpha},$$
$$p^{F*} = \frac{2(1-\theta) + \beta\left[T_t^L + (\theta-2)T_s^F\right] + \alpha w}{(4-\theta)\alpha}. \quad (17)$$

We can obtain the demands as

$$D_t^L = \frac{\theta(1-\theta) + \beta\left[(\theta-2)T_t^L + \theta T_s^F\right] + (\theta-2)\alpha w}{(4-\theta)(1-\theta)\theta},$$
$$D_s^F = \frac{2(1-\theta) + \beta\left[(\theta-2)T_t^L + T_s^F\right] + \alpha w}{(4-\theta)(1-\theta)}. \quad (18)$$

The profits are given by

$$\Pi_t^{L*} = \frac{\left[C + \beta\left((\theta-2)T_t^L + \theta T_s^F\right)\right]^2}{\theta B},$$
$$\Pi_s^{F*} = \frac{\left[A + \beta\left((\theta-2)T_s^F + T_t^L\right)\right]\left[A + \beta\left((\theta-2)T_t^L + T_s^F\right)\right]}{B}. \quad (19)$$

Proof. By backward recursion, p^L is substituted into p^F,

$$p^F = \frac{2(1-\theta) + \alpha\theta p^F + \beta\left[T_t^L + (\theta-2)T_s^F\right] + \alpha w}{4\alpha}. \quad (20)$$

So

$$p^F = \frac{2(1-\theta) + \beta\left[T_s^L + (\theta-2)T_s^F\right] + \alpha w}{(4-\theta)\alpha},$$
$$p^L = \frac{\theta(1-\theta) + \beta\left[(\theta-2)T_t^L + \theta T_s^F\right] + 2\alpha w}{(4-\theta)\alpha}. \quad (21)$$

Based on the price function,

$$D_t^L = \frac{\theta(1-\theta) + \beta\left[(\theta-2)T_t^L + \theta T_s^F\right] + (\theta-2)\alpha w}{(4-\theta)(1-\theta)\theta},$$
$$D_s^F = \frac{2(1-\theta) + \beta\left[(\theta-2)T_t^L + T_s^F\right] + \alpha w}{(4-\theta)(1-\theta)}. \quad (22)$$

By substituting the price function and demand function back into the profit function, two profit models of firms can be obtained. □

Lemma 10. *When $\beta < (2-\theta)(1-\theta) - \alpha w/ \quad (\theta-3) T_t^L + 2T_s^F$, then, $p^L < p^F$; $D_t^L < D_s^F$; $D_t^L < D_s^F$.*

Proof. We can know that $p^F - p^L = (2-\theta)(1-\theta) + \beta[(3-\theta)T_t^L - 2T_s^F] - \alpha w$, only when $\beta < (2-\theta)(1-\theta) - \alpha w/(\theta-3)T_t^L + 2T_s^F$, and we have $p^F - p^L > 0$, $p^F > p^L$; $D_s^F - D_t^L = \theta(1-\theta) + \beta[(\theta-1)(\theta-2)\, T_t^L] + 2\alpha w > 0$, which means $D_s^F > D_t^L$;

Clearly, $\Pi_t^L > \Pi_s^F$.

If the leader chooses the TPL mode (T_t^L), and the follower chooses the e-commerce platform SDL mode (T_s^F), the follower sets his pricing strategies based on the leader's strategy. Considering the behavioral factors of consumers, when the price and service sensitivity, as well as the channel sensitivity, satisfy a certain relationship, the follower sets a higher price than the leader according to the market conditions to obtain more profit. □

Lemma 11. *If* $\beta > \alpha w + (\theta - 2)(1-\theta)/(3-\theta)T_t - 2T_s$, $p_s^L > p_t^L$; $D_s^L > D_t^L$; $\Pi_s^L < \Pi_t^L$.

Proof. $p_s^L - p_t^L = (2-\theta)(1-\theta) + \beta[(3-\theta)T_t - 2T_s] - \alpha w/(4-\theta)\alpha$; only when $\beta > \alpha w + (\theta-2)(1-\theta)/\ (3-\theta)T_t - 2T_s$, $p_s^L - p_t^L > 0, p_s^L > p_t^L$; $D_s^L > D_t^L$, $D_s^L - D_t^L = \theta(1-\theta) + \beta[(\theta-1)(\theta-2)T_t] + 2\alpha w/(4-\theta)\ (1-\theta)\ \theta > 0$. Clearly, $\Pi_s^L < \Pi_t^L$. □

Lemma 12. *If* $\beta > \alpha w + (\theta - 2)(1-\theta)/(3-\theta)T_t - 2T_s$, $p_s^F > p_t^F$; $D_s^F > D_t^F$; $\Pi_s^F < \Pi_t^F$.

Proof.

$$\begin{aligned}
p_s^F - p_t^F &= \frac{(2-\theta)(1-\theta) + \beta[(3-\theta)T_t - 2T_s] - \alpha w}{(4-\theta)\alpha},\\
\beta &> \frac{\alpha w + (\theta-2)(1-\theta)}{(3-\theta)T_t - 2T_s},\\
p_s^F - p_t^F &> 0, p_s^F > p_t^F,\\
D_s^F - D_t^F &= \frac{\theta(1-\theta) + \beta[(\theta-1)(\theta-2)T_t] + 2\alpha w}{(4-\theta)(1-\theta)\theta} > 0,\\
D_s^F &> D_t^F,\\
\Pi_s^F &< \Pi_t^F.
\end{aligned} \tag{23}$$

From Lemmas 11 and 12, we can see that, in the Stackelberg game, we consider the consumer behavior factor, when the leader chooses the e-commerce platform SDL mode, and the follower chooses the TPL mode, which is more beneficial to the leader. When the leader chooses the TPL mode, the follower chooses the e-commerce platform SDL mode, which is more beneficial to the follower. □

Corollary 2. *Under the Stackelberg game scenario, we believe that competitive e-commerce firms tend to choose the TPL mode to obtain higher profits.*

Proof. From Propositions 5 and 6, it is obvious that $\Pi_s^L > \Pi_t^L$; $\Pi_s^F > \Pi_t^F$. Under the Stackelberg game scenario, competitive e-commerce firms tend to choose the e-commerce platform SDL mode to obtain higher profits. □

3.3. Parametric Analysis. This paper examines the pricing and logistics strategies of competitive e-commerce firms considering consumer behavior. In this section, we discuss how consumer behavioral and other factors influence the decisions of competitive firms. We assume that consumers have price sensitivity α; service sensitivity β; and acceptance of the TPL mode is $\theta, \theta \in (0,1)$. The demand sensitivities to its cross price are η. The cost price that shall be paid to the TPL supplier is w. Under the two firms with simultaneous choices scenario, we believe that there is only price competition between the two firms and consider the price sensitivity of consumers.

Corollary 3. *When both firms choose the e-commerce platform SDL mode, as the price sensitivity of consumers (α) increases, the profits of two firms (Π_{si}) will decrease. As the price competition between enterprises (η) increases, the profits of two firms (Π_{si}) will increase.*

Proof. When both firms choose the e-commerce platform SDL mode,

$$\frac{\partial \Pi_{si}}{\partial \alpha} = -\frac{d^2(2\alpha+\eta)}{2\alpha-\eta} < 0; \frac{\partial \Pi_{si}}{\partial \eta} = \frac{2\eta\alpha d^2}{(2\alpha-\eta)^3} > 0. \tag{24}$$

□

Corollary 4. *When both firms choose the TPL mode, as the price sensitivity of consumers α increases, the profits of the two firms Π_{ti} will decrease. As the price competition between enterprises η increases, the profits of two firms Π_{ti} will increase.*

Proof. When both firms choose TPL mode,

$$\frac{\partial \Pi_{ti}}{\partial \alpha} = -\frac{2d}{(2\alpha-\eta)^2} < 0; \frac{\partial \Pi_{ti}}{\partial \eta} > 0. \tag{25}$$

Under the Stackelberg game scenario, there are not only the price and service sensitivity of consumers, but also the logistics channels preferences of consumers, when the leader chooses the e-commerce platform SDL mode T_s^L and the follower chooses the TPL mode T_t^F. □

Corollary 5. *As consumer price sensitivity increases, both firms will reduce their prices. For the leader, when $T_t/T_s > 2-\theta$, as consumer service sensitivity β increases, the leader will set higher prices. For the follower, when $T_t/T_s < \theta/2-\theta$, as consumer service sensitivity β increases, the follower will set higher prices.*

Proof. We have

$$\frac{\partial p^L}{\partial \beta} = \frac{(\theta-2)T_s^L + T_t^F}{(4-\theta)\alpha}, \frac{\partial p^F}{\partial \beta} = \frac{(\theta-2)T_t^F + \theta T_s^L}{(4-\theta)\alpha}. \tag{26}$$

For the leader, when $T_t/T_s > 2-\theta$, $\partial p^L/\partial \beta > 0$, as consumer service sensitivity (β) increases, the leader will set higher prices. For the follower, when $T_t/T_s < \theta/2-\theta$, $\partial p^F/\partial \beta > 0$ as consumer service sensitivity (β) increases, the follower will set higher prices.

If the leader chooses the TPL mode T_t^L, the follower will choose the e-commerce platform SDL mode (T_s^F). □

Corollary 6. *As consumer price sensitivity increases, both firms will reduce their prices. For the leader, when $T_t/T_s < \theta/2-\theta$, as consumer service sensitivity β increases,* *the leader will set higher prices. For the follower, when $T_t/T_s > 2 - \theta$, as consumer service sensitivity β increases, the follower will set higher prices.*

Proof. If the leader chooses the TPL mode, and the follower chooses the e-commerce platform SDL mode, we have $\partial p^L/\partial\beta = (\theta-2)T_t^L + \theta T_s^F/(4-\theta)\alpha$, $\partial p^F/\partial\beta = (\theta-2)T_s^F + T_t^L/(4-\theta)\alpha$. For the leader, when $T_t/T_s < \theta/2 - \theta, \partial p^L/\partial\beta > 0$ as consumer service sensitivity β increases, the leader will set higher prices. For the follower, when $T_t/T_s > 2 - \theta$, $\partial p^F/\partial\beta > 0$ as consumer service sensitivity β increases, the follower will set higher prices. □

4. Numerical Analyses

In this section, we present a numerical analysis to test the previous inference and explore some properties. To explore the pricing and logistics policies in competitive e-commerce firms, we put forward the parameters value in Section 4.1 to make a mapping analysis in Section 4.2 to illustrate the influence of parameters on p_i, D_i, Π_i.

4.1. Basic Parameters. In numerical analysis, we considered that there was completely competitive market, and the total market share is 1. E-commerce firms compete between the market shares by choosing pricing and logistics strategies. We consider two different competitive scenarios, one of which is the simultaneous decision scenario, and the other is the Stackelberg game scenario. Under the simultaneous decision scenario, we only consider the consumer price sensitivity factor, as well as competitive factor among e-commerce firms. Without loss of generality, we set basic market demand $d = 10$; cost price shall be paid to the TPL supplier $w = 5$; the consumer price sensitivity factor $\alpha \in (0,1)$; the competitive factor among e-commerce firms $\eta \in (0,1)$. Under the Stackelberg game scenario, there are not only behavioral factors of consumers, but also competition among logistics distribution modes. Consumers have price sensitivity $\alpha \in (0,1)$; service sensitivity $\beta \in (0,1)$; and acceptance of the TPL mode is $\theta, \theta \in (0,1)$. We assume that the logistics service level $T_s = 5, T_t = 7, \theta = 0.8$.

4.2. Sensitivity Analysis. This section analyzes the influence of price sensitivity coefficient, service sensitivity coefficient and competition factors on e-commerce enterprise price strategy, consumer demand, and enterprise optimal profit under different scenarios. In the part of numerical cases, Matlab is used for numerical analysis. In the previous analysis, we can know that consumer behavior and competition between enterprises and game order have a great impact on the decision-making of e-commerce enterprises. This paper divides consumer behavior into price sensitivity, service sensitivity, and acceptance of logistics mode. We plot the relationship between sensitivity and price, consumer demand, and corporate income and further analyze their trends and impacts. In addition, this paper further discusses the impact of e-commerce enterprise's price and logistics decision-making on enterprise income under different game situations.

First, we can draw the price strategies and revenue situation of two competitive e-commerce firms when they choose different logistics distribution modes, respectively, under the simultaneous decision-making situation. After that, we discuss the influence of decision-making order of two e-commerce firms on price and logistics strategies under the situation of Stackelberg game. Finally, sensitivity analysis is conducted on each parameter to explore the influence of consumer behavior on the pricing and logistics policies of competitive e-commerce firms.

From the Figures 5(a) and 5(b), we can get the price decisions and revenue change trend of two competitive e-commerce firms under the simultaneous decision-making situation. Figures describe the price decision changes of two firms when they simultaneously choose the e-commerce platform SDL mode and TPL. To fit the situation, we consider the right half of the image. The change trend of the two images is basically the same. With the increase of consumer price sensitivity, firms choose to lower their prices to attract more consumers.

Figures 6(a) and 6(b) show the demand functions in the simultaneous decision situation. Under the simultaneous decision situation, only price competition exists among firms. Consumer demand is only affected by factors related to price. From Figure 6, we can see that the change trend of consumer demand is basically the same as Figure 5. When the price sensitivity of consumers increases, it means that consumers pay more attention to price changes, and their willingness to pay will decrease, thus affecting their demand.

Interestingly, we can find from Figures 7(a) and 7(b) that, under the two logistics modes, the profits of the two firms show a fission trend of increasing first and then decreasing. When the price sensitivity of consumers and the cross-price sensitivity of firms are lower than a certain threshold, the income of two firms increases sharply after a gentle increase. When the parameters exceed the threshold value, the profit of the firms decreases sharply and then decreases gently. The profit functions in the middle interval have a linear relationship with the sensitivity parameters. No matter what kind of logistics mode a firm chooses, it hopes to find this threshold to maximize its benefits. Meanwhile, all other parameters remain the same, and as the price sensitivity of consumers increases, the profits of two firms will decrease; as the price competition between enterprises increases, the profits of two firms will increase.

Similarly, Figures 8(a) and 8(b) show the price strategies and profits comparison. As the crossed price sensitivity increases, namely, the competition intensity between two firms increases, firms choose to increase their prices to ensure their competitive advantages and occupy the dominant position in the market. In Figure 8(a), we further compare the price strategies of different logistics modes. Obviously, when the two firms choose the TPL mode, the price set by them is higher than that of the e-commerce platform SDL mode, which is due to the need of outsourcing costs. We also compare the two profit functions in

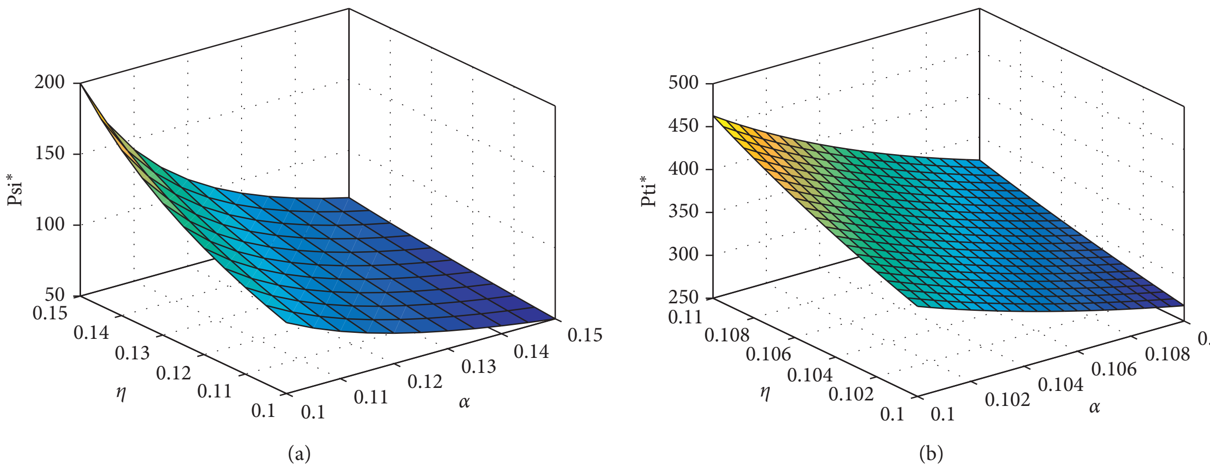

Figure 5: Price strategies in the simultaneous decision situation. (a) p^*_{si} (b) p^*_{ti}.

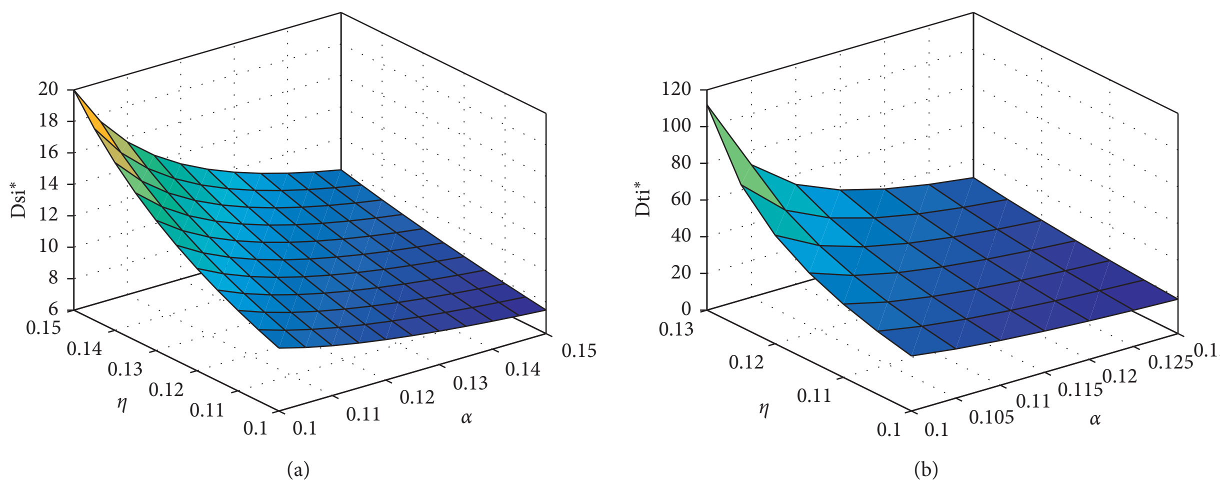

Figure 6: Demand functions in the simultaneous decision situation. (a) D^*_{si} (b) D^*_{ti}.

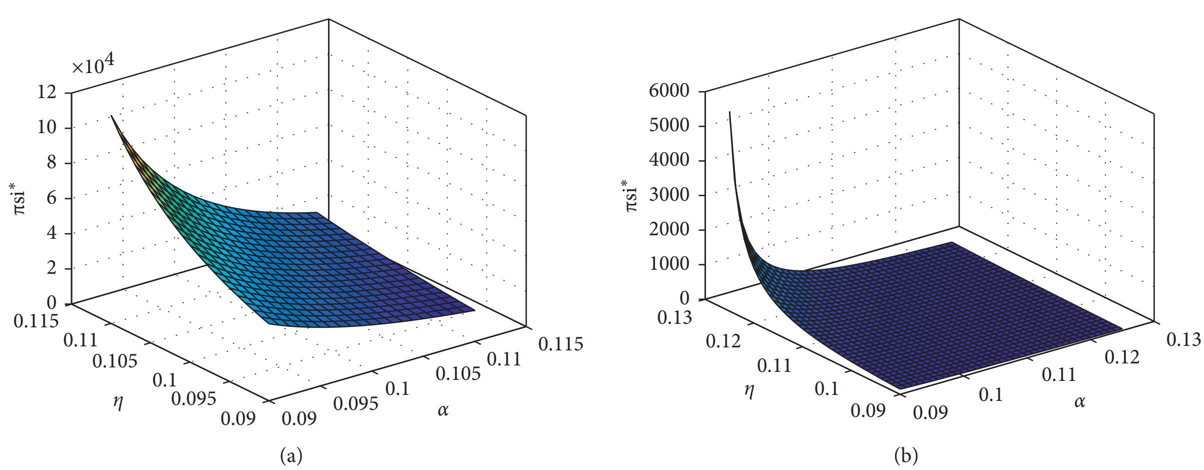

Figure 7: Profits in the simultaneous decision situation. (a) Π_{si} (b) Π_{ti}.

Figure 8(b). It can be seen that the revenue of choosing third-party logistics before functional fission is higher than that of choosing independent distribution model of e-commerce platform. After the fission, the profit of choosing the TPL is in the absolute advantage at the beginning and then lower than that of the SDL. In general, it is more advantageous for firms to choose TPL rather than SDL.

Figures 9(a) and 9(b) show the price strategies under the Stackelberg game. We discuss the decision-making of e-commerce firms in the context of the Stackelberg game. In

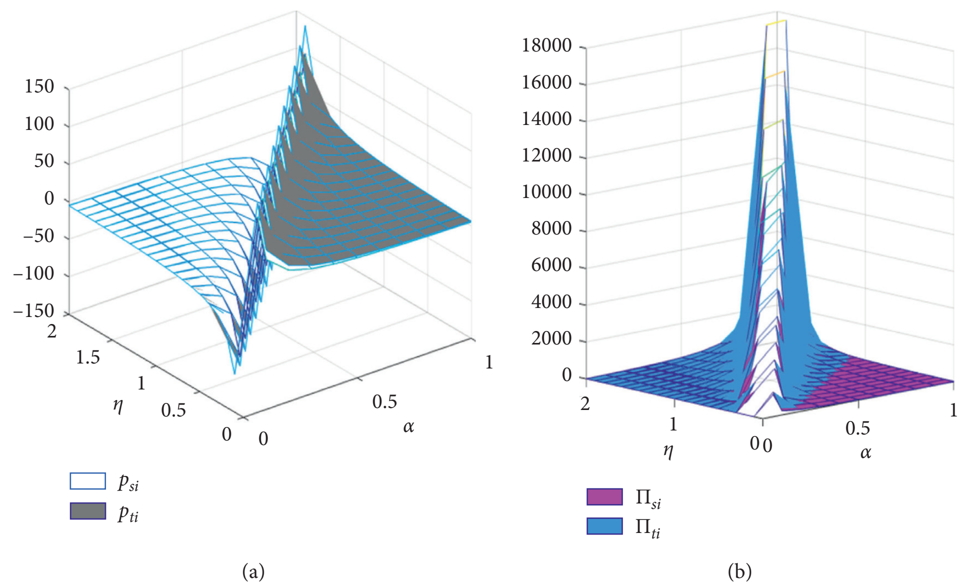

FIGURE 8: Price strategies and profits comparison. (a) p_{si} and p_{ti}. (b) Π_{si} and Π_{ti}.

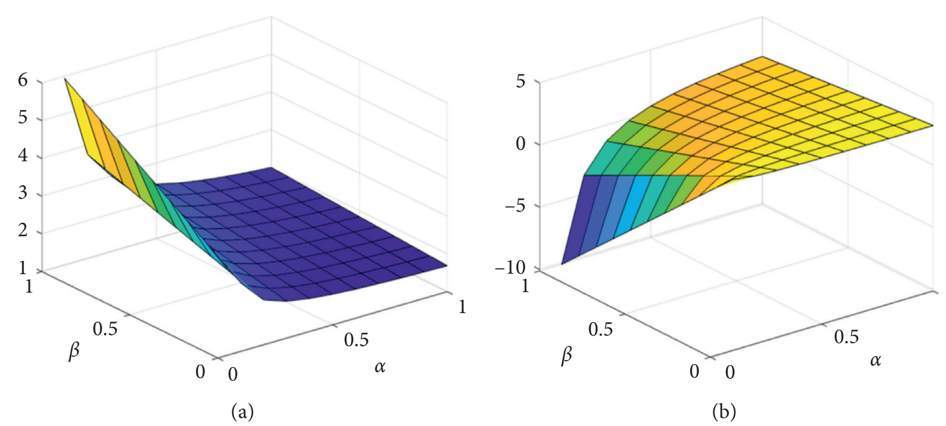

FIGURE 9: Price strategies under the Stackelberg game. (a) p^L (b) p^F.

the previous paper, we analyzed two decision sequences of two e-commerce firms in the Stackelberg game. One is that the leading firm chooses SDL, and the follower chooses TPL. The other is that the leading firm chooses the TPL, and the follower firm chooses SDL. If the leader chooses the e-commerce platform SDL mode, the follower will choose the TPL mode. We can see from Figure 9 that the behavior of consumers has a great impact on the decision-making of firms. Figure 9(a) shows that when the leading firm chooses SDL, with the increase of consumer price sensitivity, the price strategy of firm presents a downward trend. At the same time, when other parameters remain unchanged, with the increase of consumer service sensitivity, consumers pay less attention to price changes, and firms can slightly increase their prices. Figure 9(b) represents the price decision of the following firm. The follower tends to react according to the decisions of the leaders. In the figure, prices of firms follow the trend of growth, because when the leading firm reduces prices, to ensure the balance of the market, the following firm will increase its prices accordingly. By comparing the price strategies of the two firms, we find that the price set by the leader is higher than that of the follower at the beginning, and then with the increase of consumer price sensitivity, the price of the leader will gradually be lower than that of the follower. Consumer demand is showing the same trend.

Figures 10(a) and 10(b) show the price strategies and profits comparison. Similarly, we have compared the profits of the two firms, and it is obvious that the follower who chooses the TPL mode benefits much more than the leader who chooses the SDL mode. Although the leader of the firms occupies the priority to choose, the follower firm can make the best response according to the leader's decision. Showing the advantage of late mover. In addition, the choice of TPL mode to a certain extent occupies the price advantage, which can attract more consumers. If the leader chooses the TPL

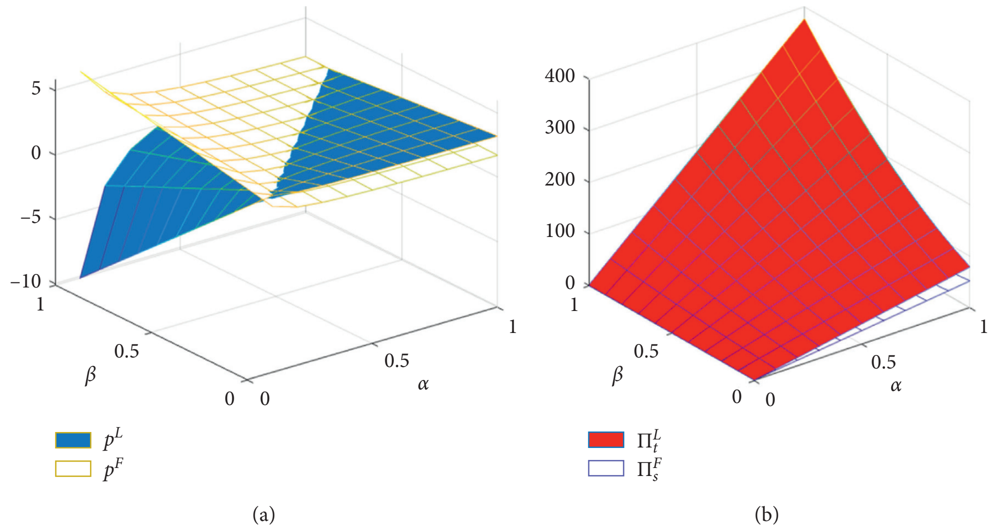

FIGURE 10: Price strategies and profits comparison. (a) p^L and p^F (b) Π_t^L and Π_s^F.

mode, the follower will choose the e-commerce platform SDL mode. When the leading firm chooses the TPL mode, and the follower firm chooses the SDL mode, we also make a comparative analysis of price strategies and profit. As can be seen from Figure 10, when the leading firm chooses the TPL, and the follower firm chooses the SDL, their price strategies and benefits are exactly interchangeable with the former decision-making situation. The price setting of the leading firm presents an upward trend with the increase of consumer price sensitivity, and the corresponding follower firm presents a downward trend. The earnings of the leader grow faster than those of the follower. By comprehensively comparing the two different logistics strategies of two competitive e-commerce firms in the context of the Stackelberg game, we can find that no matter what the decision-making order is, firms that choose the TPL mode tend to have higher profits. In addition, the decision-making of e-commerce firms is affected by the factors of consumer behavior, which plays a decisive role in the market demand.

5. Conclusions

This paper considers the pricing and logistics policies in competitive e-commerce firms. There are two logistics distribution modes with service competition: the e-commerce platform self-distribution mode and third-party logistics mode. When determining their pricing and logistics strategies, e-commerce firms need to consider not only the behavioral factors of consumers, but also the competitiveness among firms. Motivated by previous literature that seldom used models to study logistics selection, and the factors considered are relatively simple, we develop a model with consumer behavior under the simultaneous decision situation and Stackelberg game. We analyze the pricing and logistics strategies change trend of e-commerce firms under different decision-making situations and find out the optimal strategy for e-commerce firms. First, we consider the price game between two firms in the simultaneous decision situation. We analyze the price strategy and revenue change of two firms when they choose the same logistics mode. Then, under the Stackelberg game, we consider the price sensitivity and service sensitivity of consumers to establish the consumer utility model. Based on the utility model, we get the consumer demand function. Finally, we propose numerical analysis to identify our models. Based on our research, some main conclusions are obtained as follows:

(1) Consumer behavior factors have a great impact on the decision-making of e-commerce firms; not only that, but the competitiveness between e-commerce firms also has an impact on their decision-making.

(2) Under different decision-making situations, the price strategies of e-commerce firms are different, and the game right relationship among channel members has great influence on decision-making.

(3) In general, no matter what decision-making situation the two firms are in, the TPL mode makes e-commerce firms more convenient and profitable. This is consistent with the fact that a large number of firms choose logistics outsourcing in real life.

There are some limitations in this paper. Firstly, more factors can be considered in the choice of logistics mode and pricing strategies among competitive e-commerce firms. Secondly, we only consider the sensitivity of the consumer and ignore other characteristics of the customer. Thirdly, a large amount of actual data is needed to further verify the completeness and applicability of the conclusion. Therefore, further research can be done based on this paper.

Data Availability

No data were used in this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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Research Article

Spatiotemporal Evolution and Influencing Factors of China's Agricultural Environmental Efficiency

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Taking the 30 Chinese provinces in 2000–2018 as the objects, this paper measures their agricultural environmental efficiencies (AEEs) with slack-based measure (SBM) containing an undesired output. Then, the features of the spatiotemporal evolution of AEE in China were explored on ArcGIS, and the factors affecting the AEE were analyzed with a geodetector. The results show that there is a huge provincial gap in AEE across China; most provinces with a high AEE belong to eastern coastal region, while most inland provinces had a relatively low AEE. Except for a few years, the AEEs in eastern, central, and western regions changed very slightly, and the eastern region had a higher AEE level than central and western regions. The results of spatiotemporal evolution show that, with the elapse of time, the high-AEE provinces gradually shifted to the inland; the AEE trend varied from province to province; the provinces were highly polarized in terms of AEE. The AEE is mainly affected by the following factors: fiscal expenditure, fertilizer intensity, pesticide intensity, and economic growth.

1. Introduction

Since the reform and opening-up, China has achieved remarkable achievements in agricultural development. The agricultural modernization of China is accompanied by a continuous growth in mechanization level. As a result, the food yield has been significantly improved, and the production of profitable economic crops has been increased step by step. Suffice to say, agriculture, as the pillar of national economy, fills the food bowls of the 1.4 billion population and underpins the construction and development of the national economy. However, agriculture in China still follows the production model of high consumption, high input, and high waste. Lots of chemical fertilizers, pesticides, and diesel are consumed in agricultural production activities. Thus, a huge number of resources is expended, and pollutants are discharged in large quantities, resulting in an increasingly prominent contradiction between agricultural development and environmental protection.

At present, more than 80% of farmland in China has exceeded their land bearing capacity. Besides, the high carbon emissions of agricultural production activities pose severe challenges to agricultural eco-environment, food security, and human health. Against this backdrop, it is imminent to promote the sustainable development of agriculture. To coordinate the development between agricultural growth, resource utilization, and eco-environmental protection, it is of great significance to include the pollutants generated in agricultural production into the analysis framework of agricultural environmental efficiency (AEE) and adopt scientific measures to evaluate the current AEE level of China [1–3].

2. Literature Review

The emergence of problems in agricultural environment has drawn academic attention towards the AEE. Most relevant studies choose to analyze the AEE of only one country. For example, Thirtle et al. [4] evaluated the agricultural environmental production efficiency of South Africa in 1947–1991, with the total factor productivity (TFP) index. By input direction function (IDF), Tamini et al. [5] assessed the technical and environmental efficiencies of 210 farms in Quebec, Canada. Greta et al. [6] analyzed the AEE of Italy based on the directional distance function (DDF).

Some scholars incorporated resource and environmental factors into the traditional evaluation of agricultural production efficiency. For instance, Ruttan [7] and Arcelus and Arocena [8] researched the global agricultural production efficiency under the dual constraints of resource and environment and found that environmental pollution brings a certain efficiency loss to agricultural development. Nanere et al. [9] corrected the agricultural productivity of Australia and learned that the corrected agricultural productivity is, to a certain extent, affected by the cost of environmental damage.

Moreover, some scholars focused their energy on comparing the AEEs between countries. For instance, Nin et al. [10] compared the agricultural environmental production efficiencies of some developing countries. Hoang and Alauddin [11] adopted data envelopment analysis (DEA) model to measure and compare the economic, environmental, and biological efficiencies of agricultural production among members of Organization for Economic Cooperation and Development (OECD). Vlontzos et al. [12] used the DEA model to evaluate the total factor environmental efficiencies of the agricultural sector in European Union (EU) states in 2001–2008 and contrasted the results of different states.

To clarify the paths of AEE improvement, some scholars probed deep into the factors affecting the AEE. Fernandez-Cornejo and Shuway [13] studied the long-term impact of agricultural research investment and international technology transfer on the productivity of agriculture. Dono et al. [14] found that strengthening the management of climate change helps to elevate the environmental development efficiency of agriculture. After evaluating the environmental efficiency of farmlands in the Netherlands, Skevas et al. [15] explored how the AEE is affected by crop subsidy, crop rotation, and weather changes.

So far, fruitful results have been achieved on the measurement of AEE and its influencing factors. But the existing research faces two shortcomings: (1) most AEE evaluations treat the non-point source pollution of agriculture as the undesired output, failing to consider the carbon emission in agricultural production; (2) few studies have tackled the spatiotemporal evolution of the AEE. To solve these problems, this paper sets up an evaluation system for the AEE with agricultural carbon emissions as the undesired output and adopted the slack-based measure (SBM) to evaluate the AEE of each province in China [16]. Furthermore, ArcGIS was introduced to analyze how the provincial AEEs evolved in space and time. Finally, the influencing factors of the AEE were investigated with geodetector.

3. Methodology

3.1. SBM. Agricultural production is an important activity of humans to impact and respond to regional eco-environment. The results of agricultural production include both good outputs like food and bad outputs like carbon dioxide and non-point source pollution of agriculture. If the bad outputs are ignored, the AEE evaluation might be biased [17]. If directly included in the evaluation system, the bad outputs cannot be handled by early models like Charnes-Cooper-Rhodes (CCR) model and Banker-Chames-Cooper (BCC) model, which follow the maximum output hypothesis.

To solve the problem, Hailu and Veeman [18] directly incorporated bad outputs as the inputs in the efficiency evaluation system, but this practice does not meet the actual situation of production activities. Besides, traditional models like CCR and BCC, as radial, angular measurement methods, are not good at measuring the slackness in inputs and outputs, making it hard to effectively improve efficiency.

Therefore, Tone [19] established a nonradial, non-angular model called SBM. On the one hand, the model examines the slackness of inputs and outputs, facilitating efficiency improvement; on the other hand, the model perfectly solves the bad outputs in agricultural production. This paper intends to include agricultural carbon emissions as a bad output of AEE. The traditional CCR and BCC models cannot effectively evaluate efficiencies in the presence of bad output (s). This problem is perfectly solved by the SBM. To this end, this paper chooses to evaluate China's AEE using the SBM.

Suppose the target production system contains n decision-making units (DMUs). During the operation of each DMU, T production elements $X = (x_1, x_2, \ldots, x_t) \in R_+^T$ are needed to produce U desired outputs $Y = (y_1, y_2, \ldots, y_u) \in R_+^U$ and V undesired outputs $B = (b_1, b_2, \ldots, b_v) \in R_+^V$. Let $Q = \{(x, y, b)$: x can produce y and $b\}$ be the set of all possible production scenarios and $\mathrm{DMU}_k = (x_k, y_k, b_k)$ be the k-th DMU to be estimated. Then, the SBM to evaluate the efficiency of the k-th DMU DMU_k can be established as

$$
\begin{aligned}
\sigma^* &= \min \frac{1 - (1/T)\sum_{t=1}^{T}\left(s_t^{x-}/x_{tk}\right)}{1 + (1/U+V)\left(\sum_{u=1}^{U}\left(s_u^{y+}/y_{uk}\right) + \sum_{v=1}^{V}\left(s_v^{b-}/b_{vk}\right)\right)},\\
\text{s.t.}\quad x_{tk} &= \sum_{k=1}^{n} x_{tk}\lambda_k + s_t^{x-}, \quad t = 1, \ldots, T,\\
y_{uk} &= \sum_{k=1}^{n} y_{uk}\lambda_k - s_u^{y+}, \quad u = 1, \ldots, U,\\
b_{vk} &= \sum_{k=1}^{n} b_{vk}\lambda_k + s_v^{b-}, \quad v = 1, \ldots, V,\\
&\lambda > 0, s_t^{x-}, s_u^{y+}, s_v^{b-} \geq 0,
\end{aligned}
\tag{1}
$$

where $\sigma*$, T, U, and V are the AEE (evaluation target), the number of inputs, the number of desired outputs, and the number of undesired outputs, respectively, s_t^{x-}, s_v^{b-} are the redundancy of inputs and undesired outputs, respectively, s_u^{y+} is the deficiency of desired outputs, (x_{tk}, y_{uk}, b_{vk}) is the input-output of DMU_k, λ is the weight of DMU_k, σ^* is an index in the range of [0, 1]: if $\sigma^* = 1$, no input or output is redundant or deficient, and DMU_k is on the efficient frontier of DEA; if $0 < \sigma^* < 1$, at least one of $s_t^{x-}, s_u^{y+}, s_v^{b-}$ is nonzero; i.e., the DMU_k is not on the efficient frontier of DEA.

3.2. Geodetector Model. As an important statistical approach, geodetector has been widely used in nature and social sciences. It can not only reveal the spatial differentiation of AEE but also disclose the factors leading to the differentiation. The principle of the model is as follows: if the dependent variable is closely correlated with an independent variable, i.e., the change of dependent variable is greatly affected by the independent variable, then the two variables are strongly similar in spatial distribution. Inspired by Wang et al. [20], geodetector can be expressed as

$$q = 1 - \frac{1}{N\sigma^2} \sum_{z=1}^{L} N_z \sigma_z^2, \tag{2}$$

where L is the number of layers/classes of AEE influencing factors, N is the number of units in the region, N_z is the number of units on layer h, σ^2 and σ_z^2 are the discrete variances of the AEE of the region, and the AEE on layer h, q is the influence of each factor on AEE. The q value falls between 0 and 1; the closer it is to 1, the greater the influence of the factor on AEE is; the closer it is to 0, the smaller the influence of the factor on AEE is.

3.3. Inputs and Outputs. In this paper, the AEE is a technical efficiency that incorporates agricultural environment and resources into the analysis framework. It is defined as the largest agricultural output and the smallest agricultural pollutant emissions under fixed agricultural production inputs. Therefore, an evaluation system was established to measure the inputs and outputs of the AEE. Table 1 provides the details on each input and output.

Drawing on Greta et al. [6] and data availability, the inputs were determined as labor input, land input, mechanical input, fertilizer input, and agricultural irrigation. Specifically, labor input refers to the number of employees of agriculture, forestry, animal husbandry, and fishery (AFAF) in each province; land input was measured by the total sowing area of crops in each province; mechanical input was substituted by the total mechanical power of agriculture in each province; fertilizer input was characterized by the pure amount of agricultural fertilizer applied in each province; agricultural irrigation was measured by the effective irrigation area of agriculture in each province.

The outputs were divided into desired and undesired output. The desired output is the total output of AFAF in each province. The AFAFs in relevant statistical yearbooks are nominal values, including the price factor. To eliminate the effect of deflation, the gross domestic product (GDP) index was adopted to deflate the total AFAF output to the actual AFAF output with the constant price of 2000.

The undesired output is the environmental pollutant generated during agricultural production. With the mechanization of China's agricultural production, carbon dioxide becomes the leading pollutant generated by agricultural production. Meanwhile, the greenhouse effect brought by carbon dioxide has an increasing impact on agricultural production. Hence, this paper chooses agricultural carbon emissions as the undesired output to measure the AEE. Referring to Johnson et al. [21], every agricultural production activity, ranging from fertilizing, ploughing, and irrigation, could generate carbon dioxide. Inspired by their research, this paper holds that agricultural carbon emissions mainly come from three paths: (1) the indispensable production elements of agriculture, including fertilizer, pesticide, agricultural film, and diesel, which produces lots of carbon dioxide; (2) ploughing, a key operation in agricultural production, which emits a huge amount of organic carbon to the air; (3) the consumption of electricity and other energies in agricultural irrigation, which is also a large carbon emitter. Therefore, the agricultural carbon emissions can be estimated by

$$C = \sum C_i = \sum E_i * \gamma_i, \tag{3}$$

where C is the total amount of carbon dioxide generated in agricultural activities, C_i is the carbon emissions of each carbon source (six carbon sources were selected, namely, fertilizer, pesticide, agricultural film, diesel, ploughing, and agricultural irrigation), E_i is the number of each carbon source, γ_i is the carbon emission coefficient of each carbon source. Referring to Dubey and Lal [22], the carbon emission coefficients of fertilizer, pesticide, agricultural film, diesel, ploughing, and agricultural irrigation were set to 0.8956 kg/kg, 4.9341 kg/kg, 5.18 kg/kg, 0.5927 kg/kg, 3.126 kg/hm^2, and 25 kg/hm^2, respectively.

3.4. Influencing Factors. The AEE measurement involves agricultural environment and resources. Therefore, the AEE is greatly affected by a series of factors, such as economic, social, technology, and institution factors. In light of the literature, this paper determines seven factors that may affect the AEE: economic growth (X1), capitalization level (X2), fertilizer intensity (X3), pesticide intensity (X4), agricultural planting structure (X5), agricultural scientific progress (X6), and fiscal expenditure (X7). The meaning of each factor is given in Table 2.

3.5. Data Sources. Considering data availability and completeness, the sample period was set to 2000–2018, and the samples were determined as 30 provinces in China. Tibet, Hong Kong, Macao, and Taiwan were not considered, owing to the severe lack of data on multiple indices. The data

Table 1: Input-output system of the AEE.

Type	Name	Meaning	Unit
Inputs	Labor input	Total number of AFAF employees	10,000 persons
	Land input	Total sowing area of crops	1,000 hectares
	Mechanical input	Total mechanical power of agriculture	10,000 kW
	Fertilizer input	Pure amount of agricultural fertilizer applied	10,000 tons
	Agricultural irrigation	Effective area of agricultural irrigation	1,000 hectares
Outputs	Total AFAF output	Actual AFAF output with the constant price of 2000	100 million yuan
	Agricultural carbon emissions	Carbon emissions estimated by formula (3)	10,000 tons

sources for the inputs, outputs, and influencing factors include *China Statistical Yearbooks*, *Rural Statistical Yearbooks of China*, *China Environment Yearbooks*, and the local statistical yearbooks of the 30 provinces, all of which were released in 2001–2009.

4. Results and Discussion

4.1. Measuring Results on the AEE. Based on the input-output evaluation system of the AEE and the data on each input and output, this paper measures the AEEs of the 30 Chinese provinces in 2000–2018. The results in Table 3 show a clear disparity between the provinces in AEE.

Beijing and Hainan fell on the efficient frontier throughout the sample period, with a mean AEE of 1. Shanghai fell on that frontier in most years but failed to reach the frontier in a few years. Guangdong, Fujian, Liaoning, and Tianjin achieved relatively high mean AEEs (>0.8) in the sample period. The above provinces all realized desirable AEEs, and all belong to the economically developed coastal region in eastern China.

On the contrary, Hebei, Henan, Heilongjiang, Shaanxi, Anhui, Gansu, Shanxi, and Ningxia had relatively low mean AEEs (<0.6) in the sample period. The mean AEEs of Shaanxi and Ningxia were particularly low, standing at 0.4569 and 0.4562, respectively. There is a huge potential for them to improve their AEEs in future.

In short, most Chinese provinces with a high AEE belong to eastern coastal region, while most inland provinces had a relatively low AEE. To realize agricultural sustainable development, China must pay attention to the agricultural environment and resources in central and western provinces.

To further analyze the regional difference of AEE in China, Figure 1 presents the AEE trends across the country and in eastern, central, and western regions during 2000–2018. In terms of temporal evolution, the nationwide AEE and the AEEs in the three regions did not change greatly in the sample period, except for a slight variation in a few years (2014). Besides, the three regions exhibited a certain difference in AEE. In the sample period, the mean AEE in eastern region was as high as 0.8276, far greater than the national average of 0.6998; the mean AEEs in central and western regions were 0.6124 and 0.6356, and both are below the national average. To sum up, China had a generally low AEE, and the AEE in eastern region was much higher than that in central or western region.

There are two main reasons for the above results. On the one hand, since the reform and opening-up, eastern region modernized agriculture at a far faster speed than central and western regions. The agricultural productivity in this region has been significantly improved, thanks to the adequate capital, advanced agricultural machinery, and modern technology of agricultural production. That is why the eastern region outputs far more agricultural products than the central and western regions. On the other hand, the agricultural eco-environment of the central and western regions is more vulnerable than that of eastern region. The two regions are lacking in farmland water conservancy and road facilities. Coupled with the poor environmental awareness of local farmers, these factors contribute to the poor performance of the two regions in AEE.

4.2. Spatiotemporal Evolution of AEE. The AEEs of the 30 provinces were divided into 5 levels and given different colors (Figure 2) on ArcGIS 10.4.1. The results of 2000 and 2018 were selected for comparative analysis. In terms of space, high AEE provinces shifted towards the inland in central and western regions from 2000 to 2018. In terms of time, there were 4 first-level provinces in both 2000 and 2018; the number of second-level provinces increased from 4 in 2000 to 8 in 2018; the number of third-level provinces dropped deeply from 10 in 2000 to 7 in 2018; the number of provinces fell from 9 in 2000 to 6 in 2018; the number of fifth-level provinces increased from 3 in 2000 to 5 in 2018. Overall, most provinces belong to the low-efficient third to fifth levels, whether in 2000 or 2018. Hence, most provinces in China had relatively low AEEs and were highly polarized in terms of AEE.

4.3. Influencing Factors of the AEE. Based on formula (2) and Table 2, four time nodes were selected, including 2000, 2006, 2012, and 2018, to naturally divide the influencing factors into five categories. Then, geodetector was adopted to analyze each influencing factor. The results are recorded in Table 4.

According to the results of Table 4, the different factors exerted different impacts on China's AEE through the years. By multiyear average, the influencing factors of China's AEE can be ranked in turn as fiscal expenditure, fertilizer intensity, pesticide intensity, economic growth, agricultural planting structure, agricultural scientific progress, and capitalization level. Among them, the influence of four

Table 2: Influencing factors of the AEE.

Index layer	Formula	Unit
Economic growth (X1)	Total AFAF output/total rural population	10,000 yuan/ person
Capitalization level (X2)	Fixed asset investment of AFAF/number of AFAF employees	10,000 yuan/ person
Fertilizer intensity (X3)	Pure amount of agricultural fertilizer applied/total sowing area of crops	Ton/hectare
Pesticide intensity (X4)	Total amount of pesticide applied/total sowing area of crops	Ton/hectare
Agricultural planting structure (X5)	Total sowing area of food crops/total sowing area of crops	%
Agricultural scientific progress (X6)	Internal expenditure on research and development (R&D)/GDP	%
Fiscal expenditure (X6)	Fiscal expenditure on agriculture, forestry, and water (AFW) affairs/total fiscal expenditure	%

Table 3: Measured AEEs of each province in China during 2000–2018.

Province	2000	2002	2004	2006	2008	2010	2012	2014	2016	2018	Mean
Beijing	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Hainan	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Shanghai	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.7609	0.7714	0.9527
Guangdong	0.8869	0.8828	0.9207	0.9551	0.9172	0.9044	0.8784	0.8089	0.8467	0.8618	0.8830
Fujian	0.9369	0.8461	0.8733	0.8721	0.8945	0.9049	0.8793	0.8209	0.8674	0.8941	0.8753
Liaoning	0.8265	0.8091	0.8526	0.8627	0.8683	0.8305	0.8154	0.7646	0.7938	0.7998	0.8217
Tianjin	0.8495	0.7442	0.7248	0.7492	0.7673	0.7745	0.7785	0.7658	1.0000	1.0000	0.8108
Sichuan	0.7471	0.7867	0.8404	0.8583	0.8122	0.7961	0.7775	0.7078	0.7716	0.7907	0.7850
Jiangsu	0.7600	0.7448	0.7750	0.7786	0.7787	0.7862	0.7602	0.7383	0.8156	0.8256	0.7762
Zhejiang	0.8208	0.7791	0.7617	0.7633	0.7884	0.7691	0.7656	0.7120	0.7597	0.7661	0.7654
Qinghai	0.7591	0.7702	0.7815	0.7993	0.7785	0.7372	0.7127	0.6552	0.7356	0.7424	0.7327
Chongqing	0.6958	0.6959	0.7343	0.7172	0.7423	0.7364	0.7160	0.6784	0.7186	0.6977	0.7128
Jiangxi	0.7404	0.7375	0.7317	0.7285	0.7085	0.6844	0.6847	0.6479	0.7095	0.7465	0.7073
Hunan	0.7420	0.7442	0.7145	0.7269	0.7311	0.7104	0.6973	0.6282	0.6903	0.6828	0.7024
Jilin	0.7296	0.7293	0.6919	0.7179	0.7104	0.6801	0.6472	0.6127	0.6940	0.7037	0.6903
Guizhou	0.7451	0.7288	0.7384	0.7173	0.6928	0.6856	0.6393	0.6016	0.6709	0.7243	0.6867
Guangxi	0.6623	0.6563	0.6693	0.7095	0.7143	0.7032	0.6842	0.6369	0.6467	0.6517	0.6704
Yunnan	0.6632	0.6367	0.6569	0.6913	0.6783	0.6450	0.6070	0.5714	0.6008	0.6516	0.6348
Inner Mongolia	0.7470	0.7185	0.6716	0.7013	0.6108	0.5929	0.5694	0.5305	0.5891	0.5853	0.6262
Shandong	0.6673	0.5900	0.5606	0.5759	0.6430	0.6340	0.6277	0.5836	0.6605	0.7147	0.6194
Hubei	0.6671	0.6389	0.6436	0.6423	0.6251	0.6236	0.5806	0.5352	0.6100	0.6398	0.6157
Xinjiang	0.7000	0.6521	0.6261	0.6487	0.6015	0.5867	0.5450	0.5107	0.5769	0.5969	0.6083
Hebei	0.6533	0.5963	0.5405	0.5778	0.6087	0.5991	0.5963	0.5556	0.6479	0.6766	0.5988
Henan	0.6170	0.6056	0.5928	0.6232	0.6315	0.6056	0.5887	0.5377	0.5830	0.6059	0.5928
Heilongjiang	0.5932	0.5695	0.6122	0.6169	0.5637	0.5565	0.5345	0.5246	0.6142	0.6187	0.5760
Shaanxi	0.4870	0.5336	0.5639	0.6093	0.6086	0.5588	0.5112	0.5103	0.5215	0.5257	0.5653
Anhui	0.6155	0.6065	0.5746	0.5755	0.5720	0.5562	0.5524	0.4927	0.5582	0.5672	0.5578
Gansu	0.5662	0.5318	0.5414	0.5522	0.5274	0.5075	0.4980	0.4423	0.4999	0.5236	0.5131
Shanxi	0.4931	0.4994	0.4751	0.4693	0.4764	0.4619	0.4540	0.4059	0.4467	0.4514	0.4569
Ningxia	0.4604	0.4622	0.4460	0.4710	0.4411	0.4588	0.4219	0.3922	0.4586	0.4678	0.4562

Note. For the lack of space, only the AEEs in even-numbered years are given in the above table.

factors gradually weakened, and that of three gradually strengthened. In addition, the main factors affecting China's AEE are fiscal expenditure, fertilizer intensity, pesticide intensity, and economic growth, whose multiyear average q values were greater than 0.35.

With a multiyear average q value of 0.6071, fiscal expenditure is the leading factor affecting the AEE among all influencing factors. In China, the government policies on agriculture play an important role in agriculture sustainable development. The sustainable development of agriculture is a systematic and complex project, calling for massive funds from the government. The government's fiscal input is indispensable to elevating farmer income, improving agricultural infrastructure, accelerating development of agricultural resources, and enhancing eco-environmental protection. In 2000, China only spent 36.71 billion yuan on AFW affairs. Nineteen years later, the spending increased to 2,108.59 billion yuan, up by more than 57 times.

With a multiyear average q value of 0.4760, fertilizer intensity is the second largest influencing factor of the AEE. Currently, Chinese agriculture bears the typical features of petroleum agriculture. The most prominent

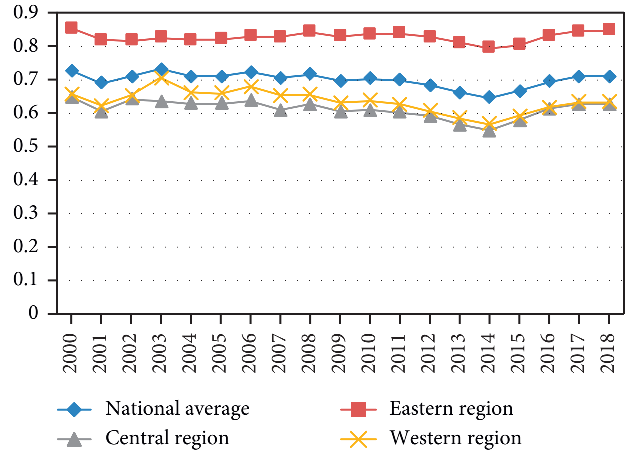

Figure 1: AEE trends across the country and in eastern, central, and western regions.

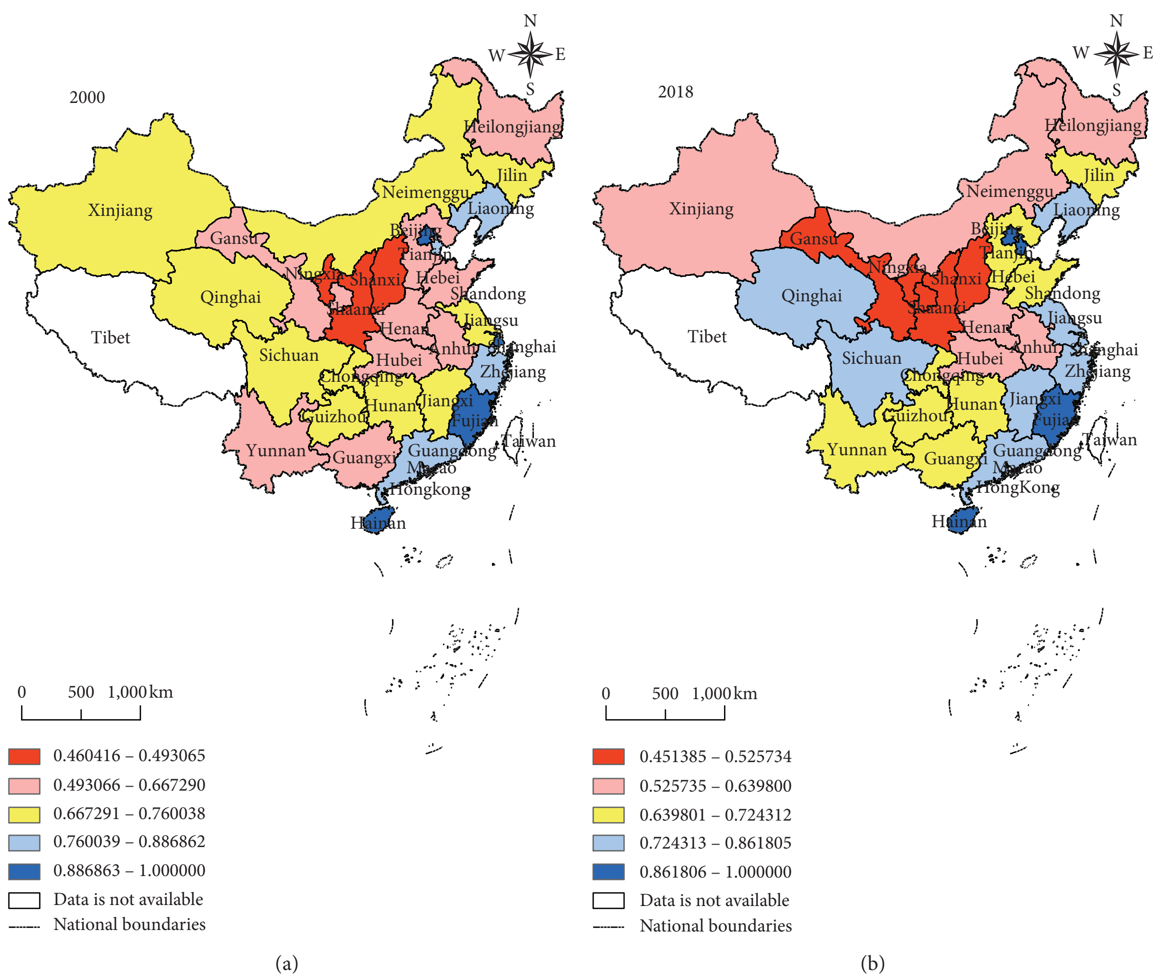

Figure 2: Spatiotemporal evolution of China's AEEs.

feature is the mass application of agricultural production materials like fertilizers. Despite promoting crop yield, increasing fertilizer intensity brings problems like soil hardening, fertility decline, non-point source pollution, and environmental degradation. To solve the eco-environmental problems in agricultural development, China must gradually reduce the fertilizer application and transform its agriculture from "petroleum agriculture" to "green agriculture."

With a multiyear average q value of 0.4211, pesticide intensity has a direct bearing on the AEE. Hoang and Nguyen [23] also found that a high pesticide intensity

Table 4: Analysis results on AEE influencing factors.

Ranking	2000 q	2006 q	2012 q	2018 q	Multiyear average q	Trend of influence
X1	0.6648	0.4465	0.3374	0.1147	0.3536	↓
X2	0.2556	0.1901	0.2056	0.2026	0.1074	↓
X3	0.2693	0.2535	0.2029	0.4051	0.4760	↑
X4	0.4324	0.4632	0.3612	0.4814	0.4211	↑
X5	0.3466	0.2487	0.2133	0.2161	0.2992	↓
X6	0.1751	0.2788	0.2593	0.4257	0.2844	↑
X7	0.2766	0.2484	0.5422	0.3979	0.6071	↓

reduces the environmental efficiency on farms. To effectively prevent agricultural pests, China has applied more and more pesticides in recent years. Admittedly, pesticides can alleviate agricultural pest harm to some extent. However, pesticide application leads to nonnegligible pollutions to the air, water, and soil. Apart from being a major source of agricultural greenhouse gases, pesticides could evaporate to the air, causing severe pollution to the air environment.

With a multiyear average q value of 0.3536, economic growth exerts an important impact on the AEE. This factor is a mixed blessing to the AEE. For one thing, farmers earn more thanks to economic growth and tend to buy more production materials like pesticides and fertilizers; the mass application of these materials will negatively affect the AEE. For another reason, with economic growth, farmers will gradually phase out traditional high-pollution production materials and switch to organic fertilizers and green pest control technologies, which help to promote the AEE. Regardless of the perspective, economic growth does have a nonnegligible influencing on agricultural eco-environment.

Furthermore, agricultural planting structure, agricultural scientific progress, and capitalization level have certain impacts on the AEE, but their impacts are not significant. Their multiyear average q values were 0.2992, 0.2844, and 0.1074, respectively. In the sample period, the three factors did not greatly improve the AEE. In future, the government policies should focus on optimizing agricultural planting structure, speeding up agricultural technology progress, and increasing fixed asset investment in agriculture.

5. Conclusions

This paper sets up an evaluation system for the AEE and evaluated the AEEs of 30 Chinese provinces with an SBM containing an undesired output. In addition, ArcGIS was adopted to analyze the spatiotemporal evolution of the AEE, and geodetector was implemented to examine the factors affecting the AEE. The results show the following:

(1) In the sample period, there is a huge provincial gap in AEE across China. Beijing, Hainan, Guangdong, Fujian, Liaoning, and Tianjin achieved desirable AEEs in the sample period, which averaged at above 0.8. Meanwhile, Hebei, Henan, Heilongjiang, Shaanxi, Anhui, Gansu, Shanxi, and Ningxia failed to achieve satisfactory AEEs in that period, which averaged at below 0.6. Overall, most provinces with a high AEE belong to eastern coastal region, while most inland provinces had a relatively low AEE.

(2) In the sample period, the AEEs in eastern, central, and western regions followed basically the same trend. Except for a few years, the AEEs in these regions remained stable, without any significant changes. By the AEE, the three regions can be ranked in descending order as eastern region (0.8276), western region (0.6124), and central region (0.6356). That is, the eastern region had the highest AEE in the sample period, followed by the western region, while the central region ranked at the bottom.

(3) The results of spatiotemporal evolution show that, in terms of space, the spatial distribution of China's AEE changed with time; in particular, the high AEE provinces shifted towards the inland from eastern coastal region. In terms of time, the AEEs in most provinces were not satisfactory, despite some changes in the sample period, calling for further improvement in future.

(4) Geodetector results suggest that the multiyear average q values of fiscal expenditure, fertilizer intensity, pesticide intensity, and economic growth stood at 0.6071, 0.4760, 0.4211, and 0.3536, respectively. These factors are the leading impactors on China's AEE. The AEE was also affected by agricultural planting structure, agricultural scientific progress, and capitalization level, but the effects of these three factors were not significant.

Data Availability

The data used in this article were obtained from the Statistical Yearbook published by the National Bureau of Statistics of China.

Conflicts of Interest

The author declares no conflicts of interest.

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Research Article

Impact of Rule Governance Mechanism on Project Performance in Public Rental Housing PPP Projects: Control Rights as a Moderating Variable

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Exploring the relationship among rule governance mechanism, project control rights allocation, and project performance in public-private partnership (PPP) projects is of great significance for optimizing control rights allocation and governance mechanism to improve project performance of PPP projects. Previous studies have mainly focused on the impact of contractual governance or rule-based governance on the performance of PPP projects, and the research on the allocation of project control rights into the analysis framework is insufficient. The goal of this study is to explore the moderating effect of the allocation of project control rights on the project's rule mechanism affecting project performance. Based on the theoretical analysis and literature review, three hypotheses are put forward, and the hypotheses are tested by structural equation model using the large sample data collected by questionnaire survey. This study shows that both the rule governance mechanism and project control right allocation have a positive impact on project performance, and the allocation of project control right has a negative moderating effect on the impact of rule governance mechanism on project performance. The public characteristics of PPP projects determine that it is inappropriate for social capital to have too much project control rights. The degree of project control rights owned by social capital should be balanced with the rule governance in the dynamic management process.

1. Introduction

With the continuous acceleration of urbanization, there are varying degrees of housing difficulties for relatively low-income groups due to the increasing urban floating population around the world. In order to solve such problems, a series of housing security plans have been launched in different countries and regions [1,2], such as the public rental housing (PRH) scheme launched by the Chinese Government in 2014 [3]. However, due to the lack of professional knowledge and experience in operation and management related to public housing in most countries, operation models of public sectors are often extensive and resource allocation efficiency is low, leading to the failure of public housing projects in the implementation process [4]. In order to improve the construction quality and operation efficiency of public rental housing and relieve the financial pressure of the government, governments of various countries began to introduce PPP mode into the construction of public housing [4–6]. However, since the private sector aims at maximizing profits [7], the private sector may have self-interested investment behavior in the process of cooperation, focusing only on the realization of its own interests and ignoring the common interests. In addition, the different participation of project participants in the project will cause information asymmetry among project stakeholders, which will further aggravate the occurrence of moral hazard and opportunistic behavior in the private sector [8]. These factors will reduce the cooperation efficiency of the organization and aggravates the possibility of project failure.

Recent research demonstrates that rule governance can coordinate the contractual relationship between the public sector and the private sector, inhibit the occurrence of opportunistic behavior, and improve the cooperative surplus. In PRH PPP projects, rule governance refers to a series of institutional arrangements that reduce transaction costs and improve cooperation efficiency throughout the life cycle of the project. It guarantees the success of the project by stipulating the project benefit distribution scheme, project investment and financing structure, project performance evaluation scheme, and so on. As the core of the project governance structure, the allocation of project control right is closely related to the project risk sharing and reward incentive mechanism [9], which also makes the rule governance mechanism under different control allocation schemes have different effects on project performance [10]. Therefore, the regulatory role of project control right should be considered in the impact of rule governance mechanism on project performance.

However, the research on control rights of PPP projects mostly focuses on discussing the allocation of control rights based on incomplete contract theory [10], which has not revealed the mechanism of action of PPP project company's control right allocation on project rule governance. In view of this, from the perspective of rule governance, the research builds a model between rule governance, control rights allocation and project performance in PRH PPP projects and explores the path of rule governance on project performance. The main aim is to provide theoretical guidance for the government to formulate appropriate control countermeasures and thus to promote the healthy development of affordable housing. The results of this study are also applicable to the construction of public rental housing projects in other regions of the world and could be used for reference in other forms of affordable housing projects. The organization of this article is as follows. It starts off with a literature review in related fields and the introduction of the relevant theories of PPP governance, which is followed by a series of hypotheses. Then, the research approaches used in the study are presented and the proposed hypotheses are tested using a questionnaire survey. Finally, the study finishes with a discussion and a conclusion.

2. Theoretical Model and Research Hypothesis

2.1. Conceptual Framework

2.1.1. Rule Governance Mechanism. Contract is the most important carrier of rule governance, so research on rule governance focuses on contract governance and generally emphasizes that the responsibilities and obligations of each participant should be clarified through formal written contracts. Some scholars also believe that restricting rule governance to contract governance greatly weakens the effect of rule governance and is not conducive to improve project performance [11]. This paper believes that PPP projects belong to a full life cycle operation, and the output quality of the previous stage directly affects the cost control of the next stage. Hence, the governance of PPP project rules should include a series of institutional arrangements for reducing costs and increasing efficiency formed during the entire life cycle of the project.

In the decision-making stage of the project, the government departments mainly conduct feasibility demonstrations of economic, social, environmental, and other aspects of the project investment opportunities through feasibility studies and project proposals and choose the most suitable project from numerous project opportunities. Choosing the right project is one of the key factors for the success of a PPP project. The future economic feasibility and financial status of the project will affect the willingness of the private sector to participate in PPP projects and the performance behavior of future cooperation and then affect the overall performance of the project. Therefore, through the control of the key control nodes in the project selection link, we can avoid the development of bad projects, realize the survival of the fittest, and increase the possibility of project success. After the approval of the implementation plan, it is necessary to conduct social capital bidding. It is generally believed that the transparent bidding mechanism is not only conducive to improve the enthusiasm of social capital participation and ensure the quality of social capital participation [12] but also can use the cost of bidding mechanism to discover functions, reduce project transaction costs, and thus improve project performance [13]. After the partner is determined, it will enter the implementation stage, which mainly focuses on three aspects from the perspective of contract governance: risk sharing, income distribution, and project supervision. Among them, risk sharing and cooperation surplus sharing are essential to the success of PPP projects. A large amount of literature described how to allocate risk between the government and the private sector [14,15].

In addition, according to the "Government and Social Capital Cooperation Model Operation Guide" (Caijin [2014] No. 113) issued by the Ministry of Finance of the People's Republic of China in 2015 [16], the operation process of the PPP project is divided into 5 stages, and each stage corresponds to a number of core achievements. The specific content is shown in Figure 1. From the operation process and corresponding core documents of PPP projects, it can be seen that there are four rule governance mechanisms in the whole life cycle of PPP projects, namely, project selection mechanism, bidding mechanism, risk-return mechanism and project supervision mechanism. Through the high-quality governance of core achievements, project performance can be improved and project success can be promoted.

Therefore, rule governance is the basis of establishing the relationship between all parties, covering the project selection mechanism, bidding mechanism, risk-return mechanism, and project supervision mechanism from project identification to project handover.

(1) Project Selection Mechanism. The function of the project selection mechanism is to screen out public rental housing projects suitable for the PPP model, which mainly involves the government's evaluation of the feasibility study report, value for money report, financial affordability report, and implementation plan. In addition, the government should carefully demonstrate the social cost of the project, the

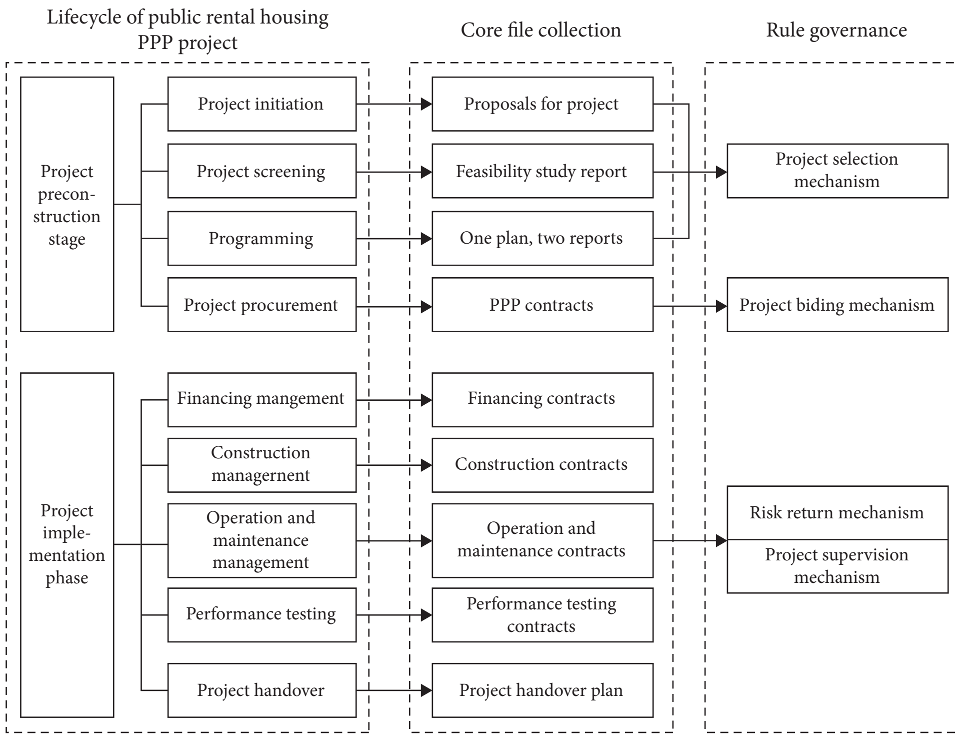

Figure 1: Content structure of rule governance of public rental housing PPP project.

affordability of the public, and the possible PPP pattern. Through literature review, theoretical analysis, and expert interviews, the key control nodes of project selection stage are obtained, including standardized project selection procedure, scientific project evaluation, efficient project decision-making, reasonable and feasible consultation report, and long-term demand stability demonstration of the project. Based on the above key nodes, the measurement indicators of project selection mechanism include fairness of prior process, scientificity of evaluation process, efficiency of in-process decision-making, feasibility of consulting scheme, practicality of policy support, and correctness of project selection.

(2) Project Bidding Mechanism. After the approval of the implementation plan, social capital bidding is needed. The function of this mechanism is to select the best bidder through reasonable competition. According to the "Government and Social Capital Cooperation Model Operation Guide" (Caijin [2014] No. 113) [16] and the "Administrative Measures for Government Procurement of Government and Social Capital Cooperation Projects" (Caiku [2014] No. 215) [17] issued by the Ministry of Finance of the People's Republic of China, the procurement process of social capital in PPP projects can be roughly divided into four steps: prequalification, preparation and review of procurement documents, confirmation of procurement results, and contract negotiation. Based on the key control nodes of the procurement process mentioned above, the measurement indexes of the bidding mechanism include compliance of procurement procedures, fairness of procurement review, standardization of procurement documents, rationality of procurement standards, competitiveness of procurement methods, and effectiveness of government supervision.

(3) Risk-Return Mechanism. After the bidding, it entered the implementation stage, which mainly focused on three aspects from the level of rule governance: risk sharing, income distribution, and project supervision. Risk sharing is a dynamic and complex process that is closely related to the contract. The contract structure of the project determines the basic structure of risk sharing and management. Therefore, the measurement of risk sharing is determined by the PPP contract guidelines issued by the Ministry of Finance of the People's Republic of China. Income distribution is a factor affecting whether the public and private parties can sign a contract and the project performance. However, due to the diverse profit models of projects, no specific measurement is involved. Therefore, the survey index and measurement items are arranged and set according to the interview and determined after professional discussion. Considering that the key to risk allocation is to adhere to the principle of risk-benefit equivalence, the allocation of risk mechanism and income mechanism is combined into risk-return mechanism. Specifically, the measurement indicators of risk-return mechanism include rationality of risk sharing, completeness of risk response, rationality of reward scheme, effectiveness of reward mechanism, symmetry of risk-return mechanism, and rationality of reward mechanism.

(4) Project Supervision Mechanism. As the initiator of public rental housing projects, the government effectively protects the public interest by approving and supervising the key control contents in the operation of the project. Specifically,

the supervision mechanism can be divided into three levels: the first level is the project company's management of the project; the second level is the government's regulation of the project; the third level is the social supervision of the government's regulation behavior and Special Purpose Vehicle (SPV) behavior. Considering that both SPV and contractor are stakeholders of social capital, there are convergence of interests, high degree of public dispersion, and limited specialty. Hence, the project supervision is mainly the government regulation of the project, including the supervision to the project cost supervision, project quality, and the project company operation. The measurement indicators of the project supervision mechanism consist of the clarity of the regulatory body, the rationality of the regulatory indicators, the effectiveness of public participation, the rationality of punishment, the openness of the evaluation results, and the effectiveness of the incentive mechanism.

2.1.2. Allocation of Control Rights. As for the connotation of control right, the classical explanation comes from incomplete contract theory, which considers that control right is the core of ownership and defines residual control right as enterprise ownership directly. Hart and Moore [18] believes that corporate control includes specific control and residual control, the latter of which is those that are not clearly stipulated in the contract. Grossman and Hart [19] demonstrated that the control right under the incomplete contract was a residual control right, that is, the right to decide how the item is used when an unexpected situation occurs. Faccio and Lang [20] believe that the control right is the exclusive dominance over the business operation and decision-making of an enterprise. In PRH PPP projects carried out in developing countries such as China, the public and private sectors usually jointly provide public products and services through the establishment of project companies [21]. As a result, the control rights of the PRH PPP projects are the corporate control rights based on resources. Sun et al. [22] believe that PPP project control rights are the collection of control rights of all parties involved in the project over the resources invested to achieve maximum benefits, including substantial control rights and residual control rights. Zhang et al. [23] agree that the reasonable allocation of residual control rights is the key to the landing and success of PPP projects.

Referring to the above views, in this study, the control right of PPP project is the institutional arrangement of the allocation of decision-making rights and income rights of the participants in the PPP contract set. Through this institutional arrangement, all partners can standardize the relationship of project responsibilities and rights, reduce conflicts, and maximize project performance. The control rights of PPP projects include specific control rights and residual control rights. The specific control right is a static control right, determined by the shareholding structure. During the operation of PPP projects, the equity structure generally does not change after the determination, and the timing of the allocation of control rights occurs in the early stage of the project. However, the public attributes of PPP projects inhibit the social capital from obtaining huge profits, which leads to the dynamic change of residual rights allocation. The allocation time point of residual control rights mainly occurs in the execution period. Therefore, according to the role of control rights in public rental housing PPP projects, the allocation of project control rights can be divided into two stages. The first stage is the project decision-making stage. In this stage, the allocation of control rights takes place before the establishment of the project company, and the subjects of control right allocation are government and social capital. In the decision-making stage, the government plays a more important role as a manager in the social public sphere, and the form of control power is mainly decision-making power. Deng [24] believes that there are five forms of decision-making according to the degree of social capital participation in decision-making, including individual decision-making right, shared decision-making rights, consultation rights of missile usage, suggestion rights, and execution rights. The second stage is the project implementation stage. The allocation of control rights occurs after the establishment of the project company. The main body of control allocation is the internal investors of the project company. At this stage, the government is one of the shareholders of the project company. The control right is the shareholder power. The shareholder power includes property rights and management participation rights [25]. Property rights are mainly embodied in asset income rights (dividend rights) and capital income rights (exit rights) [25]. The right to participate in management can be refined into the right to operate and the right to assign [25]. Property rights are the core, and the right to participate in management is the guarantee for the realization of shareholder property rights [25].

Based on the above analysis, the allocation of control rights for public rental housing PPP projects can be analysed from five aspects: decision-making rights, dividend rights, exit rights, management rights, and assignment rights.

2.1.3. Project Performance. For performance, scholars and experts have different definitions and induction. In terms of the form of performance, there are mainly three views: performance behavior view [26], performance outcome view [27], and performance behavior-outcome view [28]. Among them, it is generally accepted that performance equals the synthesis of process and result. According to the performance behavior result view, if the performance only focuses on behavior, the behavior may be short-term and lacks long-term planning, then the final result may not be realized; if the performance only focuses on the result, the necessity of behavior process, monitoring, and guidance may be ignored, which is not conducive to team cooperation, organizational coordination, and reasonable allocation of resources [29]. Therefore, from a practical point of view, a good performance should include behavior, output, and result; that is, performance not only includes the relationship between efficiency output and input but also includes the degree of effort to achieve the goal and the degree to achieve the goal.

Based on the above understanding, there are also two views on the definition of project performance in academic circles. One view is that project performance is a dynamic concept, including process performance and result performance. Leu and Lin [30] believe that project performance is the output and result formed in the process of project construction and implementation. Another point of view is that project performance should include the daily behaviors of project employees and should be defined from the perspective of behaviors related to the effective realization of project objectives. Kagioglou et al. [31] believe that project performance should not only include work output but also pay attention to relevant behaviors of employees in achieving organizational goals. Project performance is closely related to project success. Yuan believes that performance is a tool to measure whether a project is successful and is a concrete manifestation of the standard of project success [32]. The achievement of project performance is critical to project success. On the other hand, the essential feature of PPP projects is that the government provides public services. However, the mode of provision is changed from the direct provision by the government to the production led by social capital, and the government pays for performance; that is, the government and social capital cooperate to provide public goods or services. Therefore, the PPP project performance should not only consider the standard and specific embodiment of project success but also consider the recognition degree of service objects, including the satisfaction of organization members and the public. Based on the above discussion, it is concluded that PPP project performance refers to the realization degree of value for money in the whole life cycle of the project, including the achievement of the initial goal of the project and the realization of the project value, covering project construction performance, project operation and maintenance performance, and customer satisfaction.

2.2. Research Hypothesis

2.2.1. Rule Governance Mechanism and Project Performance. Mainstream opinions regard that good rule governance can have a positive effect on project performance. According to Williamson [10], formal contracts can improve project performance by influencing the level of specific investment. Roehrich and Lewis [33] believe that under strict legal provisions and normative standards, contracts can constrain the behavior of parties to ensure project performance. Cao and Lumineau [34] believe that contract governance, as a formal governance mechanism, is an important way and means to curb opportunism, which is crucial to safeguarding the interests of contract subjects and promoting the success of projects. Some scholars also believe that strictly controlled contract terms will inhibit the good cooperation will of trading partners and reduce the positive behaviors of the other party [35]. At the same time, overly strict formal contracts mean distrust or hostility towards trading partners [36], which will have a negative impact on cooperation.

Based on literature analysis and the above discussion, the research hypothesis is proposed:

H1: Rule governance mechanism has a positive effect on project performance.

2.2.2. Control Rights and Project Performance. As for the function of the allocation of control rights, the academia has carried out extensive discussions from different perspectives: firstly, the importance of the allocation of control rights has been studied. The research on contract governance structure is mainly based on the three theories of incomplete contract theory, property right theory, and principal-agent theory, through which it is proved that the reasonable allocation of control rights significantly affects the success of the project [37]. Zhang [38] and Salman et al. [39] all believe that the allocation of control rights is the driving factor for the success or survival of BOT projects. The second is to propose a series of theories around the distribution of residual control rights between the public and private sectors, such as the BG theory proposed by Besley and Ghatak [40] and the FM theory proposed by Francesconi and Muthoo [41]. The third is to use different methods to quantitatively analyse the relationship between control rights and project performance. Alonso-Conde et al. [42] analysed how the public sector grants private companies some rights while enabling private companies to obtain acceptable profits, thereby encouraging the private sector and improving its cooperation efficiency. Zhang et al. [37] established a mathematical model to verify that when an enterprise has self-interested investment, giving different degrees of control shares to the public or private sectors under different parameters can improve the PPP cooperation efficiency. According to Zhang et al. [43], the allocation of control rights has always been the focus of negotiations between the government and the project company in PPP projects, and it directly affects the decision-making behavior and cooperation efficiency of the public and private parties.

Based on literature analysis and the above discussion, the research hypothesis is proposed:

H2: Reasonable allocation of control rights has a positive effect on project performance.

2.2.3. Control Rights, Rule Governance, and Project Performance. Different from other projects, PPP project has a long cooperation period, which can be understood as a repeated game process between public and private parties. Hart and Moore believed that repetitive game is an effective cooperation mechanism to promote contracting, but this cooperation mechanism cannot effectively govern various future probable events, which requires the company to have the "distribution of residual control rights," and then this power becomes a supplementary mechanism under the framework of long-term cooperative relationship [18]. Lam et al. [44] believed that project rights and responsibilities should match each other, the allocation of control rights should be consistent with risk sharing, and the party with control rights should bear appropriate risks. Cheng and Chen [45] found that reasonable allocation of control rights was conducive to the relationship governance among cooperative organizations, thereby reducing the occurrence of relationship risks. Li et al. [9] believe that the multilayer principal-agent public-private partnership, the natural incompleteness of contracts, and the complexity of the social environment in which the project is located make it insufficient to only emphasize contract governance, and that relationship governance and allocation of control rights can synergistic improve the performance of PPP projects. This paper believes that the public rental housing PPP project contract set is a typical incomplete contract. When the contract is not complete, the conflict of interests between the parties cannot be resolved in advance, and the allocation of residual control rights becomes a key issue. At the same time, the PPP project of public rental housing has a long cooperation period. The introduction of contract governance mechanism can make the research of contract governance structure from static analysis to dynamic analysis, which is more in line with the actual situation of the project.

Based on literature analysis and the above discussion, the research hypothesis is proposed:

H3: Reasonable allocation of control right has a positive mediating effect on the relationship between the rule governance mechanism and project performance.

3. Research Methods

3.1. Moderating Effect Analysis Model. Through theoretical analysis, we propose the hypothesis that project control right plays a moderating role in the impact of rule governance mechanism on project performance. Hence, project control right is introduced as a moderator variable. According to Baron and Kenny [46], the moderating variable refers to the variable that affects the direction or strength the relationship between independent variable and dependent variable. It can be classified variable or continuous variable. The basic model of moderating effect analysis is shown in Figure 2, where Predictor is the independent variable, Moderator is the moderating variable, Outcome Variable is the dependent variable, and Predictor X Moderator is the product term of the independent variable and the moderating variable, which also becomes the interaction term. Predictor X Moderator is the product term of the independent variable and the moderator variable and also becomes the interactive term. As a new variable, Predictor X Moderator can be used to judge the regulatory effect by examining its effect on the dependent variable. If the coefficient of its path C is significant, the regulatory effect exists [46].

It is necessary to choose the corresponding analysis method according to the type of variables to analyse the regulatory effect. The project performance variables, project control variables, and rule governance variables involved in this study are all latent variables, and the structural equation model should also be used to analyse the moderating effect of latent variables. For the structural equation analysis of the interactive effects of latent variables, there are a variety of analysis methods, mainly the distribution-analytic approaches and the product-indicator approaches. The product-indicator approaches are divided into constrained approach and unconstrained approach, and the distribution-analytic approaches include the Latent Moderated Structural

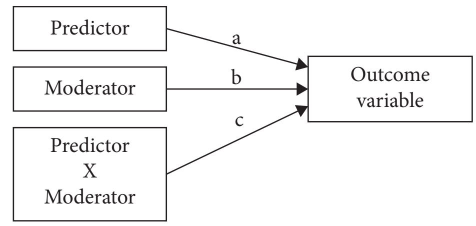

Figure 2: Regulatory effect analysis model.

Equations (LMS) approach and the Quasi-Maximum Likelihood (QML) approach [47]. Combining the characteristics of various methods, this study uses the LMS method to analyse the regulatory effect of project control.

3.2. Structural Equation Model. Structural equation model (SEM) is an important statistical method for quantitative research in the field of contemporary behavior and society. It combines the statistical techniques of “factor analysis” and “linear model regression analysis” in traditional multivariate statistical analysis and can be used for model identification, estimation and verification of various causal models [48]. Structural equation model is basically a confirmatory statistical method, which establishes a causal model on the basis of a certain theory or rule of thumb for verification. Compared with traditional statistical analysis methods, structural equation model can simultaneously estimate the measurement indicators and latent variables in the model. Based on theoretical analysis and experience, we put forward hypotheses on the complex relationship between project rule governance mechanism, project control rights, and project performance. These core variables involved in this study are also latent variables. Therefore, the structural equation model is used to conduct a confirmatory analysis on the relationship between the latent variables. In the analysis of structural equation model, Mpuls software is used to process the data and model.

4. Variable Measurement Method and Data Collection

4.1. Variable Measurement Method. We collected the first-hand data needed for the study through questionnaire survey. According to the analysis of the concept connotation and measurement of rule governance mechanism and its submechanism, project control right, and project performance, the questionnaire is designed. We distributed questionnaires to 30 experts for a trial survey, then revised some questions according to the experts’ suggestions, and finally determined the questionnaire used in this study. The main items of variables measurement in the final questionnaire are shown in Table 1, which clearly reflects how to measure each variable.

4.2. Data Collection. In order to measure variables, this study adopted a questionnaire survey method to collect data. The measurement items of all variables in this study were designed using a five-point Likert scale, from 1 (strongly

Table 1: Variable measures and questionnaire items.

Factor construct	Variables		Measurements
Rules governance (RG)	Project selection mechanism (RG1)	X1	The evaluation procedure is standard and effective, and the evaluation process is transparent and scientific
		X2	The opinions of social capital were consulted in the preparation of the scheme, and their questions were responded and fully considered
		X3	Important project decisions were made in time, and project approval was efficient and fast
		X4	The quality and depth of the project consultation report could meet the requirements, and the plan was reasonable and feasible
		X5	The project has strong policy support and strong operability
		X6	The area where the project is located has complete facilities for public buildings and a reasonable distribution of public rental housing
	Project bidding mechanism (RG2)	X7	The project bidding procedure is legal and compliant, and the bidding review is objective and fair
		X8	The contents of project bidding documents are complete, and the scoring standard is reasonable and clear
		X9	The bidding conditions of the project are set appropriately, and the reputation and qualifications of bidders are valued
		X10	The project adopts competitive bidding with sufficient competition among bidders
		X11	The government has carried out effective supervision on project bidding and tendering
	Risk reward mechanism (RG3)	X12	Project risks are allocated to those who are best able to manage them
		X13	There are reasonable solutions to unforeseen and controversial risk events
		X14	The content and calculation standard of project company's remuneration are reasonable
		X15	Income distribution is consistent with risk sharing
		X16	A reasonable economic reward mechanism is set up, and the reward degree is directly related to the efforts of all parties in the project
	Project supervision mechanism (RG4)	X17	The implementing agency has formulated clear and reasonable regulatory indicators for the project
		X18	Channels for residents to participate are set up in the project supervision mechanism
		X19	Project penalty clauses effectively improve the efforts of social capital
		X20	The government's performance evaluation results of social capital were published on relevant media
		X21	The public's response to the project has an incentive effect on the government
Project controlling right (PCR)		X22	Allocation of project decision-making rights
		X23	Allocation of project dividend rights
		X24	Allocation of project withdrawal rights
		X25	Allocation of project management rights
		X26	Allocation of project assignment rights
Project performance (PP)		X27	The quality of the project meets the quality standards agreed in the contract
		X28	The project is or will be completed on schedule
		X29	The actual investment of the project is within the budget
		X30	Project maintenance and management meet contract requirements
		X31	The vacancy rate of the project is within the contract
		X32	The living environment condition of the project is not lower than that of ordinary residence
		X33	The project meets the requirements of stakeholders
		X34	Your organization and partners are willing to continue to cooperate in the future

disagree) to 5 (strongly agree). The questionnaire was distributed by network and on site. Through online social platforms, mainly WeChat, 200 online questionnaires were distributed. The on-site distribution mainly utilizes personal network resources, supplemented by the point-to-point distribution of resources from the practical teaching bases of Jiangxi University of Finance and Economics in various regions, and a total of 256 copies are distributed. In 2017 and 2018, the authors used the summer and winter vacations to conduct face-to-face communication and questionnaire distribution to selected interview sites. The reason for selecting multiple different time points for visits is to take into account the phase characteristics of the PPP project and to make the project research process more reliable, which

Table 2: Results of validity and reliability of latent variables.

Latent variable	Items	Standard factor loading (SFL)	KMO	AVE.	Cronbach's α
Project selection mechanism (RG1)	X1	0.606	0.849	0.576	0.815
	X2	0.690			
	X3	0.641			
	X4	0.664			
	X5	0.630			
	X6	0.703			
Project bidding mechanism (RG2)	X7	0.754	0.858	0.606	0.853
	X8	0.754			
	X9	0.650			
	X10	0.741			
	X11	0.789			
Risk reward mechanism (RG3)	X12	0.767	0.848	0.634	0.856
	X13	0.714			
	X14	0.810			
	X15	0.802			
	X16	0.653			
Project supervision mechanism (RG4)	X17	0.816	0.822	0.572	0.835
	X18	0.734			
	X19	0.672			
	X20	0.676			
	X21	0.741			
Project controlling right (PCR)	X22	0.662	0.758	0.684	0.883
	X23	0.660			
	X24	0.751			
	X25	0.777			
	X26	0.671			
Project performance (PP)	X27	0.777	0.926	0.582	0.914
	X28	0.680			
	X29	0.757			
	X30	0.784			
	X31	0.741			
	X32	0.762			
	X33	0.806			
	X34	0.770			

can be compared and improved repeatedly. In this study, a total of 456 questionnaires were distributed. After deleting the returned records with missing data, 393 valid questionnaires were selected as the sample, with a valid response rate of 86.18%. After deleting records with missing data, 109 valid records were selected as the sample, with a valid response rate of 21.8%.

From a regional perspective, the respondents in this study were mainly from Jiangxi province, Hunan province, Hubei province, Chongqing City, Sichuan province, and other regions. From the educational background, 92.11% of the respondents were undergraduate and above. According to the years of the respondents engaged in PPP project research/practice, 31.55% of the respondents were more than 5 years, 32.82% were 3–5 years, 27.3% were 1–3 years, 8.27% were less than 1 year. From the number of respondents involved in PPP projects, 10 or more accounted for 11.45%, 6–10 accounted for 21.88%, 3–5 accounted for 57.5%, and 3 below accounted for 9.17%. Also, respondents were employed in private sectors (36.89%), consultancies (23.66), public organizations (29%), and other organizations (10.45) such as nonprofit organizations and law firms. Overall, the respondents have solid professional knowledge and rich working experience in the field of public rental housing construction, which ensures the reliability of the data.

5. Results

5.1. Reliability and Validity Analysis. In order to evaluate the reliability of the measured data, Cronbach's alpha coefficient is used as a measure of reliability, and SPSS 20.0 software is used to test the data collected through the questionnaire survey. The test results are shown in Table 2. In Table 2, Cronbach's alpha value of all latent variables were more than the 0.8 benchmark, which indicates that the measurements have good consistency and reliability.

The validity analysis of the questionnaire mainly involves three types: content validity, discriminant validity, and convergent validity. Since the content of the scales is based on the existing mature scales and has been carefully analysed and repeatedly discussed by experts, it can be considered that the content validity is good. In Table 2, all the Kaiser–Meyer–Olkin (KMO) values were above the 0.7 benchmark. All approximate chi-square values of the

Table 3: Standardized path coefficient.

Path	Estimate	S.E.	Est./SE	P value
PCR⟶PP	0.654	0.050	13.012	0.000
RG⟶PP	0.398	0.056	7.135	0.000

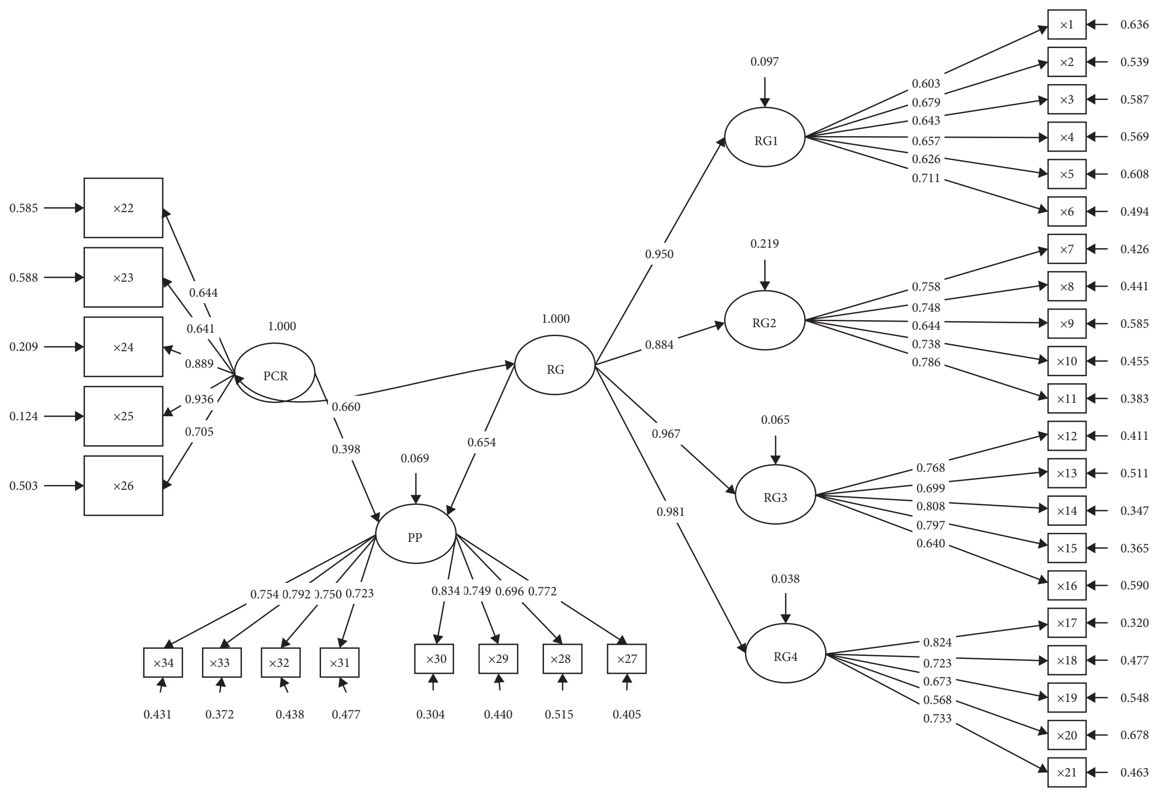

Figure 3: The impact of rule governance and project control on project performance.

Bartlett sphere test were larger, and all P values were less than 0.001. The values of the three indices indicate that the results pass the validity test and are suitable for factor analysis. From the perspective of convergence validity, it can be seen from Table 2 that the standard factor loading (SFL) of each measurement item is all more than 0.6 and significant at the significance level of 5%, The average variance extracted (AVE) value for every variable was above the 0.5 cut-off. The values of these indices indicate the good convergent validity of all latent variables.

5.2. Confirmatory Factor Analysis without considering the Moderating Effect of Control Rights. First of all, we did not consider the adjustment effect of project control rights. The interaction items between the rule governance mechanism and the allocation of project control rights were not included in the structural equation model, and the structural equation model was used for confirmatory factor analysis of the impact of the rule governance mechanism and the allocation of project control rights on project performance. This study used Mplus8 software to fit the designed structural equation model. The results of the theoretical model fit of rule governance mechanism, project control rights, and project management performance are shown in Figure 3. Table 3 shows the standard path coefficient and significance level of the model. The results showed that the rule governance mechanism and project control rights had a significant positive impact on project performance ($\beta_1 = 0.654, \beta_2 = 0.398$, $p < 0.001$). Hence, both Hypothesis 1 and Hypothesis 2 were supported.

5.3. Confirmatory Factor Analysis considering the Regulating Effect of Control Rights. Furthermore, we incorporate the interaction between rule governance mechanism and project control right into the structural equation model and use LMS method to analyse the moderating effect of project control right. The partial fitting standard indexes of the original model fitting results did not meet the requirements. The model was adjusted and optimized. As is shown in Table 4, the ratio of χ^2/degrees of freedom (Df) was 1.765, which is located in the range from 1 to 2. The root mean square error of approximation (RMSEA) value was 0.059, below the threshold level of 0.1. Furthermore, the values of GFI, AGFI, and CFI were all over the threshold level of 0.9.

Table 4: Results of goodness-of-fit (GOF) measures.

Goodness-of-fit measures	Recommended level of GOF measure	Original model	Revised model	Goodness-of-fit measures
χ^2/df	<2	2.346	1.765	χ2/df
RMR	<0.05	0.032	0.019	RMR
RMSEA	<0.05	0.059	0.032	RMSEA
GFI	>0.9	0.772	0.930	GFI
AGFI	>0.9	0.742	0.919	AGFI
PGFI	>0.5	0.682	0.786	PGFI
CFI	>0.9	0.907	0.949	CFI

Table 5: Standardized path coefficient.

Path	Estimate	S.E.	Est./S.E.	*P*-value
RG⟶PP	0.641	0.051	12.616	0.000
CR⟶PP	0.410	0.056	7.334	0.000
RG × CR⟶PP	−0.043	0.011	−3.588	0.000

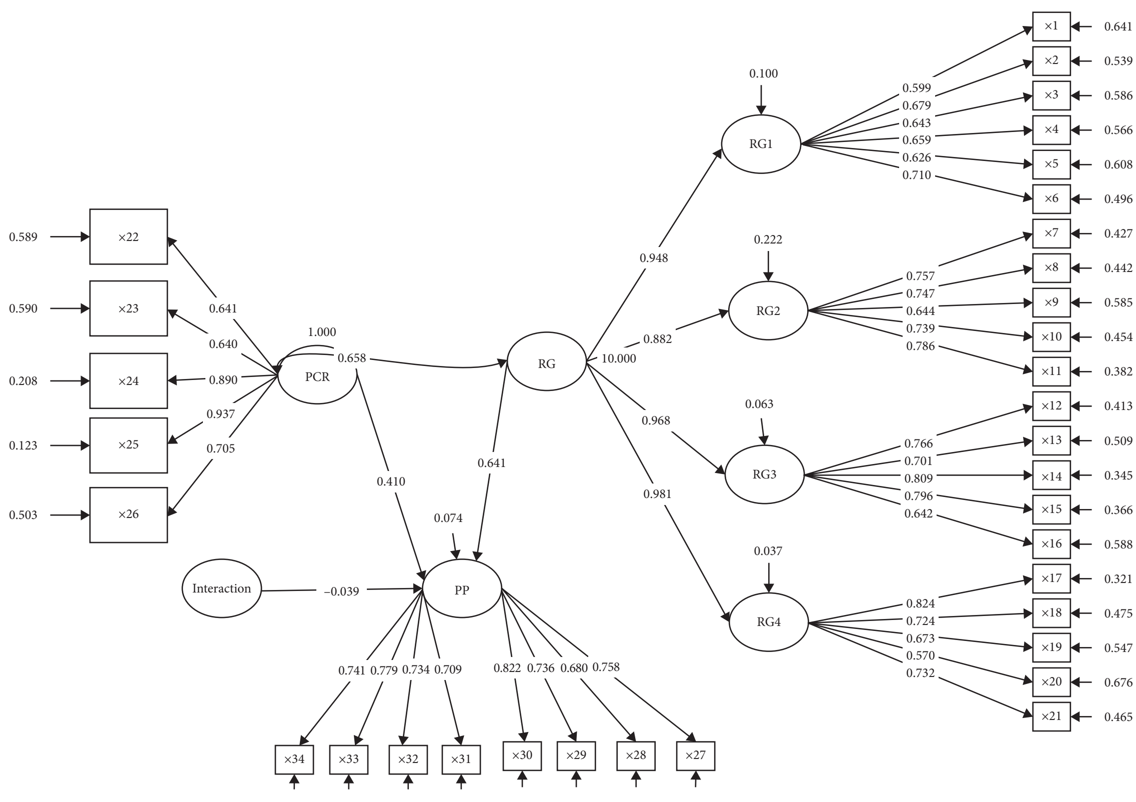

Figure 4: Impact of rule governance on project performance under the moderating effect of project control allocation.

Thus, the GOF level of the model was acceptable. The final structural equation model is shown in Figure 4. This model tested the overall moderating effect of project control right on the impact of rule governance mechanism on project performance. Table 5 shows the standardized path coefficient and significance level of the regulatory effect analysis model. In Figure 4 and Table 5, the standardized path coefficient of rule governance mechanism and project control right on project performance is still positive. However, the standardized path coefficient of the interaction between project control right and rule governance mechanism on project performance is −0.043, and it has passed the significance test at the 1% level. It indicated that the allocation of project control rights had a negative moderating effect on the impact of rule governance mechanism on project performance. Therefore, the hypothesis H2 was not valid.

6. Conclusion and Discussion

The empirical results show that project control has a negative moderating effect on the impact of rule governance mechanism on project performance. It is generally believed that reasonable allocation of project control rights can improve the positive effect of rule governance mechanism on project performance, but this view is not supported by empirical evidence. This means that giving more control rights to social capital does not necessarily improve the positive effect of the rule governance mechanism on project performance. On the contrary, it may challenge the formal rule governance mechanism and affect the impact of the rule governance mechanism on project performance. This may be explained from the following points.

First of all, from the perspective of project decision-making stage, social capital is prone to efficiency leakage caused by unscientific use of decision-making power in reality [49]. The empirical results show that the allocation of project control right has a negative moderating effect on the impact of project bidding mechanism on project performance, which means that the introduction of social capital in the early stage of the project is difficult to improve the efficiency of project decision-making [49]. Generally speaking, the government leads the preliminary work of PPP projects, and the risks arising from the preliminary work are basically borne by the government. Therefore, it is very important to improve the efficiency of the exercise of government control [50]. On the one hand, having sufficient information is the basis for making high-quality decisions. In the project approval stage, the government can obtain more information than social capital. For example, the housing management department has information on the structure of regional housing supply, and the civil affairs department has information on the income structure of local residents. Only the government can access the internal data of various departments, and social capital cannot master enough information on its own. Therefore, the government should control the decision-making power of the project in the early stage of the project [49]. On the other hand, public rental housing is related to the public interest, which will have higher quality requirements for any decision made by the government [49]. According to the research, in the early stage of the project, it is an effective way to improve the efficiency of the use of government control right to construct a reasonable participation mechanism for tenants and guide them to participate in the decision-making management of public rental housing [51,52]. For example, the project site selection determines the effect of public rental housing to a large extent. Under the existing institutional arrangements, the government only focuses on the completion of the higher-level social housing construction tasks and the number of housing units provided as the government's political performance, which determines the housing location. Insufficient attention is paid to the convenience of life of the guarantee objects, and they do not have enough information to make high-quality decisions. Therefore, in the project preparation stage, after the guarantee scope is determined, the government can choose the "Opinion Questionnaire" to investigate the demand preference of the security object, determine the demand level of the guarantee object, and then make a comprehensive decision combining with the land use of the public rental housing construction in the region, which can greatly improve the scientificity of the decision-making result.

Second, from the perspective of social capital selection stage, granting too much authority to social capital will affect the fairness and competitiveness of bidding, and thus the efficiency of the bidding mechanism. The selection of social capital for public rental housing PPP projects should follow the rules of open and fair competition, and the selection of social capital can be better achieved through the establishment and realization of a complete bidding mechanism [49,52]. As long as the bidding mechanism is perfect and market-oriented fair and open competition is implemented, more suitable social capital can be screened out, which is conducive to the improvement of project performance. Giving too much authority to social capital interferes with the fairness and competitiveness of the bidding mechanism [49], which in turn affects the efficiency of resource allocation and project performance.

Thirdly, from the internal relationship between the allocation of control rights and the risk reward mechanism of public rental housing PPP projects, the risk reward mechanism determines the distribution of interests and responsibilities of all parties in PPP projects and has a direct impact on the success of the project. In the PPP project of public rental housing, if social capital is given a larger income right, it is also necessary to make social capital bear greater risks accordingly [42,53]. In order to cope with risks and ensure the smooth progress of the project, social capital also needs to have greater project control rights in terms of management right and assignment right [54]. This means that social capital has greater stock appreciation right, withdrawal rights, and management rights. Public rental housing PPP projects have obvious public welfare and externalities. However, in a market economy, it is difficult to ensure that the performance of public rental housing projects does not deviate from the public welfare with the characteristics of social capital "economically rational people." In PPP projects, the principle of matching risks and benefits, the principle of benefit sharing, and the principle of risk sharing should be followed. The adoption of different returns mechanisms will inevitably correspond to different risk sharing mechanisms, which need different control rights allocations [55]. In PPP projects of public rental housing, the allocation of project control should not simply give more project control to social capital or the government but should be in line with the balanced allocation of risk and reward.

Fourth, from the perspective of the supervision of the construction and operation of public rental housing PPP projects, the public welfare and externality of public rental housing determine that its smooth implementation cannot be separated from the supervision and control of the government [49]. The project supervision mechanism aims to effectively inhibit the opportunistic behaviors of social capital and rent-seeking behavior of government administrators and improve the exercise efficiency of project control power [56]. However, the supervision mechanism of the government depends on the control right of PPP projects. Giving social capital more project control rights will weaken the government's supervision ability to a certain extent and also need to pay more supervision costs.

Finally, it is worth mentioning that although project control has a negative moderating effect on the impact of rule governance on project performance, it does not mean that the control right of social capital can be restricted accordingly [55]. Because giving more project control rights to social capital has a negative effect on the rule governance mechanism affecting project performance, and it cannot be directly reversed that restricting the project control right of social capital will have a positive effect on the rule governance mechanism influencing project performance. In reality, different public rental housing PPP projects have different characteristics, and their rule governance mechanisms are also different [57]. The allocation of project control rights should be determined and adjusted according to the actual situation of public rental housing PPP projects and the rule governance system. The degree of project control rights owned by social capital should be balanced with the rule governance in the dynamic management process.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Climate Change Vulnerability and Key Adaptation Trajectory of the Regional Economic System

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From the microperspective, climate change restricts human life in many aspects, and it affects the regional economic system from the macroperspective. The paper presents an inoperability input-output model (IIM) that is an extension approach of the Leontief input-output model. The IIM is able to provide a feasible methodology for measuring the impact of vulnerable economic factors on the whole economic system and identifying the key adaptation trajectory of the economic system. The IIM is applied in Tianjin to explore its dilemmas facing the increased demand for electricity, water, and public health service sectors under the RCP2.5, RCP4.5, and RCP8.5 climate scenarios. The results indicated that the inoperability ranking of all economic sectors is the same under the three climate scenarios. The key adaptation trajectory in Tianjin is S40, S27, S25, S17, S12, S02, S21, S16, S09, S24, S29, S33, S19, S13, and S15 sector in order. The costs required by the key adaptation trajectory to adapt to climate change account for more than 90% of that required by the whole economic system. These results can be helpful for policy-makers to prioritize sectors in terms of climate adaptation and understand the efficacy of climate change risk mitigation strategies.

1. Introduction

Due to the considerable inertia of greenhouse gases, even if the current greenhouse gas emissions are not increasing, global warming is expected to continue in the coming decades, which may bring significant risks related to climate warming to present and future generations [1, 2]. According to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, a list of abbreviations and symbols for the manuscript is shown in Table 1) [3], global climate warming is likely to accelerate and cause more frequent extreme climate events, making human beings and regional economic systems more vulnerable to climate change. Failure to effectively adapt to climate change could lead to serious short-term and long-term problems, which could result in huge costs to regional development [4].

A significant feature of climate change is that its impact is no longer within fixed sector boundaries [5]. Similarly, when climate change adaptation strategies primarily focus on individual sectors, it can be useless or only be valuable on a smaller scale. When some individual economic sectors in the regional economic system are affected by climate change, the sectors cannot operate normally and cannot recover quickly by themselves, which may further lead to many other sectors unable to operate as planned, and even threaten the security of the regional economic system. Therefore, more and more scholars are calling for a more holistic understanding of climate vulnerability and key adaptation trajectory of the regional economic system to coordinate the efforts of various sectors to improve the regional capacity to adapt to the inevitable climate change [6].

These climate change impact and risk may also restrict human life in many aspects [7]. Climate change adaptation aims to reduce or manage the impact of climate change on people's lives, which is bound to increase regional demand for electricity [8], water [9, 10], and health services [11, 12]. The best climate change adaptation practice in a region depends on the reasonable combination of available resource endowment and its optimal allocation [13]. Due to the limitation of social wealth accumulation, the cost of adaptation to climate change cannot be afforded by the individual vulnerable sectors [14]. Therefore, it is of great significance

Table 1: List of symbols for the manuscript.

Symbol	Description
IIM	Inoperability input-output model
IPCC	Intergovernmental panel on climate change
AR5	IPCC's fifth assessment report
RCPs	Representative concentration pathways proposed in IPCC's AR5
x_i	The output of sector i
x_{ij}	Intermediate demand of sector j from sector i
y_i	Final demand of sector i
a_{ij}	Direct-input coefficient
X	Sector outputs vector
A	Technological coefficient matrix
Y	Final demand vector
L	The Leontief inverse matrix
x_j^s	Production capacity of sector j
$b_{ij}^{(s)}$	Direct-output coefficient
v_j	Value-added component
$(X^s)^T$	Row vector of sector supply
$B^{(s)}$	Direct-output coefficient matrix
V^T	Row vector of value-added items
G	The output inverse matrix
x_k^d	Total regional demand for the products of sector k
x_k^s	Product supply of sector k
$V^{(d)}$	The value-added vector required by the economic system when the social final demand have changed
q	The sector inoperability vector of the economic system
V	The current value-added vector of the economic system
$\mathrm{diag}(V)$	a resulting diagonal matrix constructed from the given vector V
K	The sector resilience coefficient matrix
T	Temperature anomaly in period t
Elec_t	Electricity demand in period t
$\overline{\mathrm{Elec}_t}$	Electricity demand in period t without climate warming
Wate_t	Water demand in period t
$\overline{\mathrm{Wate}_t}$	Water demand in period t without climate warming
Heal_t	Regional demand for health service in period t
$\overline{\mathrm{Heal}_t}$	Regional demand for health service in period t without climate warming

to identify the key adaptation trajectory in the economic system and to further promote the efficiency of the regional economic system to adapt to climate change.

In the field of climate vulnerability and climate adaptation study, current research on the economic system climate adaptation indicates that theoretical explanations for regional economic system climate vulnerability and the key adaptation sectors are not very clear [15]. To this motivation, the paper tries to cast light on the regional economic system climate vulnerability and the key adaptation trajectory by integrating insights on the increasing demand required by adaptation to climate change, and the regional supply capacity constraint.

The remainder of this paper is organized as follows: Section 2 reviews the related literature about climate change vulnerability and climate adaptation. Section 3 elaborates the methodological framework. Section 4 presents an empirical analysis, followed by some conclusions and policy implications of the paper in Section 5.

2. Literature Review

How to adapt to climate change is a complex issue, which involves many aspects of knowledge in many fields. In this section, we introduced a series of studies related to adaptation to climate change. We conduct a systematic literature review on the driving factors and obstacles of climate change adaptation, which economic sectors are vulnerable to climate change, and key points for adapting to climate change in different regions. The existing kinds of literature are of great help to further study the climate change vulnerability and key adaptation trajectory of the regional economic system in this research.

The terminology of climate change adaptation was first proposed by the Assessment Reports of the IPCC [16], and it was dominated by general and ambiguous terms when climate change vulnerability assessment was the major field of adaption research. The diverse aspects involved together with the lack of a holistic understanding of them constitute many barriers to collaboration across disciplines in climate change adaptation studies [17].

In the last decades, more and more studies tried to find out the driving factors and obstacles of regional adaptation to climate warming, especially after the emergence of the Private Proactive Adaptation to Climate Change model proposed by Grothmann and Patt [18]. Due to the lack of systematic tools to study climate change adaptation, most research mainly focuses on qualitative research and meta-analysis of adaptation case studies. More effort is needed to better understand climate change vulnerability and facilitate the region to formulate practical strategies for climate change adaptation, especially on its aspects related to the economic conditions.

Scholars try to open the door to climate change adaptation research by studying which economic sectors are more vulnerable. The electricity sector is the first sector that attracts the attention of scholars. The literature has extensively studied how climatic variables, especially temperature, influence electricity consumption. This relationship has received increased attention in light of potential climate change because social electricity demand is increasing due to climate change. Eskeland and Mideksa explored the relationship between electricity consumption and outdoor temperature in thirty-one European countries, and their results illustrated that temperature has a statistically significant effect on electricity demand [19]. Deschênes and Greenstone suggested that the net effect of climate warming over the 21st century is likely to increase electricity demand substantially [20]. Auffhammer and Aroonruengsawat simulated the impact of warming temperatures caused by climate change on residential electricity consumption in California, and they suggested that holding the population constant, the total electricity fee for the households may increase by up to 55% by the end of the century [21]. In addition to the increasing effect, Auffhammer et al. thought the impact of climate change on the frequency and intensity of peak load will be greater [22]. Li et al. explored how electricity demand would change in Shanghai (China) in the context of climate change, and they found that a 1°C increase in daily temperatures may lead to around a 14.5% increase in electricity demand [23].

The water sector is also one of the most vulnerable sectors, which has attracted many scholars' attention. Trærup and Stephan studied the role of the water sector in the context of climate change in Lebanon, and they thought that the regional demand for water is inevitably increasing in order to adapt to climate change and water-saving technologies would be necessary in the future [24]. Harrison et al. explored cross-sectoral impact of climate change in Europe and they believed that the water sector was the key sector for regional climate change adaptation strategies [25]. Lengoasa studied the impact of climate change on water availability and considered that water security is critical for climate change adaptation [26]. Kundzewicz et al. conducted a brief assessment of climate change and associated impact on the water sector in Poland, and they suggested that ensuring the supply for various types of water is the basis of regional climate change adaptation strategies [27]. Verbist et al. conducted a vulnerability test for climate change impact on water security using climate risk-informed decision analysis, and the results emphasized the vulnerability of water sector to climate change [28].

As the threat of climate change to human health is becoming more and more obvious, the health sector has been increasingly concerned by many scholars. Both epidemiology and economics literature pointed out the detrimental effects of climate warming on mortality, prenatal health, and human health in recent years [29]. Numerous recent studies have investigated the impact of climate change on the health care and social welfare sector, both in developed and in developing countries [30, 31]. The Lancet suggested that human health has been now recognized as one of the most serious influenced areas of climate change and therefore should be a global research priority [32]. Gökçeku and Al-othman showed the health impact of climate change with projected trends in climate-related health, and they thought that climate change may affect human health in many ways: through the influences on disease environment and through changes in the daily temperature [30]. Ye et al. considered climate change is affecting human health in a profound manner, and it contributes to the regional burden of disease, which increases the demand for the health sector and makes health services scarce, especially in developing countries [11].

There are also some studies conducted on how regions and/or countries have adapted to climate change, especially in vulnerable areas. Hinkel et al. assessed the sea-level rise impact on Africa at continental and national scales as well as the benefits of applying climate adaptation measures, and they thought that in 2100, 16–27 million people would expect to be flooded per year, and annual damage costs range between US$ 5 and US$ 9 billion if no adaptation takes place [33]. Costa et al. estimated the costs of climate adaptation in developing regions by an empirical approach, and they suggested that the investments associated with the understanding and planning of climate adaptation be more significant when compared with implementing infrastructure [15]. Canosa et al. (2020) thought that climate adaptation is a priority for Arctic regions that suffer more from climate change globally, and they suggested that adaptation should be a central component of climate policy [34]. Petzold et al. studied the role of indigenous knowledge on climate change adaptation through a global evidence map of academic literature, and their results showed that there are adaptation knowledge gaps in northern and central Africa, South America, northern Asia, Australia, and urban areas [35]. Ledda et al. found out that the current climate adaptation plan in many regions could not fully work because of failing to include key adaptation sectors and actions [36]. To design effective regional climate adaptation plan, decision-makers need a state-of-the-art, regional, and sector-specific knowledge [37].

When reviewing the literature on climate change adaptation, we find that most of them focused on a single aspect of the economic system or focused on specific adaptation measures. It is necessary to scale-up insights from a single sector study to multisector economic system research on climate change adaptation. The shift toward economic system research methods requires complementing previous work on climate change vulnerability and climate adaptation with some comprehensive social science perspective. Climate change vulnerability and climate adaptation research is a typical transdisciplinary study field involving various methods originating from both natural and social science disciplines [38].

Climate change adaptation has become a practical necessity, which has been progressing from around fields concerning adaptation costs and benefits to a much wider array of aspects, related to the economic institution, development, and equity, as highlighted by the emerging climate adaptation science [39]. Hence, the array of methods applied needs to expand considerably and especially in the domain of social sciences. The input-output model and its extension approaches are particularly valuable in analyzing such dilemmas as they are adept in investigating how economic conditions give rise to certain types of regional dilemma [40]. The input-output approaches provide a possible method for regional climate adaptation research to deepen understanding of economic system climate vulnerability and key adaptation trajectory, and then formulate targeted solutions.

The aim of this study is to provide a feasible methodology for measuring the impact of vulnerable economic factors on the whole economic system and identifying the key adaptation trajectory of the economic system. While climate change directly affects many sectors, the paper can only partially select some of the most vulnerable sectors as original inducing sectors due to the lack of quantifying functions applied in measuring how climate change directly affects their demands. Nevertheless, we hope that the study can advance the disclosure of this significant and complex field of climate change vulnerability and climate adaptation in a relatively clear and structured manner.

3. Methodology

The input-output model was proposed by W. W. Leontief and has been adopted and developed by many scholars [41]. With the help of the input-output technique, we attempt to explore the response of the whole regional economic system and the key climate adaptation trajectory when some vulnerable sectors are directly affected by climate change. In our modelling framework, we take into account sector supply capacities because of the constraints of production resources.

3.1. Input-Output Model Background. The basic Leontief input-output model is mainly constructed from the observed economic data for a specific geographic area (nation, city, county, etc.). The model is elaborating on the activity of a set of industries that both produce goods (outputs) and also consume goods from other industries (inputs) in the process of producing each industry's own products. The model exhibits the economic activity among regional sectors, concerned with exploring the interdependency of a region's producing and demanding units based on their cross transactions. Its based data are the product/service flows from each of the sectors (as a producer) to each of the sectors (as a purchaser), where the interindustry flows are measured for a particular time period (usually in one year) and in monetary terms. The Leontief input-output model helps itself well to showing the interdependencies of the economic system. It is usually being used to analyze multisector modelling for policy analysis from the whole regional perspective. An economy system can be expressed by the Leontief input-output model as shown in Figure 1.

As shown in Figure 1, consider n sectors in the economic system, and the row balance equation is given as

$$x_i = \sum_{j=1}^{n} x_{ij} + y_i \Leftrightarrow x_i = \sum_{j=1}^{N} a_{ij} x_j + y_i, \quad i, j = 1, 2, \ldots, n, \tag{1}$$

where x_i is the output of sector i, x_{ij} is the intermediate demand of sector j from sector i, y_i is the final demand of sector i, and a_{ij} is the direct-input coefficient ($a_{ij} = x_{ij}/x_j$). Let

$$X = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}, \quad A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix}, \quad Y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix}. \tag{2}$$

The Leontief input-output model can be described in the following matrix form:

$$X = AX + Y, \tag{3}$$

where X is the sector outputs vector, A is the technological coefficients matrix, and Y is the final demand vector. Here, equation (3) is parallel to equation (1), which is generally used to denote a set of linear equations. Equation (3) is just a standard form in input-output analysis, and the difference between equations (3) and (1) is purely notational.

Let I be the $n \times n$ identity matrix, that is, ones on the main diagonal and zeros elsewhere:

$$I = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{bmatrix}, \tag{4}$$

then

$$(I - A) = \begin{bmatrix} (1 - a_{11}) & -a_{12} & \cdots & -a_{1n} \\ -a_{21} & (1 - a_{22}) & \cdots & -a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ -a_{n1} & -a_{n2} & \cdots & (1 - a_{nn}) \end{bmatrix}. \tag{5}$$

And then the $n \times n$ economic system shown in equation (3) can be expressed as follows:

	Industry		
Industry	Intermediate transaction $\{x_{ij}\}\ \forall\ i, j$	Final demand (Y)	Total output (X)
	Value added (V^T)		
	Total input (X^T)		

Figure 1: The Leontief input-output model.

$$(I - A)X = Y. \tag{6}$$

As for a given Y, the sector output X is given by (for a given set of Y, whether there is a unique solution of X or not depends on whether $(I - A)$ is singular or not. As in other studies, the paper also assumes that $|I - A| \neq 0$ here, so we can get $(I - A)^{-1}$)

$$X = (I - A)^{-1} Y = LY, \tag{7}$$

where L is a mnemonic for "$(I - A)^{-1}$," which is also known as the Leontief inverse. Based on equation (7), we can see that an increase in Y induces an associated increase in X.

From the economic system form depicted by the Leontief input-output model, we can see that it is a demand-driven input-output model, where the Leontief inverse connects sector gross outputs with the amount of final demand, that is, the amount of products leaving the interindustry system and directly consumed by the society. The sector output defined in the Leontief input-output model is the total output required by the economic system to meet the gross intermediate demand and final demand of the society. The basic assumption of the Leontief input-output model is the direct-input coefficients (a_{ij}) are fixed in the economic system.

3.2. Supply-Side Input-Output Model. The supply-side input-output model was presented by Miller and Blair [42]. It is an alternative input-output model based on the same economic data set that underpins the Leontief input-output model in Section 3.1. The supply-side input-output model emphasizes that the production factors in some situations may become the determinant in an economic system, when the demands are increasing or when there is a general limitation of resources. Due to the constraints of human resources, capital, and other resources, the supply capacity of the regional economic system may not be able to meet the increasing demand caused by climate change. The supply-side input-output model defines the balanced equation for the economy from the perspective of the value formation of the output of each sector. Referring to the interindustry output formation matrix given in Figure 2, we can see that the total sector output can be derived alternatively by aggregating the total value flow in the sector.

The columns in Figure 2 describe the compositions required by a particular industry output (supply). Through transposing the vertical (column) view of the interindustry system to a horizontal (row) equation, the supply-side input-output model balance equation can be given as

$$x_j^s = \sum_{i=1}^{n} x_{ij} + v_j \Leftrightarrow x_j^s = \sum_{i=1}^{n} b_{ij}^{(s)} x_i + v_j, \quad \forall j = 1, 2, \ldots, n, \tag{8}$$

where x_j^s represents the production capacity of sector j, x_{ij} represents the intermediate input from sector i to sector j to maintain the productive capacity of sector j, $b_{ij}^{(s)}$ is the direct-output coefficient ($b_{ij}^{(s)} = x_{ij}/x_i$), and v_j represents the value-added component used by sector j in order to maintain the productive capacity. The value-added component contains wages, fixed capital consumption, income, rental, and net interest, among others.

The supply-side input-output model can be described in the following matrix form:

$$\left(X^s\right)^T = \left(X^)\right)^T B^{(s)} + V^T, \tag{9}$$

where $(X^s)^T = [x_1^s, x_2^s, \ldots, x_n^s]$ represents the row vector of sector supply in the region, $B^{(s)} = [b_{ij}^{(s)}]_{n\times n}$ is the direct-output coefficients matrix derived from the regional economic input-output data, and $V^T = [v_1, v_2, \ldots, v_n]$ is the row vector of value-added items.

From equation (9), we can get (as in other studies, we also assume that $|I - A^{(s)}| \neq 0$ here, so we can get $(-A^{(s)})^{-1}$)

$$\left(X^s\right)^T = V^T (I-)^{-1} = V^T G, \tag{10}$$

where G is a mnemonic for "$(I - B^{(s)})^{-1}$," which is also called the output inverse matrix. It can be interpreted as measuring the total production that can be supplied by the economic system based on a certain amount of primary value-added.

A change in V^T can induce an associated supply (output) change as

$$\Delta\left(X^s\right)^T = \left(\Delta V^T\right) G. \tag{11}$$

The supply-side input-output model can relate sector gross production with the primary inputs, that is, the amount of value-added entering the interindustry system at the starting of the process. The basic assumption of the supply-side input-output model is the direct-output coefficients $(b_{ij}^{(s)})$ are fixed in the economic system.

3.3. Inoperability Input-Output Model. As the Leontief input-output model can relate the economic system to the social final demand and the supply-side input-output model can relate the economic system to the initial value-added entering the interindustry system, this subsection attempts to integrate the two models to investigate the impact of increases in final demand of some vulnerable sectors caused by climate change on the economic system and the initial value-added required by the society. Combining the demand side and the supply side of the economic system is a potential method for measuring the impact of vulnerable economic factors on the whole economic system and identifying the key adaptation trajectory of the economic system. Therefore, we present the inoperability input-output (IIM) model which is a combination of the Leontief input-output model

Industry		Producers as consumers (intermediate demand)						Final demand	Total demand
		Sector 1	Sector 2	$\cdots$	Sector j	$\cdots$	Sector n		
Producers	Sector 1	x_{11}	x_{12}	$\cdots$	x_{1j}	$\cdots$	x_{1n}	y_1	x_1
	Sector 2	x_{21}	x_{22}	$\cdots$	x_{2j}	$\cdots$	x_{2n}	y_2	x_2
	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\cdots$	$\vdots$	$\vdots$	$\vdots$
	Sector j	x_{j1}	x_{j2}	$\cdots$	x_{jj}	$\cdots$	x_{jn}	y_j	x_j
	$\vdots$	$\vdots$	$\vdots$	$\cdots$	$\vdots$	$\cdots$	$\vdots$	$\vdots$	$\vdots$
	Sector n	x_{n1}	x_{n2}	$\cdots$	x_{nj}	$\cdots$	x_{nn}	y_n	x_n
Value added		v_1	v_2	$\cdots$	v_j	$\cdots$	v_n		
Total supply		x_1	x_2	$\cdots$	x_j	$\cdots$	x_n		

FIGURE 2: The supply-side input-output framework.

and supply-side input-output model (here, the direct-input coefficients and direct-output coefficients in the inoperability input-output model are assumed to be fixed simultaneously. Although this assumption is not completely strict, it is relatively reasonable under the condition that the technological level and social circumstances are stable). The IIM can relate the economic system to both the social final demand leaving the interindustry system and the initial value-added entering the interindustry system.

3.3.1. Static IIM. Supposing that the demand for sector k has increased due to climate change, the balance equations of sector k can be expressed from both the demand side and supply side as the following two equations:

$$x_k^d = \sum_{j=1}^{n} x_{kj} + y_k, \tag{12}$$

$$x_k^s = \sum_{i=1}^{n} x_{ik} + v_k, \tag{13}$$

where x_k^d is the total regional demand for the products of sector k and x_k^s is the product supply of sector k in the region. We illustrate equations (12) and (13) in the following intuitive form:

$$\begin{cases} x_{11} + x_{12} + \cdots + x_{1k} + \cdots + x_{1n} + y_1 = x_1^d, \\ x_{21} + x_{22} + \cdots + x_{2k} + \cdots + x_{2n} + y_2 = x_2^d, \\ \vdots \\ x_{k1} + x_{k2} + \cdots + x_{kk} + \cdots + x_{kn} + y_k = x_k^d, \\ \vdots \\ x_{n1} + x_{n2} + \cdots + x_{nk} + \cdots + x_{nn} + y_n = x_n^d, \end{cases} \tag{14}$$

$$\begin{cases} x_{11} + x_{21} + \cdots + x_{k1} + \cdots + x_{n1} + v_1 = x_1^s, \\ x_{12} + x_{22} + \cdots + x_{k2} + \cdots + x_{n2} + v_2 = x_2^s, \\ \vdots \\ x_{1k} + x_{2k} + \cdots + x_{kk} + \cdots + x_{nk} + v_k = x_k^s, \\ \vdots \\ x_{1n} + x_{2n} + \cdots + x_{kn} + \cdots + x_{nn} + v_n = x_n^s, \end{cases} \tag{15}$$

where each specific equation in equation (14) describes the distribution of demand for a specific sector, and each specific equation in equation (15) describes the distribution of inputs required by a specific sector to maintain its supply. We express equations (14) and (15) in matrix form as follows:

$$X^d = AX^d + Y, \tag{16}$$

$$X^s = \left(B^{(s)}\right)^T X^s + V, \tag{17}$$

where the variables in equation (16) are consistent with those corresponding to equation (3) and the variable in equation (17) is the transposed matrix of the corresponding variable in equation (9).

From equations (16) and (17), we have

$$X^d = (I - A)^{-1} Y, \tag{18}$$

$$X^s = \left[I - \left(B^{(s)}\right)^T\right]^{-1} V. \tag{19}$$

Combining equations (18) and (19), we can see that an increase in final demand (Y) will induce a higher output (X^d), which needed a corresponding supply (X^s) that requires sufficient regional value-added (V) to maintain the needed high supply capacity. Regrettably, the available regional value-added is not unlimited usually; thus, we need to consider the issue of value-added shortage caused by climate change. Based on equations (18) and (19), the formulation relationship between the final demand and the initial added value required by the economic system is given as follows:

$$V^{(d)} = \left[I - \left(B^{(s)}\right)^T\right] (I - A)^{-1} Y = G^{-1} L Y, \tag{20}$$

where $V^{(d)}$ is the value-added vector required by the economic system when the social final demand vector is Y, and the other variables are the same as above in this paper.

In order to quantitatively measure the climate change vulnerability of an economic sector, we introduce a new variable, inoperability [43]. In the paper, the sector inoperability is defined as the percentage of the needed increasing amount of value-added caused by climate change relative to the current amount of value-added. Formally, climate change induced inoperability of the economic sector is formulated as

$$q = \left[(\operatorname{diag}(V))^{-1} \left(V^{(d)} - V \right) \right], \quad (21)$$

where $q = [q_1, q_2, \ldots, q_n]^T$ is the sector inoperability vector of the economic system; $V^{(d)} = [v_1^d, v_2^d, \ldots, v_n^d]^T$ is the value-added vector required by the economic system when the social final demand is increasing induced by climate change; $V = [v_1, v_2, \ldots, v_n]^T$ is the current value-added vector of the economic system; $\operatorname{diag}(V)$ is a resulting diagonal matrix constructed from the given vector V; and $\operatorname{diag}(V)$ is illustrated as

$$\operatorname{diag}(V) = \operatorname{diag}\left([v_1, v_2, \ldots, v_n]^T \right) = \begin{bmatrix} v_1 & 0 & \cdots & 0 \\ 0 & v_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & v_n \end{bmatrix}. \quad (22)$$

By introducing sector inoperability, the paper can quantitatively measure the climate change vulnerability of an economic sector. With the help of the regional input-output table, we can use the IIM to investigate the impact of vulnerable economic factors on the whole economic system and identifying the key adaptation trajectory of the economic system. The IIM implicitly assumed that if an industry's supply cannot satisfy its demand, the intermediate demands needed by other sectors are served in priority. It means that, in the case of shortage, social final demands are the last demands to be met compared with intermediate demands needed by other sectors. The priority given to intermediate demands is justified by several facts [44]. When climate change needs additional final demands for some sectors, it is beneficial for local society only if intermediate demand can be met priority.

3.3.2. Dynamic IIM. In the above IIM, the inoperability levels of each sector are static. In this section, we take sector resilience factors into the dynamic IIM to model its dynamic evolution over time. Note that the concepts and definitions in the above static IIM are all applicable to the dynamic IIM, which expands the static IIM with farther dynamic and stochastic factors. Referring to one of the most widely used dynamic Leontief input-output model forms [45–47], the dynamic IIM is given as

$$q_{(t)} = \left[\left(\operatorname{diag}\left(V_{(t)} \right) \right)^{-1} G^{-1} L \left(Y_{(t)}^{(d)} - Y_{(t)} \right) \right]. \quad (23)$$

Let $(\operatorname{diag}(V_{(t)}))^{-1} (Y_{(t)}^{(d)} - Y_{(t)}) = V_{(t)}^*$ and $G^{-1} L = B^*$, and by introducing sector resilience component, the dynamic IIM can be formally shown as

$$q_{(t+1)} = q_{(t)} + K \left[B^* V_{(t)}^* - q_{(t)} \right], \quad (24)$$

where the diagonal matrix K is the sector resilience coefficient matrix, and its ith nonnegative diagonal element k_i represents the ability of the industry to recover from an inoperability level caused by climate change. A greater k_i indicates a faster response of the economic system to an imbalance in supply and demand [48].

The value of k_i is determined from the initial inoperability of sector i and the time $q_i(T_i)$ required by the sector to recovery to a predefined inoperability level from the initial level of inoperability $q_i(0)$. The formulation of k_i can be given as

$$k_i = \frac{\ln \left(q_i(0) / q_i(T_i) \right)}{T_i \left(1 - b_{ii}^* \right)}. \quad (25)$$

where the term in the numerator measures the recovery rate and the denominator represents the reliance of the sector on itself, and the notion b_{ii}^* represents the ith diagonal element in the matrix B^*.

It should be pointed out that the economic data used in both the theoretical IIM and the following empirical analysis are given in monetary units. In order to avoid the price effects on the results, we assume that the prices of all products/services during the study period are constant.

4. Empirical Applications and Discussion

In this section, the IIM elaborated in Section 3 is applied in Tianjin to explore its climate change dilemmas. Tianjin is one of the four municipalities in China, which is located in the northeast part of North China Plain (38°34′–40°15′ N, 116°43′–118°04′ E) [49]. Tianjin is a megacity with a population of over 15 million, and it is representative of the surrounding areas. Therefore, in this paper, Tianjin is chosen as an interesting case to provide experience for the North China.

4.1. Data Source and Processing

4.1.1. Input-Output Table of Tianjin. The empirical study is based on the 2012 input-output table of Tianjin in monetary units, and the input-output table consists of 42 sectors, whose names and codes are shown in Table 2. We process the input-output table as follows. The subdividing final demand and value-added inputs are combined into a single final demand and total value-added, respectively, and we have removed the effects of regional inflows and regional outflows in order to accurately grasp the impact of vulnerable economic factors on the whole economic system and identify the key adaptation trajectory of the economic system.

4.1.2. Climate Data. Additionally, the future prediction data of climate change by the end of the century from the IPCC's Fifth Assessment Report [50–52] are also used in the study. The IPCC's Fifth Assessment Report has proposed four representative concentration pathway scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5), and the projected temperature changes of Eastern Asia are shown in Figure 3 [53].

In this paper, we chose RCP2.6, RCP4.5, and RCP8.5 to, respectively, represent the low climate change scenario, medium climate change scenario, and high climate change scenario to study the Tianjin case. Based on the temperature change projections of Eastern Asia simulated in the RCP scenarios, the paper assumes future predictions of temperature change in Tianjin as listed in Table 3.

Table 2: Sector code and name in the Tianjin input-output table.

Code	Sector name
S1	Farming, forestry, husbandry, and fishery
S2	Mining and wasting of coal
S3	Extraction of petroleum and natural gas
S4	Mining of metal ores
S5	Mining and processing of nonmetal ores
S6	Manufacture of foods and tobacco
S7	Manufacture of textile
S8	Manufacture of textile wearing apparel
S9	Manufacture of timbers and furniture
S10	Papermaking and manufacture of articles
S11	Processing of petroleum, and coking
S12	Chemical industry
S13	Manufacture of nonmetallic mineral
S14	Smelting and rolling of metals products
S15	Manufacture of metal products
S16	Manufacture of general purpose machinery
S17	Manufacture of special-purpose machinery
S18	Manufacture of transport equipment
S19	Manufacture of electrical machinery
S20	Manufacture of communication equipment
S21	Manufacture of measuring instrument
S22	Other manufacture
S23	Scrap and waste processing
S24	Repair services of machinery and equipment
S25	Electric power and thermal power
S26	Production and distribution of gas
S27	Water production and distribution
S28	Construction
S29	Wholesale and retail trade
S30	Transportation, storage, and post
S31	Hotel and restaurants
S32	Information transmission and computer
S33	Finance
S34	Real estate trade
S35	Tenancy and commercial service
S36	Scientific research and technical service
S37	Environment and municipal conservancy
S38	Resident services and repair services
S39	Education
S40	Health care and social work
S41	Culture, art, sports, and recreation
S42	Public management and social service

4.2. Vulnerable Sector and Climate Adaptation Function. Through reviewing the literature about climate change research of the last 20 years, we find that electricity, water, and health sector are the first three most vulnerable sectors to climate change. Its microfoundations are the increasing demand for electricity, water, and health services needed by people to maintain their lives in the context of climate change. In this empirical analysis of Tianjin, the paper selects electricity, water, and health sector as original inducing sectors to investigate the impact of the three climate-vulnerable sectors on the whole economic system and identifying the key adaptation trajectory of Tianjin's economic system. Here, we introduce the climate adaptation function of the three vulnerable sectors, which is a function of sector demand changes with respect to future climate changes. While this certain quantitative relationship is difficult to assess, we refer to a number of the empirical literature and examine the functions used in the current climate-economy models, and then we have defined the form and parameters of climate adaptation function of electricity, water, and health service sector, respectively.

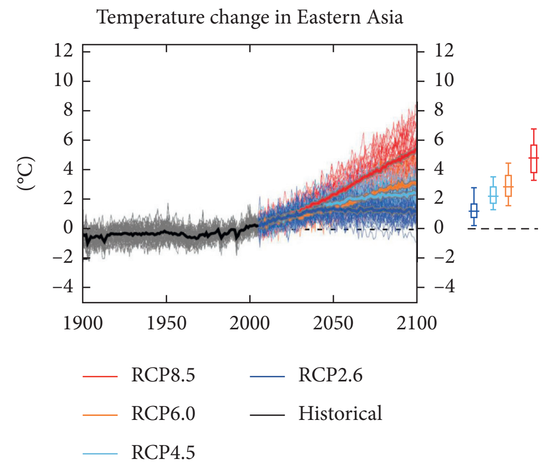

Figure 3: Time series of temperature change in Eastern Asia (20°N to 50°N, 100°E to 145°E). Note: thin lines represent one ensemble member per climate model and thick lines donate the multimodel mean. On the right-hand side, the 5th, 25th, 50th (median), 75th, and 95th percentiles of the distribution are illustrated in the four RCP scenarios. The temperature projection data in Figure 3 are sourced from IPCC's Fifth Assessment Report.

Table 3: Future predictions of temperature change in Tianjin under the three climate scenarios.

Scenarios	Projected change by 2100
RCP2.6	+1.2°C
RCP4.5	+3.1°C
RCP8.5	+4.8°C

Note: changes in temperature are based on the 2012 benchmark.

4.2.1. Electricity Sector. Through reviewing the broad empirical literature, we found that there is a U-shape relationship between electricity demand and temperature, and the net effect of climate change over the 21st century is likely to increase electricity demand substantially. When the temperature rises, the electricity demand may increase nonlinearly. Considering the nonlinear impact of climate change on electricity demand [25, 54, 55], the paper assumes that the effect of temperature rise on electricity demand is defined as

$$\mathrm{Elec}_t = \left(1 + 0.06T + 0.02T^2\right)\overline{\mathrm{Elec}_t}, \qquad (26)$$

where $Elec_t$ represents the electricity demand in period t, T represents this period's temperature anomaly, and $\overline{\mathrm{Elec}_t}$ denotes the electricity demand in period t in the absence of climate warming.

4.2.2. Water Sector. Regional water demand is also sensitive to climate change [26–28]. It is generally suggested that climate change will trigger more water demand [7, 9, 10]. Through reviewing the related literature [24, 25], the paper assumes that the effect of temperature rise on water demand is defined as

$$\mathrm{Wate}_t = \left(1 + 0.05T + 0.01T^2\right)\overline{\mathrm{Wate}_t}, \tag{27}$$

where Wate_t represents the regional water demand in period t, T represents this period's climate anomaly, and $\overline{\mathrm{Wate}_t}$ denotes the regional water in period t in the absence of climate warming.

4.2.3. Health Sector. Both epidemiology and economics literature pointed out the detrimental effects of climate warming on mortality, prenatal health, and human health in recent years [29]. As the impact of climate change on human health is more and more significant, there is a growing demand for the health service sector [11, 12]. Through reviewing the related literature [30, 31], the paper assumes that the effect of temperature rise on health service demand is defined as

$$\mathrm{Heal}_t = \left(1 + 0.03\,T + 0.01T^2\right)\overline{\mathrm{Heal}_t}, \tag{28}$$

where $Heal_t$ represents the regional demand for health service in period t, T represents this period's climate anomaly, and $\overline{\mathrm{Heal}_t}$ denotes the regional demand for the health service sector in period t in the absence of climate warming.

4.3. Results Analysis and Discussion

4.3.1. RCP2.6 Scenario. In the IPCC's Fifth Assessment Report, the RCP2.6 scenario is a low climate change scenario, which supposed that the global temperature will rise within 2°C. Based on the 2012 input-output table of Tianjin, we apply the IIM elaborated in Section 3 to explore the impact of increased demand for electricity, water, and health service sectors caused by climate change on the whole economic system and identifying the key adaptation trajectory of the economic system. For simplicity of display, we illustrate the 15 sectors with the largest inoperability in Figure 4.

As shown in Figure 4, when the regional demand for the electricity sector (S25), water sector (S27), and health sector (S40) is increasing due to climate change in Tianjin, the most vulnerable 15 sectors are S40, S27, S25, S17, S12, S02, S21, S16, S09, S24, S29, S33, S19, S13, and S15 sector in order. In the RCP2.6 scenario, except for the original three inducing sectors (S25, S27, and S40), the inoperability of other sectors are all less than 0.006. The inoperability of the special equipment manufacturing sector (S17) is 0.0058, which should be the most important sector to be concerned about. Tianjin also needs to pay more attention to S17, S12, S02, S21, and S16 sectors when adapting to climate change, as the inoperability of those sectors are all bigger than 0.001. In the RCP2.6 scenario, except for S40, S27, S25, S17, S12, S02, S21, and S16 sector, the other 34 sectors' inoperability are all less than 0.001. On the whole, in the RCP2.6 scenario, climate change has relatively modest impact on Tianjin's economic system, but certainly not negligible.

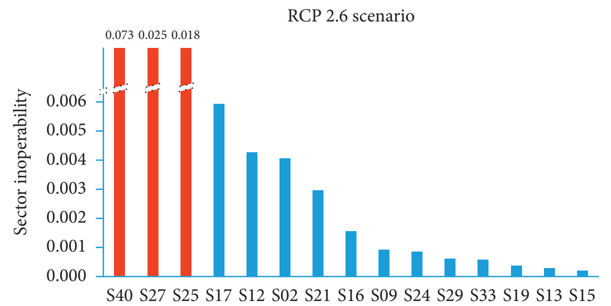

Figure 4: The 15 sectors with the largest inoperability in the RCP2.6 scenario. Note: the three red histograms represent the electricity, water, and health sector, respectively, which have been truncated because they are too high relative to other sectors. The sectors represented by the codes in the figure are shown in Table 2.

4.3.2. RCP4.5 Scenario. The RCP4.5 scenario is a medium climate change scenario, and Figure 5 illustrates the 15 sectors with the largest inoperability of Tianjin under the RCP4.5 scenario.

As shown in Figure 5, when the regional demand for the electricity sector (S25), water sector (S27), and health sector (S40) is increasing due to climate change, the most vulnerable 15 sectors are S40, S27, S25, S17, S12, S02, S21, S16, S09, S24, S29, S33, S19, S13, and S15 sector in order. In the RCP4.5 scenario, the inoperability of health sector (S40) is 0.275, which means that the initial value-added of health sector is facing a gap of 27.5% in meeting the increasing social demand. Except for the inducing sectors (S25, S27, and S40), the inoperability of the special equipment manufacturing sector (S17) is the highest, 0.022, which should be the most vulnerable sector to be concerned about. Tianjin also needs to pay more attention to S12, S02, S21, and S16 sectors when adapting to climate change, and these sectors' inoperability are all greater than 0.005. In the RCP4.5 scenario, climate change has obvious impact on Tianjin's economic system. Therefore, it is necessary to take measures to adjust production resources to reduce the inoperability of those vulnerable sectors, so as to avoid the imbalance of the whole economic system.

4.3.3. RCP8.5 Scenario. In the IPCC's Fifth Assessment Report, the RCP8.5 is a high climate change scenario, which supposed that the global temperature will rise around 5°C. Figure 6 illustrates the 15 sectors with the largest inoperability of Tianjin under the RCP8.5 scenario.

As shown in Figure 6, when the regional demand for the electricity sector (S25), water sector (S27), and health sector (S40) is increasing due to climate change, the most vulnerable 15 sectors are S40, S27, S25, S17, S12, S02, S21, S16, S09, S24, S29, S33, S19, S13, and S15 sector in order. In the RCP8.5 scenario, the inoperability of health sector (S40) is 0.544, which means that the initial value-added of health sector is facing a 54.4% gap in meeting the increasing social

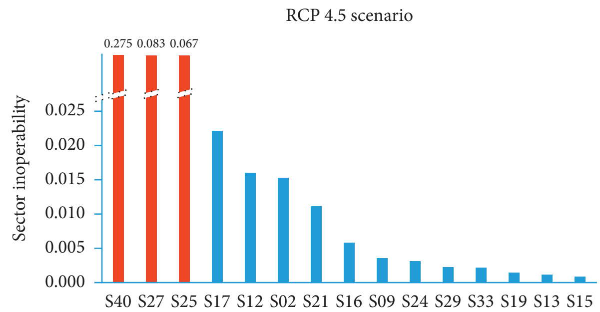

Figure 5: The 15 sectors with the largest inoperability in the RCP4.5 scenario. Note: the three red histograms have been truncated because they are too high relative to other sectors, and the sectors represented by the codes in the figure are shown in Table 2.

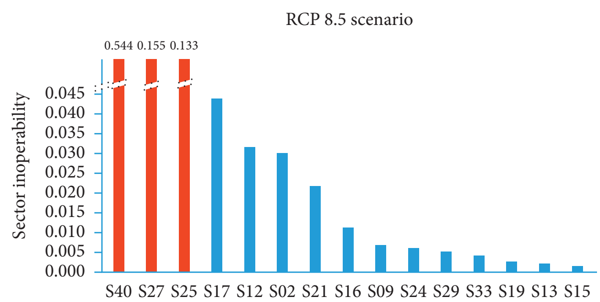

Figure 6: The 15 sectors with the largest inoperability in the RCP8.5 scenario. Note: the three red histograms have been truncated because they are too high relative to other sectors, and the sectors represented by the codes in the figure are shown in Table 2.

demand. Except for the inducing sectors (S25, S27, and S40), the inoperability of the special equipment manufacturing sector (S17) is 0.022, which should be paid more attention to. The inoperabilities of S17, S12, S02, S21, S16, S09, and S24 sectors are all bigger than 0.005. In the RCP8.5 scenario, climate change has significant impact on Tianjin's economic system. It is essential to take measures to reduce the inoperability of those vulnerable sectors, so as to avoid the paralysis of the whole economic system.

4.3.4. Inoperability Dynamics Analysis. In this subsection, the dynamic IIM is applied in Tianjin to analyze the inoperability trajectories. Taking the RCP4.5 scenario as an example, we simulate the inoperability dynamics of Tianjin's economic system. In the initial time, the sector inoperability of the electricity sector (S25), water sector (S27), and health sector (S40) is 0.067, 0.083, and 0.275, respectively, induced by climate change, and the sector inoperability of the other sector is zero. Assume that each sector can recovers to a level of 0.1% of the initial inoperability in each period, and Figure 7 displays the inoperability dynamics of the top 12 impacted sectors except for S25, S27, and S40.

From Figure 7, we can see that the most impacted 12 sectors are S17, S12, S02, S21, S16, S09, S24, S29, S33, S19, S13, and S15 sector in order, which is consistent with the

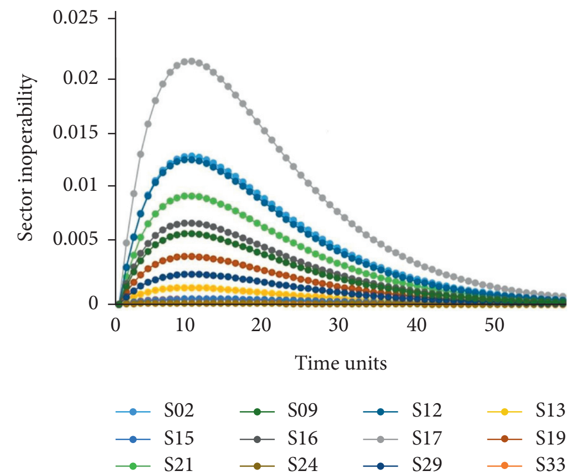

Figure 7: Inoperability dynamics of the top 12 impacted sectors in the RCP4.5 scenario.

static IIM analysis above. Mastering this key climate adaptation trajectory and allocating resources according to the sector inoperability is the practical basis of the climate adaptation scheme in Tianjin. Even if the initial state is not affected by climate change, the inoperability of the rest of the economic sectors will gradually increase affected by the electricity sector (S25), water sector (S27), and health sector (S40). From the dynamic analysis, we can also see that it may take almost 50 periods for the economic system to return to the original state when the recovery ability is 0.1% of the initial inoperability in each period. As shown, the difference in sector inoperability between the 12 sectors is relatively large. The results may be applied by policy-makers to prioritize sectors in terms of protection and understand the efficacy of climate risk mitigation strategies.

4.3.5. Comprehensive Results Analysis. In order to better understand the impact of increased demand for electricity, water, and health service sectors caused by climate change on the whole economic system and identifying the key adaptation trajectory of the economic system in Tianjin, we present the comprehensive results in multiple dimensions in this section.

In Table 4, we introduce a new variable, aggregate inoperability, which measures the proportion of the change in value-added required by the whole economic system due to climate change. As shown in Table 4, the impact of climate change on the health sector (S40) induced the most significant cascading influence on the whole economic system compared with the electricity sector (25) and water sector (27). Taking RCP4.5 scenario for example, the increasing proportion of regional demand for the electricity sector, water sector, and health sector is 0.3782, 0.2511, and 0.1892, respectively, but their inducing aggregate inoperability of the whole economic system is 0.00050, 0.00007, and 0.00578, respectively. It indicates that the health sector may play a critical role in adapting to climate change for the whole economic system. Our results also indicated that climate

Table 4: Aggregate results of RCP2.6, RCP4.5, and RCP8.5 scenarios.

Scenarios	Inducing sector	Changes in final demand	$X^{(d)}$ (million RMB yuan)	$TVA^{(d)}$ (million RMB yuan)	Aggregate inoperability
RCP2.6	Electricity (S25)	0.1008	5738307.2	2994429.9	0.00013
	Water (S27)	0.0744	5736547.1	2994096.9	0.00002
	Health (S40)	0.0504	5742545.3	2998643.7	0.00154
	Combined (S25, S27, and S40)		5744823.9	2999107.0	0.00170
RCP4.5	Electricity (S25)	0.3782	5743864.2	2995525.7	0.00050
	Water (S27)	0.2511	5737162.8	2994251.4	0.00007
	Health (S40)	0.1891	5759765.8	3011335.8	0.00578
	Combined (S25, S27, and S40)		5768217.1	3013049.3	0.00635
RCP8.5	Electricity (S25)	0.7488	5751288.3	2996989.5	0.00099
	Water (S27)	0.4704	5737926.9	2994443.3	0.00014
	Health (S40)	0.3744	5782772.0	3028292.1	0.01144
	Combined (S25, S27, and S40)		5799411.4	3031661.3	0.01257

Note: the column of changes in final demand represents change proportion of final demand for the corresponding sector in different climate scenarios, and the row of combined (S25, S27, and S40) represents corresponding results when the final demand for S25, S27, and S40 sector is affected by climate change at the same time, where $X^{(d)}$ and $TVA^{(d)}$ are the same variables defined in Section 3.

change also affects regional economic conditions and thus may exacerbate adaptation dilemma or create new ones, which is consistent with the studies by Hashemi [56] and Nguyen et al. [7].

4.4. Discussion. These results analyzed in the above subsection indicated that the impact of climate change on individual sectors varies substantially, which is indicative of a need for sector distinct strategies to adapt to climate change. The key climate adaptation sector trajectory of the economic system in Tianjin is stable, that is, S40, S27, S25, S17, S12, S02, S21, S16, S09, S24, S29, S33, S19, S13, and S15 sector. The individualization adaptation strategy of each sector should be formulated based on this key climate adaptation sector trajectory. This sector heterogeneity in climate vulnerability would depend, of course, on the interconnection of the local economic system. In other words, sector differences are likely to persist in this form, although perhaps not in some ways we are anticipating.

It is worth noting that the overall impact of climate change adaptation on the economic system seems not obvious because the aggregate inoperability of the economic system has been smoothed by those sectors that are barely affected. This result implied that the overall impact found to date in the literature may not uncover its actual impact and unable to point out the direction of regional adaptation to climate change. For example, in Tianjin, while the aggregate inoperability is 0.0126 by the end of the century for RCP8.5 scenario, the sector inoperability of S40, S27, S25, S17, S12, S02, and S21 is 0.544, 0.155, 0.133, 0.044, 0.032, 0.030, and 0.022, respectively. To meet the total increased demand caused by climate change at current prices would cost around 37.6 billion RMB yuan in Tianjin under the RCP8.5 scenario, of which the abovementioned key sectors will need 34.3 billion yuan, accounting for 91.2% of the total. These key sectors might determine the security of the economic system facing climate change.

We caution that the paper is meant to illustrate the impact of vulnerable sectors on the whole economic system and analyze the key adaptation trajectory of the economic system in a business-as-usual setting. In other words, the IIM we estimate holds prices, economic growth, and current technology constant, used in many economic modelling contexts [22]. Constant prices and economic growth assumption means that the economic system in the current stable environment can ensure that all sectors in the economic system keep the balance of supply and demand without climate change. Changes in technology may mitigate the demand for electricity, water, and health service demand required by climate change, in the following ways. Efficient air conditioning technologies may reduce the electricity demand of society to adapt to climate change. Water-saving technology can also reduce the water demand required to adapt to climate change. Hierarchical diagnosis and treatment technology may also improve the efficiency of health services and better meet the needs of social health services to adapt to climate change. As technology factors may have great uncertainty in the future, so the paper does not consider them.

Despite the limitations, this study provides a more comprehensive view of the impact of vulnerable economic factors on the whole economic system and identifying the key adaptation trajectory of the economic system. Compared with the existing single sector climate vulnerability studies, this study provides a complementary perspective to understand the impact of climate change, which has more guiding significance for the study of regional adaptation to climate change. It may provide policy-makers with a significant indication of the climate adaptation efforts associated with economic activities that are foundational for the successful implementation of adaptation strategic decisions.

5. Conclusions and Future Work

This study presents a systematic approach to analyzing the impact of climate-vulnerable sectors on the whole economic system and the key adaptation trajectory of the economic system. The IIM elaborated in the paper is applied in Tianjin to explore its climate change dilemmas.

The results of RCP2.5, RCP4.5, and RCP8.5 scenarios indicated that the inoperability ranking of all economic sectors in Tianjin is the same under the three climate scenarios, which implies the key adaptation trajectory of Tianjin's economic system is stable. The key adaptation trajectory in Tianjin is S40, S27, S25, S17, S12, S02, S21, S16, S09, S24, S29, S33, S19, S13, and S15 sector in order. The costs required by the abovementioned key adaptation trajectory to adapt to climate change account for more than 90% of that required by the entire economic system. Mastering this key climate adaptation trajectory and allocating resources according to the sector inoperability is the practical basis of the climate adaptation scheme in Tianjin.

Our results also imply that it seems that the impact of climate change on the whole economic system seems to be not great, but it will have significant impact on some vulnerable sectors and their closely interconnected sectors. In particular, these sectors closely interconnected to the vulnerable sectors are easy to be ignored, which requires policymakers to focus on, in order to formulate appropriate climate adaptation policies to ensure regional economic system security.

The individualization adaptation strategy of each sector should be formulated based on its sector inoperability. Timely adjustment of resource allocation among sectors of the economic system according to sector inoperability may be the direction for the climate adaptation strategy of the whole economic system. This sector heterogeneity in climate vulnerability would depend on the interconnection of the local economic system, which is likely to persist in this form, although perhaps not in some ways we are anticipating. We can envision several strategies to mitigate the impact of the key climate adaptation trajectory we estimate. A hopeful effort is launching a climate change adaptation fund to improve the supply capacity of the key sectors and to finance their access to resources.

Future research might extend the proposed methodology to further correctly calibrate the climate adaptation function of the electricity, water, and health sector. Moreover, the IIM presented in this paper is on the assumption that direct-input coefficients and direct-output coefficients in the economic system are constant. This is probably not a very actual situation in much of the regional economic system. Although the IIM's assumptions on the characteristics of the economic system may not be realistic, we still believe that this is a meaningful attempt, and we hope it can advance the discourse of this complex issue in a relatively clear and structured manner. Another work may assess regionally available production resources and introduce them into the input-output table, so as to build optimization allocation models to better promote adaptation to climate change.

Data Availability

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

Conflicts of Interest

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

Authors' Contributions

Pengbang Wei and Yufang Peng contributed equally to this work.

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Research Article

Corporate Governance, Agency Costs, and Corporate Sustainable Development: A Mediating Effect Analysis

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The economy is an essential factor in constructing a resilient city, and listed companies play a vital role in the local economy. From the microbehavior of corporate governance, we examine the relationship among corporate governance, agency costs, and corporate sustainable development for a panel sample of 690 state-owned firms in China during 2015–2019. We found that agency costs mediate the relationship between board size, management compensation, debt ratio, dividend policy, and corporate sustainable development. Specifically, decreasing the board size can reduce agency costs and enhance the company's sustainable development capabilities. The existing compensation system is to the disadvantage of the sustainable development of the company. Increasing the salaries of managers will increase agency costs and reduce the company's ability to develop sustainably. Although increasing liabilities can reduce agency costs, increasing liabilities will increase financial risks. The bankruptcy costs caused by increasing liabilities are more significant than agency costs, which leads to a decline in the company's ability to develop sustainably. The implementation of cash dividend policies will help reduce agency costs, thereby increasing their sustainable development capabilities. This also provides new ideas for the Modigliani–Miller (MM) theory and agency cost theory.

1. Introduction

The challenge from global environmental developments has become a significant barrier to sustainable human growth, and the process of sustainable development has become much more complicated. The resilient city is an important supplement to fill the gaps in the sustainable development strategy. The resilient city refers to the response and adaptation of the urban system to disasters and individuals and communities' ability to adopt coping strategies when and after external shocks occur to avoid potential losses [1]. The resilient city is based on a linear and predictable world view which solves the sudden external pressure according to existing capabilities. At the same time, it can integrate natural capital and human capital through planning and design. The city continues to move forward steadily while maintaining its necessary capability. The research on the resilient city's evaluation index can predict the whole process of resilient city development, which is an important research content of resilient science. Assessing man and nature's impact on the urban system can increase the city's resilience and strengthen its risk resistance. To make a resilient city more systematic, there must be a complete and mature standard or indicator system to guide it. When constructing resilient city indicators, some scholars considered the urban economy [2–4]. Under the conditions of a modern market economy, making full use of the capital market, especially the securities market, has a noticeable and profound effect on economic development. Therefore, research on listed companies is significant to the research on the resilient city.

Sharifi and Yamagata [5] found that the development of resilient cities requires the joint efforts of the government, state-owned enterprises, and private enterprises. Acuti et al. [6] examined 138 sustainability reports from Italy and Japan to gain insight into how companies contribute to the resilience of cities and regions. Listed companies can reduce the vulnerability of territories and improve urban connectivity. The sustainable development of listed companies has a strong effect on enhancing the local economic vitality and improving local economic resilience. Levine and Zervos [7] claimed that the listed companies had a substantial degree of importance to regional economic growth and that the development of the companies listed was conducive to the efficient allocation of regional capital and enhanced regional resilience. The Chinese government and companies have always emphasized sustainability in cities and have made substantial progress [8]. To enhance economic growth, preserve urban viability, and boost urban disaster resistance, the companies in China are starting to recognize the local elements of a resilient city [9, 10]. In China's economic system, state-owned enterprises occupy a vital position. When researching China's economic system, research on state-owned enterprises is indispensable. This paper starts with the research on the sustainable development of state-owned enterprises, hoping to provide suggestions for developing a resilient city.

The influence of corporate governance on corporate sustainability is still a core subject in the financial sector. Modigliani–Miller (MM) theory first proposed that corporate governance can affect the sustainable development of enterprises [11]. The trade-off theory believes that the increase in debt during the development of a company can provide tax shields for the company, but it will also increase corporate bankruptcy risk [12]. When studying the sustainable development of enterprises, more and more scholars pay attention to corporate governance. However, these theories often have relatively strict assumptions, making these theories not practicable in the real world. Centered on this consideration, we hope to clarify the partnership between corporate governance and corporate sustainability growth by incorporating agency expense as a mediating aspect.

Jensen and Meckling [13] first proposed the concept of agency cost. Agency cost is caused by the conflict of interest between management and business owners. The special nature of the separation of state-owned enterprise managers and owners leads to agency cost. Reducing the agency cost of state-owned enterprises is a significant problem faced by various countries. The Chinese government has been committed to reducing agency costs of state-owned enterprises, enhancing state-owned enterprises' sustainable development capabilities, and increasing city resilience. The formation of the stock market in the 1990s and the restructuring of the equity market in 2005 are of considerable importance for improving the sustainable growth of state-owned companies and reducing the expense of agency activities for state-owned enterprises [14]. Therefore, it has vital comparison significance to take Chinese state-owned enterprises as an illustration for researching agency costs.

In this paper, we have three key goals. First, we investigate the effects of corporate governance on corporate sustainable development and agency cost and aim to identify avenues to improve the potential for sustainable development and decrease an agency's cost. Specifically, we examine the impact of corporate governance on corporate sustainable development from two directions: management structure and equity structure. Through the above tests, we are looking for ways to reduce state-owned enterprises' agency costs, improve their sustainable development capabilities, and enhance urban resilience. Second, we examine the mediating effect of the agency cost and clear its impact on corporate sustainable development and provide empirical support for agency costs theory. Third, we may provide other countries with reference opinions on the governance of state-owned companies through the analysis of Chinese state-owned enterprises.

2. Literature Review and Hypothesis Development

2.1. The Effect of Corporate Governance on Corporate Sustainable Development. In the economic growth of corporations, corporate governance plays a critical position. Effective corporate governance will have ample cash flow and a stable equity structure conducive to the sustainable development of companies [15]. Therefore, we will discuss two aspects: management structure and corporate governance. Specifically, we will analyze the impact of corporate governance on agency costs and the company's availability from the perspective of board size, board independence, management compensation, equity concentration, dividend policy, and debt structure.

2.1.1. Board Size and Corporate Sustainable Development. The board of directors is the highest authority for the company to perform daily affairs. If board members have suitable authorities, they can contribute to business competitiveness and promote its overall success. The size of the board of directors plays a vital role in corporate management [16]. However, in empirical research, Yermack [17] found that an increase in the size of the board of directors leads to a decline in corporate sustainable development and reduces corporate sustainability. In subsequent research on listed companies in Singapore and Malaysia, Mak and Kusnadi [18] also discovered the inverse relationship between board size and corporate sustainability. This situation may be the lack of effective communication among board members and the decentralization of power. At present, the excessive size of the board of directors of Chinese state-owned listed companies may lead to the above situation. Therefore, we believe that the size of the board of directors is negatively related to the company's sustainable development capabilities.

Hypothesis 1. The board size is negatively associated with the corporate sustainable development of state-owned listed companies.

2.1.2. Board Independence and Corporate Sustainable Development. The purpose of establishing independent directors is to prevent management's internal control from damaging its overall interests. In empirical research, scholars have obtained different results from the research of listed companies in different regions. Jackling and Johl [19] found that board independence positively impacts corporate sustainable development for Indian firms. Haniffa and Hudaib [20] find in Malaysia that board independence does not impact business growth. China introduced independent directors in 2001, but the independent director system is still imperfect. Therefore, we believe that the independence of the board of directors of Chinese state-owned listed companies is negatively related to the sustainable development of the company.

Hypothesis 2. The board independence has a negative relationship with the corporate sustainable development of state-owned listed companies.

2.1.3. Management Compensation and Corporate Sustainable Development. The management of the company plays a crucial role in the overall long-term viability of the enterprise. A reasonable salary system is essential because it motivates and sustains corporate growth. Basu et al. [21] found an inverted U-shaped relationship between executive compensation and corporate sustainable development; that is, when the company has excess compensation, corporate sustainable development does not increase but decreases. Elsayed and Elbardan [22] also confirmed this view. At present, the Chinese state-owned enterprise managers' compensation system is complete, and managers' compensation is strictly restricted. Therefore, we believe that the management compensation of state-owned listed companies is conducive to the sustainable development of the company.

Hypothesis 3. The management compensation has a positive relationship with the corporate sustainable development of state-owned listed companies.

2.1.4. Equity Concentration and Corporate Sustainable Development. For the economic growth of businesses, equity stabilization is a requirement. The stability of equity will give an optimistic signal to the sector and benefit corporate sustainability growth. In terms of the relationship between the ownership structure and corporate sustainable development, Jensen and Meckling [13] believe that the increase of the proportion of internal shareholders who have control over the company can effectively increase corporate value. Rashid [23] tested 110 firms and found that the equity concentration level positively affected corporate sustainable development. Chinese state-owned enterprises have a relatively high degree of equity concentration, but due to the separation of state-owned enterprise management and ownership, the increase in equity concentration has a low impact on corporate sustainable development.

Hypothesis 4. Equity concentration has no significant correlation with the corporate sustainable development of state-owned listed companies.

2.1.5. Dividend Policy and Corporate Sustainable Development. There is still no unified conclusion about whether the dividend policy positively or negatively impacts a company's operating performance so far. Modigliani and Miller [24] first proposed that any dividend policy decision will not affect its value. However, in subsequent empirical studies, research on listed companies in the United States, China, and other regions found that corporate dividend policies are conducive to the sustainable development of companies, and dividend policies can provide positive signals [25, 26]. State-owned enterprises have sufficient cash flow, but the moral hazard caused by excessive cash flow will reduce the sustainable development ability of the enterprise. The implementation of the cash dividend policy can reduce corporate cash flow and at the same time send a signal to the market for sustainable development. Therefore, we believe that the dividend policy of state-owned listed companies is conducive to the sustainable development of the company.

Hypothesis 5. Dividend policy has a positive correlation with the corporate sustainable development of state-owned listed companies.

2.1.6. Debt Structure and Corporate Sustainable Development. According to the existing empirical evidence on the impact of debt structure and company performance, most studies indicate a positive relationship between debt and corporate sustainable development [27–29]. However, some studies, especially those conducted in emerging markets and developing countries, have shown a negative correlation between debt structure and corporate sustainable development. Le and phan [30] tested all Vietnamese nonfinancial listed companies, suggesting that the overall debt levels had a negative connection to corporate sustainable growth and assuming that the tax shield of debt gains would be smaller than the expense of financial distress. China is a developing country, and the Chinese financial market's development is not perfect. SOEs have a single financing method and high financing costs. The bankruptcy costs of state-owned enterprises may be higher than the debt benefits. We, therefore, propose the following hypothesis.

Hypothesis 6. The debt ratio has a positive correlation with the corporate sustainable development of state-owned listed companies.

2.2. The Effect of Corporate Governance on Agency Cost

2.2.1. Board Size and Agency Cost. The board of directors plays a critical function in the company's growth as a corporate decision-making entity. The existence of the board of directors can quickly generate agency costs. On the one side, the rise in the size of the board of directors will increase reciprocal oversight between members and reduce agency costs. However, on the other hand, it will reduce the efficiency of communication. Scholars also have considerable disputes in the empirical study of the relationship between the board of directors and agency costs. Isik and Ince [31] found a significantly positive effect between board size and agency cost. However, Eisenberg et al. [32] hold different ideas.

The election of the Chinese state-owned listed enterprises' board of directors is quite strict. Increasing the size of the board of directors can bring new resources to the company, which will reduce agency costs. Thus, we assume that the board's size is adversely linked to the expense of the agency.

Hypothesis 7. The board size is negative associated with agency cost.

2.2.2. Board Independence and Agency Cost. After an enterprise develops and grows, it will inevitably face the separation of enterprise ownership and management. Ensuring that managers will not deviate from the owner's goal and control agency costs has become a significant issue in corporate governance. By establishing an independent director structure, companies may supervise and balance executive managers to ensure that operators do not deviate from the owner's objectives, facilitate the consistency of values between the organization and the customer, and increase operating performance. In observational studies, several researchers have also confirmed this opinion [33–35]. Independent directors of state-owned listed companies can effectively supervise the corporate board of directors, so board independence is negatively related to agency costs.

Hypothesis 8. The board independence is negative associated with agency cost.

2.2.3. Management Compensation and Agency Cost. Management compensation is regarded as an important way to alleviate agency conflicts. Jensen and Murphy [36] found that increasing executive compensation can reduce agency costs, but the effect is weak. Andjelkovic et al. [37] studied the New Zealand listed companies in 2002 and reached a similar conclusion. However, Krivogorsky [38] believed there is no relationship between management compensation and agency cost. Chinese state-owned listed companies have a complete compensation system, and increasing executive compensation can reduce agency costs.

Hypothesis 9. The management compensation is negative associated with agency cost.

2.2.4. Equity Concentration and Agency Cost. The equity structure has an important influence on the internal supervision of listed companies. It is difficult for shareholders to reach a consensus in a company with dispersed ownership. The agency costs caused by conflicts between owners and managers are difficult to solve. Managers will seek more private interests and harm the interests of enterprises so that agency costs will rise. Conversely, companies with relatively concentrated equity will have a positive regulatory effect, and the owners can supervise the managers, thereby reducing the company's agency costs. Some scholars confirmed this view through empirical analysis [15, 39, 40].

At present, the concentration of state-owned enterprises in China is relatively high. Therefore, we believe that the concentration of state-owned enterprises' equity is relatively high, and agency costs are low. We, therefore, propose the following hypothesis.

Hypothesis 10. Equity concentration has a negative correlation with agency cost.

2.2.5. Management Compensation and Agency Cost. Jensen [41] found that the dividend policy can reduce management's disposable cash flow and reduce agency costs. In recent years, many scholars have tested the relationship between dividend policy and agency cost, which verified Jensen's view that dividend policy is negatively correlated with agency cost [42, 43]. State-owned enterprises have sufficient cash flow, and the implementation of dividend policies can reduce agency costs. Therefore, we propose the following assumptions.

Hypothesis 11. Dividend policy has an inverse relation with agency cost.

2.2.6. Debt Structure and Agency Cost. According to the MM theory, increasing liabilities can increase the value of the company, but at the same time, increasing liabilities will increase the bankruptcy risk of the company. To prevent the bankruptcy of the company, corporate managers usually make decisions carefully, so increasing debt can reduce agency costs. Besides, under the condition that the company's investment and the manager's stock remain unchanged, debt financing can increase the manager's shareholding ratio and make the manager's target functions consistent with shareholders. Pandey and Sahu [44] confirmed this view. Therefore, we infer that increasing the debt level of SOEs can reduce agency costs significantly.

Hypothesis 12. The debt structure is negatively associated with agency cost.

2.3. The Effect of Agency Cost on Corporate Sustainable Development. The conflict of interests between the shareholders and managers is known as agency cost since it is a kind of internal cost. This kind of internal expense leads to reduced corporate sustainable development and is not conducive to long-term development. Since it was proposed, many scholars have analyzed the impression of agency cost on corporate sustainable development from various aspects. From the perspective of ownership structure, Songini and Gnanfound [45] found that agency costs are negatively related to corporate sustainable development. From the perspective of governance variables, Hastori et al. [46] found that agency costs are negatively associated with corporate sustainable development. The separation of management and ownership of Chinese state-owned listed companies will inevitably lead to agency costs. Therefore, agency costs will lead to the loss of state-owned assets, which is not conducive to the sustainable development of state-owned enterprises.

Hypothesis 13. Agency cost has a negative correlation with corporate sustainable development.

2.4. The Mediating Effects of Agency Cost on the Relationship between Corporate Governance and Corporate Sustainable Development. We claim that corporate governance does not explicitly impact corporate sustainable development but implicitly influences corporate sustainable development through agency costs. As discussed in Section 2.1, corporate governance is likely to affect corporate sustainable development. Moreover, as we discuss in 2.3, agency cost is associated with corporate sustainable development. We theoretically question whether mixed results regarding corporate governance and corporate sustainable development might be the effect of corporate governance on corporate sustainable development mediated by agency cost. We propose several possible explanations to understand why agency costs could mediate the relationship between corporate governance and corporate sustainable development.

The impact of corporate governance on corporate sustainable development is often through the influence of managers so that the management can make decisions that are conducive to the long-term development of firms. The increase in the size of the board of directors can better supervise the company, reduce agency costs, and increase the company's sustainability. The responsibilities of independent directors are mainly to supervise the company's daily routine, reduce agency costs, and provide the impetus for the sustainable development of the company. In enterprises with high equity concentration, the owners can strictly supervise the management, reducing the agency cost, and improving the enterprise value. When an enterprise increases its debt, external creditors will impose strict external supervision on the enterprise. Simultaneously, due to the increased bankruptcy risk, enterprise management will carefully manage the enterprise, reduce agency costs, and increase enterprise value. The implementation of dividend policy can reduce the enterprise's free cash flow, reduce the agency cost of the management, and increase enterprise value. Equity incentives plans can make enterprise management and owners' interests consistent, reduce agency cost, and increase corporate sustainable development. According to the above analysis, corporate governance impacts corporate sustainable development by affecting agency costs. Therefore, we propose the following hypothesis.

Hypothesis 14. Agency cost mediates the effect of corporate governance on corporate sustainable development.

3. Materials and Methods

3.1. Research Methodology. We would address some of the leading techniques of data processing in this sector that can be used to evaluate our theories. The mediating impact of agency costs on corporate governance on corporate sustainable growth is our primary research problem. Through empirical analysis of state-owned listed companies, we find the relationship between corporate governance and corporate sustainable development and verify the mediating effect of agency costs. Furthermore, we try to improve the analysis results by comparing state-owned listed companies with private companies.

In this paper, we examine the mediating effect of agency costs on the effects of corporate governance on corporate sustainability growth using quantitative approaches. To research the relationships of the variables, multiple regression analysis was conducted on the panel data. In general, pooled OLS, fixed effects estimation, and random effects estimation methods are standard techniques for estimating panel data.

A sequence of panel OLS regressions of corporate sustainability development on corporate governance and a collection of control variables are calculated to determine the influence of corporate governance on corporate sustainable development. To test which model is the most suitable, we first use the LR test and the Chow test to test whether the pool OLS model is suitable or not and then use the Hausman test to test the fixed-effect model or random-effect model. Finally, we consider the individual fixed-effect model.

To test Hypotheses 1–6, which predict the effect of corporate governance on corporate sustainable development, we estimate a series of equation (1) using panel OLS regressions as follows:

$$Z\text{score}_{i,t} = \alpha_0 + \alpha_1 \text{CG}_{i,t} + \alpha_2 Z_{i,t} + \varepsilon_{i,t}, \quad (1)$$

$$EPS_{i,t} = \gamma_0 + \gamma_1 \text{CG}_{i,t} + \beta_2 Z_{i,t} + \varepsilon_{i,t}, \quad (2)$$

where $Z\text{score}_{i,t}$ is the indicator used to predict the corporate sustainable development capability for firm i at time t and $\text{EPS}_{i,t}$ is earning per share for firm i at time t. We use Zscore and EPS to measure corporate sustainable development capability. CG is a vector of a firm's corporate governance variables (i.e., the board size, board independence, management compensation, debt ratio, equity concentration, and dividend policy). Z is a vector of firm-level control variables.

To test Hypotheses 7–10, which predict the effect of corporate governance on agency cost, we estimate a series of equation (2) using panel OLS regressions as follows:

$$MER_{i,t} = \beta_0 + \beta_1 CG_{i,t} + \beta_2 Z_{i,t} + \varepsilon_{i,t}, \quad (3)$$

$$TAT_{i,t} = \delta_0 + \delta_1 CG_{i,t} + \delta_2 Z_{i,t} + \varepsilon_{i,t}, \quad (4)$$

where $MER_{i,t}$ is the ratio of for management expense for firm i at time t and $TAT_{i,t}$ is the ratio of total asset turnover rate for firm i at time t. We use MER and TAT to measure the agency cost. CG is a vector of a firm's corporate governance variables (i.e., the board size, board independence, management compensation, debt ratio, equity concentration, and dividend policy). Z is a vector of firm-level control variables.

To test Hypothesis 13, which predict the effect of agency cost on corporate sustainable development, we estimate a series of equation (3) using panel OLS regressions as follows:

$$\text{Zscore}_{i,t} = \mu_0 + \mu_1 MER_{i,t} + \mu_2 CG_{i,t} + \mu_3 Z_{i,t} + \varepsilon_{i,t}, \quad (5)$$

$$EPS_{i,t} = \theta_0 + \theta_1 MER_{i,t} + \theta_2 CG_{i,t} + \theta_3 Z_{i,t} + \varepsilon_{i,t}, \quad (6)$$

$$\text{Zscore}_{i,t} = \pi_0 + \pi_1 TAT_{i,t} + \pi_2 CG_{i,t} + \pi_3 Z_{i,t} + \varepsilon_{i,t}, \quad (7)$$

$$\text{EPS}_{i,t} = \vartheta_0 + \vartheta_1 TAT_{i,t} + \vartheta_2 CG_{i,t} + \vartheta_3 Z_{i,t} + \varepsilon_{i,t}, \quad (8)$$

where $MER_{i,t}$ is the ratio of for management expense for firm i at time t, $TAT_{i,t}$ is the ratio of total asset turnover rate for firm i at time t, $Z\text{score}_{i,t}$ is the indicator that used to predict the corporate sustainable development capability for firm i at time t, and $EPS_{i,t}$ is earning per share for firm i at time t. We use MER and TAT to measure the agency cost and use Zscore and EPS to measure the corporate sustainable development capability. CG is a vector of a firm's corporate governance (i.e., the board size, board independence, management compensation, debt ratio, equity concentration, and dividend policy). Z is a vector of firm-level control variables.

To test Hypothesis 14, which predicts the mediating effects of agency cost on the relationship between corporate governance and corporate sustainable development, we use the causal step approach raised by Baron and Kenny [47]. To test the mediating effect of agency cost, we need equations (1)–(3). If we want to test the agency cost mediation effect, we need to perform a series of equation (4).

$$Y = cX + e_1, \quad (9)$$

$$M = aX + e_2, \quad (10)$$

$$Y = c'X + bM + e_3, \quad (11)$$

where Y represents the dependent variable, that is, company performance, M represents the mediating variable, that is, agency cost, and X represents the independent variable, that is, corporate governance. If the coefficients a, b, and c are significant and c' is also significant, we have partial mediation.

3.2. Sample Selection and Data Sources. The initial sample is 2018 A-share companies listed on the main boards of Shanghai and Shenzhen stock exchanges. The sample period is from January 1, 2015, to December 31, 2019. Further screening is as follows: (1) excluding the financial industry samples; (2) excluding special treatment companies and samples with incomplete data; (3) only keeping the company attributes as central state-owned enterprises, local state-owned enterprises, and private enterprises. After screening, 1115 companies were obtained. There are 690 state-owned enterprises and 425 private enterprises. The data in this paper mainly come from the Wind financial data terminal and RESSET database. The empirical part is mainly realized by STATA and Excel.

3.3. Variables

3.3.1. Measure of Agency Cost. It is challenging to measure agency costs directly, so some scholars use other indexes and ratios to describe agency costs indirectly. Scholars often use asset turnover and expense ratios to measure agency costs [48, 49]. Management expense is the manager's power which can reflect the manager's on-the-job consumption behavior, so we use the management expense rate to measure the agency cost. To prevent the loss of state-owned assets, the Chinese government and the China Securities Regulatory Commission focus on utilizing state-owned enterprises' assets. Therefore, it is of great practical significance to use the total asset turnover rate as an indicator to measure agency costs. Based on the above analysis, we select the total asset turnover ratio (TAT) and management expense ratio (MER) to measure agency costs.

3.3.2. Measure of Corporate Sustainable Development. Edward Altman [50] proposed Z-scores (Zscore) to analyze the sustainable development capabilities of enterprises. Zscore consists of five parts: the proportion of corporate working capital, the proportion of retained earnings, the proportion of preinterest and tax profit, the market value, and the proportion of operating income. Earnings per share (EPS) can also be used to measure the sustainability of a company. Earnings per share can indicate the ability of a company to continue its profitability and grow steadily over a long period.

3.3.3. Measure of Corporate Governance. As discussed in Section 2, we will test the impact of corporate governance on agency costs and company performance from six aspects: board size, board independence, management compensation, debt structure, equity structure, and dividend policy. Board size can be measured as the number of directors on the board of directors (BS). Board independence is measured by the number of independent directors (IND). Management compensation is calculated using the natural logarithm of executive salary (LNSALRY). Debt structure can be measured as total debt to total equity (DAR). We use the proportion of the top ten shareholders (TOP) to measure equity concentration. Moreover, dividend policy is measured by dividend payout ratio (DIVR) and annual cumulative cash dividend (DIV).

3.3.4. Control Variables. To make our results more accurate, we need to reduce the internal and external changes, which is consistent with previous studies that may affect the company's results [51, 52]. We include revenue (LNREV), free cash flow (FCF), revenue growth rate (REVGROWTH), net income growth rate (NIGROWTH), and firm age (AGE) (see Table 1).

3.4. Descriptive Statistics. Table 2 presents the descriptive statistics of the variables used in this paper for the final sample of 5575 firm-year observations over 2015–2019. There are 690 state-owned enterprises and 425 private enterprises. The mean (median) value of the Zscore is 5.49 (2.78). The mean (median) value of EPS is 0.38 (0.24). The mean (median) value of board size is 8.83 (9.00). The mean

Table 1: The variables used in the study.

Variable code	Variable name	Variable description
Zscore	Z-scores	The index of corporate sustainable development
EPS	Earnings per share	The ratio of profit after tax to total equity
BS	Board size	The number of directors on the board of directors
IND	Board independence	The number of independent directors
LNSALARY	Management compensation	The natural logarithm of executive salary
DAR	Debt to asset ratio	The ratio of total debt to total assets
TOP	Equity concentration	The proportion of the top ten shareholders
DIVR	Dividend ratio	The ratio of cash dividends to the profit
DIV	Dividend per share	The cash dividends paid by the company divided by the number of shares
MER	Management expense	The ratio of management expenses to operating income
TAT	Total asset turnover	The ratio of the company's net sales revenue to the average total assets
LNREV	Operating revenue	The natural logarithm of operating revenue
FCF	Free cash flow	The free cash flow (FCF) of the firm
REVGROWTH	Revenue growth rate	The revenue growth rate of the firm
NIGROWTH	Net income growth rate	The net income growth rate of the firm
AGE	Firm age	The number of years since the firm was founded

(median) value of LNSALARY is 15.50 (15.48). The mean (median) value of IND is 3.26 (3.00). The mean (median) value of DAR is 48.40 (48.91). The mean (median) value of TOP is 58.07 (58.08). The mean (median) value of DIVR is 28.90 (26.30), and the mean (median) value of DIV is 0.13 (0.05). In addition, Table 3 provides the correlation between variables.

We further analyze the data of state-owned enterprises and private enterprises. We can find that the management expense ratio (MER) of state-owned enterprises is lower than the management expense (MER) of private enterprises and the total asset turnover ratio (TAT) of state-owned enterprises is higher than the total asset turnover ratio (TAT) of private enterprises, which means that the agency cost of state-owned enterprises is lower than that of private enterprises. However, the corporate sustainable development of SOEs is lower than that of private enterprises. The Z-score and earnings per share (EPS) of state-owned enterprises are lower than private enterprises. The agency cost of state-owned enterprises is significantly lower than that of private enterprises, indicating that the Chinese government has effectively managed state-owned assets. However, it should be noted that the sustainable development capacity of state-owned enterprises is lower than that of private enterprises, which is not conducive to the long-term economic development of the region.

Through the analysis of the management structure, we found that the board size, management salary, and the number of independent directors of state-owned enterprises are higher than those of private enterprises. When analyzing corporate governance, we found that the concentration of state-owned enterprises' equity is slightly lower than that of private enterprises, which is contrary to the previous assumptions. The debt ratio (DAR) of state-owned enterprises is higher than that of private enterprises. The dividend ratio of state-owned enterprises is higher than that of private enterprises, but the annual cumulative cash dividend is slightly lower than that of private enterprises.

4. Results and Discussion

In this section, we will analyze the results of the empirical test from the impact of corporate governance on corporate sustainable development, the impact of corporate governance on agency costs, the impact of agency costs on corporate sustainable development, and the mediated effect of agency costs on the effect of corporate governance on corporate sustainable development.

4.1. The Effect of Corporate Governance on Corporate Sustainable Development. We use individual fixed effects models to test the impact of corporate governance on corporate sustainable development. Table 4 presents panel OLS regression where the dependent variable is corporate sustainable development (Z-score and EPS). The coefficient of board size (BS) is negative and significant. The size of the board of directors of a state-owned enterprise is negatively correlated with the company's sustainable development capability. This is in line with our hypothesis, indicating that the decrease of board members of a state-owned enterprise can optimize corporate management and is beneficial to the sustainable development of the enterprise. However, in private enterprises, this effect is not obvious. The coefficient of management compensation (LNSALARY) is negative and significant, indicating that increasing managers' compensation hurts the sustainable development of enterprises. This has also been confirmed in private enterprises. The coefficient of board independence (IND) is positive and significant. Independent directors can provide support for the management of the company. Although China's existing independent director system is not perfect, independent directors are still conducive to the sustainable development of state-owned enterprises. However, increasing the independence of the board of directors in private enterprises cannot significantly enhance the sustainable development capability of the enterprise.

The coefficient of equity concentration (TOP) is not significant, which is consistent with our hypothesis that

Table 2: Descriptive statistics on key variables.

Variables	All samples						Private enterprises		State-owned enterprises		T test
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(8)–(10)
	N	Mean	Median	S.D.	min	Max	N	Mean	N	Mean	Diff
BS	5575	8.83	9.00	1.78	0.00	17.00	2125	8.77	3450	8.86	−0.09**
LNSALARY	5575	15.50	15.48	0.73	12.81	18.95	2125	15.45	3450	15.53	−0.08***
IND	5575	3.26	3.00	0.64	0.00	8.00	2125	3.22	3450	3.28	−006***
TOP	5575	58.07	58.08	15.65	13.28	101.20	2125	59.02	3450	57.48	1.54***
DAR	5575	48.40	48.91	20.52	0.84	180.00	2125	45.82	3450	49.98	−4.16***
DIVR	5575	28.90	26.30	53.88	−386.10	1445.00	2125	28.24	3450	29.31	−1.07**
DIV	5575	0.13	0.05	0.41	0.00	17.02	2125	0.16	3450	0.12	0.04***
Zscore	5575	5.49	2.78	12.88	−4.98	419.80	2125	6.69	3450	4.75	1.93***
EPS	5575	0.38	0.24	0.94	−6.40	32.80	2125	0.44	3450	0.34	0.11***
TAT	5575	0.66	0.53	0.57	0.00	9.81	2125	0.63	3450	0.67	−0.04**
MER	5575	9.93	7.28	16.56	0.13	482.00	2125	9.42	3450	8.24	1.18***
FCF	5575	355.70	61.62	6063.00	−79052.00	154217.00	2125	275.50	3450	405.20	−129.67**
REVGROWTH	5575	19.20	7.05	182.50	−98.17	8748.00	2125	18.18	3450	19.84	−1.66
NIGROWTH	5575	-65.82	10.19	2130.00	−97990.00	50580.00	2125	−55.75	3450	−72.02	16.27***
AGE	5575	22.15	22.00	5.35	5.00	61.00	2125	21.61	3450	22.49	−0.87***
LNREV	5575	22.11	22.04	1.61	15.50	28.72	2125	21.91	3450	22.23	−0.32***

This table reports summary statistics for key variables for the sample of 5575 firm-year observations over 2015–2019. Please see Table 1 for the variable description. *, **, and *** represent statistical significance at the 10%, 5%, and 1% levels, respectively.

Table 3: Correlation coefficients.

	BS	LNSALARY	IND	TOP	DAR	DIVR	DIV	Zscore	EPS	TAT	MER	FCF	REVGROWTH	NIGROWTH	AGE	LNREV
BS	1															
LNSALARY	0.181***	1														
IND	0.766***	0.199***	1													
TOP	0.112***	0.111***	0.137***	1												
DAR	0.115***	0.182***	0.150***	−0.007	1											
DIVR	0.021	0.089***	0.022*	0.103***	−0.095***	1										
DIV	0.005	0.150***	0.055***	0.150***	−0.086***	0.145***	1									
Zscore	−0.116***	−0.098***	−0.098***	−0.029**	−0.402***	−0.021	0.030**	1								
EPS	0.001	0.191***	0.046***	0.154***	−0.107***	0.052***	0.870***	0.032**	1							
TAT	0.02	0.071***	0.026*	0.034**	0.050***	−0.001	0.049***	−0.022*	0.061***	1						
MER	−0.090***	−0.083***	−0.068***	−0.128***	−0.125***	−0.017	−0.044***	0.294***	−0.073***	−0.211***	1					
FCF	0.034**	0.002	0.039***	0.099***	−0.042***	0.037***	0.064***	−0.008	0.048***	0.045***	−0.019	1				
REVGROWTH	−0.044***	0.002	−0.027**	−0.008	0.045***	−0.023*	−0.005	0.009	0.009	0.057***	−0.02	−0.014	1			
NIGROWTH	0.016	0.031**	0.011	0.012	−0.032**	0.029**	0.024*	−0.042***	0.103***	0.016	−0.056***	0.009	0.030**	1		
AGE	−0.041***	−0.016	−0.064***	−0.221***	0.061***	−0.039***	−0.016	0.003	0.007	0.022*	0.060***	−0.035***	0.039***	0.01	1	
LNREV	0.256***	0.461***	0.301***	0.317***	0.396***	0.069***	0.187***	−0.313***	0.221***	0.378***	−0.430***	0.141***	−0.006	0.021	−0.061***	1

This table reports correlation coefficients between key variables for a sample of 5575 firm-year observations covering 2015–2019. Please see Table 1 for the variable description. *, **, and *** represent statistical significance at the 10%, 5%, and 1% levels, respectively.

Table 4: Panel OLS regression of the effect of corporate governance on corporate sustainable development.

Variables	(1) State-owned enterprises Zscore	(2) State-owned enterprises EPS	(3) Private enterprises Zscore	(4) Private enterprises EPS
BS	−0.243*	−0.020*	−0.384	−0.007
	(−1.87)	(−1.80)	(−1.29)	(−0.69)
LNSALARY	−1.000***	−0.010*	−1.600***	−0.040**
	(−3.72)	(−1.84)	(−2.74)	(−2.11)
IND	0.817*	0.055*	0.075	−0.018
	(1.88)	(1.75)	(0.09)	(−0.61)
TOP	−0.002	−0.001	0.044	0.002**
	(−0.14)	(−1.01)	(1.50)	(2.08)
DAR	−0.198***	−0.011***	−0.249***	−0.005***
	(−18.71)	(−12.00)	(−11.65)	(−7.26)
DIVR	0.006***	0.001***	−0.008	−0.003***
	(2.80)	(4.81)	(−1.51)	(−11.56)
DIV	1.849**	1.365***	1.159*	1.897***
	(2.18)	(24.57)	(1.76)	(93.66)
FCF	0.000	0.000	0.000	0.000
	(0.26)	(1.03)	(0.09)	(1.25)
REVGROWTH	0.000	0.000*	0.000	−0.000
	(0.61)	(1.65)	(0.09)	(−0.79)
NIGROWTH	0.000	0.000***	0.000***	0.000***
	(1.12)	(11.63)	(5.36)	(6.33)
AGE	−0.141***	0.006	−0.224**	0.004*
	(−3.23)	(1.16)	(−2.56)	(1.83)
LNREV	−1.643***	0.144***	−1.995***	0.071***
	(−10.20)	(8.52)	(−5.53)	(6.93)
_cons	38.371***	−2.372***	42.498***	−1.813***
	(7.73)	(−4.17)	(3.84)	(−6.32)
Firm	Yes	Yes	Yes	Yes
N	3450	3450	2125	2125
r^2	0.308	0.309	0.321	0.596

This table presents panel OLS regressions of the effect of corporate governance on corporate sustainable development. Please see Table 1 for the variable description. After the Chow test, the LR test, and the Hausmann test, we choose the individual fixed-effect model. Firm-fixed effects are included in all regressions. *t* statistics in parentheses. $^{*}p < 0.1$, $^{**}p < 0.05$, and $^{***}p < 0.0$.

equity concentration has little effect on the sustainable development of enterprises. The coefficient of debt ratio (DAR) is negative and significant. The increase in debt is not conducive to the sustainable development of enterprises. Under the current debt situation, the financial pressure caused by the increase in debt is even greater. The coefficient of dividend policy (DIVR and DIV) is all positive and significant. The payout of cash dividends by state-owned enterprises is conducive to enterprises' future development, and the dividend policy can provide a positive signal to the market. This has also been proved in private enterprises. We found some differences between private enterprises and state-owned enterprises. The board of directors of state-owned enterprises has greater power. Increasing the size of the board of directors is not conducive to the sustainable development of enterprises. On the contrary, independent directors of state-owned enterprises are conducive to the development of enterprises. This point illustrates the rationality of the current election system for independent directors of state-owned enterprises.

Based on the above analysis, we draw the following conclusions: (1) board size is positive with the sustainable development of the company. (2) Companies that rely on the wage structure are not beneficial to the company's sustainable growth. (3) The restructuring of the Chinese state-owned enterprises' independent director structure has begun to work, and the introduction of new independent directors is beneficial to the future growth of enterprises. (4) There is insufficient evidence that equity incentive policies are related to corporate sustainable development. (5) The level of debt hurts both the state-owned company and private company sustainable development. (6) Companies adopting active dividend policies are conducive to their sustainable development. Hypotheses 1 and 4–6 have been confirmed.

4.2. The Effect of Corporate Governance on Agency Costs. We use individual fixed effects models to test the impact of corporate governance on agency cost. Table 5 presents panel OLS regression where the dependent variable is agency cost (TAT and MER). When we use the total asset turnover rate (TAT) to measure the agency cost, the higher the total asset turnover rate, the lower the agency cost. In contrast, the lower the management expense ratio (MER), the lower the agency cost. The coefficients of the board size (BS) are statistically significant. Decreasing the board size in state-owned enterprises can effectively reduce agency costs. The influence of board independence (IND) on agency costs needs further research for private and state-owned enterprises. The coefficients of the management compensation (LNSALARY) are significant. Increasing salary will lead to an increase in agency costs.

Excessive salary has led to slack in the management, which is not conducive to the development of the enterprise. However, for private enterprises, this is just the opposite. The coefficients of the equity concentration (TOP) are −0.004 and 0.127, respectively, and both are significant at the 99% confidence level. Equity concentration has led to an increase in agency costs. This is contrary to our hypothesis. We thought that the increase in equity concentration would lead to conflicts between corporate management and owners, which will increase agency costs. The coefficients of debt ratio (DAR) are statistically significant. Increasing corporate liabilities can reduce corporate agency costs. The financial risks caused by the increase in corporate liabilities can enable corporate management to make daily decisions more cautiously, reducing agency costs. According to the empirical data results, the corporate dividend ratio (DIVR) has nothing to do with agency costs, while cash dividends (DIV) are negatively related to the agency costs of state-owned enterprises. The cash dividend policy directly leads to a reduction in corporate cash flow, thereby reducing corporate agency costs.

According to the above analysis, we draw the following conclusions: (1) The size of the board of directors is positively correlated with the agency costs of enterprises. (2) The relationship between the board independence and agency cost still needs to be further verified. (3) Increasing the salary of the management has led to an increase in the agency costs of enterprises. (4) Equity concentration is positively related

Table 5: Panel OLS regression of the effect of corporate governance on agency cost.

Variables	(1) State-owned enterprises TAT	(2) State-owned enterprises MER	(3) Private enterprises TAT	(4) Private enterprises MER
BS	−0.202**	0.667**	0.018***	−0.048
	(−2.37)	(2.17)	(3.17)	(−0.26)
IND	0.010	−2.902***	0.003	0.017
	(−0.66)	(−3.36)	(0.19)	(0.03)
LNSALARY	−0.032*	3.017***	0.026*	−1.534***
	(−1.92)	(5.67)	(1.91)	(−3.44)
TOP	−0.004***	0.127***	−0.002**	0.085***
	(−5.47)	(4.37)	(−2.35)	(3.94)
DIVR	−0.000	−0.000	0.000	−0.001
	(−0.85)	(−0.10)	(0.10)	(−0.29)
DIV	0.030*	−6.601***	0.002	0.738
	(1.88)	(−3.88)	(0.17)	(1.64)
DAR	0.002***	−0.133***	−0.001***	0.072***
	(4.94)	(−6.43)	(−2.80)	(5.01)
FCF	0.000	0.000**	0.000	0.000
	(0.59)	(2.31)	(0.97)	(0.79)
REVGROWTH	0.000***	−0.010***	0.000	−0.005***
	(7.13)	(−7.92)	(0.48)	(−5.61)
NIGROWTH	0.000	0.000	0.000	−0.000***
	(0.47)	(0.36)	(0.41)	(−4.57)
AGE	−0.014***	0.210**	−0.028***	0.678***
	(−6.18)	(2.50)	(−9.92)	(7.41)
LNREV	0.238***	−8.697***	0.231***	−7.918***
	(32.41)	(−27.69)	(21.46)	(−22.59)
_cons	−3.809***	133.813***	−3.932***	184.008***
	(−15.53)	(13.96)	(−11.91)	(17.09)
Firm	Yes	Yes	Yes	Yes
N	3450	3450	2125	2125
r^2	0.330	0.242	0.237	0.289

This table presents panel OLS regressions of the effect of corporate governance on agency cost. Please see Table 1 for the variable description. After the Chow test, the LR test, and the Hausman test, we choose the individual fixed effects model. Firm-fixed effects are included in all regressions. t statistics in parentheses. $^{*}p < 0.1$, $^{**}p < 0.05$, and $^{***}p < 0.01$.

to agency costs. (5) The debt level is negatively related to agency costs. (6) Cash dividends are negatively related to corporate agency costs. Although we rejected hypothesis tests 7, 9, and 11, we found that companies cannot increase board size and management salaries to reduce agency costs. This contradicts some traditional agency theories. The increase in corporate equity concentration will lead to intensified conflicts between management and owners, which will lead to an increase in agency costs.

4.3. The Effect of Agency Costs on Corporate Sustainable Development. We use individual fixed effects models to test the impact of agency costs on corporate sustainable development. Table 6 presents panel OLS regression where the dependent variable is corporate sustainable development (Zscore and EPS). Model 1 to Model 4 reflect the impact of state-owned enterprises' corporate governance on corporate sustainable development, and Model 5 to Model 8 are used as references that reflect the impact of private enterprise corporate governance on corporate performance. The coefficients of total asset turnover ratio (TAT) and management expense ratio (MER) and in Model 1 to Model 4 are 1.867, −0.078, 0.029, and −0.002, respectively, and all are significant. Furthermore, the coefficients of total asset turnover ratio (TAT) and management expense ratio (MER) and in Model 5 to Model 8 are 3.655, −0.139, 0.052, and −0.001, respectively, and the first three coefficients are significant. For both state-owned enterprises and private enterprises, the agency costs are negatively correlated with corporate sustainable development. Therefore, Hypothesis 3 is supported by empirical data.

4.4. The Mediating Effects of Agency Cost on the Relationship between Corporate Governance and Corporate Sustainable Development. According to Hypotheses 1 to 6, the board size and dividend policy are positively correlated with state-owned enterprises' performance, and the debt ratio and management compensation are negatively correlated with the performance of state-owned enterprises. Combined with equation (4), the coefficient c is significant. Based on hypotheses 7 to 12, the board size, cash dividends, and debt ratio of state-owned enterprises are negatively associated with agency costs, and the management compensation has a positive relation with agency costs. Combined with equation (4), the coefficient a is significant. According to Hypothesis 3, agency costs are negatively related to the corporate

Table 6: Panel OLS regression of the effect of agency cost on corporate sustainable development.

variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	State-owned enterprises				Private enterprises			
	Zscore	Zscore	EPS	EPS	Zscore	Zscore	EPS	EPS
TAT	1.867***		0.029*		3.655***		0.052*	
	(5.00)		(1.71)		(3.64)		(1.83)	
MER		−0.078***		−0.002***		−0.139***		−0.001
		(−8.14)		(−3.01)		(−3.67)		(−0.62)
BS	−0.243*	−0.094*	−0.014*	−0.020*	−0.333	−0.370	−0.008	−0.007
	(−1.87)	(−2.48)	(−1.88)	(−1.76)	(−1.12)	(−1.24)	(−0.75)	(−0.67)
LNSALARY	−1.135***	−0.232	−0.035***	−0.007	1.569***	1.532***	0.038**	0.038**
	(−4.22)	(−0.57)	(−2.68)	(−0.31)	(2.70)	(2.66)	(2.02)	(2.01)
IND	0.803**	0.279	0.007	0.051	0.249	−0.079	−0.022	−0.020
	(2.01)	(0.50)	(0.32)	(1.61)	(0.28)	(−0.09)	(−0.74)	(−0.67)
TOP	0.008	−0.073***	0.000	−0.002	0.048	0.039	0.002**	0.002**
	(0.54)	(−2.78)	(0.25)	(−1.37)	(1.64)	(1.37)	(2.02)	(2.09)
DAR	−0.192***	−0.283***	−0.005***	−0.011***	−0.241***	−0.251***	−0.005***	−0.005***
	(−18.15)	(−18.09)	(−10.68)	(−12.30)	(−11.26)	(−11.89)	(−7.46)	(−7.25)
DIVR	−0.006***	−0.004*	−0.001***	−0.001***	−0.008	−0.008	−0.003***	−0.003***
	(−2.70)	(−1.87)	(−7.71)	(−4.76)	(−1.54)	(−1.53)	(−11.54)	(−11.54)
DIV	1.872**	1.700*	1.765***	1.355***	1.226*	1.050	1.895***	1.897***
	(2.22)	(1.73)	(41.00)	(24.35)	(1.87)	(1.61)	(93.48)	(93.54)
FCF	0.000	0.000	−0.000**	0.000	0.000	−0.000	0.000	0.000
	(0.29)	(0.24)	(−2.03)	(1.02)	(0.11)	(−0.01)	(1.20)	(1.22)
REVGROWTH	0.000	0.001	0.000**	0.000**	−0.000	0.001	−0.000	−0.000
	(0.12)	(1.18)	(2.15)	(2.10)	(−0.03)	(0.64)	(−0.75)	(−0.75)
NIGROWTH	0.000	0.000	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***
	(1.10)	(1.54)	(11.95)	(11.58)	(5.32)	(5.48)	(6.35)	(6.35)
AGE	−0.141***	−0.875***	0.009***	0.004	−0.197**	−0.218**	0.004*	0.004*
	(−3.24)	(−9.49)	(4.57)	(0.69)	(−2.25)	(−2.57)	(1.81)	(1.79)
LNREV	−2.020***	−0.395	0.076***	0.173***	−2.605***	−1.451***	0.081***	0.075***
	(−11.40)	(−1.15)	(9.25)	(8.89)	(−6.57)	(−3.74)	(7.04)	(6.51)
_cons	42.317***	54.172***	−1.904***	−2.978***	51.820***	30.965***	−1.925***	−1.860***
	(8.46)	(5.07)	(−8.44)	(−4.94)	(4.58)	(2.77)	(−6.57)	(−6.27)
Firm	Yes	Yes	Yes	Yes	Yes	Yes	YES	Yes
N	3450	3450	3450	3450	2125	2125	2125	2125
r2	0.308	0.196	0.702	0.535	0.175	0.219	0.596	0.596

This table presents panel OLS regressions of the effect of agency cost on corporate sustainable development. Please see Table 1 for the variable description. After the Chow test, the LR test, and the Hausman test, we choose the individual fixed effects model. Firm-fixed effects are included in all regressions. t statistics in parentheses. $^{*}p < 0.1$, $^{**}p < 0.05$, and $^{***}p < 0.01$

sustainable development of SOEs. Combined with equation (4), the coefficient b is significant.

As be seen in Table 6, the coefficients of the board size (BS), management compensation (LNSALARY), debt ratio (DAR), and dividend policy (DIVR and DIV) are all statistically significant. Therefore, the coefficient c' in equation (4) is also statistically significant. Therefore, we can draw the following conclusion that agency costs play a mediating effect on the impact of board size, management compensation, debt ratio, and dividend policy on the sustainable development of state-owned enterprises. However, agency costs only play a mediating effect on the impact of management compensation and debt ratio on the company's sustainable development capabilities for private enterprises. Specifically, reducing the size of the board of directors and management compensation can effectively reduce agency costs and increase the sustainable development capabilities of state-owned enterprises. Increasing the level of corporate debt can reduce agency costs. However, at the same time, it will increase corporate financial burdens and bankruptcy risks, and the increased financial burdens and bankruptcy risks are more significant than the reduced agency costs, so the company's sustainable development capabilities are reduced. Increasing cash dividends for companies can effectively reduce agency costs and increase their sustainable development capabilities.

4.5. Robustness Test. Some financial indicators such as ROE and ROA can also be used to measure the sustainable development ability of a company. ROE is measured as return to total equity, and ROA is measured as return to total asset. Furthermore, current asset turnover (CAT) is also used to measure agency costs. Therefore, we test the robustness of the results by using ROE and ROA as an alternative measure of corporate sustainable development and current asset turnover (CAT) as an alternative measure of agency costs.

Table 7 presents panel OLS regressions of the effect of agency costs on corporate sustainable development. The results shown in Table 7 indicate that the coefficients of the agency costs (CAT), the coefficient of board size (BS),

Table 7: Robustness test of the effect of agency costs on corporate sustainable development.

Variables	(1) State-owned firm ROE	(2) State-owned firm ROA	(3) Private enterprises ROE	(4) Private enterprises ROA
CAT	−0.001***	−0.000*	−0.004***	−0.000
	(−3.82)	(−1.70)	(−3.08)	(−0.59)
BS	−0.384*	−0.113*	0.639	−0.012
	(−1.66)	(−1.75)	(0.79)	(−0.09)
LNSALARY	0.090**	0.029**	2.897**	0.486**
	(2.22)	(2.21)	(2.02)	(2.13)
IND	−1.020	−0.441**	−2.120	−0.487
	(−1.57)	(−2.01)	(−0.91)	(−1.32)
TOP	0.053***	0.033***	0.095	0.038***
	(2.71)	(4.75)	(1.52)	(3.34)
DAR	−0.131***	−0.128***	−0.288***	−0.141***
	(−8.66)	(−24.12)	(−5.82)	(−17.12)
DIVR	−0.012**	−0.007***	0.003	−0.002
	(−2.20)	(−4.39)	(0.21)	(−1.09)
DIV	19.308***	9.134***	2.480*	2.185***
	(12.46)	(18.04)	(1.65)	(8.71)
FCF	−0.000	−0.000	−0.000	0.000
	(−0.66)	(−0.06)	(−0.31)	(1.21)
REVGROWTH	0.006***	0.001***	0.006	0.003***
	(3.69)	(3.35)	(1.01)	(4.04)
NIGROWTH	0.001***	0.000***	0.007***	0.002***
	(12.92)	(12.91)	(8.45)	(16.53)
AGE	0.183***	0.058***	0.031	−0.039
	(3.27)	(2.79)	(0.19)	(−1.35)
LNREV	1.399***	0.835***	2.260***	0.955***
	(5.76)	(9.91)	(2.94)	(7.39)
_cons	−28.105***	−12.823***	−78.498***	−17.886***
	(−4.39)	(−5.51)	(−3.74)	(−4.72)
Firm	Yes	Yes	Yes	Yes
N	3765	3445	2070	2070
r2	0.051	0.483	0.209	0.449

This table presents panel OLS regressions of the effect of agency cost on corporate sustainable development. Please see Table 1 for the variable description. After the Chow test, the LR test, and the Hausman test, we choose the individual fixed effects model. Firm-fixed effects are included in all regressions. t statistics in parentheses. $^{*}p<0.1$, $^{**}p<0.05$, and $^{***}p<0.01$.

management compensation (LNSALARY), equity concentration (TOP), debt ratio (DAR), and dividend policy (DIVR and DIV) remain statistically significant. This is consistent with the conclusion we discussed earlier.

5. Conclusions

Based on the above empirical analysis, we believe that the following issues deserve attention. First, according to the statistical results, we found that the agency cost level of state-owned enterprises is generally lower than that of private enterprises. It shows that the Chinese government, the State-owned Assets Supervision and Administration Commission, and other departments have been influential in managing state-owned enterprises. Second, the size and independence of the board of directors of state-owned enterprises are positively related to the company's sustainable development capability; that is, increasing board members and independent directors is beneficial to the future development of the company. Third, enterprises should establish a complete management compensation system. The existing compensation system is not conducive to the sustainable development of the company. Increasing the salaries of managers will increase agency costs, thereby reducing its ability to develop sustainably. Fourth, increasing the equity concentration will intensify the conflict between management and shareholders, thereby increasing agency costs. Fifth, the implementation of cash dividend policies will help reduce agency costs, thereby increasing their sustainable development capabilities. Sixth, although increasing liabilities can reduce agency costs, increasing liabilities will increase financial risks. The bankruptcy costs caused by increasing liabilities are more significant than agency costs, which leads to a decline in the company's ability to develop sustainably. Seventh, the relationship between board size, management compensation, debt ratio, dividend policy, and corporate sustainable development is mediated by agency costs. Finally, further research is needed on the impact of equity concentration on the company's sustainable development capabilities and the impact of management independence on agency costs.

The economy is an important factor in constructing a resilient city, and listed companies play a vital role in the local economy. Starting from the microbehavior of corporate governance, exploring the impact of corporate governance on the sustainable development of enterprises is conducive to the stable development of the regional economy and contributes to constructing resilient cities. As an example of a developing country, China is committed to building resilient cities, so it has vital practical significance to take China as an example. In this paper, we take Chinese state-owned enterprises as the research object to explore the impact of corporate governance on corporate sustainable development and introduce agency cost as a mediating variable to perfect the logical chain of "corporate governance-agency cost-corporate sustainable development." We use a large sample covering state-owned enterprises and private enterprises listed in China during 2015–2019. We found that agency costs mediate the relationship between board size, management compensation, debt ratio, dividend policy, and corporate sustainable development. This also provides new ideas for trade-off theory and agency cost theory.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Spatial Analysis of Industrial Green Development and Sustainable Cities in the Yellow River Basin

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The Yellow River Basin (YRB) is an important ecological defense and economic zone in China and occupies a very important position in the economy and society of China. Premise condition of ecological protection and development of high quality in YRB is the greening of the industry. Based on the data of 35 cities in YRB in 2012, 2015, and 2018, this paper constructs an evaluation index system for the industrial green development (IGD) and explores spatial differentiation characteristics of the IGD by the exploratory spatial data analysis (ESDA) method. On this basis, this paper uses the geographical weighted regression (GWR) model to analyze the influencing factors. The results indicate the following: (1) in general, IGD in YRB shows an upward trend. (2) The Global Moran's *I* index of IGD shows a small increase; the distribution of local spatial correlation is basically unchanged. (3) There are obvious regional differences in the influencing factors of IGD. The degree of influence of each factor on IGD is openness > industrial upgrading index > urbanization rate > science and technology expenditures > reduction rate of energy consumption.

1. Introduction

China's economy has been improving rapidly and plays an important role in the world in recent years. However, insufficient awareness of ecological protection in the course of economic development has led to the emergence of many environmental problems, seriously affecting people's lives, health, and happiness, which has attracted great attention of the state. In China, the concept of "green development" was first put forward at a meeting of the Political Bureau of the CPC Central Committee in 2015. In the 18th CPC National Congress, "lucid waters and lush mountains are invaluable assets" was proposed. The 19th CPC National Congress set the building of a beautiful China as the goal of socialist modernization. This process reflects the state's policy of gradually attaching great importance to ecological and environmental protection.

Ecological protection and high-quality development of YRB have become a national strategy in 2019. The development of YRB has been ushered in unprecedented opportunities, and great efforts must be made to greatly harness and protect YRB. In order to promote the high-quality development and ecological protection [1] of YRB, it is essential to build a modern industrial development system and realize IGD. Therefore, scientific evaluation and accurately grasping the influencing factors that cause the difference of IGD in various regions can provide the decision-making basis for the industrial pattern of YRB and promote the high-quality development of YRB.

Based on this, in this paper, we use YRB as the research sample and construct IGD evaluation system. The entropy method is used to assess it, while exploratory spatial data analysis (ESDA) is used to analyze spatial characteristics. Further, this paper uses GWR model to analyze the influencing factors of IGD in YRB, with expectation of providing a reference basis.

2. Literature Review

In the new era, green development is a kind of sustainable development pattern of harmonious coexistence between human and nature. Green development originates from "ecological economy" and "green economy," with the increasingly prominent role of ecological environment, and green economy, as a new development model, has been widely concerned by international organizations (institutions) and scholars. In addition, industrial development is the main source of material wealth and one of the main reasons for the destruction of the ecological environment [2]. Therefore, it is particularly important to explore IGD.

2.1. Connotation of IGD. IGD originated from "green economy" [3]. Its purpose was to construct a sustainable development mode with harmonious economy, ecology, and society. Green development refers to the ecological environment under the control of capacity and resources bearing capacity, by protecting the natural environment to realize the sustainable development of the new development pattern and the concept of ecological development [4]. Its core is to establish and form a coordinated interaction mechanism of economy, nature, and society [5]. Sustainable development models, such as "green economy," "low-carbon economy," "ecological economy," and "circular economy," all embody the concept of green development from different perspectives [6]. Although being with the same connotation of sustainable development, green development emphasizes the symbiosis of "green" and "development" without compromising the ability to regenerate resources and environment, and without reducing the level of economic and social welfare [7], it is more prominent in the "development" on the basis of sustainability. IGD requires sustainable development and ecological civilization construction from the industrial level, aiming at building an industrial structure and production model with high science and technology content, low resource consumption, and less environmental pollution, so as to realize the organic coordination between economic development and resource environment.

2.2. Evaluation of IGD. IGD is requirement of green development from the industrial level. Measuring green development falls into two categories: efficiency of green development and comprehensive index system [8]. The first is to assess green development by introducing the efficiency [8–12]. Another approach is to establish an index system to comprehensively measure IGD. According to the different regions and emphases of the research, the comprehensive index system is mainly established from the following aspects: the first green development indicators were set up by the OECD [13]. Based on this index system, many scholars have carried out a series of researches. Existing researches mainly construct IGD index system from three dimensions of industry, resource environment, and government policy [14–16]. There are also some studies evaluating the index from different industrial structures [17, 18].

2.3. Influencing Factors of IGD. There is still no complete conclusion on the factors affecting IGD, which mainly include the following aspects: environmental policy, government investment [19, 20], advances in technology, industrial structure [21], economic opening [22, 23], and urban size [24, 25]. Some studies showed that government regulation [16] and environmental regulation [19] had a significant positive effect on IGD, promoting industrial transformation and upgrading through government regulation [18], to promote the process of IGD. Besides, the government increasing investment in science, technology, energy conservation, and environmental protection through financial means was also beneficial to IGD [26]. At the same time, we cannot ignore the negative impact of the rapid urban expansion [27], low energy utilization [23], and blind utilization of foreign capital [22] on IGD.

2.4. Summary. Through combing the existing literatures, it is found that the evaluation and influencing factors of IGD are relatively mature, which provides a relatively perfect research basis for this paper. However, the existing researches are deficient in spatiotemporal differentiation. Compared with the existing researches, the innovations of this paper are as follows. (1) Research sample: ecological protection and high-quality development of YRB have become a national strategy, and the study of this region has great practical significance. (2) Research conclusions: by comparing the regression coefficient, it is found that the influence of openness is greater than that of industrial advanced index on the IGD in YRB, which is different from the previous conclusion [28]. The sample of this paper is YRB, which is relatively targeted, so it has certain reference value for the policy formulation of high-quality development of YRB.

3. Research Area and Research Methods

3.1. Overview of Research Area. On the basis of YRB trunk stream area demarcated by the Yellow River Commission of the Ministry of Water Resources, comprehensively considering the natural conditions, administrative divisions, and economic development of each city, as well as the representativeness and availability of data, this paper determines 35 cities in 7 provinces of Shanxi, Inner Mongolia, Shandong, Henan, Shaanxi, Gansu, and Ningxia (Figure 1).

3.2. Research Method

3.2.1. Entropy Method. The entropy method is an impersonal assignment. It determines the weight of each index according to its own statistical attribute, avoiding subjective incompleteness [29–31]. Therefore, entropy method is adopted in this paper to measure IGD of 35 cities along YRB. According to Chen et al. [32], the specific calculation steps are as follows:

(1) Data standardization: because the dimensions and orders of magnitude of the original data for each indicator are different, standardized processing is required to eliminate the impact on the evaluation.

Positive indicators:

$$Y_{ij} = \frac{X_{ij} - \min\left(X_{ij}\right)}{\max\left(X_{ij}\right) - \min\left(X_{ij}\right)}. \quad (1)$$

Negative indicators:

$$Y_{ij} = \frac{\max\left(X_{ij}\right) - X_{ij}}{\max\left(X_{ij}\right) - \min\left(X_{ij}\right)}. \quad (2)$$

Among them, Y_{ij} is the standardized matrix, and X_{ij} is the original data matrix.

(2) Calculate the entropy value of index:

$$e_j = -k\sum_{i=1}^{n} P_{ij}\ln\left(P_{ij}\right). \quad (3)$$

Among them, $k = 1/\ln(n)$, $P_{ij} = Y_{ij}/\sum_{i=1}^{n} Y_{ij}$; e_j is the entropy value, $n = 35$.

(3) Calculate index weight:

$$W_{ij} = \frac{\left(1 - e_{ij}\right)}{\sum_{i=1}^{m}\left(1 - e_{ij}\right)}. \quad (4)$$

Among them, W_{ij} is the index weight, $m = 18$.

(4) Calculate the comprehensive score:

$$S_i = \sum_{i=1}^{m} W_{ij}P_{ij}. \quad (5)$$

Among them, S_i is the level of IGD.

3.2.2. Exploratory Spatial Data Analysis. ESDA is a data-driven method to study spatial distribution characteristics, which mainly includes global spatial autocorrelation and local spatial autocorrelation. We use ESDA to study spatial distribution characteristics of IGD in YRB.

(1) Global Spatial Autocorrelation. Global spatial autocorrelation can measure the clustering degree of the study area. In this paper, Global Moran's I is selected to evaluate spatial characteristics of the IGD level in YRB and find out their correlation and differences. According to Ren et al. [33], the calculation formula is

$$\text{Moran's } I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}\left(X_i - \overline{X}\right)\left(X_j - \overline{X}\right)}{S^2\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}}. \quad (6)$$

Among them, $\overline{X} = (1/n)\sum_{i=1}^{n} X_i$; $S^2 = (1/n)\sum_{i=1}^{n}\ (X_i - \overline{X})^2$; n is the sample size; X_i and X_j are the IGD levels of regions i and j; W_{ij} is the spatial weight matrix. Usually, the range of Moran's I is (−1, 1). If Moran's I >0, the areas with similar IGD are clustered, while Moran's I <0 means that IGD is scattered.

(2) Locally Spatial Autocorrelation. This paper adopts the cold and hot spot analysis method and uses Getis-Ord G∗ index to evaluate the local regional spatial characteristics of industrial development in YRB. The calculation formula is in accordance with Hu et al. [34]:

$$G_i^*(d) = \frac{\sum_{i=1}^{n} W_{ij}(d)X_i}{\sum_{i=1}^{n} X_i}. \quad (7)$$

Among them, X_i is the IGD of region i. If $G_i^*(d)$ >0, IGD around city i is relatively high, and it is a hot spot; while if $G_i^*(d)$ <0, IGD around city i is relatively low, and it is a cold spot area.

3.2.3. Geographical Weighted Regression Model. GWR model was proposed by Fotheringham [35]. Based on local regression analysis, the spatial position of data is embedded into regression parameters to measure the spatial instability of various geographical variables, which is conducive to the exploration of spatial law. Therefore, the GWR model is adopted in this paper to analyze the spatial heterogeneity of the driving forces of IGD in YRB. According to Chen et al. [36], the calculation formula is

$$y_i = \beta_0(u_i, v_i) + \sum_{j=1}^{n}\beta_j(u_i, v_i)x_{ij} + \varepsilon_i. \quad (8)$$

Among them, y_i is the global dependent variable, x_{ij} is the influencing factor, $\beta_0(u_i, v_i)$ is a constant term, (u_i, v_i) are the spatial coordinates of the i-th region, $\beta_j(u_i, v_i)$ is the parameter of region x_{ij}, and ε_i is the random error term.

3.3. Index System Establishment and Data Source. The connotation of IGD requires that economic development of high quality should be compatible with ecological protection. It emphasizes that economic development also takes into account ecological protection. From the perspective of IGD, it is required that urban economic development should focus on quality improvement on premise of sustainable development. The IGD in YRB needs green transformation through three industries together to achieve green and high-quality economic growth [37]. Industrial development changes with the utilization of resources and ecological environment. The essence of green development is sustainable development, by raising the utilization rate of resources, improving the environmental conditions to relieve the contradiction between economic development and ecological protection [38]. However, only depending on market regulation is not enough while pursuing the dynamic balance of economic development and ecological protection, and support of the government is quite essential [16]. Therefore, based on the previous, we construct an evaluation index system of IGD in 35 cities in YRB from three dimensions of green economic growth, resource, and environment carrying capacity and government support (Table 1).

In terms of green economic growth, it mainly measures economic level of the region and the green level of the three industries [39]. The economic density and per capita GDP are used to reflect the economic development status of the region to measure the green growth potential. The green development level of primary industry is measured by grain yield and fertilizer use. The secondary industry is the main reason for green development, which is measured by GDP of industries above designated scale, number of enterprises above designated scale, and comprehensive utilization rate of solid waste. The proportion of the added value of the tertiary industry in GDP and the number of employees in the tertiary industry will be used to assess IGD of the tertiary industry.

In terms of resource and environment carrying capacity, the index system is mainly used to measure the abundance of regional resources and the environmental governance status of enterprises [40]. Cities around YRB are rich in resources. Considering the availability of data, the abundance of resources is measured by the total amount of water resources. The emission of waste water, the emission of sulfur dioxide, and the emission of soot are used to measure the environmental governance status of enterprises.

In terms of government support, the role of government in IGD is extremely important [41]. The established indicator system measures the government's investment in environmental protection from three aspects: (1) expenditure on energy conservation and environmental protection; (2) green coverage rate and per capita park area in built-up areas; (3) harmless treatment rate of domestic waste and sewage treatment rate.

Considering the timeliness and availability of data, and there must be at least three years to study the change of IGD, the data in this paper are 2012, 2015, and 2018. The sources are mainly China City Statistical Yearbook in 2013, 2016, and 2019, Statistical Yearbooks for all provinces of YRB, Statistical Yearbooks for all cities, and Bulletin of National Economic and Social Development. Some of the missing data were supplemented by interpolation method.

4. Spatial Differentiation of IGD in YRB

4.1. Comprehensive Analysis of IGD. The scores of IGD level of 35 cities in YRB in 2012, 2015, and 2018 are calculated by entropy method. We find that the change of IGD in YRB has certain rules (Figure 2). (1) From the perspective of spatial weight, that of green economic growth (0.6652) in the criterion layer is the largest, followed by government support (0.2281), and the smallest is resource and environment carrying capacity (0.1067). This shows that the indicators of green economic growth have a greater impact on IGD in YRB, while those of government support and resource and environment carrying capacity are decreasing in order. (2) From the perspective of spatial distribution, IGD in YRB shows trend of "high in the east and low in the west." The scores of Zhengzhou, Dezhou, Zibo, and Heze are relatively high, while those of Baiyin, Zhongwei, Wuzhong, and Shizuishan are low. This is because Zhengzhou is the national central city in YRB, taking the lead in transformation and upgrading of industries, and is the main position of high-tech industry transfer. In addition, the tertiary industry accounts for a relatively high proportion. In urban areas, most of them are high-value-added industries. Pollution and low-value-added enterprises have been eliminated, transferred, and upgraded, which have little negative impact on the ecological environment. Therefore, Zhengzhou's IGD level is higher. Baiyin and Zhongwei are located in the western region. Due to backward economic development and small proportion of the tertiary industry, they are difficult to develop high-value-added industries by relying on their own strength. They have become the traditional manufacturing industry's undertaking site and are highly dependent on energy and resources, so their green development level is relatively low. (3) From the perspective of spatial evolution characteristics, the spatial pattern of IGD in YRB in 2012, 2015, and 2018 is relatively stable, while the polarization difference is relatively obvious. The average score of IGD in each city rose from 0.2968 in 2015 to 0.3132 in 2018, and the range rose from 0.4371 in 2012 to 0.5448 in 2018, indicating that IGD in each region of YRB has been improved, but the gap between cities is getting larger and larger. This is because the Central Plains city group was approved as a national city group relatively early and has a large leading advantage, while the Lanxi city group was approved as a national city group in 2018 and started late, leading to a relatively significant phenomenon of spatial polarization.

4.2. Spatial Characteristics of IGD

4.2.1. Overall Spatial Characteristics of IGD. For quantitatively studying the spatial pattern evolution of IGD in YRB, Queen's adjacency matrix is adopted as the spatial weight, and ArcGIS10.2 is used to calculate the Global Moran's I at the comprehensive level of IGD in YRB in 2012, 2015, and 2018. The results show that the Global Moran's I in the three years are all positive and passed the test at the significance level of 0.01 (Table 2). This indicates that IGD in YRB presents a significant positive spatial autocorrelation in 2012, 2015, and 2018. The rising trend of Global Moran's I reflects the increasing spatial concentration. This is because the development of urban agglomerations and metropolitan areas has achieved remarkable results, and national policies are increasingly inclined to overall planning, which has strengthened the links between cities.

4.2.2. Local Spatial Correlation Characteristics of IGD. In order to make up for the influence of global autocorrelation that cannot reflect local correlation characteristics and further reveal the spatial correlation pattern of IGD in YRB, the cold and hot spot analysis method is adopted, and ArcGIS10.2 is used to draw the spatial cold and hot spot distribution map of IGD in YRB in 2012, 2015, and 2018 (Figure 3). Figure 3 shows that, overall, there is no substantial change in the pattern of cold and hot spots for the

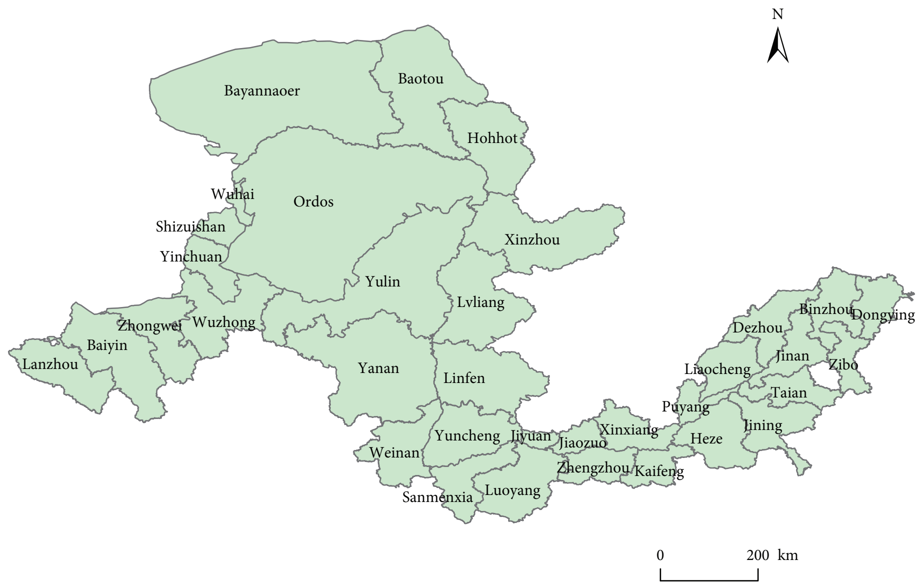
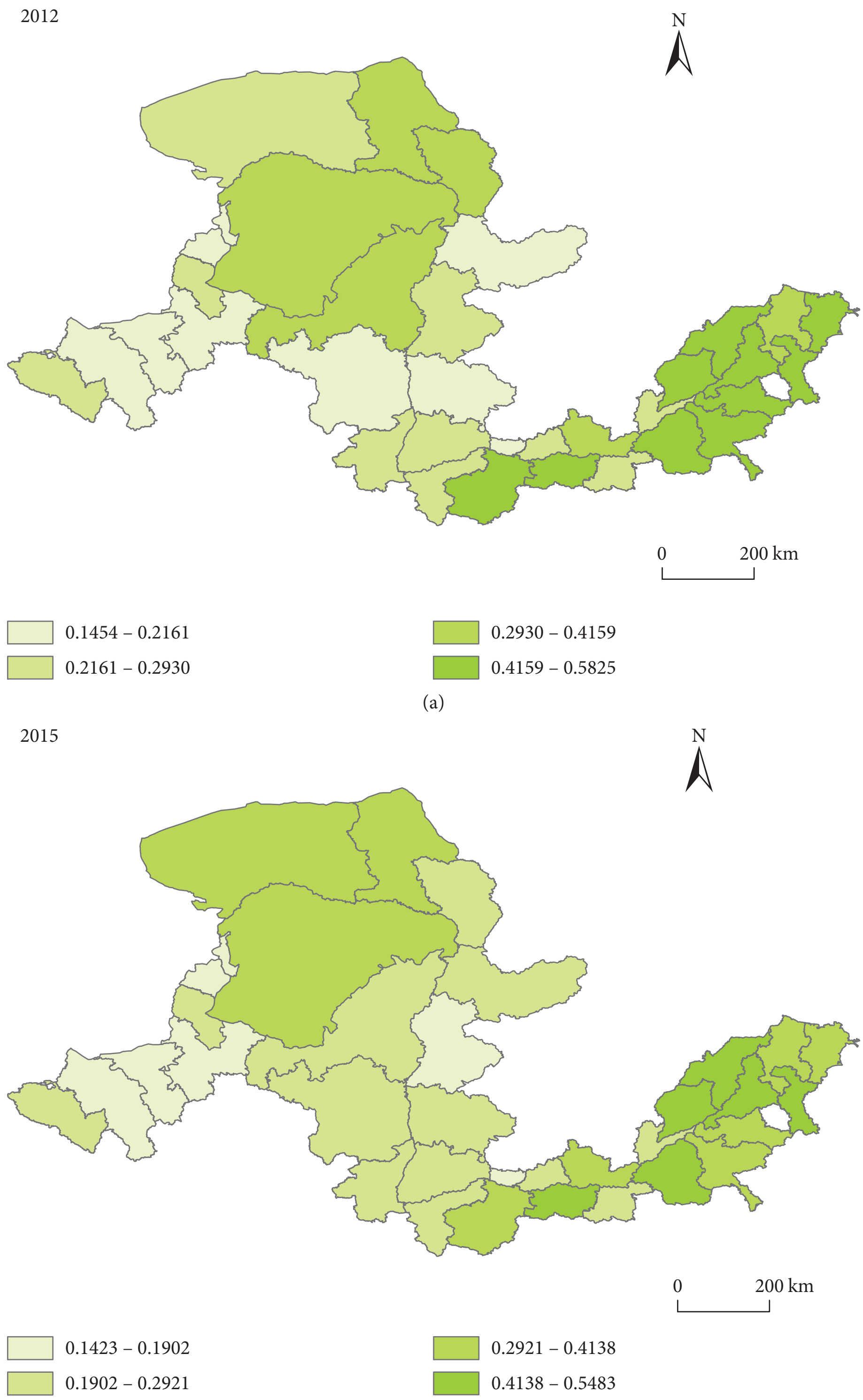


Figure 1: Topographic map of YRB and sample of this paper.

Table 1: IGD evaluation index system of cities in YRB.

Target layer	Criterion layer	Variable	Index
Industrial green development level	Green economic growth	Green growth potential	Economic density
			Per capita GDP
		Primary industry	Grain yield
			Fertilizer use
		Secondary industry	The gross output value of industries above designated scale
			Number of enterprises above designated scale
			Comprehensive utilization rate of solid waste
		Tertiary industry	Proportion of added value in GDP
			Number of employees in the tertiary industry
	Resource and environment carrying capacity	Abundance of resources	Total amount of water resources
		Environmental conditions	Emission of waste water per unit of GDP
			Emission of sulfur dioxide per unit of GDP
			Emission of soot per unit of GDP
	Government support	Government investment	Expenditure on energy conservation and environmental protection
		Infrastructure	Green coverage rate
			Per capita park area in built-up areas
		Environmental governance	Harmless treatment rate of domestic waste
			Sewage treatment rate

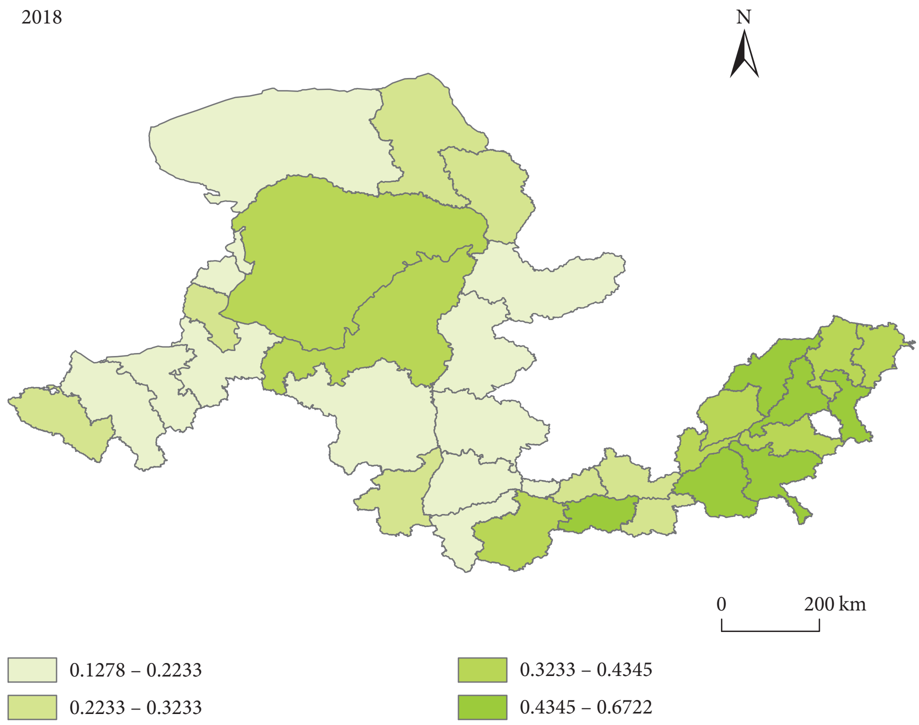
IGD in YRB, which maintains the characteristic of "high in the east and low in the west." From the point of economic development, Shandong and Henan are better than Inner Mongolia, Shanxi, and Gansu. It can be said that economic development can drive the local of IGD. In the three years, the hot spots are concentrated in the east (Jinan, Binzhou, Zibo, Tai'an, Liaocheng, and Dezhou), while the cold spots are mainly in the west (Baiyin, Zhongwei, and Wuzhong), with clear polarization between the east and the west. From the perspective of the number of cold and hot spots, the hot is increasing, from 9 in 2012 to 11 in 2018. The increasing cities are Zhengzhou, Xinxiang, Liaocheng, and Jining. The number and spatial distribution of cold spots remained basically unchanged, increasing from 9 in 2012 to 11 in 2018. This is because there are many hot spots in Shandong province, among which Jinan and Dezhou have played a



(a)

(b)

Figure 2: Continued.



(c)

Figure 2: IGD of cities in YRB in 2012, 2015, and 2018.

Table 2: Moran's I of IGD in YRB in 2012, 2015, and 2018.

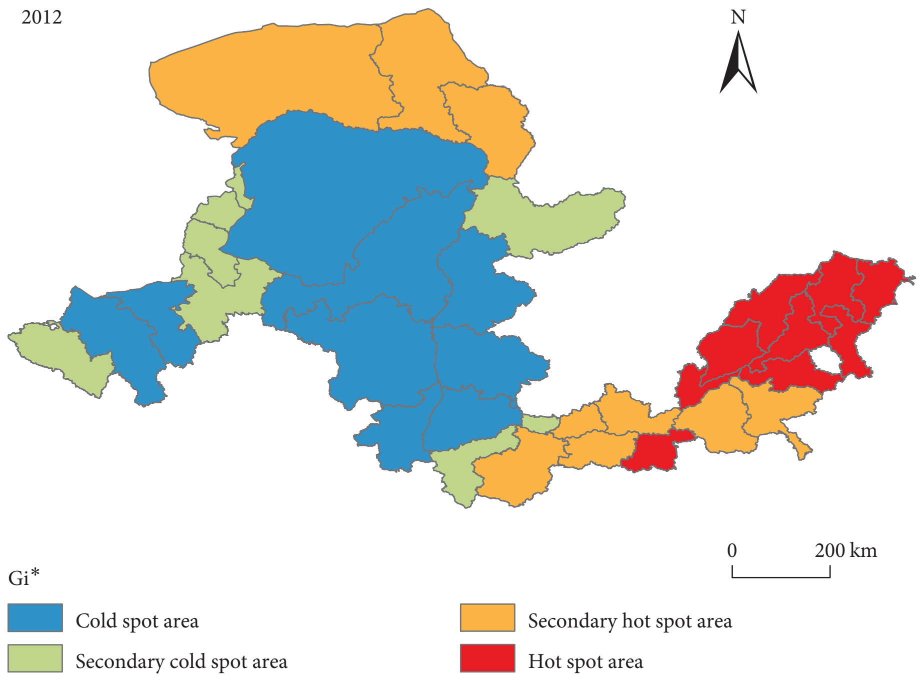
Year	Moran's I	E (I)	Z (I)	P (I)
2012	0.3258	−0.2941	3.0308	0.0024
2015	0.3522	−0.2941	3.2763	0.0010
2018	0.3680	−0.2941	3.4517	0.0006

leading role in the surrounding cities. Zhengzhou's relatively rapid development has driven the development of Kaifeng, Xinxiang, and other cities, while the western region lacks hot cities to drive the green development of regional industries. In addition, from 2012 to 2018, the number of hot spot areas and secondary hot spot areas decreased, and the number of cold spot areas and secondary cold spot areas increased, indicating that the gap in industrial green development level of IGD within the YRB is narrowing.

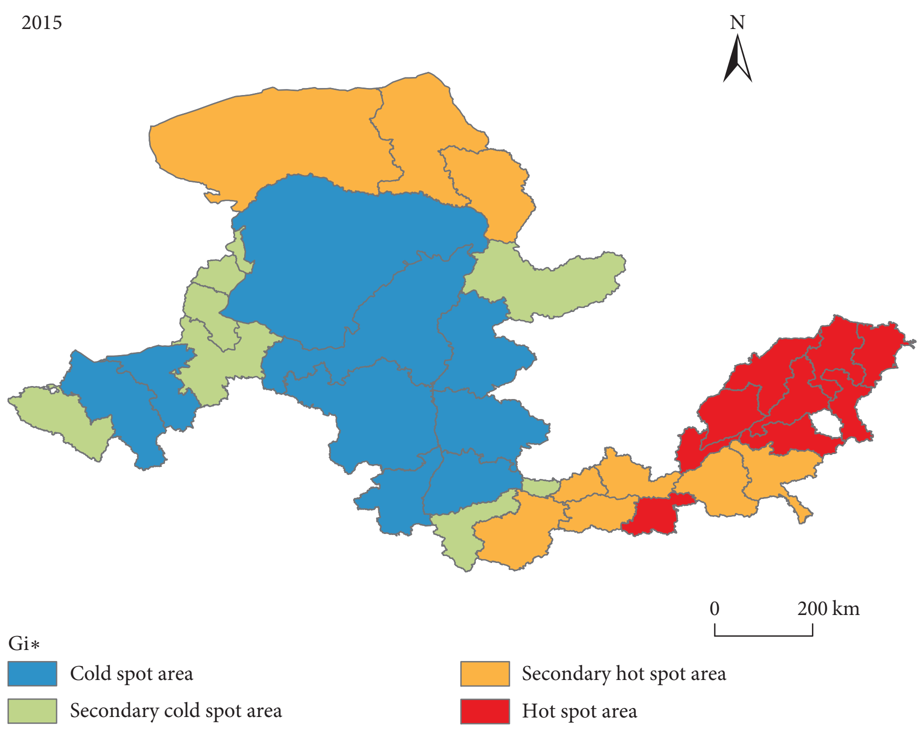
5. Analysis of Influencing Factors on IGD in YRB

5.1. Influencing Factor Analysis Framework. The level of IGD is affected by many factors, and the formation mechanism is relatively complex. Combing existing literatures, scholars generally believe that industrial structure [21, 26], urban development potential [8, 42], energy efficiency [23, 42], degree of openness [16, 22], and government support [20, 42] have significant effects on IGD. Therefore, this paper selects these five aspects as the influencing factors (Table 3). In order to prevent the collinearity of the indicators from causing deviations in the research results, SPSS is used to conduct collinearity test for these five indicators (Table 4). The results showed that the variance inflation factor (VIF) was less than 10, and the conditional index (CI) was less than 30, indicating that there is no collinearity.

5.2. Spatial Heterogeneity of Influencing Factors. In this paper, ArcGIS10.2 is used to conduct OLS regression analysis for these 5 indicators, and the results are shown in Table 5. In Table 5, $R^2 = 0.24$, AICc $= -35.52$, indicating that this model could only explain 24% of the variables, with poor fitting degree. Based on the geographical weighted

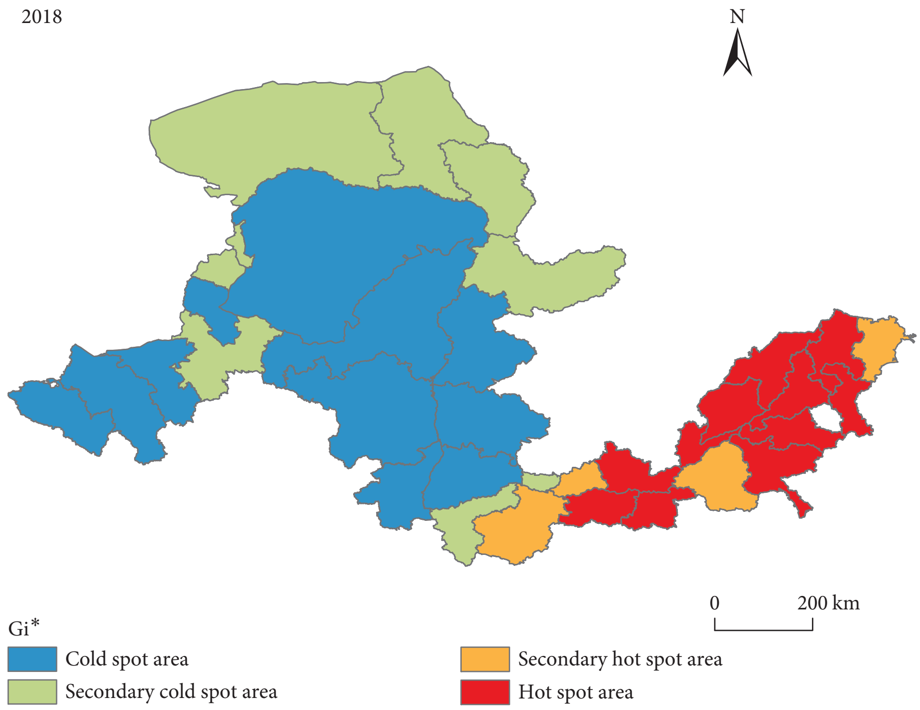


(a)



(b)

Figure 3: Continued.



(c)

Figure 3: Spatial distribution of cold and hot spots of IGD in YRB in 2012, 2015, and 2018.

regression (GWR) analysis, the core type ADAPTIVE is selected, the bandwidth is AICc, and the result is $R^2 = 0.60$, AICc = −42.51. The R^2 of the GWR model is much larger than that of the OLS model, and the difference of AICc is greater than 3. Relevant studies [43] show that if the difference of AICc is greater than 3, the GWR model is better. Hence, GWR model is selected for analysis in this paper.

Table 6 shows the regression coefficients of the calculation results. It can be seen from the results that the influence of each variable on IGD in each city is quite different. From the positive and negative aspects of the regression coefficients, industrial upgrading index, urbanization rate, total import and export to GDP, and science and technology expenditures show significant positive effects. The reduction rate of energy consumption varies from city to city. From the mean value of the regression coefficient, the influences of the five variables on IGD in YRB are ratio of total imports and exports to GDP > industrial upgrading index > urbanization rate > science and technology expenditures > reduction rate of energy consumption.

Figure 4 shows that the industrial upgrading index has a positive impact on IGD. To be specific, the regression coefficient of the industrial upgrading index of all cities in YRB is positive, which is distributed within the range of 0.0264–0.1742. It indicates that the higher the industrial upgrading index, the higher the IGD. This is because the tertiary industry, represented by high-tech industry, is the gathering place of technical factors and talent factors. Its products are mainly products and services with high added value, which can promote IGD. At present, the secondary industry is still dominated by the traditional manufacturing industry, and the production factors are mainly raw materials and land. It is a pollution-intensive industry, which has an impeding effect on IGD. Therefore, theoretically speaking, the tertiary industry accounts for a larger proportion, while the secondary industry accounts for a smaller proportion, so the level of IGD in this region will be higher. In space, it presents the distribution characteristic of decreasing from the central region to the east and the west. The cities with high regression coefficient include Yuncheng, Sanmenxia, Luoyang, Jiyuan, Jiaozuo, Xinxiang, Kaifeng, and Zhengzhou. IGD of these cities is most affected by the industrial upgrading index. Yuncheng, Sanmenxia, and Jiaozuo are resource-based industrial cities with a large proportion of the secondary industry. In recent years, with the continuous upgrading of the industrial structure, the traditional manufacturing industry has gradually shifted to the service manufacturing industry. Both the proportion of tertiary industry and the level of IGD increased. Zhengzhou and Luoyang are big cities in economy, population, and

Table 3: Influencing factors of IGD.

Influence factor	Variable	Definition
Industrial structure	Industrial upgrading index	Added value of tertiary industry/secondary industry
Urban development potential	Urbanization rate	Urban population/total population
Energy efficiency	Reduction rate of energy consumption per unit of GDP	1. Energy consumption per unit of GDP this year/energy consumption per unit of GDP last year
Degree of openness	Total imports and exports to GDP ratio	Total imports and exports/GDP
Government support	Science and technology expenditures	—

Table 4: Collinearity test of influencing factors.

Variable	Variance inflation factor (VIF)	Tolerance (T)	Conditional index (CI)
Industrial upgrading index	1.054	0.949	2.931
Urbanization rate	1.109	0.901	3.45
Reduction rate of energy consumption per unit of GDP	1.143	0.875	4.485
Total imports and exports to GDP ratio	1.046	0.956	7.024
Science and technology expenditures	1.083	0.923	14.555

Table 5: Comparison of OLS regression and GWR regression results.

	OLS	GWR
R^2	0.24	0.60
AICc	−35.52	−42.51

transportation with rich regional resources. The growth of industrial upgrading index means that the proportion of tertiary industry is rising, and the level of industrial greening is improving. There are 12 cities with regression coefficient between 0.0246 and 0.0480, including Wuhai, Zhongwei, and Baiyin, with the smallest regression coefficient and the lowest influence degree. This is because Wuhai and Zhongwei are located in the west. They are still dominated by the secondary industry, and their economic strength and infrastructure are relatively weak. They can only undertake the traditional manufacturing industry eliminated by the east. It is difficult to develop the high-tech industry by relying on their own strength. Besides, the tertiary industry development is slow, and the industrial upgrading index of these regions has little impact on IGD.

In Figure 5, the regression coefficient of urbanization rate is positive, ranging from 0.0254 to 0.1079, indicating that urbanization rate has a positive impact on IGD. The improvement of urbanization rate can drive IGD and is an important thrust for IGD in YRB. This is because the improvement of urbanization level is accompanied by the population gathering, the improvement of urban functions, and the optimization of spatial layout. These factors have created good conditions for IGD. The urbanization rate has a driving impact on IGD, while the influence degree of each city in YRB is different. The spatial distribution is low in the middle and high in both sides. 9 cities, including Lanzhou, Yinchuan, Ordos, Zhongwei, and Baiyin, are located in high-value districts. And IGD of these cities is most affected by the urbanization rate. The urbanization rate of Zhongwei, Wuzhong, and Baiyin is low, which is only 30.45%, 50.18%, and 50.62% in 2018, far lower than other cities. The improvement potential is large, and IGD is strongly influenced by urbanization rate. The other high-value areas are mainly concentrated in western cities such as Lanzhou and Yinchuan. There are two reasons: on the one hand, these cities are located to the west of the "Hu Line." China has implemented the western development policy, which promotes the population agglomeration of western cities. On the other hand, the urbanization rate of Lanzhou and Yinchuan reached 81.03% and 77.58% in 2018. It has reached the later stage of urbanization, and urban development is in urgent need of support from talents. In 2017, many cities began the "war for talents." In order to retain talents, Lanzhou lowered the threshold of becoming urban residents, which increased the urban population and provided talent support for IGD. The low-value areas of regression coefficient are mainly concentrated in 8 cities, including Xinzhou, Luliang, Linfen, and Jiaozuo. This may be because most of these cities are close to the provincial capitals, which have a greater radiation effect on them. Compared with provincial capitals, the attraction to talents, especially high-end talents, is lower, and the accumulation of human capital is slower. There is no sufficient support of talents, transformation and upgrading of industries are slow, and the promotion of IGD is less.

Figure 6 shows that the change rate of energy consumption has positive and negative impact on IGD. In other words, the faster the reduction rate of energy consumption in some regions, the higher the IGD level. This can be caused by two reasons: first, more than 70% of China's current

Table 6: Results of the GWR model.

	Minimum	Lower quartile	Mean	Upper quartile	Maximum
Industrial upgrading index	0.0264	0.0445	0.0858	0.1158	0.1743
Urbanization rate	0.0254	0.0508	0.0708	0.0964	0.1079
Reduction rate of energy consumption per unit of GDP	−0.1506	−0.1112	−0.0231	0.0600	0.0809
Ratio of total imports and exports to GDP	0.0282	0.1467	0.1997	0.2551	0.3002
Science and technology expenditures	0.0148	0.0274	0.0514	0.0652	0.0847

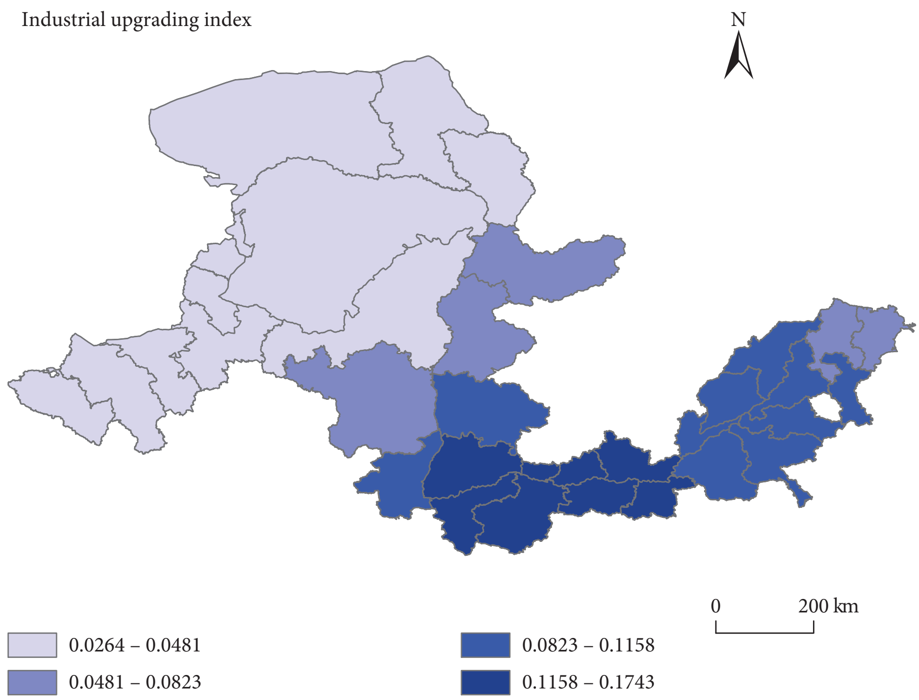


Figure 4: Spatial distribution of regression coefficient of the industrial upgrading index on IGD.

energy use is nonclean. Energy consumption is accompanied by the generation of pollutants and wastes, which has a negative impact on environmental development. Improving the utilization rate of energy, using clean energy, advocating "green economy," and opposing "black economy" can effectively protect the ecological environment, which is conducive to IGD. Second, the total amount of fossil energy is limited. Coal is a nonrenewable and highly polluting energy source. For high-polluting enterprises, the effective way to reduce the use of polluting energy is to increase the utilization rate of resources and create more value with less resource. In this way, the reduction of energy consumption promotes IGD. From the perspective of spatial distribution, reduction rate of energy consumption in each city has different impacts on IGD, showing a spatial distribution decreasing from west to east. The most influential cities are Shizuishan, Yinchuan, Hohhot, etc., with the regression coefficient being between −0.1505 and −0.1082. There are two main reasons: on the one hand, the rate of decline in energy consumption is relatively high, which makes the level of IGD improve rapidly. According to the original data, the energy consumption of Shizuishan and Yinchuan decreased by 9.5% and 12%, respectively, much faster than the national average. On the other hand, clean energy consumption reduces energy consumption. Statistics show that clean energy consumption in these cities accounted for nearly 40% in 2019, well above the national average. The use of clean energy is bound to reduce the use of polluting energy, which is conducive to driving down the rate of energy consumption. Based on the above two reasons, the reduction rate of energy consumption in these cities has a great negative impact on IGD. The reduction rate of energy consumption in Henan and Shandong provinces has a small and basically positive influence on IGD. This may be because the development of the two provinces is in a dominant position in YRB, and the development degree of dependence on traditional energy is small. Reduction rate of energy consumption is much lower than that of other regions, and the rate of decline is not as fast as that of other regions. Therefore, the reduction rate of energy consumption in these two provinces promotes IGD.

In Figure 7, openness has a positive impact on IGD. The regression coefficient of the total imports and exports to GDP is positive, between 0.0282 and 0.3001, indicating that the more open the economy, the more conducive to IGD. This shows that all regions in YRB have successfully crossed the stages of "pollution refuge effect" and "pollutant paradise hypothesis." With the deepening of the

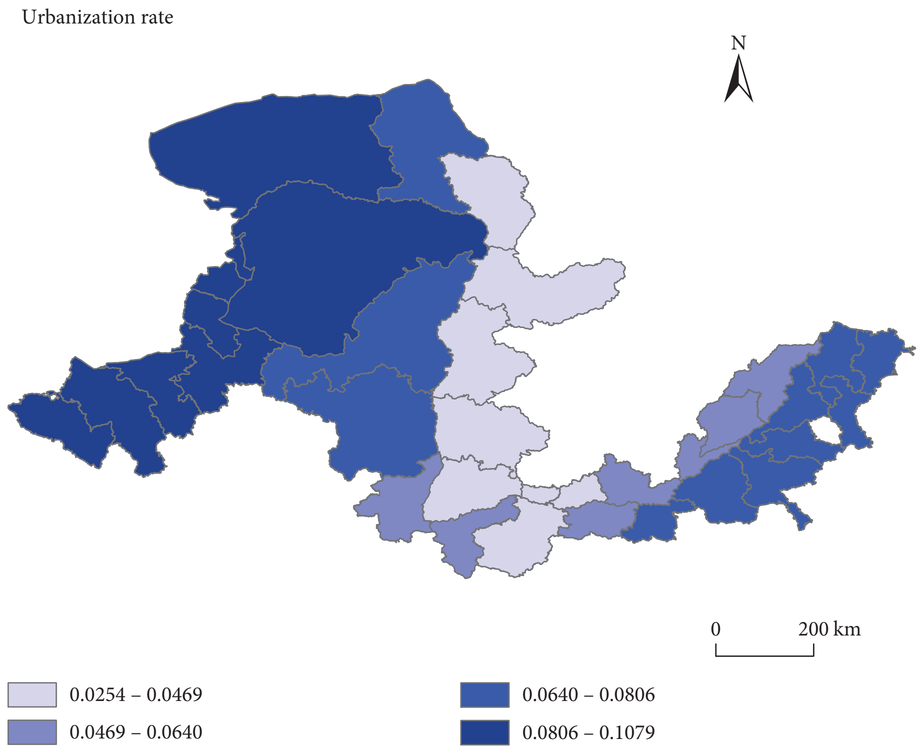


Figure 5: Spatial distribution of the coefficient of urbanization rate to IGD.

concept of sustainable development, the requirement of the import and export goods is increasing. From the perspective of spatial layout, the regression coefficient shows the spatial feature of decreasing from the center to both sides. The coefficient of Zhengzhou, Jiaozuo, Luoyang, and Linfen is larger, and IGD of these cities is greatly influenced by the open economy; conversely, the influence of Bayannaoer and Baotou is smaller. The reason mainly has the following two aspects: on the one hand, Zhengzhou and other cities have relatively developed transportation facilities and are closely connected with the world. Zhengzhou is an important transportation hub in China, and Zhengzhou Aviation Port Area is the only national aviation port economic comprehensive experimental area in China, with relatively perfect infrastructure and conditions for the transformation to an export-oriented city. However, Bayannaoer and Baotou are located in the western region of China, where all kinds of transportation modes are relatively backward and have few economic connections with the world. Although the ratio of total imports and exports to GDP promotes local IGD, it is relatively small. On the other hand, the added value of import and export goods is different. Zhengzhou is a new major city of China, and the added value of import and export products is higher compared to Bayannaoer.

Figure 8 shows that science and technology expenditures have a significant positive influence on IGD, and the degree of impact varies from city to city. Specifically, the regression coefficient of science and technology expenditures is between 0.0148 and 0.0847. The high-value areas include Linfen, Luliang, and Hohhot, and the regression coefficient is between 0.0651 and 0.0847. It may be because the level of science and technology in these cities is low, and the marginal effect of investment in science and technology is significant. The 2019 government work report shows that, in 2018, Hohhot strategic emerging industries output value accounts for 30% of industrial output value above designated scale, and the contribution rate of science and technology to economic growth increased to 56%. It proves that the input of science and technology in Hohhot is in direct proportion to the output, and increasing the expenditure of science and technology is conducive to IGD. The low-value areas of regression coefficient are Bayannaoer, Baiyin, Ordos, Lanzhou, Shizuishan, Wuhai, Wuzhong, Zhongwei, Yinchuan, and Baotou, whose scientific and technological expenditure had little influence on IGD. There are two reasons: on the one hand, there is time lag of science and technology expenditures. Science and technology expenditures are mainly used for scientific research and cultivating talents. These cities are not that attractive to high-end talents. The implementation of western development policy has attracted some talent; however, it still needs time to translate them into innovative results. On the other hand, the innovation efficiency of these cities needs to be improved. These cities cannot ignore the insufficient investment in science and education in green development and low efficiency in research and development. Due to low efficiency, the innovation results are not timely and accurately applied to the green industry, which has little impact on IGD.

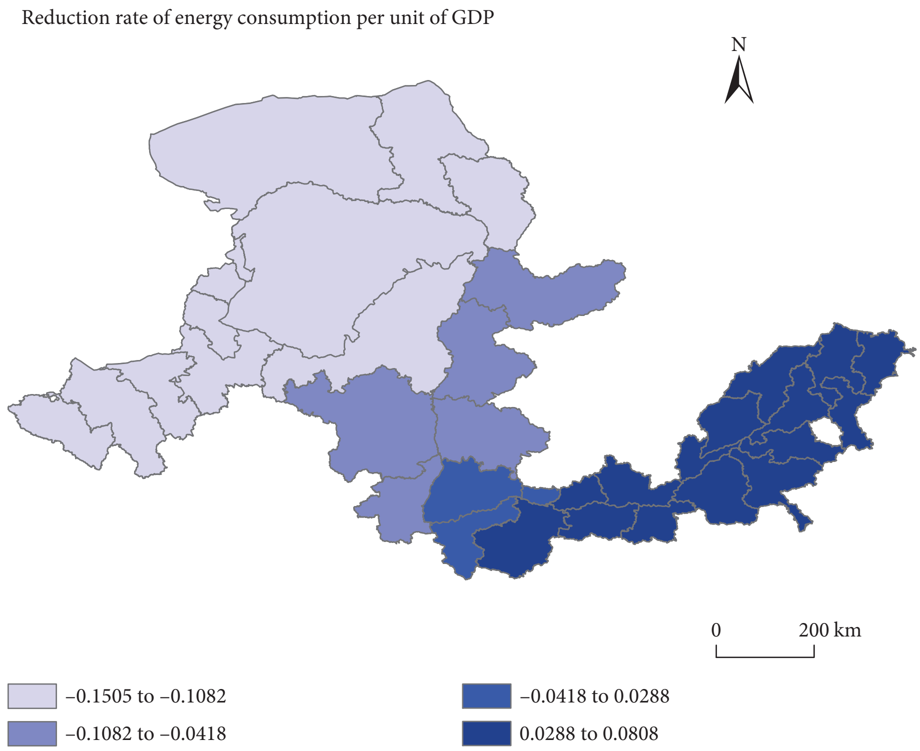


FIGURE 6: Spatial distribution of the regression coefficient of the reduction rate of energy consumption on IGD.

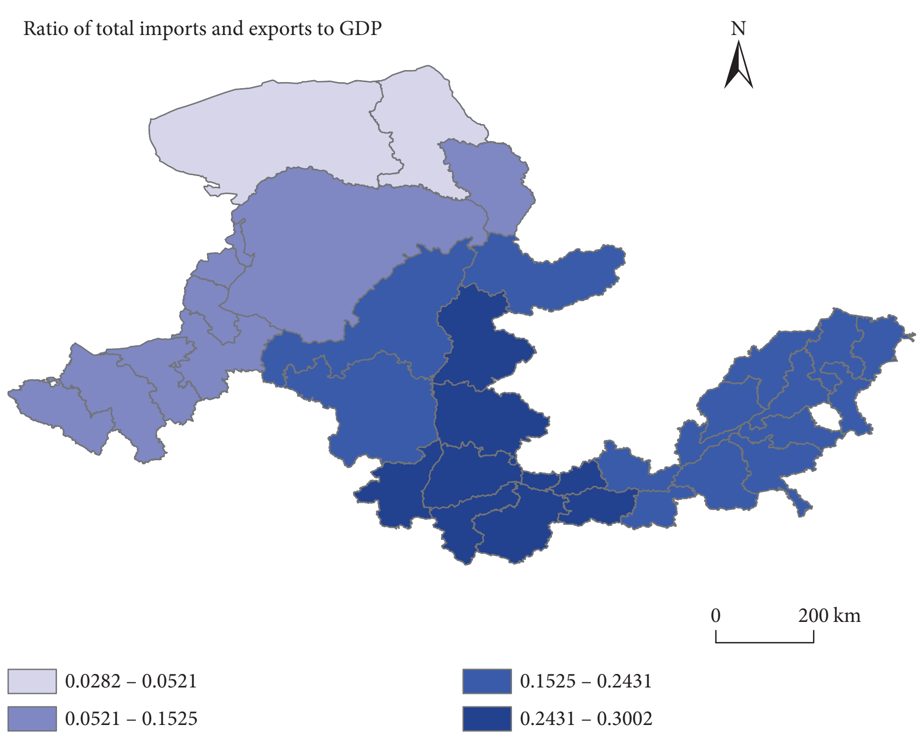


FIGURE 7: Spatial distribution of regression coefficient of total imports and exports to GDP on IGD.

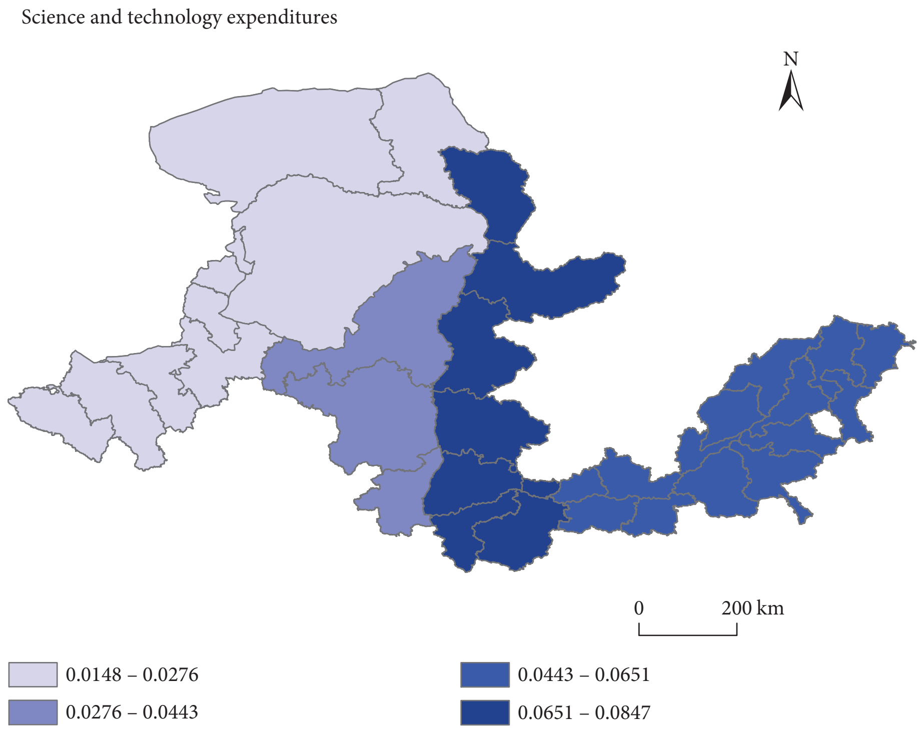


FIGURE 8: Spatial distribution of the regression coefficient of science and technology expenditures on IGD.

6. Conclusion and Recommendation

6.1. Conclusion. This paper constructs an evaluation index system for IGD in YRB through three dimensions: economic green growth, resource and environmental carrying capacity, and government support. The spatial evolution characteristics of 35 cities in YRB in 2012, 2015, and 2018 are investigated by using ESDA. And we use the GWR model to analyze the influencing factors of IGD in YRB. The main conclusions and recommendations are as follows.

First, IGD in YRB is generally on the rise. From the perspective of time, IGD in all cities in YRB in 2018 has increased compared with that in 2012. From the perspective of spatial dimension, IGD is still high in the east and low in the west, and the gap is getting larger and larger. Zhengzhou and Jinan are high-value areas, while Zhongwei and Wuzhong are low-value areas for IGD.

Second, there is a spatial positive correlation among IGD in YRB. The Global Moran's I in 2012, 2015, and 2018 are all positive with a small change, indicating that the spatial distribution of IGD in YRB is relatively stable. There is no substantial change in the local analysis pattern of cold and hot spots, which maintains the distribution characteristics of "high in the east and low in the west." Jinan, Dezhou, and Zhengzhou are always hot spots, driving IGD of surrounding, while there are no hot spots in the western region.

Thirdly, there are obvious regional differences in the factors influencing IGD in YRB. In general, the degree of influence of each influencing factor on IGD is as follows: openness > industrial upgrading index > urbanization rate > science and technology expenditures > reduction rate of energy consumption. Among them, industrial upgrading index, urbanization rate, openness, and science and technology expenditures show significant positive effects. The reduction rate of energy consumption varies with cities.

6.2. Recommendation. First, the government should play its full role and strengthen environmental control. The government has a very important influence on IGD. It is found from the previous research that the government plays a vital role in IGD in the YRB. In terms of policy formulation, the government needs to set targets to constrain enterprises. Although some achievements have been made, the target system is not perfect enough, and the discharge of waste water and waste gas from industrial enterprises still needs to be solved. Therefore, the government should formulate corresponding policies according to local conditions to supervise enterprises and limit their discharge of waste water, gas, and waste. From a financial point of view, the government will increase spending on energy conservation and environmental protection to help enterprises achieve green transformation. Application of new energy and new technology is accompanied by the rising cost of enterprises. It is far from enough to drive the application of new energy only by the social responsibility of enterprises. At this time, the government needs to subsidize new energy and new technologies and encourage their application in production to realize green production and clean production.

Second, use urban agglomeration to increase the efficiency of rural areas. Rural areas in YRB are relatively weak links in IGD. It is difficult to improve IGD only by relying on the rural strength. Therefore, on the one hand, it is necessary to encourage the cultivation of industrial chain links between urban and rural enterprises. At the same time, the government can guide urban residents to increase localized consumption of agricultural products, support the joint development of public marketing platforms for agricultural products or rural industries between regions and between urban and rural areas, and enhance the radiation driving effect of urban industrial transformation and upgrading and IGD in rural. On the other hand, the development of tourism in YRB should make use of the metropolitan area. Relying on the magnificent and beautiful natural landscape and time-honored historical culture of YRB, combined with the characteristics of each city, the metropolis circle is utilized to develop tourism in YRB, drive the development of related industries, as catering, trade and logistics, and tourism commodity manufacturing, and enhance IGD.

Third, realize industrial transformation and upgrading and support the high-tech industries. Traditional industries are the main body of pollutant discharge, so transforming and upgrading them and eliminating backward industries are conducive to IGD. The cities in YRB have a large proportion of traditional industries. Due to relatively backward economy, they are the receiving places for industrial transfer of foreign-funded enterprises and the Yangtze River Delta region. When undertaking industrial transfer, the standard should be improved to avoid becoming a “pollution refuge.” At the same time, existing industries should be transformed and upgraded from the root and increase the added value of products and reduce energy consumption. High-tech products have high added value. Generally speaking, cities with high-tech industries have a high level of green development. These require cities, on the one hand, to make full use of technical factors, personnel factors, and capital factors to develop local high-tech industries and, on the other hand, to improve the infrastructure of the city and enhance the soft power of the city, to encourage high-tech industries to cluster together.

Fourth, building a mechanism for regional coordination and cooperation enhances interconnected regional industrial development. Region industrial development is one of the effective ways to realize the coordinated development of regions. Different cities in YRB have different levels of IGD. Generally speaking, the level of IGD in the east of YRB is higher than that in the west. A cooperation mechanism should be established within the region. On the one hand, establish sharing mechanisms. The mechanism of regional coordination and cooperation should be shared first, emphasizing information sharing, resource sharing, and infrastructure sharing, which can effectively reduce the disordered industrial competition in cities along the route and improve the systematization and coordination of industrial development in YRB. On the other hand, resources in the upstream and downstream should be integrated to promote the division of labor and cooperation. There is a big gap between the upstream and downstream of YRB. Cities in YRB should give play to their comparative advantages, build platforms for undertaking industrial transfer in the upper, middle, and lower reaches, and cultivate characteristic industrial parks to promote the integrated development of upstream and downstream industries.

Fifth, cultivate scientific research and innovation teams and facilitate the integrated industrial development, universities, and research institutes. Scientific and technological innovation is the source of vitality for IGD, and cultivating R&D teams is conducive to IGD. At present, the industry in YRB lacks innovation vitality. In agriculture, the use of chemical fertilizers and pesticides is relatively much, and the cultivation of new varieties to promote the development of agricultural mechanization requires the efforts of scientific research teams. In industry, the coverage rate of clean production and green production is low, resulting in high pollution level of enterprises and incomplete industrial chain structure. This requires the extension of industrial chain and the search for new growth points of the industry, as well as scientific research support. In the tertiary industry, it is necessary to keep innovative vitality to promote enterprises in an invincible position. However, there is a disconnect between education, research, and business. Universities, research centers, and enterprises lack cooperation. This requires cities in YRB to strengthen the integrated development of industry, education, and research. For colleges and universities to train corresponding talents for enterprises, the research center develops much-needed technology for enterprises, and enterprises provide employment opportunities for colleges and universities, provide financial support for scientific research centers, and promote long-term win-win cooperation.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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Review Article

Resilient City: A Bibliometric Analysis and Visualization

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Resilient city has attracted global attentions as a new concept for cities to deal with risks and challenges in recent years. Numerous researchers have successively conducted in-depth studies on the resilient city from different perspectives. To acquire an overview of resilient city and grasp the current research hotspots, a bibliometric analysis and visualization of the past decade of research on the resilient city was made. The data were collected from 1249 articles published in the Web of Science database from 2010 to 2019. As the widely used bibliometric analysis tools, CiteSpace and VOSviewer were adopted in this study. The temporal distribution of resilient city research, including annual publication outputs and high-cited papers, was symmetrically analyzed. Then, the spatial distribution of resilient city research, including countries, categories, institutions, co-citation journals, author collaboration network, and author co-citation network, was investigated. Hot topics and evolution trends of resilient city were revealed. The results show that the research of resilient city experienced three periods, namely, germination, rapid diffusion, and reflection and innovation periods. Current research focuses on four aspects, including psychological resilience at the microcommunity and group levels, assessment of urban disaster resilience, multiple theoretical frameworks of urban resilience, and urban resilience promotion strategy. Therefore, this study helps scholars and practitioners to gain a comprehensive understanding of the current research progress and evolution trends of the resilient city field.

1. Introduction

As a large and complex socio-ecological system, cities are characterized by concentration, mobility, integrity, and activity. City labels, e.g., low carbon city, eco city, green city, resilient city, and sustainable city, were used to briefly express essential features of urban development and construction goals. Cities are increasingly vulnerable to natural or artificial disasters due to large population, numerous building, and complicated social network. Resilient city construction has become an important issue during the global urbanization process. Research on the resilient city has attracted wide attentions from the academia and society. There have been abundant theoretical and practical studies in the world. Therefore, a clear and systematic overview can help scholars form a comprehensive understanding of the resilient city research.

Resilience originated from physics and was used to describe the ability of an object to recover from deformation under an external force. Then, resilience was introduced into ecosystems. Ecological resilience emphasizes the ability to adapt to external shocks and control interactive changes [1, 2]. Subsequently, the concept of resilience was extended to the engineering technology and socio-economic fields. Engineering resilience focuses on the stability of the physical system, emphasizing its ability to recover to the predisturbance state [3–5]. In the social economy domain, psychological resilience [6], organizational resilience [7], and industrial resilience [8] were proposed from the perspective of the system level.

Due to complex internal factors and multiple external disturbances, cities have been suffering from a series of challenges, e.g., climate change, natural disasters [9], environmental pollution, disease transmission [10], and terrorist attacks [11]. Since 2002, the concept of urban resilience was presented at the American Annual Conference on Ecology [12]. The representative one, which was defined by the Rockefeller Foundation, refers to the capacity of individuals, communities, institutions, businesses, and systems within a city to survive, adapt, and grow regardless of chronic or acute shocks they experience [13]. Current research on city resilience mainly focuses on the system characteristics [14–16], construction [17–19], evaluation index system [20, 21], and policy [22–24]. Although current studies are of great importance, the comprehensive overview on resilient cities' research is still lacking. The resilient city is a significant interdisciplinary research field, covering ecological environment, engineering technology, computer science, economics, social science, etc. To comprehensively understand the research progress and hotspots of the resilient city, it is necessary to conduct a bibliometric analysis.

Bibliometric analysis is a popular tool for scientific and technological text mining, which can quantitatively analyze the literature published in a specific field [25, 26]. Mapping knowledge domain is a kind of graph that shows the relationship between the development process and structure of scientific knowledge. It can be used to grasp hotspots and frontiers of research in a certain field and make a panoramic representation by using its unique visualizations. Recently, bibliometric analysis tools, e.g., CiteSpace and VOSviewer, have been widely applied in various fields. CiteSpace can analyze node structure and characteristics, which usually works as an effective tool for researchers to extract network relations [27]. VOSviewer can provide detailed information about the literature, such as hot topics [28].

The objective of this study is to present a bibliometric analysis and visualization of the past decade of resilient city research. This paper is organized as follows. The first section describes the data source and methods. The second section shows the results of bibliometric analysis from six main aspects, namely, publication, subject category, country, institution, journal, and author. Finally, the hot research topics and emerging trends in the field are summarized.

Using the bibliometric analysis approach, this study explores the following research questions (RQ):

RQ1: what is the overall publication trend and discipline distribution of resilient city research?

RQ2: which authors, articles, journals, institutions, and countries have been most influential in resilient city research?

RQ3: what are the hotspots and emerging trends in the study of the resilient city?

RQ4: what recommendations or guidelines can be drawn for researchers of the resilient city field in the future?

2. Data Acquisition and Method

2.1. Data Acquisition. To obtain comprehensive and abundant literatures in terms of resilient city, Web of Science (WoS) was used as the data source. The Web of Science (WoS) online database contains almost all the important research papers, which also provides built-in analytical tools to generate representative data [29]. Detailed information, including publication year, country, author, institution, and journal source, was exported from WoS. The retrieval conditions were "resilience and urban," "resilience and city," "resilient and urban," and "resilient and city" to explore relevant theories and research contents in this field. The retrieval type was mainly keyword, and the time span was from 2010 to 2019 because the literatures on the resilient city were few before 2010. In total, 1249 valid literatures were obtained.

2.2. Methodology. Developed by Professor Chaomei Chen of Drexel University in the United States, CiteSpace software is used to map and visualize co-occurrence networks and clustering in the research field, identify the coupling relationship between different nodes, and discover the knowledge characteristics in a specific period [30]. In this paper, CiteSpace was adopted to generate knowledge maps, including country, institution, author, journal, and references citation bursts (Section 3). VOSviewer, which was developed by Eck and Waltman, is an effective visualization tool that can be used to construct keyword mappings based on co-occurrence data [31]. VOSviewer was used to implement topic clustering (Section 4) in this study. The writing framework of this paper is shown in Figure 1. After the data were collected (Stage 1), visualization of research was made from temporal and spatial distributions (Stage 2). To be specific, temporal distribution analysis contains publication output and high-cited references. The spatial distribution analysis includes five aspects, i.e., country, category, institution, co-citation journal, and author collaboration network. Subsequently, hot topics and evolution trends were analyzed by the clustering and sequential analysis methods (Stage 3). Finally, conclusions and recommendations were presented (Stage 4).

3. Temporal and Spatial Distribution of Resilient City Research

3.1. Temporal Distribution of Resilient City Research

3.1.1. Distribution of Annual Publication Outputs. The amount of publications can visually present the research interest of a certain research topic in a specific period. The trend of publication outputs can provide an overall grasp of the research progress of the topic and play a strong guiding role in the development of future research. Through the retrieval of articles in the field of resilient cities from 2010 to 2019, a distribution map of the publication output of resilient cities was drawn in Figure 2. Annual publication output in the resilient city field was 24 in 2010, and there was an overall upward trend from 2010 to 2019. The number of annual publications remarkably increased, and the maximum difference was 249 articles. Specifically, from 2010 to 2014, the number of publications on the resilient city grew slowly with an average annual publication volume of only 58. After 2015, with the acceleration of global urbanization and the surge of various natural and artificial disasters, the vulnerability of cities has become increasingly obvious.

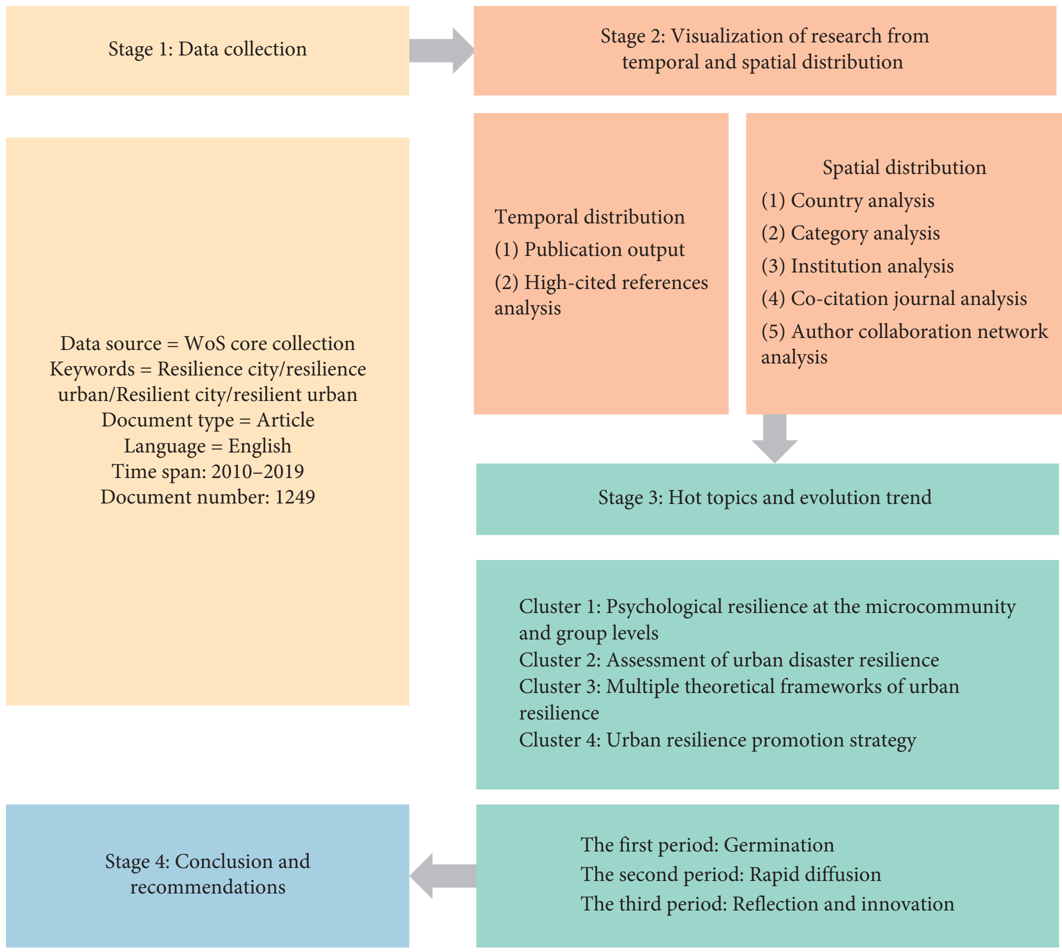

Figure 1: Bibliometric analysis framework of this paper.

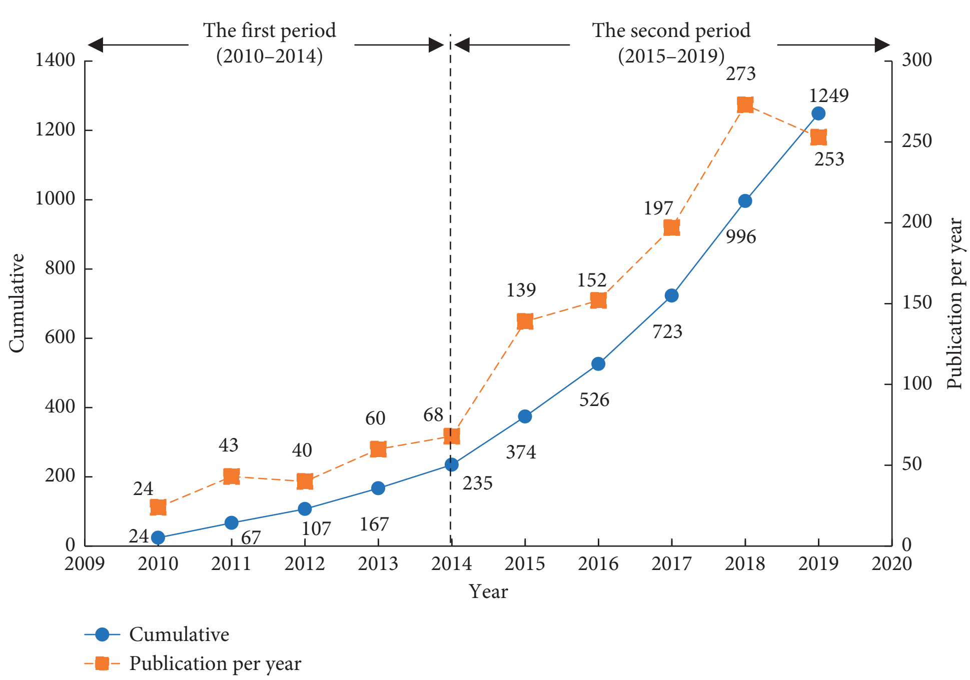

Figure 2: Distribution of annual publication outputs in the resilient city field from 2010 to 2019.

Therefore, exploring the construction of the resilient city has become a significant path to achieve sustainable urban development. In 2015, the number of related papers began to grow substantially, exceeding 100 for the first time. In 2018, publication outputs reached the peak in the past decade, at 273. The average increase in the number of articles published in 2015–2019 was 45, which was 4 times that of 2010–2014. The quantity of publications issued in 2019 declined slightly, but it remained at a relatively high level. Obviously, the boom in resilient city research has formed in the past decade.

3.1.2. Distribution of High-Cited References. The chronological distribution of articles is a time-series presentation in the dimension of research quantity, while the distribution of high-cited papers can be regarded as a time-series analysis in the dimension of research quality. The citation frequency of an article can reveal the influence and intelligence value of the article to some extent. Highly cited papers refer to academic papers that are cited frequently and have a long citation cycle. Papers with high citation frequency are usually regarded as authoritative and high-quality literature resources in this field.

This study used CiteSpace to count the top ten most frequently cited papers in Web of Science, which was ranked according to the frequency of citations, as shown in Table 1. The first highly cited document is "Defining urban resilience: a review" written by Meerow Sara, published in "Landscape and Urban Planning" in 2016 and was cited 101 times. Based on a systematic review of the definition of the resilient city, this article summarized and put forward the connotation, extension, and characteristics of the resilient city and deeply revealed the nature and characteristics of the resilient city. This article has become an important reference for multidisciplinary research on the resilient city [12]. The second high-cited article is a collection of essays on resilience research, which contains six subpapers. The authors explained resilience from different perspectives. Simin Davoudi discussed the significance of resilience and Keith Shaw raised questions about the politics of resilience; the third and fourth papers were published by L. Jamila Haider, Allyson E. Quinlan, Garry D. Peterson, and Cathy Wilkinson, both described the experience of integrating resilience into planning practice using examples from rural northern Afghanistan and urban northern Sweden; Hartmut Fünfegld and Darryn McEvoy discussed the main disaster management methods in climate change adaptation strategies and how to use resilience to change this situation; Libby Porter and Simin Davoudi raised some key questions about planning resilience [32]. "From fail-safe to safe-to-fail: sustainability and resilience in the new urban world" is the third highly cited article. It focused on the engineering field of urban resilience and proposed a set of strategies intended to build urban resilience capacity, including multifunction, redundancy and modularity, diversity (biological and social), multiscale network and connectivity, and adaptive planning and design to enhance the sustainability of urban development [33]. The fourth highly cited document "Planning the resilient city: concepts and strategies for coping with climate change and environmental risk" constructed an innovative conceptual framework: the resilient city planning framework (RCPF), which included the four related concepts of urban vulnerability matrix analysis, uncertainty-oriented planning, urban governance, and prevention. It also solved a key question of what cities and their communities should do to move towards a more resilient country in the future, which provides a comprehensive understanding of urban resilience [34]. From Table 1, the output of high-quality publications on the resilient city field was concentrated in 2010–2014, which indicates that the theoretical construction in the early stage provides a solid foundation for subsequent multidisciplinary research on the resilient city.

Burst detection is an effective tool to detect emergencies or major information within a certain period [35]. Figure 3 shows the top 25 strongest citations detected by CiteSpace from 2010 to 2019. The blue line represents the time interval, and the red part of this line means the time interval when the citation occurred. The largest citation burst strength was 13.7683, which started in 2010 and ended in 2014. This article is titled "Resilience: The emergence of a perspective for social-ecological systems analysis" by Carl Folke. It integrated the concept of resilience into the study of socio-ecological dynamic systems, focusing on the sustainability of resilience in terms of governance capabilities such as renewal, restructuring, and development [36]. Norris et al. published the article "Community Resilience as a Metaphor, Theory, Set of Capacities, and Strategy for Disaster Readiness" in 2008. Its citation burst intensity was 8.8638, which ranked second in burst intensity, starting in 2013 and ending in 2016. This article proposed the theory of community resilience to provide strategies for disaster prevention from a microscopic perspective. The theory is based on four main sets of adaptive capacities, including economic development, social capital, information and communication, and community capacity [37]. In addition, it can be seen from citation cycle analysis that the longest citation cycle of the 25 highly cited references was 6 years, while the shortest citation cycle was only 2 years.

3.2. Spatial Distribution of Resilient City Research

3.2.1. Distribution of Countries. Using the national network analysis function in CiteSpace, the node type was set as "country" and the visualization map was optimized to generate a country distribution network map, as shown in Figure 4. The larger the circle, the more the number of publications. The thickness of the outer pink circle represents the size of centrality. The greater the centrality, the closer the connection with other countries and the more obvious the bridge function. The top 10 countries according to publication output are shown in Table 2. In general, there is a large gap in the research on the resilient city across countries. The United States is the first country to carry out research on the resilient city with the most studies of 284 (22.74% of the total). The United Kingdom followed behind with 149 (11.93% of the total). The average number of

Table 1: Top 10 cited references in the resilient city field from 2010 to 2019.

Rank	Citations	Year	Title	Source	Author
1	101	2016	Defining urban resilience: a review	Landscape and urban planning	Meerow Sara
2	91	2012	Resilience: a bridging concept or a dead end?	Planning theory & practice	Simin Davoudi et al.
3	75	2011	From fail-safe to safe-to-fail: sustainability and resilience in the new urban world	Landscape and urban planning	Ahern Jack
4	59	2011	Planning the resilient city: concepts and strategies for coping with climate change and environmental risk	Cities	Jabareen Yosef
5	59	2013	Climate change and urban resilience	Current opinion in environmental Sustainbility	Leichenko Robin
6	51	2012	A framework for urban climate resilience	Climate and development	Tyler Stephen
7	40	2013	Designing, planning, and managing resilient cities: a conceptual framework	Cities	Desouza Kevin C.
8	39	2010	Urban transitions: on urban resilience and human-dominated ecosystems	AMBIO	Ernstson Henrik
9	37	2010	The politics of resilient cities: whose resilience and whose city?	Building research and information	Vale Lawrence J.
10	37	2014	Resilience thinking: integrating resilience, adaptability and transformability	Ecology and society	Folke Carl

References	Year	Strength	Begin	End	2010–2019
Barthel S, 2005. Ecol Soc, V10, P0	2005	2.8782	2010	2013	
Coaffee J, 2008, New Secur Chall, V0, P1 , DOI	2008	3.0358	2010	2015	
Folke C, 2006, Global Environ Chang, V16, P253, DOI	2006	13.7683	2010	2014	
Berkes F, 2003, Navigating Social EC, V0, P0	2003	3.2579	2010	2011	
Gallopin GC, 2006, Global Environ Chang, V16, P293, DOI	2006	2.9515	2011	2013	
Walker B, 2004, Ecol Soc, V9, P0	2004	3.8574	2011	2012	
Newman P, 2009, Resilient Cities Res, V0, P0	2009	4.8572	2011	2016	
McGranahan G, 2007, Environ Urban, V19, P17, DOI	2007	4.0385	2011	2015	
Campanella TJ, 2006, J Am Plann Assoc, V72, P141, DOI	2006	3.2382	2011	2014	
Vale L J, 2005, Resilient City Moder, V0, P0	2005	5.3217	2011	2013	
Walker B, 2006, Resilience Thinking, V0, P0	2006	7.037	2011	2014	
Folke C, 2005, Annu Rev Env Resour, V30, P441, DOI	2005	3.0935	2012	2013	
Barthel S, 2010, Global Environ Chang, V20, P255, DOI	2010	3.5029	2013	2015	
Andersson E, 2007, Ecol Appl, V17. P1267, DOI	2007	3.0012	2013	2015	
Pelling M, 2008, Environ Plann A, V40, P867, DOI	2008	2.5	2013	2015	
Brand FS, 2007, Ecol Soc, V12, P0	2007	5.0106	2013	2015	
Colding J, 2007, Landscape Urban Plan, V81, P46, DOI	2007	5.3325	2013	2014	
Ernstson H, 2010, Ambio, V39, P531, DOI	2010	7.0959	2013	2015	
Norris FH, 2008, Am J Commun Psychol, V41, P127, DOI	2008	8.8638	2013	2016	
Evans JP, 2011, T I Brit Geogr, V36, P223, DOI	2011	4.8585	2013	2015	
Colding J, 2013, Ecol Econ, V86, P156, DOI	2013	3.8497	2013	2015	
Grimm NB, 2008, Science, V319, P756, DOI	2008	4.6033	2013	2016	
Adger WN, 2009, Climatic Change, V93, P335, DOI	2009	2.5	2013	2015	
Gomez-Baggethun Erik, 2013, ---, V0, P175	2013	2.61	2014	2016	
Pike A, 2010, Camb J Reg Econ Soc, V3, P59, DOI	2010	3.1582	2014	2016	

Figure 3: Top 25 references with strongest citation burst.

citations issued by the two countries is about 18, which is also at a relatively high level. This shows that they are two major countries in the field of resilient city research. The Dutch centrality is 0.7, and the average number of citations of published articles is about 24.75, indicating that the Netherland plays an important role in the overall research and acts as a knowledge intermediary and information flow controller.

3.2.2. Distribution of Categories. In CiteSpace, "category" was taken as the network node and the time slice was set as 1 year. The co-occurrence map of the category network is shown in Figure 5. The larger the circle, the more the number of articles, and the thicker the connecting line, the closer the correlation. The complex connections established by multiple nodes indicate that the resilient city is a research field with significant interdisciplinary attributes.

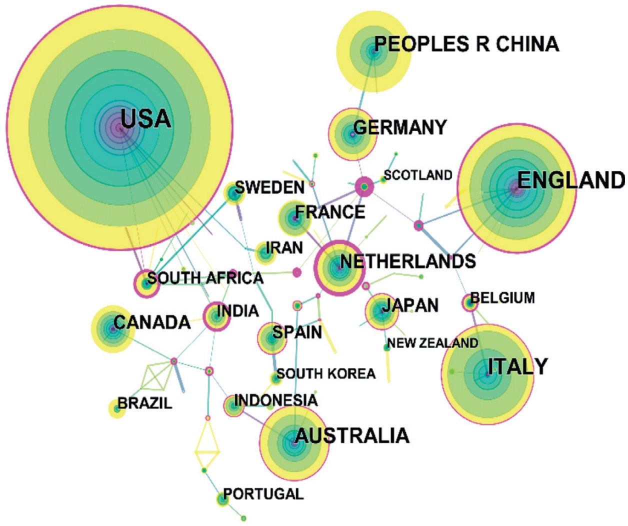

Figure 4: Visualization map of main countries in resilient city research from 2010 to 2019.

To further visualize the co-occurrence network map of categories, the annual distribution trend of the top 6 subject categories is shown in Figure 6. Among them, the most closely related category is environmental sciences and ecology with 412 articles published, accounting for 32.99%. The second-ranked category is urban studies with 262 articles, which accounts for 20.98% of the total. The engineering field is the third category of resilient city research. A total of 216 articles have been published, accounting for 17.29%. The top 6 categories also include other topics of science and technology, water resources, and public administration. It can be clearly seen from Figure 6 that, in the first stage of resilient city research (2010–2014), the resilient city study in various disciplines was in a groping stage and the number of publications fluctuated slightly on a relatively small basis. The resilient city research grew rapidly after 2015. The number of papers issued by the environmental sciences and ecology rose gradually and reached the peak in 2019. There was an upward trend in other disciplines despite of the largest fluctuations in the engineering field. It should be noted that the attention of other disciplines in the field of resilient cities greatly weakened except the environmental sciences and ecology in 2019.

3.2.3. Distribution of Institutions. The cooperation network of institutions was analyzed through setting the node type as “institution” in CiteSpace. Figure 7 shows the visualization map of institution in resilient city research. It is found that the connection between various institutions is loose. The cooperative networks have remarkable small group characteristics, e.g., King’s College London and Arizona State University. However, single-line cooperation networks existed between most institutions. Divergent academic cooperation is still lacking in the resilient city field. Therefore, it is necessary to strengthen the partnership between cross-regional institutions and build a multicenter cooperation network. Top 10 productive institutions in resilient city research are shown in Table 3. The institution with the largest number of articles is the University of Naples Federico II in Italy, with 20 papers. Institutions with more than 15 articles published include Arizona State University in the United States and the University of Melbourne in Australia. Seven universities, including the University of Exeter in the UK, Stockholm University in Sweden, the University of British Columbia in Canada, King’s College London in the UK, Columbia University in the USA, the University of Cape Town in South Africa, and RMIT University in Australia have published more than 9 papers.

3.2.4. Distribution of Co-citation Journals. The number of publications and the frequency of literature citations are important indicators for measuring journals in a research field. Table 4 shows the top 5 productive journals in the field of resilient city. “Global Environmental Change-Human and Policy Dimension” is the most prolific journal in the field of resilient city research (with 362 publications), followed by “Ecology and Society” (with 305 publications). It is worth noting that the top two journals have a higher total citation frequency at 6311 and 6169, respectively, which indicates that the two journals have higher reference value in the resilient city field than other journals. H-index, as an academic evaluation index, has now become an important criterion for journal assessment. The H-index of “Global Environmental Change-Human and Policy Dimension” ranks first with a value of 147, which indicates that the articles included in this journal play a key role in the study of the resilient city. The average number of citations of a journal can reflect the overall quality of papers published in a certain journal. The articles published in “Ecology and Society” and “Annual Review of Ecology and Systematics” have high-quality characteristics, and the average number of citations of journal articles can reach above 20. The subject classification of five journals shows that the fields of ecology and environmental sciences have received the most attention.

The time-span presentation of cited journals in the field of resilient city research can reflect the outstanding contribution of the high-quality cited journals to the development of resilience urban. According to the time zone view of the co-citation journal in Figure 8 (node type: cited journal), the two journals named “Global Environmental Change-Human and Policy Dimension” and “Ecology and Society” took a leading position in the past decade. By 2011, the journal “Landscape and Urban Planning” received widespread attention and gradually developed into a key journal in the field of resilient city research. In the next few years, “Thesis” and “Sustainability” gradually attracted wide attention in resilient city research.

3.2.5. Distribution of Author Collaboration Network and Author Co-citation Network. Using BICOMB2 software for calculation and analysis, a total of 3186 authors were found to participate in the research on resilient cities from 2010 to 2019. Price [38] defined high-yield authors in his book named “Little Science, Big Science.” He believed “half of the

Table 2: Top 10 countries according to publications.

Rank	Country	Publications	Percentage	Centrality	TC	TC/P
1	USA	284	22.74	0.27	5213	18.36
2	England	149	11.93	0.27	2684	18.01
3	Italy	118	9.45	0.12	798	6.69
4	Peoples Republic of China	98	7.85	0.08	1121	11.44
5	Australia	91	7.29	0.13	788	8.66
6	Germany	65	5.20	0.12	574	8.83
7	Canada	61	4.88	0.04	950	15.57
8	Netherlands	61	4.88	0.7	1510	24.75
9	France	46	3.68	0	558	12.13
10	Japan	45	3.60	0.19	416	9.2

Note that the symbols TC and TC/P refer to the total citations and the average number of citations per paper for a country, respectively.

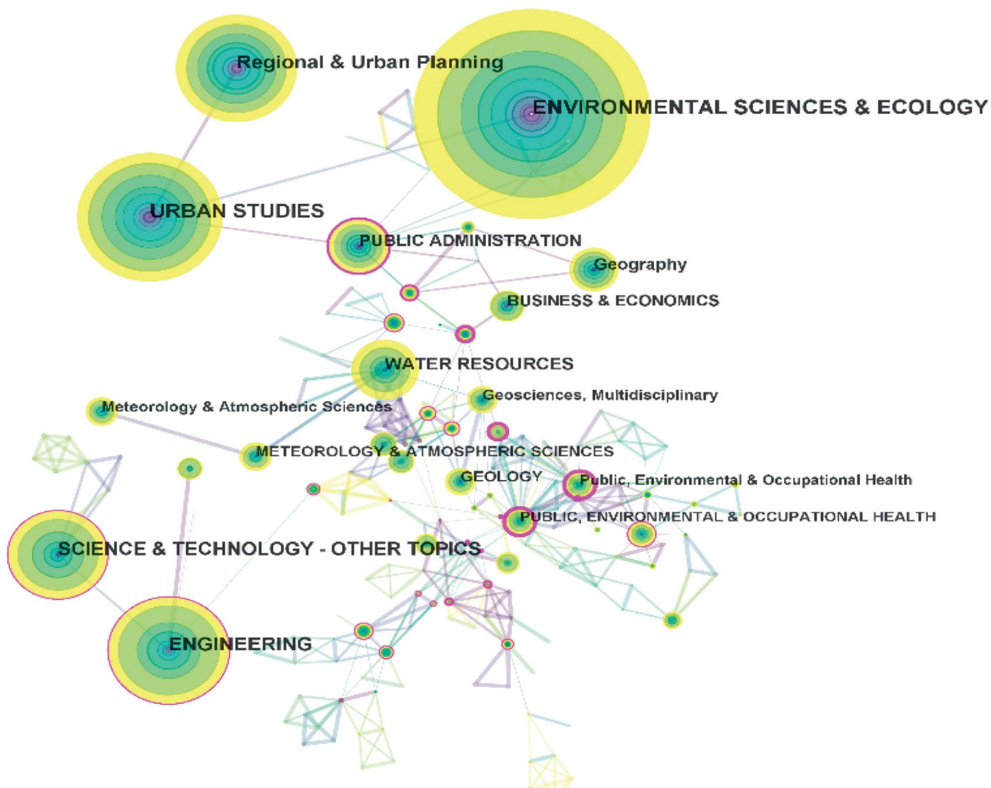

Figure 5: Visualization map of subject categories in resilient city research from 2010 to 2019.

papers are written by a group of highly productive authors and the number of author sets is approximately equal to the square root of the total number of authors." The mathematical quantification of Price's law is $\sum_{m+1}^{i} n(x) = \sqrt{N}$, where i represents the number of works published by the most productive author, m is the minimum number of works published by core authors, $n(x)$ refers to the quantity of authors who wrote x works, and N is the total number of authors [38]. After calculation, it is obtained that there are 136 high-yield authors in the resilient city research in the past decade, who published more than 3 papers (including 3).

According to Table 5, David Butler is the author who has published the most papers in the resilient city field, with 9 articles. This scholar is currently a professor in the field of water conservancy engineering at the University of Exeter in the UK, mainly engaged in water resources management, sustainable and resilient water systems, urban drainage systems, and other fields. The scholar constructed an overall resilience analysis method for urban drainage and supply systems, which can provide a flexible assessment of functional failures caused by unknown risk factors [39,40]. His research achievements have received extensive attention from the academic community. Leire Labaka is a new author in the research field of resilient city, whose most articles were published in the past two years. He mainly focuses on the resilience of urban key infrastructure and proposed a resilience maturity model, which provides an implementation roadmap for urban resilience construction and builds a public-private partnership framework for resilient cities

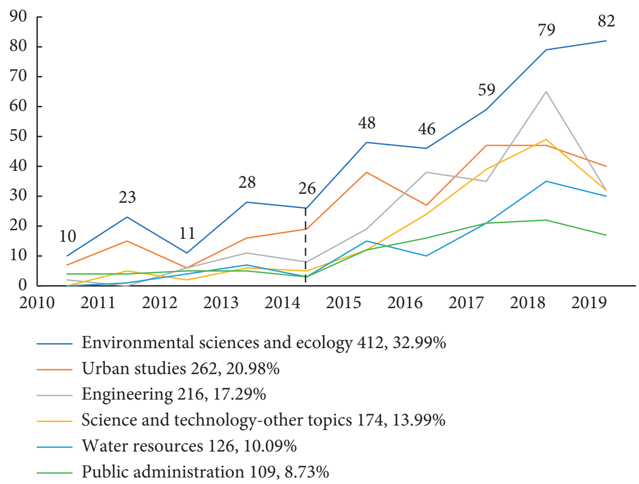

Figure 6: Trend of subject categories in the resilient city field with years.

[41, 42]. In addition, the authors who conducted extensive theoretical and practical research in the resilient city field include Josune Hernantes, Mark Pelling, and Eui Hoon Lee, who together constitute the core group of authors in the field of resilient city research.

In Figure 9, the high-yield author's cooperation network map is presented to better display the knowledge cooperation of scholars in the field of resilient city research (node type: author). The nodes in Figure 9 represent authors. The larger the node, the more important the position of the author in the collaborative network and the greater the number of published papers. The lines mean that two authors appear in the paper at the same time, and the thicker the line, the closer the cooperative relationship. From the perspective of the overall cooperation network, the cooperation network density of authors in the field of resilient city research is 0.0044. Obviously, the network density is low, and its overall structure is relatively loose, indicating that the current knowledge and information dissemination and penetration in the field of resilient city research are weak. The breadth and depth of interaction between network nodes need to be further strengthened. The research team, which contains Takefumi Suzuki, Hiroyuki Uchida, Kenichiro Kubo, Masaru Mimura, Yasushi Imasaka, and Kazunari Yoshida, is the most prominent in the author collaboration network. The groups represented by Leire Labaka and David Butler both have a relatively high frequency of cooperation and extensive cooperative relationship. Figure 9 indicates that the academic exchanges between authors in the field of resilient cities need to be deepened. Therefore, the field of resilient city in the future should focus on strengthening more extensive exchanges and communication among scholars.

By setting the "cited author" node, the co-cited author network graph is shown in Figure 10. The node represents the author, and the size of the node represents the frequency of citations. The thickness of the connection between the nodes represents how often the author is cited. The top 10 authors who are frequently cited are listed in Table 6. Holling C. S. is the most cited author (frequency 242 and centrality 0.29). As an expert in the ecology field, he first proposed the concept of resilience. Holling believed that ecosystems have two attributes, including resilience and stability, and specifically divided resilience into engineering resilience and ecology resilience, which promoted resilience research gradually from the field of natural ecology to the field of human ecology [43]. As one of the top 10 highly cited authors, the centrality of Holling C. S. is also particularly remarkable, which indicates that the author has laid a very important knowledge foundation for this research field and made outstanding contributions to knowledge dissemination. Ranked second is Carl Folke (frequency 237 and centrality 0.02), who systematically sorted out the evolution of the resilience perspective and gradually developed from the branch of ecology to social-ecosystem resilience [36]. The third place is Adger (frequency 173 and centrality 0.06), who comprehensively reviewed the fragility tradition and its evolution process. It is believed that vulnerability, adaptation, and resilience of the social-ecological system have common goals and foundations [44]. The author analyzed the significant correlation between ecological resilience and social resilience, which has attracted widespread attention from scholars in resilience urban research [45]. Others of the top 10 highly cited authors are Walker B., Cutter S. L., Meerow S., Davoudi S., Pelling M., Ahern J., and Berkes F.

4. Analysis on Hot Topics and Evolution Trends of the Resilient City

4.1. Analysis of Hot Topics in Resilient City Research. Keywords are the refinement and summary of the content of the article, and thus, the frequency analysis of keywords is usually used to reveal the research hotspots of a specific domain. In the case of numerous literatures and various keyword categories, the keyword co-occurrence map drawn by VOSviewer has the advantages of clear clustering, strong readability, and hard label overlap [31]. Therefore, VOSviewer was utilized in this study to draw a keyword co-occurrence analysis map to present the distribution of hot topics in the resilient city research. In the VOSviewer, the threshold of word frequency statistics was set as 10. The first 120 keywords were selected to conduct keyword co-occurrence analysis of resilient city research in the paper, as shown in Figure 11. The size of the circle represents the frequency of keyword occurrence, the lines between each circle node represent the co-occurrence relationship, and the nodes with the same color represent the same clustering attribute. From the holistic perspective, "practice," "assessment," "measure," and "sustainability" appear frequently, which are hot topics in the field of resilient city. The hot topics of the resilient city can be divided into the following four categories:

Cluster #1 (Yellow): Study on Psychological Resilience at the Micro Community and Group Levels. The keywords are African American, group, child, family, factors, residents, relationships, community resilience, education, violence, etc. Research on specific groups in the

Figure 7: Visualization map of institution in resilient city research from 2010 to 2019.

Table 3: Top 10 productive institutions according to publications.

Rank	Institution	Publications	Centrality	Country
1	University of Naples Federico II	20	0	Italy
2	Arizona State University	17	0.03	USA
3	The University of Melbourne	17	0	Australia
4	University of Exeter	14	0.01	England
5	Stockholm University	13	0.04	Sweden
6	University of British Columbia	10	0.03	Canada
7	King's College London	10	0.02	England
8	Columbia University	9	0.01	USA
9	The University of Cape Town	9	0	South Africa
10	RMIT University	9	0	Australia

Table 4: Top 5 productive journals in the resilient city field during the period of 2010 to 2019.

Journal	Pa	Percentage (%)	TCb	TC/Pc	H-Index	IF	Subject
Global environmental change-human and policy dimension	362	28.98	6311	17.43	147	10.47	Environmental sciences
Ecology and society	305	24.42	6169	20.23	119	3.89	Ecology
Landscape and urban planning	291	23.30	4478	15.39	132	5.44	Ecology, geography, and physical
Cities	212	16.97	2854	13.46	51	4.80	City planning and urban design
Annual review of ecology and systematics	202	16.17	4109	20.34	N/A	6.15	Evolutionary biology and ecology

Note that the symbols Pa, TCb, TC/Pc, and IF represent the total publications, the total citations, average number of citations per paper, and impact factor of a journal in the latest year, respectively.

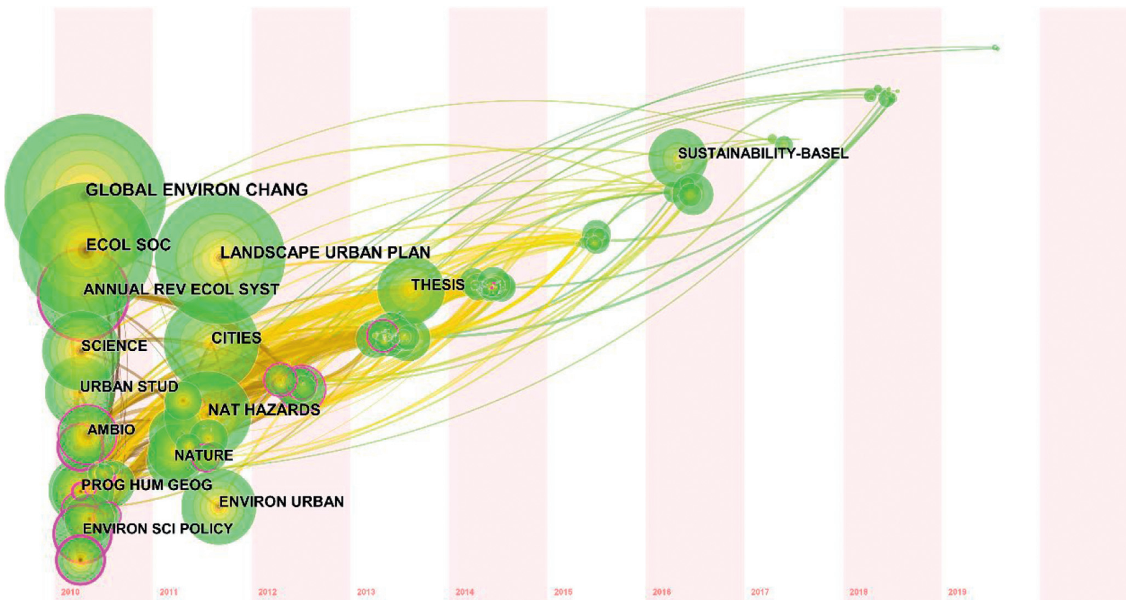

Figure 8: Time zone view of the co-citation journal network in resilient city research from 2010 to 2019.

Table 5: Top 10 productive authors in the resilient city field from 2010 to 2019.

Rank	Publications	Author	Institution	Country
1	9	David Butler	University of Exeter	England
2	7	Leire Labaka	University of Navarra	Spain
3	5	Josune Hernantes	University of Navarra	Spain
4	5	Mark Pelling	King's College London	England
5	5	Eui Hoon Lee	Chungbuk National University	South Korea
6	5	Sara Meerow	Arizona State University	USA
7	5	Ayyoob Sharifi	Hiroshima University	Japan
8	5	Domenico Asprone	University of Naples Federico II	Italy
9	4	Youssef Diab	Lab LabUrba	France
10	4	Kenichiro Kubo	Jikei University	Japan

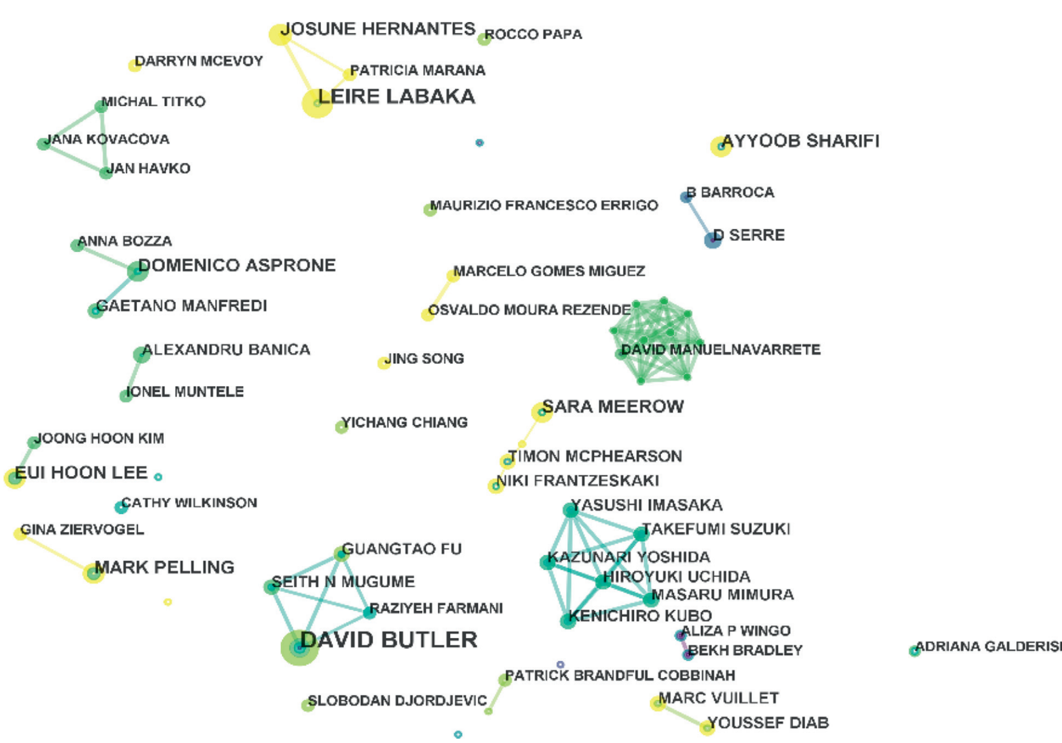

Figure 9: Visualization map of the author cooperation network in the resilient city field.

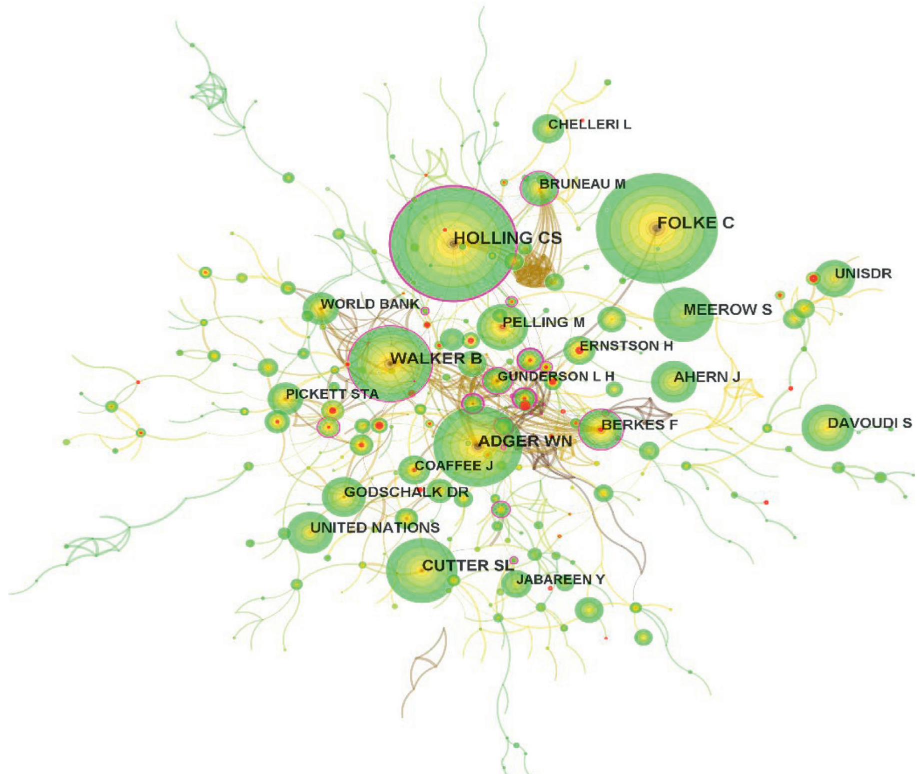

Figure 10: Visualization map of the co-cited author in resilient city research.

Table 6: Top 10 cited authors in the resilient city field from 2010 to 2019.

Rank	Author	Frequency	Centrality	Year	H-Index	Institution
1	Holling C. S.	242	0.29	2010	37	University of Florida
2	Folke C.	237	0.02	2010	92	Stockholm University
3	Adger W. N.	173	0.06	2010	60	University of Exeter
4	Walker B.	163	0.13	2010	58	Australian National University
5	Cutter S. L.	140	0.02	2011	8	University of South Carolina System
6	Meerow S.	118	0.01	2016	11	Arizona State University
7	Davoudi S.	105	0.02	2013	22	Newcastle University-UK
8	Pelling M.	105	0.02	2011	30	King's College London
9	Ahern J.	94	0	2013	10	University of Massachusetts System
10	Berkes F.	93	0.14	2010	45	University of Manitoba

context of community is an early focus of urban resilience, which embodies the application of the concept of resilience in the psychology field. Community is the main unit of urban construction, and human beings are an important part of the urban system. These studies believed that, in times of adversity, the leadership of individuals, the trust and support of the organization network, and the vision for the future are the significant factors for building urban resilience [46–48]. The high citation articles during this period focused on the psychological resilience and mental health of children or adolescents. Laura Camfield found that children with stronger social abilities were more likely to recover quickly from adverse experiences than children with personal abilities in developing countries based on a long-term follow-up survey of four adolescents in Ethiopia [49]. Due attention should be paid to developing children's social capacity to enhance psychological resilience. Fergus Stevenson and Zimmerman Marc A. conducted a study on adolescent psychological resilience at risk and discussed three elastic models, including compensation, protection, and challenge [50]. They argued that parental support and personal social networking skills can help youth overcome risks and avoid negative outcomes.

Cluster #2 (Green): Study on Assessment of Urban Disaster Resilience. The prime keywords are disaster, flood, earthquake, adaptability, assessment, method, uncertainty, recovery, indicators, etc. Natural disasters are the earliest area of concern for urban resilience. Research contents involve the construction of the

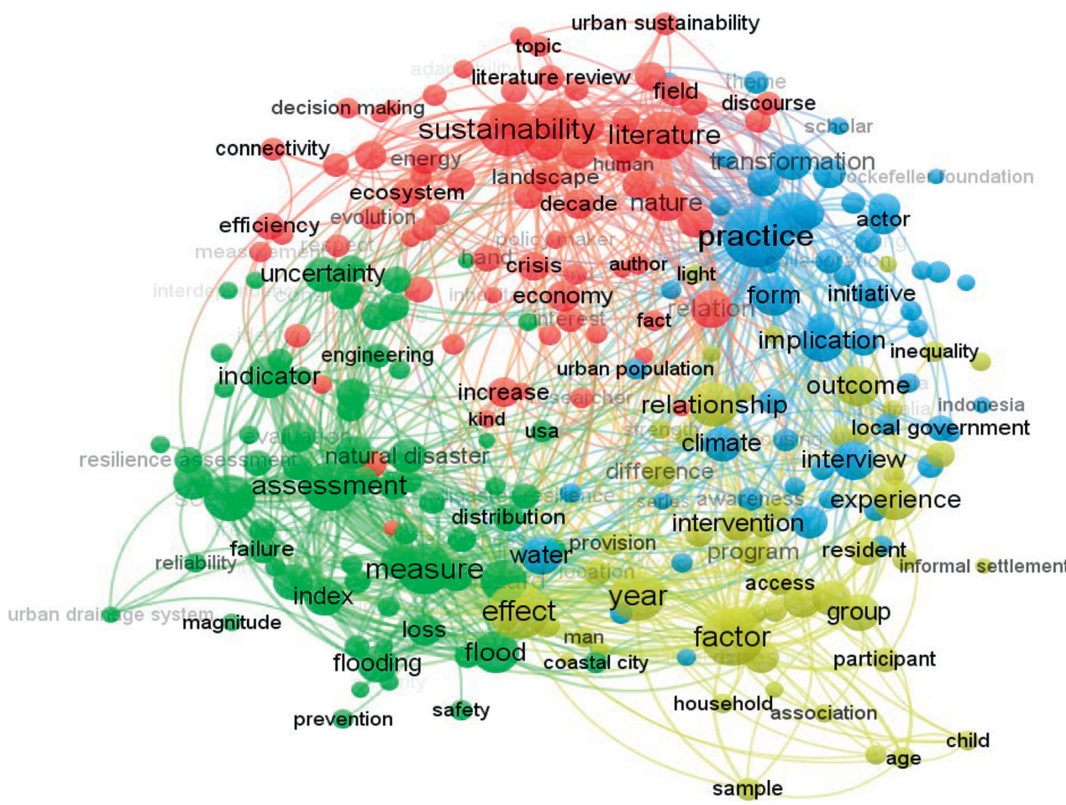

Figure 11: Network visualization map of keyword co-occurrence in resilient city research.

resilience capacity index system from the perspective of natural disasters, the experience reference of the resilient city case, and the discussion on the path of resilient cities to cope with natural disasters. The research of this cluster focuses on the capacity of urban infrastructure to withstand disaster risk. Hence, the construction of urban disaster recovery framework mainly pays attention to the features of facility redundancy, resource usefulness, and reflection when cities face risks. In 2003, Godschalk initiatively defined the resilient city from the perspective of urban disaster prevention and mitigation [18]. Additionally, he proposed a comprehensive urban disaster reduction strategy and considered that strengthening cooperation among professional teams and expanding urban systems research are important paths to build the resilient city [18]. Cutter et al. proposed the disaster resilience of place (DROP) model for communities to cope with natural risks, aiming to improve comparative assessments of disaster resilience at the local or community level [51]. León and March argued that the resilience in response to the tsunami can be enhanced by pooling regional urban resources through street networks [52]. Conducting the research on community parks in New York City under the impact of Hurricane Sandy, Chan et al. found that community parks not only strengthen food and ecosystem security but also play a crucial part in fostering community citizens' awareness of greening public spaces and social ecological restoration after disasters [53].

Cluster #3 (Red): Study on the Multiple Theoretical Frameworks of Urban Resilience. The prime keywords are sustainability, landscape, urban systems, economic resilience, ecosystems, transformation, theoretical framework, etc. Resilience Alliance is one of the earliest organizations to conduct research on urban resilience. The alliance believed the research on the resilient city can be divided into four priority areas, namely, infrastructure environment, metabolic flow, regulatory network, and social level. In fact, it emphasized different emphases of the construction of the resilient city from the perspectives of economy, infrastructure, society, and ecology [54]. The Rockefeller Foundation put forward the City Resilience Framework (CRF) in 2014, which believes that a resilient city should include four main dimensions, including health and well-being, infrastructure and environment, economy and society, and leadership and strategy, with three specific driving factors in each dimension [55]. Desouza and Flanery believed that cities are composed of physical and social systems and cities need to resist natural, technological, economic, and human pressures through case studies [14]. Cutter et al. established a multidimensional resilience framework system for cities and communities to carry out resilience planning and evaluation for different subjects [17, 51].

Cluster #4 (Blue): Study on Promotion Strategy for Urban Resilience from the Perspective of Social Governance and Urban Planning. The prime keywords are governance, government, practice, case study, food safety, green infrastructure, water resources, climate adaptation, housing supply, land use, etc. With the transition from ecological resilience to evolutionary resilience (social ecological resilience), the traditional "security defense" response strategy is no longer effective, and the "security free" strategy is exactly what is advocated in the modern construction of the resilient city [33, 36]. Some scholars provided resilience as the core of the promotion strategy. For example, Ahern offered a suite of strategies intended to build urban resilience capacity, including multifunctionality, redundancy and modularization, diversity (biological and social), multiscale networks and connectivity, and adaptive planning and design [33]. Case study is a commonly used research method from the perspective of social resilience. Through the tsunami event in Chile, León and March believed that the design of the urban space and street layout can improve the resilience of a city to cope with the tsunami and thus summarized the strategy of planning resilience improvement [52]. Wardekker et al. took the specific city of Rotterdam as a case to put forward resilience strategies to deal with climate change and flood risk, aiming to provide a corresponding basis for the city's decision-making and planning [54, 56].

4.2. Analysis on the Evolution Trend of the Resilient City Theme. CiteSpace was used to present the time zone map and emerging word view of the keywords in resilient city research, as shown in Figure 12 and Table 7, respectively. According to the generated time zone map, the research on the resilient city can be roughly divided into three periods, namely, germination, rapid diffusion, and reflection and innovation periods.

4.2.1. The First Period: Germination Period (2010–2011). In the early years of this period, the theme of resilient city studies involved the psychological resilience of specific groups of human beings, mainly children and adolescents, with high frequency keywords such as adolescent development, community violence, resilience, protection, and African Americans. Meanwhile, with the development of ecological resilience in this field, the academic community has begun to pay extensive attention to the ability of cities to adapt to climate change. From the perspectives of ecology, engineering, and social politics, Kim and Lim presented a conceptual framework for analyzing urban resilience in the context of climate change, aiming to shed light on future urban planning and policies for adapting to climate change [57]. Similarly, Tyler and Moench proposed a framework of resilience to climate change, which includes the characteristics of urban systems, the agents (individuals and organizations) that rely on and manage these systems, the institutions that link systems and agents, and patterns of exposure to climate change [58]. The viability of the framework by the literature [58] was demonstrated through examples from 10 cities across Asia. Although the research literature on psychological resilience and ecological resilience dominated during this period, the resilience characteristics of urban systems began to attract attention from all sectors of society and generated research topics such as urban resilience planning, governance and transformation, sustainability, and management.

4.2.2. The Second Period: Rapid Diffusion Period (2012–2016). During the rapid diffusion period, resilience was applied to the functional construction of various subsystems of the city. Some themes related to urban resilience emerged, including community resilience, flood control resilience, critical infrastructure resilience, building environment resilience, earthquake mitigation resilience, and water resource resilience. The range of disciplines involved is increasingly wide, including energy, environmental science, engineering, geography, economics, management, and regional planning. Most of the multidisciplinary and multidimensional studies in this period focused on the construction of evaluation index system for different urban subsystems and the construction of the systematic comprehensive urban resilience framework. A typical example is the Baseline Resilience Indicators for Communities (BRIC) model proposed by Cutter et al. based on 6 aspects of community capital, society, economy, system, housing and infrastructure, and environment, with 49 indicators [51]. Frazier et al. added two influencing factors, place and time, into the BRIC model and emphasized the important role of the two factors in community resource allocation and measures improvement [59]. Frazier et al. also carried out a specific study and application of community resilience indicators in Sarasota County, Florida.

4.2.3. The Third Period: Reflection and Innovation Period (2017–2019). During this period, the publications continued to increase. High-frequency keywords in this stage include green infrastructure, economic crisis, economic resilience, social resilience, urban resilience, sustainable development, and flood risk management. In addition to the diversity of research perspectives, there began to be some reflections on urban resilience paths and solutions, as well as the reconstruction of urban resilience indicators and theoretical framework. Kaika made a profound reflection on the construction of resilient cities, arguing that it would be difficult to make substantial progress if the resilient city study continues to adopt old methodological tools, institutional frameworks, and techno-managerial solutions [60]. Ziervogel et al. believed that the practice of resilience may be not consistent due to the difference in the development level between the global North and South, especially African cities, and proposed four entry points for integrating the right and justice into urban resilience [61]. Resilient city research is a dynamic and complex process from the perspective of the development needs of the city. Resilient city construction needs to pay equal attention to theory and practice.

The future trend of resilient city research is to put the research under the multilevel framework of environment, economy, society, and management, construct an operable

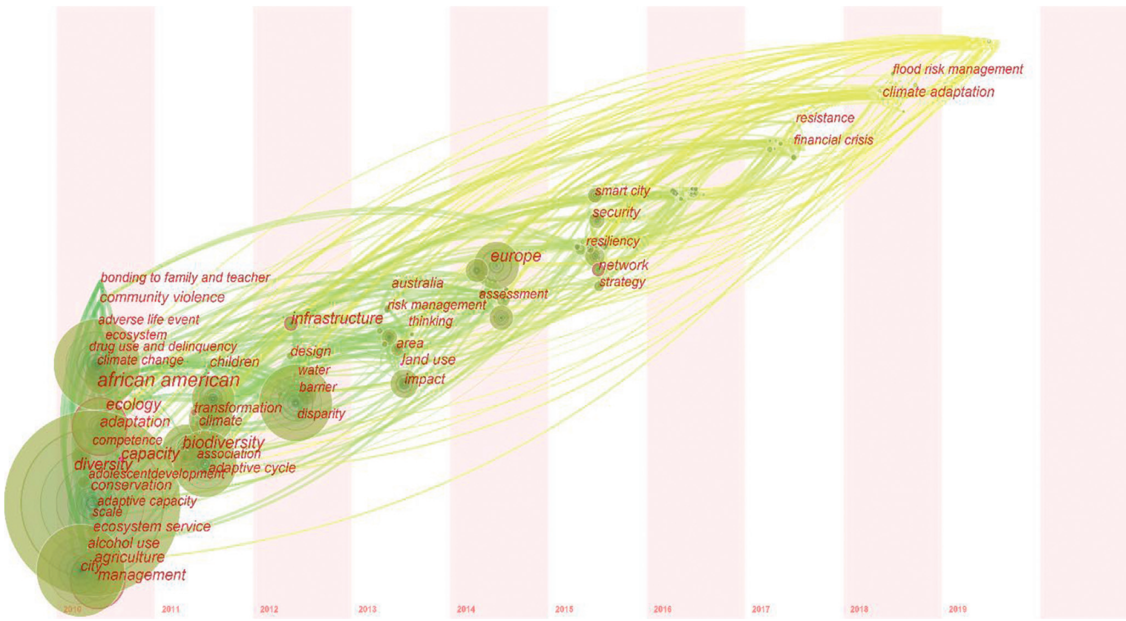

Figure 12: Visualization time zone map of keywords in resilient city research from 2010 to 2019.

Table 7: Annual high-frequency keywords.

Frequency	Centrality	Years	Keywords
334	0.02	2010	Resilience
170	0.08	2010	City
167	0.05	2010	Climate change
114	0.15	2010	Adaptation
112	0.16	2010	Management
67	0.03	2010	Governance
45	0.05	2010	Disaster
30	0.02	2010	Climate change adaptation
30	0.03	2010	Ecosystem service
124	0.02	2011	Vulnerability
92	0.04	2011	Risk
90	0.07	2011	Sustainability
86	0	2011	System
51	0.05	2011	Urbanization
41	0.07	2011	Urban
32	0.02	2011	Resilient city
30	0.03	2011	Urban planning
138	0.04	2012	Urban resilience
39	0	2012	Challenge
34	0.16	2012	Infrastructure
22	0.08	2012	Design
14	0.06	2012	Built environment
57	0.06	2013	Impact
37	0.06	2013	Health
28	0.03	2013	Lesson
18	0.01	2013	Complexity
17	0.05	2013	Risk management
16	0.01	2013	Landscape
15	0.02	2013	Area
94	0.02	2014	Framework
51	0.01	2014	Policy
44	0	2014	Model
30	0.03	2014	Politics
20	0.04	2014	Mitigation

Table 7: Continued.

Frequency	Centrality	Years	Keywords
41	0	2015	Community resilience
33	0.03	2015	Indicator
30	0.05	2015	Smart city
26	0.13	2015	Network
26	0.07	2015	Perspective
25	0.08	2015	Strategy
18	0.01	2015	Flood
16	0	2015	Performance
16	0.04	2015	Security
21	0.01	2016	Hazard
14	0.1	2016	Disaster resilience
13	0.01	2016	Earthquake
13	0.02	2016	Recovery
12	0.02	2016	Social ecological system
11	0.05	2016	Poverty
10	0.01	2016	Climate resilience
16	0.01	2017	Green infrastructure
12	0.03	2017	Flood risk
11	0.02	2017	Economic resilience
7	0	2017	Knowledge
7	0.01	2017	Natural disaster
7	0.01	2017	Social resilience
10	0.03	2018	City resilience
10	0	2018	Sustainable development
9	0.05	2018	Flood risk management
8	0	2018	Regional resilience
8	0.03	2019	Flood resilience
6	0.02	2019	Index
5	0	2019	Flooding
5	0	2019	Justice
5	0	2019	Knowledge system
5	0	2019	Rotterdam

implementation framework, and formulate time-sensitive strategies for resilience improvement. The academic community believes that emerging technologies such as the Internet of Things, big data and cloud computing, artificial intelligence, and blockchain will serve as the development path for the construction of resilient cities. Smart technologies can provide a starting point in enhancing the city's disaster response, prevention capacity. and resilience of postdisaster recovery, which facilitate building a smart, safe, and resilient city. Importantly, smart, safe, and resilient city research is being highly focused, which has become the forefront of resilient city research.

5. Conclusion

Since the 21st century, the concept of resilience has been widely applied to the socio-ecological field and the research on resilient cities has shown a rapid growth trend. In this paper, CiteSpace and VOSviewer bibliometric softwares were used to analyze the temporal and spatial distribution of the research on the resilient city. Moreover, the research hotspots were revealed under the topic clustering of the co-occurrence network based on keywords. Finally, the thematic evolution trend of the resilient city was summarized according to the time zone distribution characteristics of keywords. The following conclusions were drawn:

(1) The research of the resilient city presents the characteristics of multiscale, multidimensional, and interdisciplinary knowledge systems. In the context of different disciplines, the study of the resilient city has formed four aspects of subject clustering, including psychological resilience at the microcommunity and group levels, assessment of urban disaster resilience, multiple theoretical frameworks of urban resilience, and urban resilience promotion strategy.

(2) According to the evolution trend of the theme, the research of the resilient city has experienced three periods, namely, germination, rapid diffusion, and reflection and innovation periods. With the adoption and application of the concept of resilience in various fields, the subject of research on resilient cities has become more and more extensive, from psychological resilience and ecological resilience in the early period to diversified research in different dimensions and processes in the social domain. The research issues have also expanded from the early restoration of natural ecology and spiritual level to urban regional planning, infrastructure construction, reconstruction of the built environment, water supply, and other issues. Thus, the theoretical framework and evaluation system for the construction of modern resilient cities have emerged.

(3) From the perspective of co-authors and institutions, the research teams and institutions are relatively concentrated and the author cooperation network is loose as a whole. Knowledge dissemination and permeability are poor, and research cooperation depth and breadth are insufficient. The cooperation network shows fragmentation characteristics. In future research, scholars and institutions should break down barriers and explore cross-team, cross-school, and cross-regional collaboration.

(4) In terms of the characteristics of the literature knowledge structure, the research on the resilient city is on the upsurge. The research methods are mostly theoretical, while the research from positivism is rare. The research focuses more attention on the construction of the theoretical system, and the practical exploration lags behind the theoretical analysis. Future research needs to combine theory with practice and carry out more cases and exploratory analysis.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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Research Article

Experimental and Numerical Study on Gas-Liquid Flow in Hilly-Terrain Pipeline-Riser Systems

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In offshore oil and gas transport, gas-liquid mixed transport is a basic flow phenomenon. In general, pipeline undulations are caused by seabed topography; therefore, it is of great significance to study the mechanisms underlying gas and liquid flows in hilly-terrain pipeline-riser systems. This study established a hilly-terrain pipeline-riser experimental system in an indoor laboratory. The flow pattern and its flow mechanism were studied via experimental observation and pressure detection. Experimental results showed that the gas-liquid flow pattern in the hilly-terrain pipeline-riser system can be divided into four types: severe slugging, dual-peak slug, oscillation flow, and stable flow, where dual-peak slug flow is a special flow pattern in this pipeline system. Hilly-terrain units obstruct the downstream gas transport, weaken the gas-liquid eruption in the riser, and increase the cycle of severe slugging. In this paper, gas is regarded as power in the flow of gas and liquid, and the accumulation of liquid in low-lying areas is regarded as an obstacle. Then, the moment of gas-liquid blowout is studied as main research object, and the mechanism of flow pattern transformation is described in detail. This study investigated the accuracy of the OLGA 7.0 simulation results for the gas-liquid two-phase flow in the hilly-terrain pipeline-riser. The results show that OLGA 7.0 achieves a more accurate calculation of severe slugging and stable flow and can predict both the pressure trend and change characteristics. However, the simulation accuracies for dual-peak slug flow and oscillation flow are poor, and the sensitivity to gas changes is insufficient.

1. Introduction

In offshore oil and gas transport, pipeline-riser systems are used to transport products from different wells to offshore platforms. In these pipelines, gas-liquid flow forms the basic flow phenomenon. Therefore, studying the two-phase flow characteristics and underlying laws in the pipeline-riser system forms the basis to ensure the safe and efficient operation of offshore oil and gas production systems [1–3].

Severe slugging is one of the most dangerous flow patterns in such a riser system [4]. Yocum [5] first reported the phenomenon of severe slugging in 1973. Schmidt et al. [6–8], Fabre et al. [9], and Pots et al. [10] studied the occurrence mechanism of severe slugging and established the relevant occurrence criterion. Taitel [11] identified unstable gas-liquid flow in the pipeline as the cause of severe slugging. In response to low gas-liquid velocity, the slug head reaches the top of the riser before the gas enters the riser at the slug growth stage. This is a necessary condition for the occurrence of severe slugging. Based on this, the criterion of stable flow is proposed, which was revised by Wang et al. [1] and Ma et al. [12].

The flow pattern of gas-liquid flow not only depends on the physical properties, flow rates, and other flow parameters [13], but is also affected by the geometry and position of the pipeline. The flow pattern of gas-liquid flow in pipeline-riser systems has been studied before. Schmidt [6] conducted experimental research to compare the differences between severe slugging and hydraulic slug flow. Severe slugging was divided into severe slugging of type I and severe slugging of type II according to whether liquid slug is formed in the downward pipe. In addition, if formed in the horizon-riser pipeline system, severe slugging is called severe slugging of type III. This classification method proposed by Schmidt [6] is relatively vague and does not contain specific descriptions of flow processes and characteristics. New classification criteria and flow characteristics of severe slugging flow were proposed by Ma et al. [12] through experimental observation.

Severe slugging occurs only at low gas-liquid flow. Many scholars have studied gas-liquid flow patterns within a wide gas-liquid flow range. According to the flow characteristics of gas-liquid flow, Mokhatab and Towler [14] classified the flow patterns in the pipeline-riser system into stable flow and unsteady flow. Wang et al. [1] identified irregular severe slugging in experiments. When irregular severe slugging occurs, both gas and liquid flow stably for most of the time, but are occasionally subjected to strong fluctuations of pressure and outlet velocity. However, this flow pattern does not commonly occur in experiments. In an experimental study, Malekzadeh et al. [15] found unstable oscillation flow, in addition to the three types of severe slugging (SS I, SS II, and SS III) and steady flow. Unstable oscillation flow is characterized by oscillating liquid holdup in the pipe and continuous flow of gas and liquid from the downward pipe into the riser; the pressure fluctuation is much less than in severe slugging. Malekzadeh et al. [16] have also carried out experimental studies in a horizon-riser pipeline system and observed a total of four flow patterns: stable flow, severe slugging of type III, unstable oscillation flow, and dual-frequency severe slugging flow. Dual-frequency severe slugging was reported for the first time, and the authors focus on its research.

The flow pattern in the pipeline-riser system was initially divided into unstable flow and stable flow and then further subdivided into various flow patterns. The basis of this division has gradually become more precise and clearer, and the formation mechanism of gas-liquid flow, especially for severe slugging, was gradually deepened. However, because of the influence of the topographic structure of the seabed, it is difficult to avoid ups and downs of the gathering and transportation pipeline. In previous research, gas-liquid flow in an undulation-riser system was rarely reported [17]. Therefore, it is necessary to study the change of gas-liquid two-phase flow patterns and flow mechanisms when the gathering and transportation pipeline fluctuates. This study established an experimental hilly-terrain pipeline-riser system in the laboratory, and the flow pattern and flow mechanism were studied via experimental observation and pressure detection. The gas-liquid flow pattern was classified more scientifically and comprehensively, and a new flow pattern was identified: dual-peak slug flow. Then, the flow pattern transition mechanism and the effect of hilly-terrain units on the flow are discussed. Finally, the accuracy of the OLGA 7.0 simulation results of gas-liquid two-phase flow in the hilly-terrain pipeline-riser is studied.

2. Experimental Apparatus and Methodology

The experimental system of this study consists of four parts: gas-liquid supply, test loop, gas-liquid separation, and measurement and shooting part, as shown in Figure 1. The media used in the experiment are water and air. To ensure an adequate liquid supply, water was first stored in a tank and then pressurized via a centrifugal pump, using a precision regulator to regulate the liquid inlet flow. A GA37VSDAP-13 twin screw gas compressor was used to compress the air, and the compressed air was then stored in the gas buffer tank. The maximum pressure can reach up to 1.3 MPa by changing the speed of the inverter driving motor in the compressor and maintain stable pressure in the buffer tank. In the experiment, the pressure of the buffer tank was set to 8 bar, considering factors such as the pressure of the buffer tank and the stable air source. The gas in the buffer tank is regulated by a stop valve and a precision regulator, which provides a steady gas flow for the experimental system. After the gas and liquid were measured, respectively, they enter the test pipe section through the gas-liquid mixer and flow into the gas-liquid separation section at the end of the test pipe. The separated gas is then discharged into the atmosphere and the liquid enters the return line from the bottom of the separator, from where it returns to the tank.

The test loop consists of a horizontal pipe, a hilly-terrain pipe, a downward pipe, and a riser pipe. The pipes (with an inner diameter of 51 mm) are connected by flanges. The horizontal pipe has a length of 69.4 m, and a transparent polymethyl methacrylate pipe of 4 m length was used to facilitate the observation of the flow pattern, while the rest of the pipe consists of stainless steel. The hilly-terrain segment structure is shown in Figure 2; it has an undulating angle of 45° and a height of 1 m, which was installed 58 m away from the entrance. The downward pipe is 11.5 m in length, and the downward angle is −4°. The height of the riser is 6.9 m. To observe the flow condition of the gas-liquid in the pipe, hilly-terrain pipe, downward pipe, and riser pipe consist of transparent polymethyl methacrylate. Pressure data are collected at key points in the test loop: the pressure difference between the bottom of the hilly-terrain pipe and the bottom of the riser and the pressure at the bottom of the riser. Combined with the video captured in the experiment, the flow state and characteristic parameters of the gas-liquid flow in the pipe can be obtained by using these pressure data.

The top of the riser is connected to a vertical gravity separator. After the gas-liquid mixture enters the separator, because of the influence of gravity, the gas is discharged into the atmosphere through the upper outlet valve of the separator, and the liquid phase accumulates in the lower part of the separator. The liquid then enters the return pipeline through the bottom outlet pipe, from where it finally flows into the water tank. A magnetic reversal liquid level meter is mounted on the separator to monitor the liquid level in the separator, and a pressure gauge is mounted on top of the separator to measure pressure in the separator. In addition, the gas outlet pipe is equipped with an emergency exhaust valve to prevent safety accidents in the separator caused by

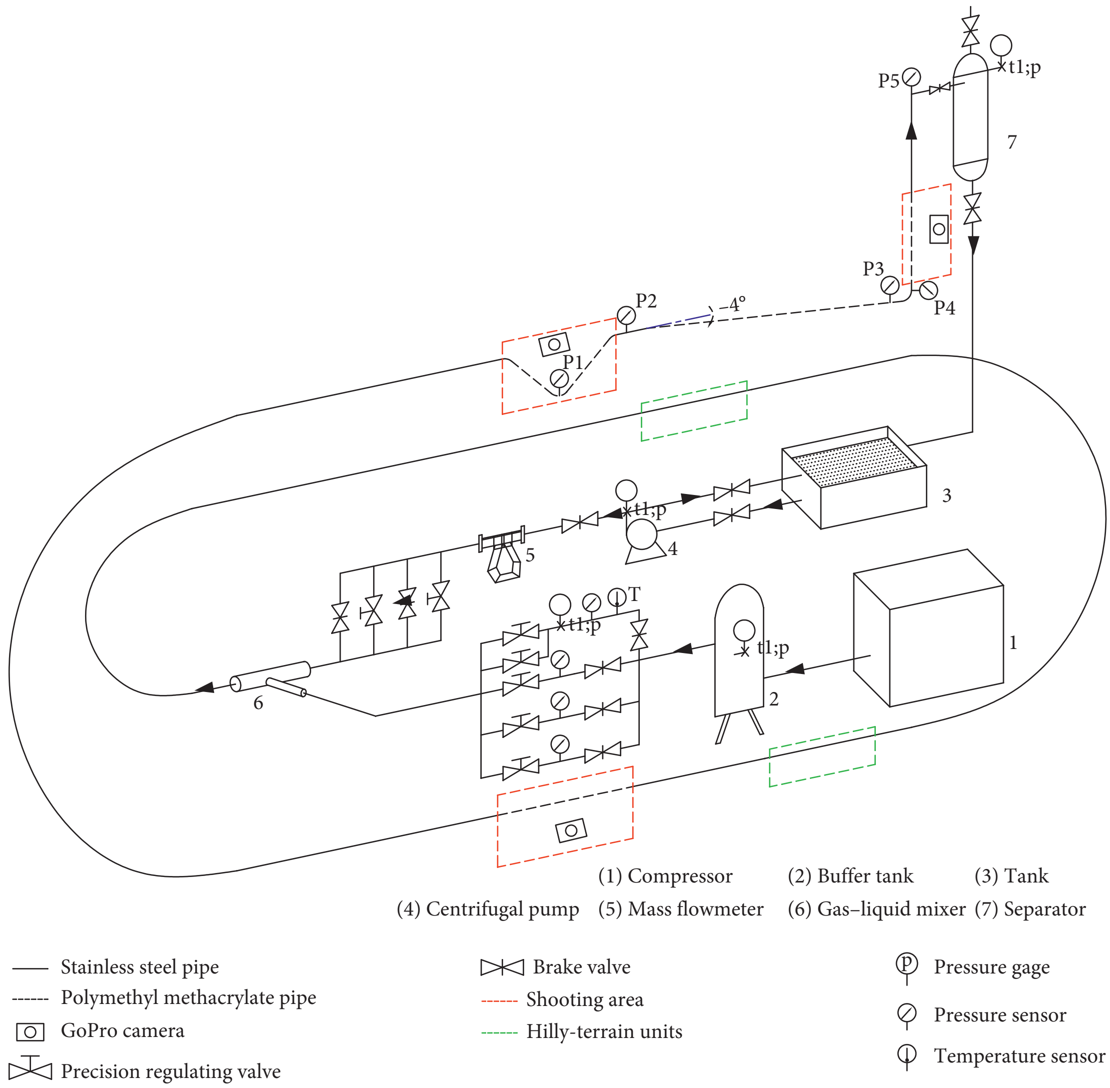

Figure 1: Experimental hilly-terrain pipeline-riser system.

overpressure. In this experiment, the gas-phase valve was fully open and the pressure in the separator was close to atmospheric pressure.

The following physical quantities were measured in this study: flow rate, temperature, and pressure. Because many times of micro and precise regulation of the gas flow are needed, an EJA115 micro-orifice flowmeter was used to measure the gas flow. To meet specific requirements, three types of orifice plates were used in this study. The orifice plate diameter and flow range were 0.864 mm, 2.527 mm, and 6.350 mm, as well as 1.85–12.9 nL/min, 14.6–105 nL/min, and 89–630 nL/min, respectively. The input voltage of the orifice flowmeter is 12 V; the output current signal ranges within 4–20 mA, and the measurement error level is 0.2. A Keller PR25Y piezoresistive pressure transmitter and ROSEMOUNT 3595 capacitive pressure transmitter were used to measure pressure. The Keller PR25Y piezoresistive pressure transducer, with a frequency limit of 2 kHz, output current of 4–20 mA, and a maximum error of 0.25%, achieved high precision, repeatability, and temperature stability. It is suitable for high-precision, high-speed data acquisition and was installed at the bottom of the riser in the experiment. The Rosemount 3595 capacitor-based pressure transmitter had a frequency response of 22 Hz and an output current signal of 4–20 mA. It was equipped with a microprocessor, LCD screen, and adjustable range for measuring inlet pressure, differential pressure of hilly-terrain, and riser pipes. A RWBPA61 temperature sensor, with an accuracy of 0.5 level and a measurement range of 0–120°C, was used for

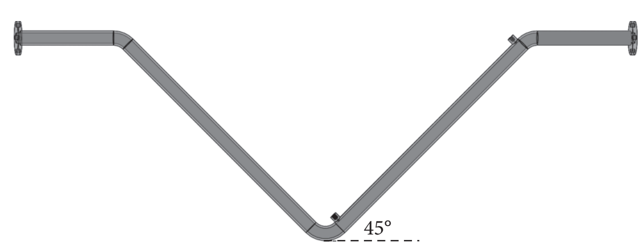

Figure 2: Schematic diagram of a hilly-terrain unit.

temperature measurement. It was calibrated using a standard mercury thermometer.

LabVIEW software was used to collect experimental data. The data acquisition system includes a PCI-6255 high-speed A/D acquisition card, a SCB-68 junction box, a DC-stabilized power supply, and a PC. NI PCI-6255 is a high-speed M-series multifunctional DAQ board card that can maintain high precision even at high sampling rate. The acquisition card has a 16-bit 80-way analog channel and a 40-way differential channel. An SCB-68 signal input/output junction box is attached to the acquisition card and connected to a self-made circuit board. A 250 Ω resistance is welded on the circuit board to convert the 4–20 mA current signal output by the instrument into a 1–5 V voltage signal, which is then transmitted to a DAQ board card through the junction box, thus realizing data acquisition and transmission. In addition, in the experiment, three high-resolution GoPro cameras were used to shoot three areas (indicated with the red dotted line in Figure 1). The GoPro cameras enabled adjustment of the field of vision and frame number according to user requirements and recorded the flow state of gas-liquid in the pipeline.

3. Flow Patterns in Hilly-Terrain Pipeline-Riser Systems

Based on previous simulation and exploratory experiments, orthogonal superficial gas and liquid velocity was designed in this study to conduct further tests of working conditions. The superficial gas velocity range was 0.227–12.218 m/s, and the superficial liquid velocity range was 0.024–0.610 m/s. LabVIEW was used to collect pressure data, and the GoPro camera was turned on to shoot the transparent section of the horizontal pipe, the hilly-terrain section, and the downward pipe-riser section. In this study, the flow pattern of gas-liquid two-phase flow was divided according to the fluctuation characteristics of the pressure at the bottom of the riser and experimental observations. According to the fluctuation range of the bottom pressure of the riser, the flow pattern was classified into four types: severe slugging, dual-peak slug, oscillating flow, and stable flow. Each flow type was further divided according to different characteristics. Severe slugging was classified as severe slugging of type I, severe slugging of type II, and severe slugging of type III. Oscillating flow was classified as low-frequency oscillation and high-frequency oscillation. Stable flow was classified as irregular and regular stable flows. Compared with other studies, the present study applies a more detailed and comprehensive classification of flow patterns, which is more conducive to deepening the understanding of gas-liquid flow characteristics in pipeline-riser systems.

3.1. Severe Slugging. Ma [12] divided severe slugging into severe slugging of types I–III. However, Ma regarded the flow pattern between severe slugging and stable flow as a transition flow pattern, which is too rough to be further divided. In a hilly-terrain pipeline-riser system, severe slugging exists only when the riser is filled with liquid during the gas-liquid flow. In other words, when severe slugging occurs, the maximum pressure at the bottom of the riser is equal to the static pressure when the riser is full of liquid (68 kPa in this experimental system), and the impact and damage to the pipeline system are most "severe."

3.1.1. Severe Slugging of Type I (SS I). SS I is typical severe slugging, complete with four cycles: slug growth, slug production, gas-liquid blowout, and liquid fallback. However, because of the hilly-terrain pipe before the downward pipe, the gas-liquid flow state of SS I changes at different stages. The curves of pressure at the bottom of the riser (P_r) and the pressure difference between the bottom of the hilly-terrain pipe and the bottom of the riser (ΔP_{hr}) are shown in Figure 3. The flow process diagram is shown in Figure 4.

Liquid fallback is assumed as initial stage, and the gas-liquid flow process within a cycle is described as follows.

Liquid fallback (Figure 4(a)): because of the influence of gravity, the liquid in the riser falls back to the bottom of the riser, which leads to an increase in P_r. The slug tail is then pushed upstream by the pressure difference, and the height of the slug in the riser decreases, which results in a decrease of P_r. With the inflow of gas into the downward pipe, the slug tail stops to move backward, the liquid and liquid film in the riser fall back continuously, and P_r continues to increase until the maximum static pressure value (resulting from the height of the falling liquid) is reached. At the initial stage of liquid fallback, the liquid in the hilly-terrain pipe is still carried downstream by the gas, the height of liquid slug between the bottom of the riser and the bottom of hilly-terrain pipe decreases, and thus, ΔP_{hr} decreases. With more fluid in the riser falling back and the decreasing gas energy, the fluid in the horizontal pipe accumulates toward the bottom of the hilly-terrain pipe, and thus, ΔP_{hr} increases.

Gas discharging (Figure 4(b)): falling liquid accumulates at the bottom of the riser and the bottom of the hilly-terrain pipe, respectively, both of which enclose the gas space V_{hr}. The liquid continuously flows into the downward pipe and the riser pipe, the head and tail of the riser slug increase, and P_r continues to increase. The gas space V_{hr} is continuously compressed and its volume decreases; therefore, the pressure increases continuously. The gas-liquid interface is then pushed forward until the gas in V_{hr} enters the riser and is released through the riser slug. At this time, bubble flow happens in the riser, as shown in Figure 4(b). After gas discharge from V_{hr}, the pressure decreases, part of the riser slug flows back into the downward pipe, and thus, P_r decreases. When the gas in P_r cannot pass through the riser slug, the gas discharging stage ends.

Slug growth (Figure 4(c)): after the gas in V_{hr} is discharged, the slug in the riser and the downward pipe continues to grow. The gas in V_{hr} is enclosed in the downward pipe, and the hilly-terrain slug is connected to the riser slug, as shown in Figure 4(c). Gas continuously accumulates in the gas space V_h of the horizontal pipe, upstream of the hilly-terrain pipe, and therefore, the pressure V_h increases, but the speed of this increase is always less than that of the pressure at the bottom of the hilly-terrain pipe;

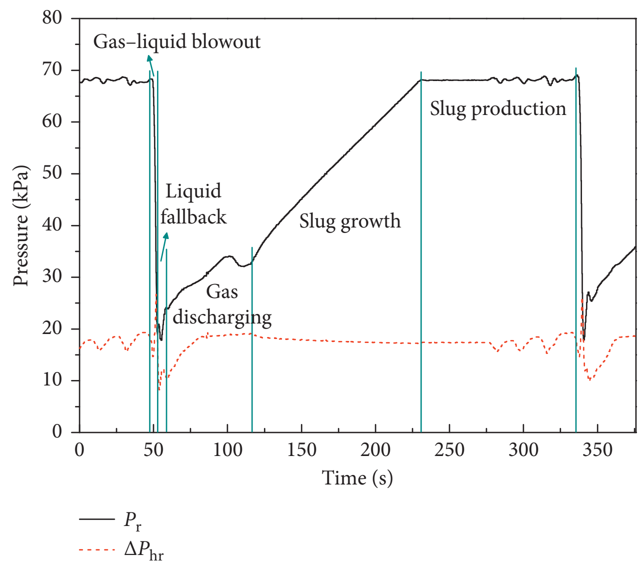

Figure 3: Pressures of P_r and ΔP_{hr} for severe slugging of type I.

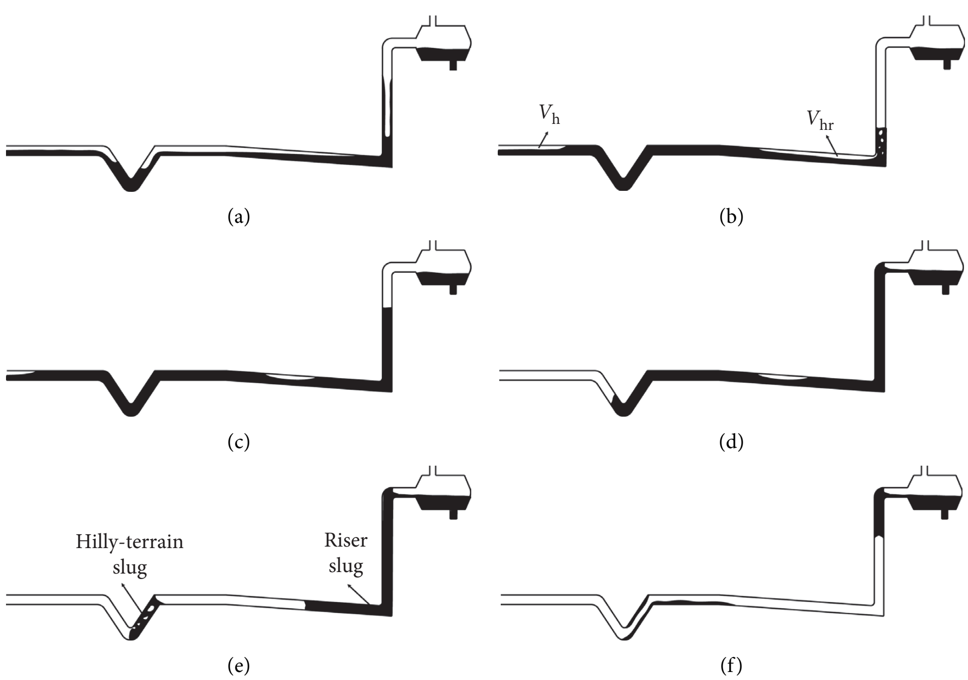

Figure 4: Schematic diagram of the gas-liquid flow cycle for severe slugging of type I. (a) Liquid fallback. (b) Gas discharging. (c) Slug growth. (d) Slug production (gas does not penetrate the slug). (e) Slug production (gas has penetrated the slug). (f) Gas-liquid blowout.

consequently, the gas cannot pass through the hilly-terrain slug. During this process, the riser slug grows continuously; therefore, P_r increases, while the height of the slug between the bottom of the riser and the bottom of the hilly-terrain pipe changes little; therefore, ΔP_{hr} remained basically unchanged.

Slug production (Figures 4(d) and 4(e)): after the head of the riser slug reaches the top of the riser, the riser slug flows into the terminal treatment equipment. Because of the in-flow of inlet gas, the volume V_h continuously increases, thus pushing the tail of the hilly-terrain slug forward (as shown in Figure 4(d)). When the tail of the slug reaches the bottom of the hilly-terrain pipe, the gas in V_h penetrates the slug and then enters the downward pipe, thus resulting in a decrease of ΔP_{hr} and an increase of V_{hr} and forward movement of the tail of the slug. The pressure of V_h gradually decreases, until the gas cannot penetrate the slug. Liquid in hilly-terrain pipe and horizontal pipe flowed backward and then accumulated in the hilly-terrain pipe, thus resulting in the tail of the slug moving back and ΔP_{hr} increasing. The inlet gas accumulates again in V_h, and the process is repeated until the tail of the riser slug enters the riser; then, the slug production stage ends. At this stage, the riser slug height remains unchanged; therefore, P_r basically remains constant. Because of the passage of gas and liquid backflow, ΔP_{hr} shows periodic fluctuation during the later period.

Gas-liquid blowout (Figure 4(f)): the gas in V_{hr} enters the riser, and the length of the slug shortens, which results in a decrease of P_r, and then, the gas expands and the flow accelerates. The P_r reduction caused by the shorter slug is mutually promoted with the gas expansion, which causes the gas to push the slug toward accelerating the flow out of the riser. The rapid outflow of the slug results in a sharp decrease in P_r, and the upstream pressure of the hilly-terrain pipe basically remains unchanged at this moment. Driven by the large pressure difference, the liquid in the hilly-terrain pipe erupts, which accelerates the flow to the rear pipe. Part of this fluid enters the downward pipe and the other part returns to the hilly-terrain pipe, where it accumulates and forms the riser slug and the hilly-terrain slug, respectively. The stage ends when the gas pressure in the riser is insufficient to allow liquid outflow.

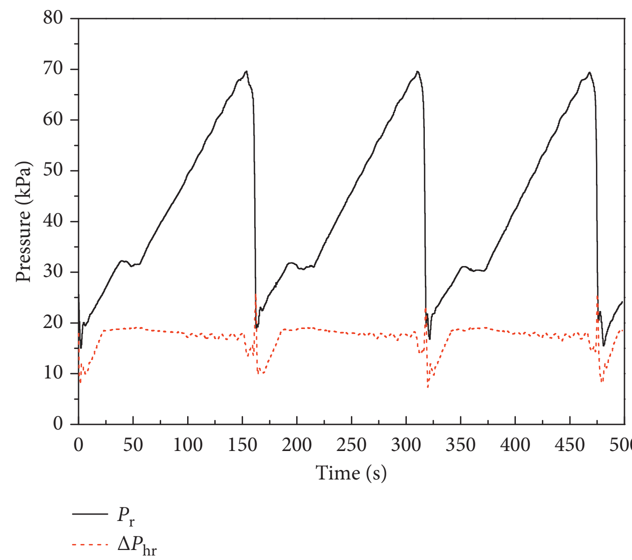

Figure 5: Pressure of P_r and ΔP_{hr} for SS II.

3.1.2. Severe Slugging of Type II (SS II). Based on SS I, when the speed of the inlet gas increases, the gas-liquid flow pattern transitions to SS II; the resulting P_r and ΔP_{hr} curves are shown in Figure 5. SS II still shows obvious periodicity. However, because of the influence of the hilly-terrain pipe, in this study, the highest P_r value of SS II is still the highest pressure caused by the riser height of the liquid slug, which differs from the SS II in other pipe systems. In essence, there is no difference in flow characteristics and process between SS II and SS I. Consequently, only the differences that exist between both are described in the following.

In the gas-liquid blowout stage, SS II erupts more violently than SS I, and more liquid in the riser pipe flows into the separator; therefore, the liquid slug generated during the SS II liquid fallback stage is shorter. A comparison of Figures 3 and 5 shows that the maximum pressure at the bottom of the riser during the SS I liquid fallback stage is higher than that of SS II.

SS II also has a gas discharging stage, but it has less fallback liquid; therefore, the slug generated in the riser is shorter, and the gas space V_{hr} is more easily penetrated through the riser slug after being compressed. In addition, because of the larger inlet gas velocity and the faster gas accumulation velocity in V_h, the time for the gas discharging stage of the SS II is shorter than that of SS I.

When the head of the riser slug grows to the top of the riser, the gas in V_h enters the riser and triggers a gas-liquid blowout. Therefore, there is no slug production stage in SS II, which is the main difference from SS I.

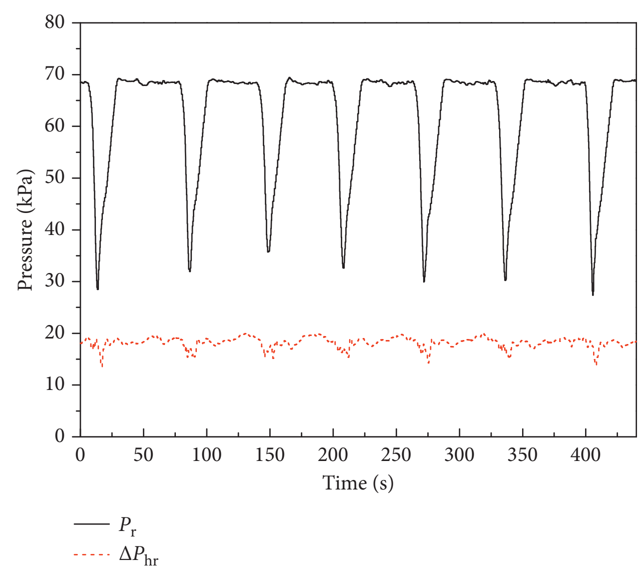

Figure 6: Pressure of P_r and ΔP_{hr} for SS III.

3.1.3. Severe Slugging of Type III (SS III). Based on SS I, increasing the inlet liquid volume, the gas-liquid flow changes to SS III, and the P_r and ΔP_{hr} curves change as shown in Figure 6. The following details the differences between SS III and SS I.

Because of the high inlet liquid velocity, the amount of liquid in the pipeline, and the relatively low gas velocity, which results in less liquid backflow during the gas-liquid blowout stage, the liquid slugs generated in the riser and the hilly-terrain pipe are longer. Figure 7 shows that after the liquid fallback stage, P_r reaches about 45 kPa, which is much larger compared with SS I. The falling liquid will also seal the gas space V_{hr} in the downward pipe; however, because of the high hydrostatic pressure generated at the bottom of the riser after liquid fallback, the pressure of V_{hr} is insufficient to overcome the obstruction of the liquid slug; therefore, there is no longer a gas discharging stage. The above two points indicate the main differences between SS III and SS I.

During the gas-liquid blowout stage, the energy of gas accumulation is relatively insufficient, and the severity of SS III gas-liquid eruption is weaker than that of SS I. Therefore, the pressure at the bottom of the riser after this stage is comparatively higher (25 kPa).

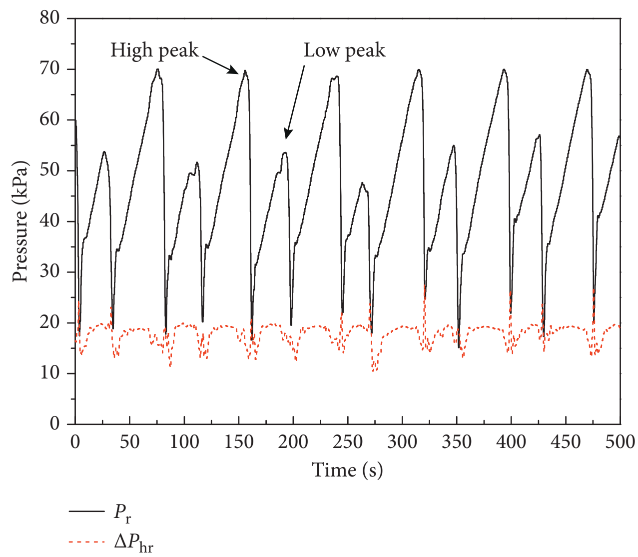

Figure 7: Pressures of P_r and ΔP_{hr} for dual-peak slug.

3.2. Dual-Peak Slug. In this study, a special flow pattern was discovered: dual-peak slug (DPS). DPS has obvious periodicity, and the P_r fluctuation curves have two different peaks (as shown in Figure 7). A clear difference exists between these two peaks: the larger peak value reaches the highest hydrostatic pressure value when the riser is fully filled with liquid, which reached 68 kPa; the smaller peak is between 30 and 55 kPa (the working condition as shown in Figure 7 is between 45 and 55 kPa).

When DPS flow occurs, slug growth and gas-liquid eruption occur successively in the pipeline system, and there is no slug production stage. Two different peaks appear alternately in the P_r fluctuation curve, indicating that the riser slug height is different at the beginning of the gas-liquid blowout stage; moreover, the gas-liquid eruption intensity of the two adjacent cycles is also different. According to the severity of the eruption, the two adjacent cycles were named "large eruption" and "small eruption." The DPS flow can be considered as a flow pattern in which gas-liquid "large eruption" and "small eruption" alternation. The process will be analyzed in detail in the following.

When dual-peak slug occurs, the superficial gas velocity is larger; therefore, when the hilly-terrain slug erupts, it continually triggers the riser slug eruption. The "big eruption" cycle of gas-liquid eruption is more intense and thus causes the gas to drive out most of the liquid from the pipeline system. Therefore, the slug generated in the liquid fallback stage is shorter, and the hydrostatic pressure generated at the bottom of the hilly-terrain pipe is smaller. Under constant gas-liquid input, in the next cycle, the slug tail in the hilly-terrain pipe can flow through the bottom relatively quickly, which in turn causes gas-liquid eruptions in the hilly-terrain pipe and the riser pipe. Because the gas-liquid eruption happens earlier and the maximum height of the riser slug is smaller, the pressure peak at the bottom of the riser in this cycle is smaller. Because of insufficient gas accumulation and low energy, the gas-liquid eruption is lighter, which is called a "small eruption." In this "small eruption" cycle, the slug generated in the liquid fallback stage is longer, which causes a large hydrostatic pressure at the bottom of the hilly-terrain pipe; consequently, the next cycle takes longer to push the slug tail in the hilly-terrain pipe through the bottom. Eventually, a long slug is generated in the riser, and the pressure fluctuation at the bottom of the riser produces a large peak, which causes a "large eruption." Therefore, because of the influence of the hilly-terrain pipe, the "large eruption" cycle alternates with the "small eruption" cycle.

3.3. Oscillation Flow. The variation curves of P_r and ΔP_{hr} of the oscillation flow are shown in Figure 8. The main feature of these curves is the irregularity of P_r fluctuations. The fluctuation amplitude exceeds the static pressure of the water column at 1/5 of the riser height (14 kPa in this experiment). The gas-liquid eruption and the slug growth in the riser alternate continuously. The severity of the gas-liquid eruption and the maximum length of the riser slug are random. The frequency of P_r fluctuations differs greatly. By performing a FFT conversion on the P_r signal, it can be divided into low-frequency oscillation flow (<0.1 Hz) and high-frequency oscillation flow (>0.1 Hz) according to the differences of the main frequency.

3.3.1. Low-Frequency Oscillation. The low-frequency oscillation (LFO) evolves from DPS, and the P_r fluctuation ranges between 5 and 50 kPa, as shown in Figure 8(a). Similar to the DPS, high and low peaks alternate on the P_r fluctuation curve for LFO; however, the riser gas-liquid eruption frequency is higher, and the fluctuation amplitude is lower. The reason is that the larger the inlet gas velocity is, the faster the gas in V_h pushes the slug forward, and the gas is faster conveyed through the hilly-terrain pipe down the downward pipe and therefore causes more frequent slug growth and gas-liquid eruption.

3.3.2. High-Frequency Oscillation. High-frequency oscillation (HFO) occurs at a large inlet superficial liquid velocity (>0.28 m/s in this study). The fluctuation of P_r basically ranges within 15–40 kPa. Compared with LFO, the fluctuation amplitude of P_r under the HFO flow pattern is relatively low, but the fluctuation frequency is high. This is mainly caused by the high inlet fluid velocity. Under the same gas-liquid ratio conditions as in LFO, the HFO inlet gas-liquid velocity is higher, and the gas accumulation velocity in V_h and liquid slug growth velocity in the riser are faster; therefore, the gas-liquid eruption frequency is higher, resulting in high-frequency P_r fluctuations.

3.4. Stable Flow. The variation curves of P_r and ΔP_{hr} under stable flow are shown in Figure 9. The characteristic of this stable flow is that the fluctuation amplitude of P_r is less than 1/5 of the static pressure caused by the water column at riser height (14 kPa in this study); moreover, the gas-liquid flow in

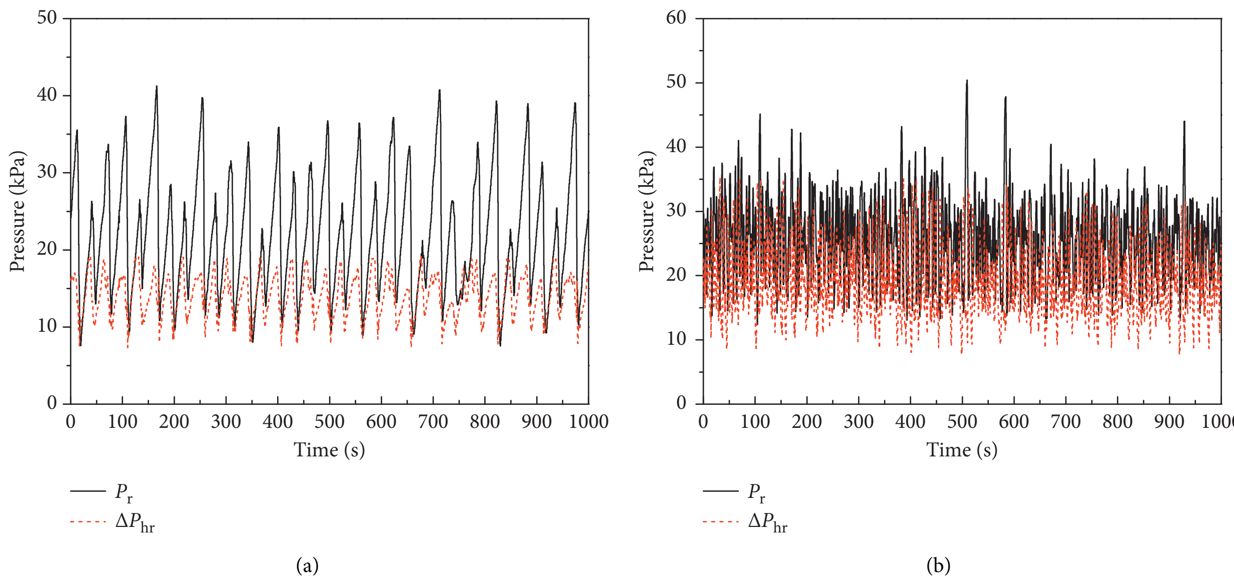

FIGURE 8: Pressure of P_r and ΔP_{hr} for low-frequency oscillation flow (a) and high-frequency oscillation flow (b).

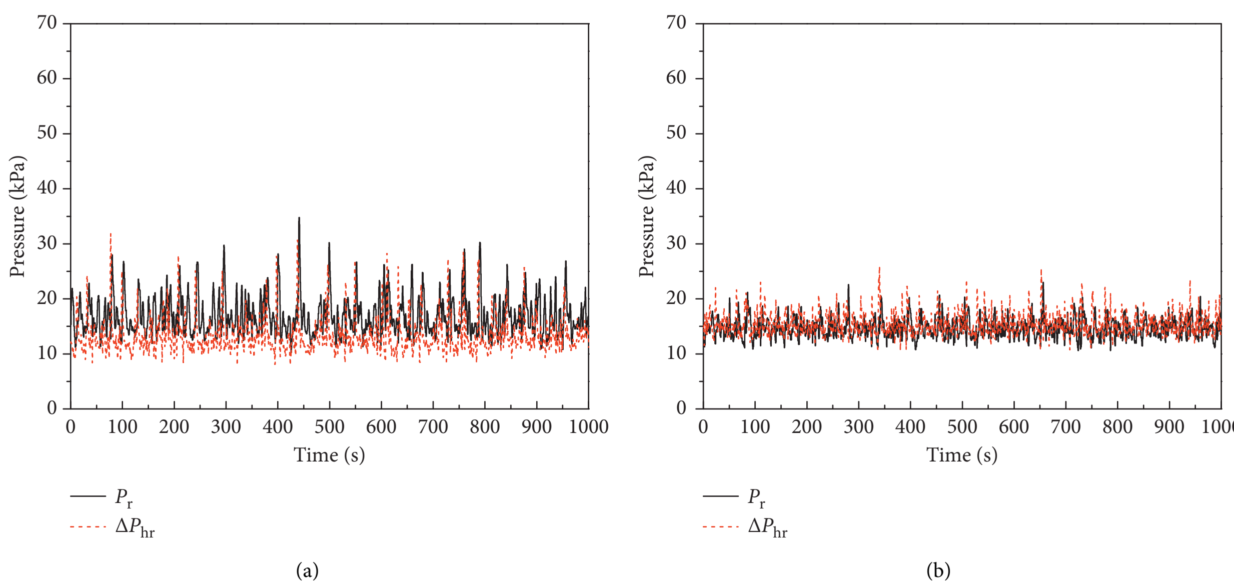

FIGURE 9: Pressure of P_r and ΔP_{hr} for irregular-stable flow (a) and regular-stable flow (b).

the riser follows a hydraulic slug flow pattern. Stable flow evolves from oscillation flow. If a liquid fallback and a gas-liquid eruption are regarded as a flow cycle, because of the influence of the hilly-terrain pipe, with increasing inlet gas velocity, not all cycles of P_r fluctuations decrease synchronously. According to the different characteristics of P_r fluctuations, the stable flow can be divided into irregular-stable flow and regular-stable flow.

3.4.1. Irregular-Stable Flow. After several stable flow periods (where the P_r fluctuation amplitude is less than 14 kPa), a "large eruption" occurs; i.e., a higher P_r fluctuation amplitude occurs. This type of flow is called irregular-stable flow (IST). The P_r fluctuation curve is shown in Figure 9(a). The reason for this change in amplitude is that after multiple stable flow cycles, the gas in V_h is not replenished sufficiently, and the pressure drops, which results in an increase of the amount of liquid falling in the hilly-terrain pipe. When the eruption occurred again, the riser liquid slug had grown to a higher height, thus resulting in a larger P_r fluctuation pressure during this period.

3.4.2. Regular-Stable Flow. When the fluctuation range of P_r during all flow periods is less than 14 kPa, it is called regular-stable flow (RST). The gas in the hilly-terrain pipe and riser flows at high speed. Although the liquid appears to briefly fall back, it is carried downstream by the gas and flows. There is no liquid accumulation at the bottom of the hilly-terrain pipe and the riser. This flow state causes the least damage to the pipeline system and is the most ideal state for gas-liquid flow in pipeline-riser systems.

4. Results and Discussion

4.1. Frequency Domain and Probability Density Function Characteristics of P_r. P_r is an important characteristic parameter when assessing the flow pattern. This study investigated the frequency domain characteristics and probability density function (PDF) characteristics of P_r under different flow patterns. The processing results are shown in Figure 10. The frequency domain characteristics of P_r are obtained by fast Fourier transform (FFT). To arrive at a more widely applicable PDF feature, the pressure in the PDF distribution image has been standardized, and the processing method can be calculated with the following equation:

$$p_i^* = \frac{p_i - \overline{p}}{S_i}. \tag{1}$$

In the formula,

$$\overline{p} = \frac{1}{N}\sum_{i=1}^{N} p_i,$$
$$S_i = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(p_i - \overline{p}\right)^2}, \tag{2}$$

The frequency domain distribution diagram of P_r shows that severe slugging has strong periodicity, and the frequency domain curve of P_r shows a distinct single-peak distribution, especially for SS II. For SS III, because of the large difference in the height of the liquid slug formed in the riser after eruption, the periodicity of the fluctuation curve is slightly weaker; therefore, there is a subprimary frequency. In general, the frequency distribution of severe slugging is narrow, and the main frequency is clear. Under DPS, there are three peaks in the frequency domain curve of P_r. The frequency domain characteristics of the oscillating flow differ greatly, mainly because of differences in oscillating frequencies. The frequency domain for LFO is narrowly distributed and has a single-peak characteristic. Its main frequency is less than 0.1 Hz. HFO has a wide frequency domain distribution, the main frequency of which is higher than 0.1 Hz. The frequency distribution of the stable flow is relatively wide, and gas-liquid eruptions happen after a few stable cycles. Therefore, the frequency domain curve of P_r shows a double-peak characteristic, while RST shows a single-peak characteristic with a small main frequency.

Analysis of the PDF distribution characteristics of P_r under different flow patterns indicates that severe slugging has clear single-peak characteristics, especially for SS I and SS III. The peak value is the highest pressure; therefore, the pipeline system is in a high-pressure state most of the time. Since SS II has no liquid production stage, the peak pressure is not the highest value. For DPS, P_r has two peaks, and its PDF distribution also has two peaks; however, the distribution area is wider than that in severe slugging. The fluctuation of the P_r curve for the oscillation flow is relatively large; therefore, the PDF is widely distributed. Compared with LFO, the peak of PDF distribution for HFO is on the right. This is because the HFO flow pattern has a larger inlet flow rate, and the riser contains more liquid during the flow, which results in a higher pressure at the bottom of the riser. The PDF distribution of the stable flow is more in line with a normal distribution, which is the ideal flow pattern.

4.2. Flow Evolution of Gas-Liquid. For a specific pipeline system, when the inlet flow rate changes, the gas-liquid flow conditions change accordingly. This is a gradual process without mutation. There is no obvious boundary between different flow patterns, and therefore, these patterns are artificially classified according to different flow characteristics; therefore, the flow pattern change cannot be viewed from the perspective of splitting. The mechanism of flow pattern transition is discussed in the following by combining experimental phenomena and flow pattern diagrams (as shown in Figure 11).

In gas-liquid flow, because of the influence of gravity, liquid accumulates at the bottom of the hilly-terrain pipe and the bottom of the riser, which obstructs the flow. Only when the gas overcomes this barrier, it can be transported downstream. Before the gas breaks through the slug, the slug grows and the gas pressure continues to increase. The way for the gas to break through this obstacle is to penetrate the slug tail and then continuously increase its flow speed because of the expansion force, which triggers an eruption, and liquid fallback after the eruption. It can be considered that most of the flow patterns contain gas-liquid eruptions and liquid fallbacks. The moment of gas-liquid eruption determines the highest pressure in the riser, i.e., the pressure fluctuation range of the riser, and therefore, this is used as the key point of the analysis.

In the hilly-terrain pipeline-riser system, the gas-liquid eruption starting time is determined by the time when the gas enters the bottom of the hilly-terrain pipe and the bottom of the riser. The moment when the gas enters the bottom of the hilly-terrain pipe is determined by the relative magnitude of the upstream gas pressure P_{tg} and the bottom hydrostatic pressure P_{tl}. When P_{tg} exceeds P_{tl}, the hilly-terrain slug tail is pushed forward; otherwise, it either grows backward or stops. The moment when the gas enters the riser is mainly related to the speed of conveying the gas through the hilly-terrain pipe down the inclined pipe.

With regard to the flow under any working condition, the liquid slug generated after the liquid fallback stage is the obstacle the gas needs to overcome, i.e., this is the starting point of the analysis. Using the inlet superficial liquid velocity $v_{sl} = 0.065$ m/s as an example, when the inlet superficial gas velocity is low ($v_{sg} < 0.245$ m/s), the gas-liquid eruption is lighter and more liquid falls back. Therefore, the obstacle the gas needs to overcome is greater, and P_{tg} is much smaller than P_{tl}. The gas accumulation rate in V_h is relatively slow, resulting in a slow increase in P_{tg}. At the same time, the liquid is continuously transferred to the riser, and the riser slug grows; therefore, P_{tl} increases relatively quickly. When

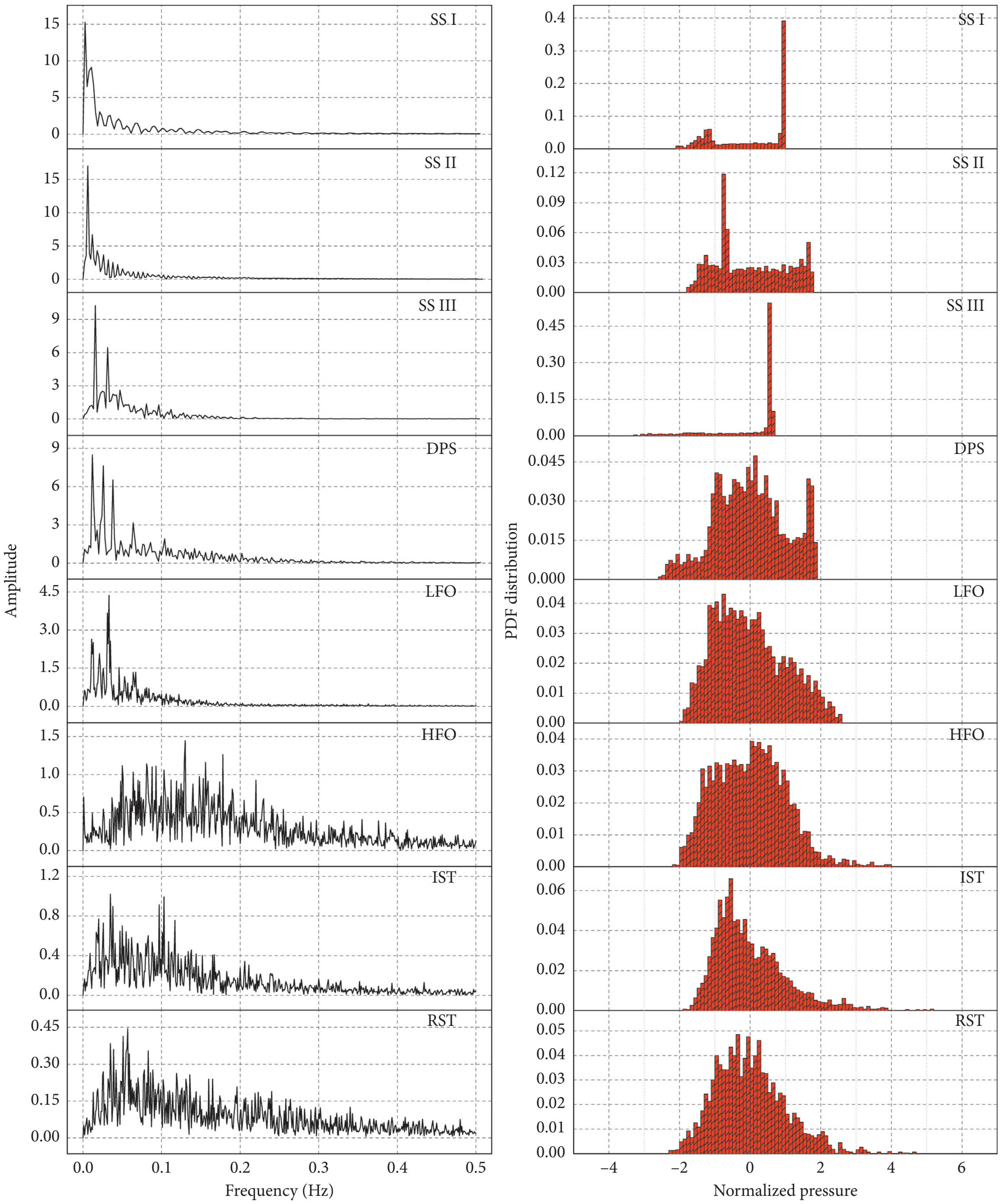

Figure 10: Frequency domain and probability density function characteristics of P_r for various flow patterns.

the riser is filled with liquid, P_{tl} no longer changes, while P_{tg} continues to increase because of gas accumulation. When $P_{tg} > P_{tl}$, the hilly-terrain slug tail is pushed forward until the gas passes through the bottom of the hilly-terrain pipe. At this time, upstream gas has insufficient energy and cannot cause a gas-liquid eruption in the hilly-terrain pipe. The gas can only be intermittently sent downstream in the form of bubble flow until the riser slug tail is pushed into the riser, thus causing a riser gas-liquid eruption. In this process, there is the slug production stage, which is SS I. When the inlet gas velocity becomes large, the P_{tl} increasing rate basically remains unchanged, but the P_{tg} increasing rate increases. When the gas enters the bottom of the hilly-terrain pipe, the speed of delivering the gas downstream is accelerated;

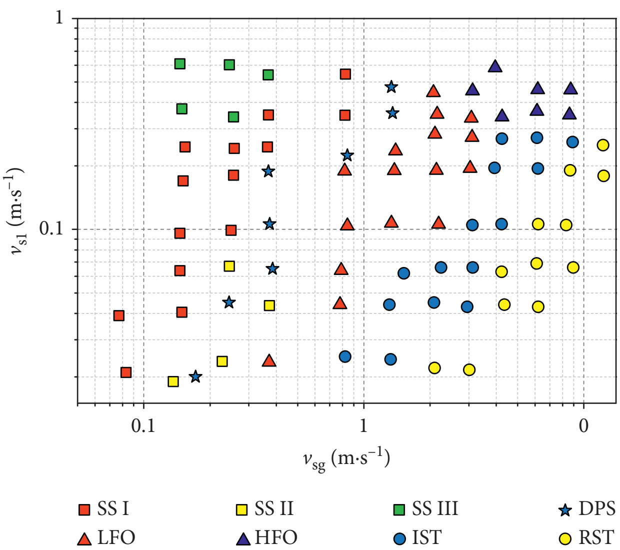

FIGURE 11: Gas-liquid flow pattern in a hilly-terrain pipeline-riser system (SS: severe slugging; DPS: dual-peak slug; LFO: low-frequency oscillation; HFO: high-frequency oscillation; IST: irregular-stable flow; and RST: regular-stable flow).

however, it still has the form of bubble flow. Therefore, the time for the gas to enter the riser is shortened, and the period of the slug production stage is shortened. When the slug production period becomes zero, it is SS II.

Unlike the horizontal-downward-riser system, in the hilly-terrain pipeline-riser system, when the inlet gas velocity increases, the maximum length of the riser slug will not gradually shorten, thereby causing gas-liquid eruption in advance. The reason is that the liquid accumulates at the bottom of the hilly-terrain pipe, which obstructs gas transportation. It is therefore necessary for the gas to first push the slug tail into the bottom of the hilly-terrain pipe. However, when the pressure V_h is insufficient to quickly advance the long liquid slug, the moment of the gas-liquid eruption in the riser is mainly affected by the length of the slug produced by the falling liquid in the hilly-terrain pipe. When the gas-liquid eruption in the riser is violent, there is little falling liquid, and the gas-liquid eruption is advanced in the next cycle, but it will be less severe. In the next cycle, a longer fallback slug will be generated, and the eruption time will be delayed. Therefore, two peaks can be observed in P_r fluctuations, i.e., DPS. Furthermore, as the gas velocity increases, the maximum pressure in the "small eruption" cycle gradually decreases.

As the inlet gas velocity increases, the obstruction of the liquid in the hilly-terrain pipe weakens, and the speed of the downstream gas delivery increases, thus causing gas-liquid eruption when the slug head grows to the middle of the riser. However, because of the inconsistent intensity of each eruption and the different amount of the falling liquid, the length of the maximum riser slug differs. Therefore, the pressure at the riser bottom fluctuates with different peaks, which is LFO. When the inlet gas velocity continues to increase, the power provided by the gas is higher, thus resulting in a weaker liquid blocking effect; therefore, the riser slug length decreases. Consequently, the pressure fluctuation amplitude decreases gradually, while the frequency increases, and the gas-liquid flow pattern changes to stable flow.

4.3. Influence of Hilly-Terrain Unit. This study used P_r to characterize the effect of the hilly-terrain pipe on the flow. The hilly-terrain pipe was replaced with a horizontal pipe with the same inner diameter. Under the same operating conditions, the fluctuation curves of P_r in the hilly-terrain pipeline-riser system and the horizontal-riser system are shown in Figure 12.

In Figure 12(a), severe slugging has occurred in both pipeline systems. However, because of the influence of the hilly-terrain pipe, the period of severe slugging is clearly prolonged, and the slug generated during the liquid fallback stage is longer, which indicates that the gas-liquid eruption is less severe. Figure 12(b) shows that when a hilly-terrain pipe is tested, the flow pattern is DPS, while it is oscillation flow for the horizontal-riser system. Figure 12(c) shows a larger liquid volume and a smaller pressure fluctuation in the hilly-terrain pipeline-riser system. In Figure 12(d), these two are similar.

The influence of hilly-terrain pipe on the gas-liquid flow can be summarized in the following: For a specific riser system that contains a hilly-terrain unit, there is a critical gas velocity for a certain liquid volume. When the gas velocity is lower than the critical gas velocity, liquid accumulates in the hilly-terrain pipe, which obstructs the gas, resulting in a slower gas transport downstream and a less severe eruption. When the critical gas velocity is exceeded, the gas can quickly push the liquid, thus making it difficult for the liquid to accumulate at the bottom of the hilly-terrain pipe. At this time, the hilly-terrain unit exerts less influence on the flow. When the inlet liquid velocity is large, part of the falling liquid accumulates in the hilly-terrain pipe, and therefore, the growth height of the riser slug is small. Consequently, the P_r fluctuation is reduced.

5. Numerical Simulation

OLGA is the industry standard tool for transient simulation of multiphase petroleum production. OLGA is used for networks of wells, flowlines and pipelines, and process equipment [18], covering the production system from bottom hole into the production system [19, 20]. OLGA comes with a steady-state preprocessor included which is intended for calculating initial values to the transient simulations, but which also is useful for traditional steady-state parameter variations. However, the transient capabilities of OLGA dramatically increase the range of applicability compared with steady-state simulators. In the software OLGA 7.0, the same geometric model as in the laboratory is established, and the same working conditions are input to simulate the gas-liquid flow. A comparison of P_r fluctuation curves between these two is shown in Figure 13.

The flow patterns shown in Figures 13(a)–13(c) indicate severe slugging. In general, the amplitude and change trend

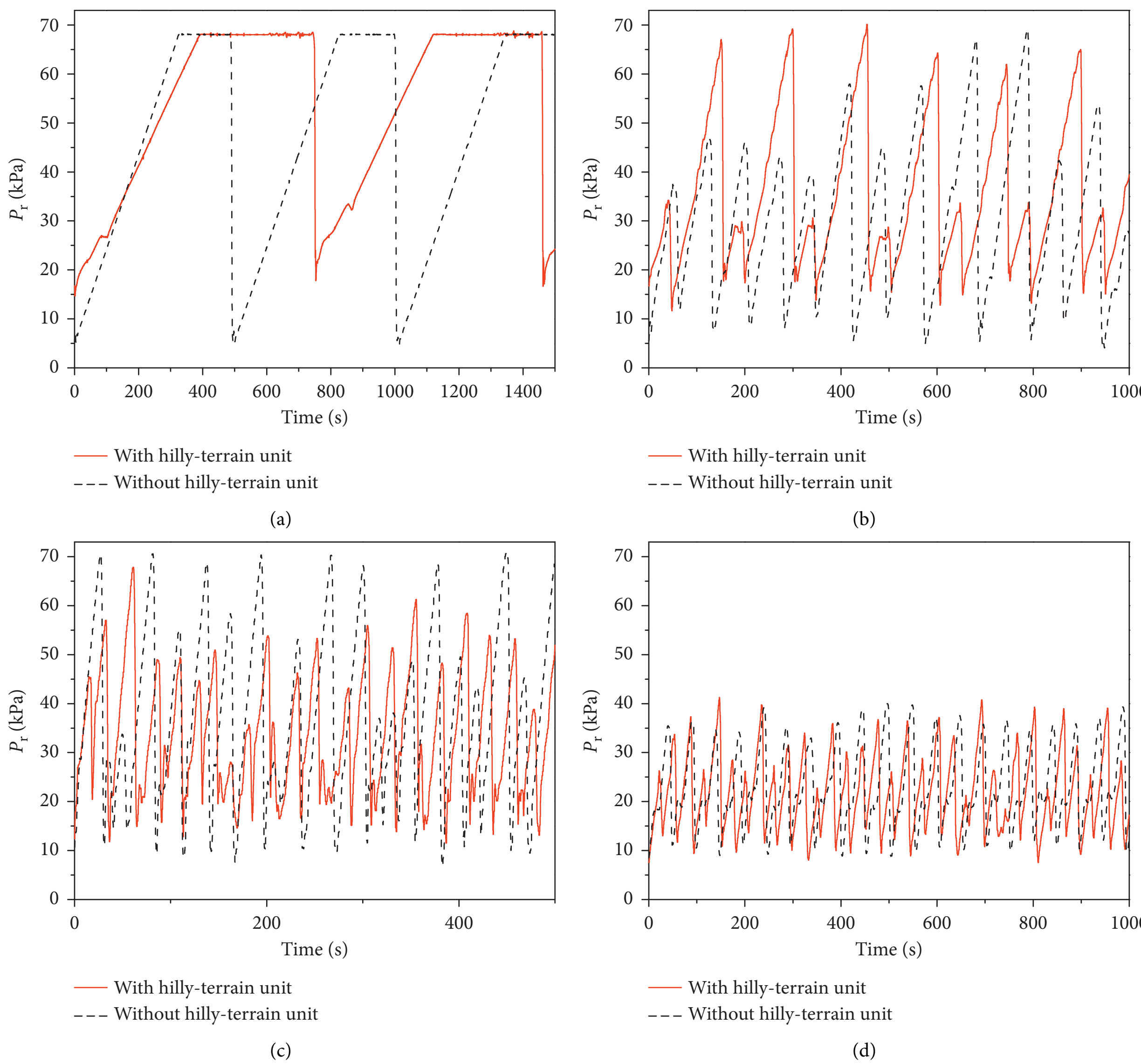

Figure 12: Comparison of P_r in pipeline systems with or without hilly-terrain unit. (a) $v_{sl} = 0.039$ m/s, $v_{sg} = 0.077$ m/s. (b) $v_{sl} = 0.065$ m/s, $v_{sg} = 0.371$ m/s. (c) $v_{sl} = 0.239$ m/s, $v_{sg} = 1.356$ m/s. (d) $v_{sl} = 0.064$ m/s, $v_{sg} = 0.789$ m/s.

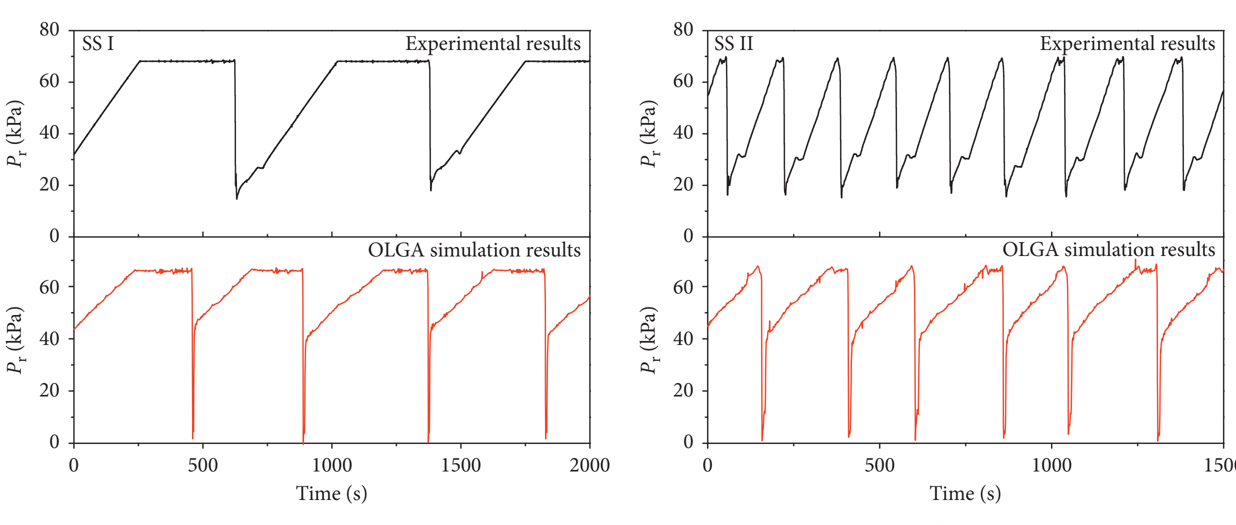

Figure 13: Continued.

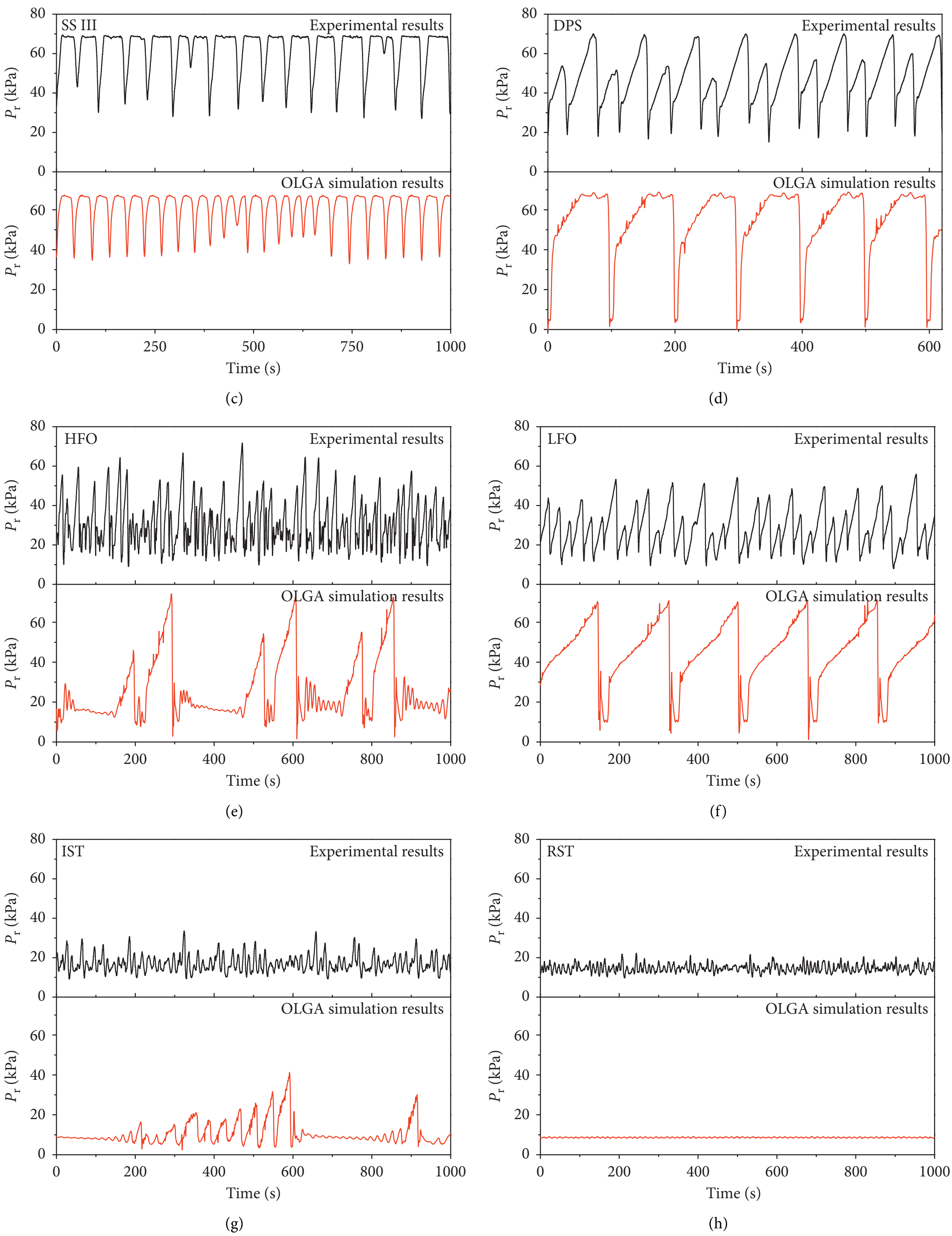

FIGURE 13: Comparison of OLGA simulation results and experimental results. (a) $v_{sl} = 0.039$ m/s, $v_{sg} = 0.077$ m/s. (b) $v_{sl} = 0.067$ m/s, $v_{sg} = 0.245$ m/s. (c) $v_{sl} = 0.6095$ m/s, $v_{sg} = 0.146$ m/s. (d) $v_{sl} = 0.188$ m/s, $v_{sg} = 0.369$ m/s. (e) $v_{sl} = 0.352$ m/s, $v_{sg} = 2.154$ m/s. (f) $v_{sl} = 0.104$ m/s, $v_{sg} = 0.843$ m/s. (g) $v_{sl} = 0.105$ m/s, $v_{sg} = 3.113$ m/s. (h) $v_{sl} = 0.106$ m/s, $v_{sg} = 6.184$ m/s.

of P_r between the two are basically the same. The OLGA simulation results are consistent with the characteristics of severe slugging. Specifically, in the OLGA simulation results, severe slugging has poor periodicity, and the calculation of the period length is inaccurate. The prediction results for SS I and SS III flow patterns are too small, while the calculation results for SS II are too large. This indicates that the calculation result of OLGA is not as sensitive to the change of gas velocity as the experiment. In addition, in SS I and SS III flow patterns, the minimum pressure of the simulation is close to zero, indicating that there is a time when the riser slug length is zero. In this experiment, because of the influence of hilly-terrain pipe, the gas-liquid eruption is not severe, and there is always a liquid slug in the riser; therefore, the pressure fluctuation calculated by OLGA is larger.

Figure 13(d) shows the DPS, which is a special flow pattern because of the influence of the hilly-terrain pipe; however, OLGA cannot calculate and identify this pattern. In OLGA, the flow pattern when $v_{sl} = 0.188\,\mathrm{m/s}$ and $v_{sg} = 0.369\,\mathrm{m/s}$ is SS I. OLGA also results in deviations in the calculation of oscillation flow (Figures 13(e) and 13(f)). The pressure fluctuation amplitude and change trend differ from the experimental results. This is also because of the insensitivity of the OLGA calculation results to changes in gas velocity.

The OLGA calculation of stable flow is relatively accurate. In Figure 13(g), the pressure change trend indicates a large eruption after a few cycles of stable flow. The difference is that the period calculated by OLGA is longer and the pressure fluctuation range is larger. In Figure 13(h), OLGA accurately predicts the pressure fluctuation trend for regular-stable flow, but the pressure value is slightly lower.

6. Conclusion

This study investigated gas-liquid flow in a hilly-terrain pipeline-riser system. Using experimental observation and pressure detection, the flow pattern is scientifically and comprehensively divided. Four types of flow patterns were identified in this study: severe slugging (of type I, type II, and type III), DPS, oscillation flow (LFO and HFO), and stable flow (IST and RST). Among these, DPS is a special flow pattern caused by the hilly-terrain pipe and is composed of alternating periods of "large eruptions" and "small eruptions." In this paper, the division of flow patterns is more comprehensive and reasonable, which helps to deepen the understanding of gas-liquid flow in pipeline-riser systems.

The hilly-terrain unit was included in the pipeline-riser system studied in this paper. This study showed that the hilly-terrain pipe obstructs the transportation of gas downstream, which results in a slower gas accumulation rate. Therefore, the gas-liquid eruption in the riser is weakened and the period of severe slug flow increases. However, for a particular hilly-terrain pipe, a critical gas velocity exists. When the inlet gas velocity exceeds this value, the influence of the hilly-terrain pipe can be ignored.

No obvious boundary exists between flow patterns, and the change of the flow state is a slow process. In this study, gas was regarded as the driving force of the observed gas-liquid flow, and the accumulation of liquid in low-lying places is regarded as an obstacle. By analyzing the occurrence time of gas-liquid eruptions, the mechanism underlying the flow pattern transition in the hilly-terrain pipeline-riser system is described.

Furthermore, the accuracy of OLGA's simulation of gas-liquid flow in the hilly-terrain pipeline-riser system was investigated. By comparing the pressure fluctuation curves at the bottom of the riser, OLGA was found to be more accurate in calculating both severe slugging and stable flow and can predict the pressure trend and change characteristics. However, the calculation accuracy of OLGA for DPS and oscillation flow is poor, and the sensitivity to gas changes is insufficient.

Slug dissipation and generation behaviors will be infected by the inclination angle of hilly-terrain section. So, the effect of different styles of pipe section on the two-phase flow behaviors can be studied in the future.

Data Availability

All data, models, and code generated or used during the study are included within the article.

Additional Points

Highlights. The gas-liquid flow pattern was classified more scientifically and comprehensively. A new flow pattern was identified: dual-peak slug flow. Hilly-terrain pipelines are included in the studied riser system, and their influence on flow is discussed. The simulation accuracy of OLGA 7.0 on gas-liquid flow in the hilly-terrain pipeline-riser system was evaluated.

Conflicts of Interest

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

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Research Article

The Impact Mechanism and Scenario Simulation of Energy Internet on Transition

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We analyse the direction of the energy revolution from the dimensions of cleanness, electrification, intelligence, and ubiquity. Based on this, we highlight the importance of electricity in the Energy Internet and analyse the challenges faced by the development of the power grid. Then, we propose an electricity-centered energy comprehensive optimization model and set up baseline scenario and carbon neutral scenario, to achieve a systematic simulation of the path of Energy Internet to boost energy transition. The results show that the Energy Internet accelerates the process of clean energy supply, effectively promotes the development of the energy transition, and contributes to the realization of the carbon neutral goal. There are still many problems in the development of the Energy Internet. In order to accelerate the transformation of the energy system and the power industry, it is necessary to establish a sound energy policy system, encourage clean energy consumption, and use the construction of the Energy Internet to achieve optimal allocation of resources.

1. Introduction

Energy is an important productivity foundation that supports economic growth and social development, and rapid economic growth is often accompanied by serious problems, such as environmental pollution [1] and resource shortages [2]. Since the twenty-first century, people's requirements for the environment have increased [3] and, a new round of energy revolution marked by the large-scale development and utilization of new energy has been launched worldwide [4]. This round of energy revolution has four directions. The first direction is clean, that is, the increase in the proportion of nonfossil energy in primary energy consumption, the development trend of low-carbon energy instead of high-carbon energy, and zero-carbon energy instead of low-carbon energy. The second is to realize electrification, which means that clean energy generation gradually replaces fossil energy power generation, the proportion of electric energy in terminal energy consumption has increased, and the use of electricity is extended. The third is intelligence, which means to realize the application of a series of advanced technologies such as digital technology and control technology in energy and power systems. The fourth is ubiquity, which means a wide range of optimizing resource allocation and multienergy cosupply, making the scope of electric energy allocation more extensive. In this process, with the application of new technologies and the development of new business and new formats, the trend of network interconnection and mutual benefit among energy subsystems such as electricity, heating, cooling, oil, natural gas, transportation, and so on is increasingly prominent. The concept of "Energy Internet" gradually emerged.

Since 2010, Energy Internet has gradually changed from concept to practical action. In 2011, Jeremy Rifkin, an American science and technology writer, published "The Third Industrial Revolution" [5]. Later, he published the monograph "The Zero Marginal Cost Society" [6], which described the Energy Internet system in which everyone can become an "Energy Prosumers," which has attracted widespread attention and research on the Energy Internet and has begun to heat up. In 2015, at the United Nations

Development Summit, Chinese President Xi Jinping proposed to build a global Energy Internet and promoted the "China Initiative" to meet global electricity demand in a clean and green way, which received a positive response from the international community. In 2018, the State Grid Corporation of China took the lead in the world to put forward the corporate strategic goal of building an Energy Internet company and carried out a series of active explorations such as source-network-load-storage collaborative interaction, smart energy services (new energy cloud), construction and operation of "SGCC Online," the application of new energy big data in the development of industrial chain, intelligent Internet of vehicles platform, and so on. The construction of China's Energy Internet has thus entered a stage of rapid development.

In 2020, China put forward the vision of "carbon neutrality and carbon peak" at the 75th United Nations General Assembly, in which carbon dioxide emissions strive to reach the peak before 2030 and achieve carbon neutrality by 2060, and further clarified that the specific targets for 2030 have been set to inject strong impetus into the transition to clean and low-carbon energy. Accelerating the upgrade of the power grid to the Energy Internet is an important direction for China's energy transition to achieve carbon neutrality. On the one hand, the Energy Internet can effectively meet the needs of large-scale grid connection of new energy sources and realize the interconnection, efficient configuration, and comprehensive utilization of various energy sources such as electricity, gas, cold, heat, and hydrogen. On the other hand, it can realize source network load, and the coordination and interaction of storage and storage can effectively support the "plug and play" of various new energy-using facilities. At the same time, it can give birth to new energy business, and new business models and new models facilitate the development of green industries such as energy efficiency services, platform businesses, and the digital economy and promote the entire energy industry system upgrade and evolution. There are three main challenges in upgrading the power grid to the Energy Internet. The first is the challenge of balancing power supply and demand. Wind power and solar power have obvious characteristics of intermittency, volatility, randomness, and antipeak regulation. After large-scale and high-proportion access to the power system, it poses a challenge to the balance adjustment capability of the grid. The second challenge is to keep the system safe and stable. The "weak moment of inertia" of wind power and the "zero moment of inertia" of photovoltaics have led to a significant reduction in the equivalent moment of inertia of the power system and a decline in antidisturbance capability. Distributed energy, electric vehicles, and other "prosumers and consumers" are connected on a large scale, and the system operation characteristics have changed from a one-way flow mode of power flow from the grid to users to two-way interaction, and the complexity of system control has increased significantly. The third is to meet the challenge of upgrading service demand. With the advancement of energy technology and the penetration of Internet technology, user-side needs have become increasingly diversified, personalized, and interactive, which has brought a huge test to the service capability of the power grid. The design standards and operation modes of traditional power grids (mainly distribution networks) cannot meet the above requirements well.

We analyse the challenges faced in the transition from the power grid to the Energy Internet, build an electricity-centered energy comprehensive optimization model, conduct a simulation analysis of the Energy Internet boosting the energy transition, and propose relevant countermeasures and suggestions. The innovation of paper is to electricity-centered energy comprehensive optimization model and conduct a comparative analysis. Not only can it highlight the role of the Energy Internet in the energy transition but it can also identify current challenges and take corresponding measures. This paper is of great significance for exploring the role of the Energy Internet in the energy transition, discovering deficiencies and making corresponding recommendations.

The rest of the paper is organized as follows. Section 2 briefly reviews the related literature on the concept, technology, and application of the Energy Internet. The electricity-centered energy comprehensive optimization model is created in Section 3. In Section 4, on the basis of the model, we carry out the simulation analysis of the Energy Internet boosting the energy transition. Finally, conclusions and suggestions are presented in Section 5; meanwhile, we look forward to the future research content.

2. Literature Review

Energy Internet is the product of the integration of energy and Internet, representing the new productivity of the energy system, and has become the focus of attention of domestic and foreign scholars. Jeremy Rifkin believed that characterized by the deep integration of new energy technology and information technology, a new energy utilization system is about to appear, which can be named Energy Internet. Energy Internet is a distributed, open, and shared network based on renewable energy [5, 6]. The "Guidelines on promoting the development of Internet Plus Smart Energy" proposed by China's National Development and Reform Commission, National Energy Administration, and Ministry of Industry and Information Technology believe that Internet Plus Smart Energy (Energy Internet) is a new form of energy industry development that deeply integrates the Internet and energy production, transmission, storage, consumption, and energy markets. It has the main characteristics of intellectualization of equipment, multifunctional collaboration, information symmetry, decentralized supply and demand, flat system, open transaction, and so on. Global Energy Interconnection Development and Cooperation Organization believes that the Global Energy Internet is based on the UHV power grid as the backbone (channel) and is dominated by the transmission of clean energy, which is a strong smart grid with global interconnection and ubiquity [7]. Zhou Xiaoxin considered that Energy Internet is a networked physical system that directly or indirectly connects the production, transmission, storage, and conversion devices of various primary and secondary energy sources, as well as their information communication control and protection devices [8]. State Grid Corporation of China believes that Energy Internet is centered on electricity, based on a strong smart grid, and deeply integrates advanced information and communication technology, control technology, and advanced energy technology to support clean and low-carbon transformation of energy and power, optimize comprehensive energy utilization efficiency, and connect multiple subjects flexibly and conveniently. Energy Internet is a smart energy system with clean, low-carbon, safe and reliable, ubiquitously interconnected, efficiently interactive, and intelligent open feature.

There are four main categories of Energy Internet concepts. The first type emphasizes the expression of the structure of the Energy Internet. This recognition is based on the power grid and uses the Internet to form a new energy network characterized by backbone networks, local area networks, and related connected networks [9, 10]. The second category focuses on the expression of the information Internet, which is the transformation of the existing energy system by the Internet thinking. It is manifested in the free transmission of energy by the open interconnection of multiple energy sources and open peer access [11]. The third type emphasizes the deep combination of Internet technology and energy network to realize the two-way communication between energy and information [12]. The last category emphasizes the combined transmission and optimized use of electricity, heat, and chemical energy. The Internet uses key technologies such as advanced energy storage technology, new energy generation technology, and power electronic technology to realize the close integration of energy networks such as power grids, gas grids, heating power grids, and transportation networks [13–17]. Throughout the many concepts of the Energy Internet, the cores are interlinked, such as source-network-load-storage balance, wide application of digital technology, information communication technology, and control technology, user-side participation, co-construction, sharing, open interconnection, and so on. This fully shows that the Energy Internet is actually the result of the superposition of energy technology, digital technology, and Internet thinking.

With the in-depth study of Energy Internet, the application of relevant technologies has also become a research focus. Multiple technologies such as distributed generation, Internet technology, energy storage technology, and intelligent technology have been widely used in practical work [14, 17, 18]. Zhang Xiaoping and others believed that the key factors for the smart grid to switch to the Energy Internet are the development of virtual power plants and demand response technologies and put forward the concept of virtual power systems based on the global power Energy Internet and distribution power energy Internet and compared and analysed virtual power similarities and differences between the system and the virtual power plant [19]. Zha Yabing and others summarized and analysed the 6 key technologies of the Energy Internet: advanced energy storage technology, electronic power transformer technology, intelligent energy management technology, intelligent fault management technology, reliable and secure communication technology, and system planning analysis technology. Related theories have been meaningfully discussed [17]. Yang Fang and others discussed the basic concept of the Energy Internet from the perspective of energy system value and believed that the rapid development of information systems is triggering changes in the way energy system values are created [20]. Based on the analysis of the research status of Energy Internet-related projects at home and abroad, Tian Shiming and others summarized the technical connotation, technical characteristics, technical elements, and technical forms of the Energy Internet and proposed key research technologies for the Energy Internet [14].

In summary, although there have been abundant research contents on Energy Internet, most of them focus on the conceptual framework and technical application of the Energy Internet and less on the impact of Energy Internet on the energy transition. The continuous growth of energy demand has caused the world to face many energy-related challenges, including energy sustainability and global warming. These challenges promote the development and utilization of renewable energy [21]. New energy has advantages, such as being found in large reserves and being clean and renewable, and vigorously developing the new energy industry is an important measure to promote energy transition [22]. Although the promotion of the development and utilization of renewable energy is a common trend in the energy policies of various countries and regions [23], the Energy Internet is based on the future energy system. Under the influence of the multiple goals of the energy development strategy [24–27], the realistic constraints such as cost, risk, resource constraints [28], and the uncertainty [29, 30], the impact of the Energy Internet is different. Therefore, we propose an electricity-centered energy comprehensive optimization model to simulate and analyse the Energy Internet to promote the energy transition and explore the impact of the Energy Internet on the energy transition.

3. Electricity-Centered Energy Comprehensive Optimization Model

Energy Internet covers multiple energy resource systems such as coal, oil, natural gas, electricity, and heat. We build an electricity-centered energy comprehensive optimization model to realize the coordination and complementation of multiple energy sources in energy development, transmission, conversion, and comprehensive utilization so as to optimize the energy structure and promote the clean and low-carbon transformation of the energy system. We decompose the problem of comprehensive energy allocation optimization into two modules, which are energy system planning and power system planning. The two modules are gradually refined from top to bottom. The overall framework of the model is shown in Figure 1.

The energy system planning module can simulate the whole process of various energy supply, processing, conversion, and terminal utilization. Among them, the energy supply segment covers coal, oil, natural gas, power, and other industries, while the terminal energy utilization segment covers transportation, business, and other subdivided

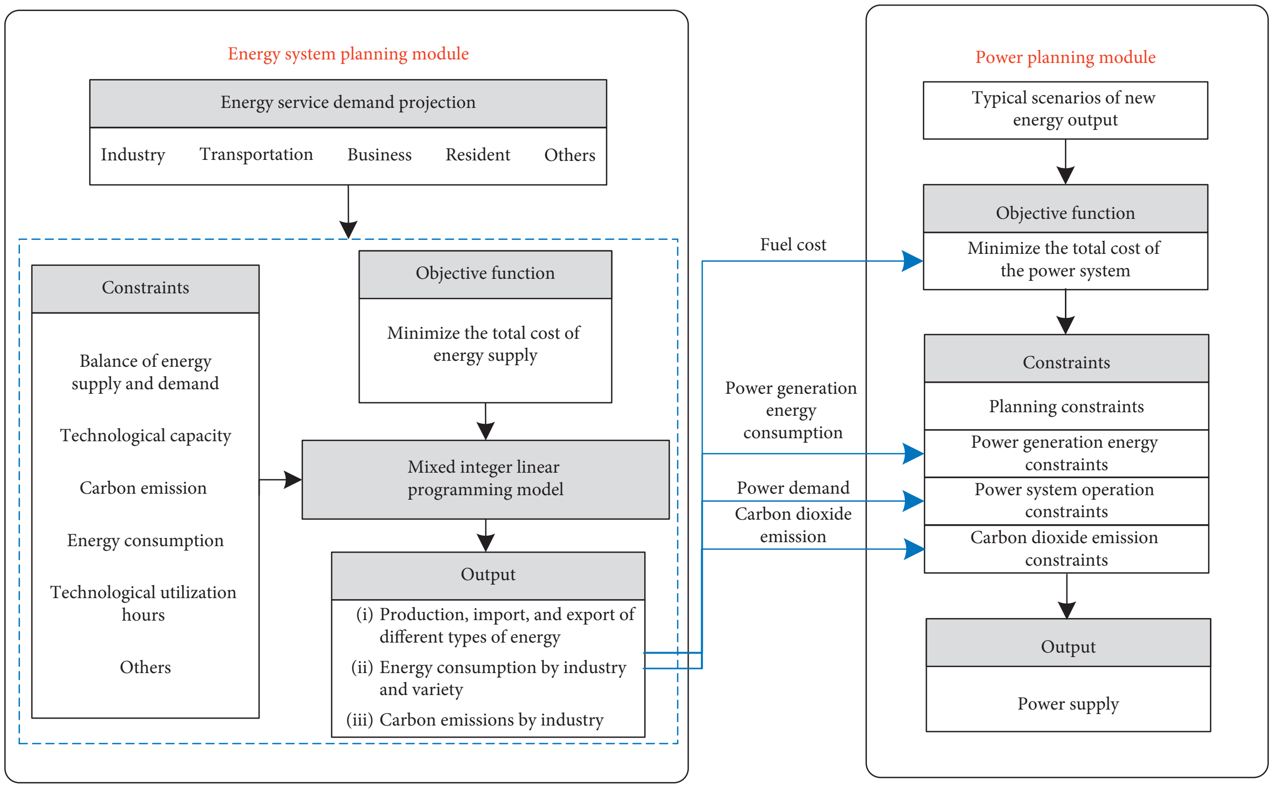

Figure 1: Framework of the electricity-centered energy comprehensive optimization model.

industries [31]. Firstly, the energy service demand of various industries can be forecasted by regression analysis, trend extrapolation model, and other methods. The influence factors are economic development, industrial structure, urbanization rate, population, and so on. Based on that the terminal energy demand is obtained by optimizing the terminal energy consumption technology. Then, with the goal of minimizing the total cost of energy supply, considering the national carbon emission target, the development potential of various nonfossil energy sources, and the economics of various energy technologies, various energy resources are optimally allocated to provide boundary conditions of power generation energy consumption, carbon dioxide emissions, and power demand for the power planning module.

The power planning module describes the volatility of large-scale new energy generation in detail through multiple typical scenarios. Under the constraints of the total carbon dioxide emissions of the power system, power generation energy consumption, and system operation, the power supply situation of different future years is optimized to promote the transformation and upgrading of the power grid to the Energy Internet.

3.1. Energy System Planning Module. The optimization goal of energy system planning is to select the technology combination scheme with the minimum total cost of energy supply while meeting the terminal energy demand and various constraints [32, 33]. We have the following objective function:

$$\mathrm{Min} \sum_{t=1}^{T} \frac{\mathrm{ANNCOST}(t) - \mathrm{ANNBENIFIT}(t)}{(1+r)^{t-1}}, \qquad (1)$$

where t represents the index of the year, T is the planning horizon, and r is the discount rate. ANNCOST (t) represents cost of the energy system in year t, including investment cost, operation and maintenance cost, emission cost, and fuel cost of various industries. ANNBENIFIT (t) is the income of the energy system in year t, including equipment residual value.

Energy system planning mainly considers constraints such as balance of energy supply and demand, technological capacity, carbon emission, energy consumption, and technological utilization hours.

3.1.1. Constraint on the Balance of Energy Supply and Demand. In a given year, the local production of coal, oil, natural gas, and other types of energy products plus foreign imports should be balanced by consumption, exports, and changes in inventories.

$$\begin{aligned}\mathrm{Ire}_{t,c,\mathrm{imp}} + \sum_{m\in m(c,\mathrm{out})} \mathrm{Flow}_{t,m,c} - \sum_{m\in m(c,\mathrm{in})} \mathrm{Flow}_{t,m,c} \\ - \mathrm{Ire}_{t,c,\,\mathrm{exp}} - \mathrm{Tra}_{t,c,\mathrm{res}} = 0.\end{aligned} \qquad (2)$$

In formula (2), $m(c,\mathrm{out})$ and $m(c,\mathrm{in})$ represent the technology set with output and input of energy product c, $\mathrm{Flow}_{t,m,c}$ is the input or output of energy product c from technology m in the year t, $\mathrm{Ire}_{t,c,\,\mathrm{exp}}$ and $\mathrm{Ire}_{t,c,\mathrm{imp}}$ represent the export and import volume of energy product c in the year

t, respectively, and $\mathrm{Tra}_{t,c,\mathrm{res}}$ is the inventory change of energy product c in the year t. For electricity and heat, the annual inventory change is set to 0.

3.1.2. Technical Capacity Constraint. Various energy extraction, processing, conversion, and terminal utilization technologies need to meet the following formula:

$$\mathrm{Cap}_{t,m}^{G} = \mathrm{Cap}_{t-1,m}^{G} + \mathrm{Cap}_{t,m}^{NG} - \mathrm{Cap}_{t,m}^{OG}. \quad (3)$$

In formula (3), $\mathrm{Cap}_{t,m}^{G}$ is the cumulative installed capacity of technology m in the year t, $\mathrm{Cap}_{t,m}^{NG}$ represents the newly installed capacity of technology m in the year t, and $\mathrm{Cap}_{t,m}^{OG}$ is the decommissioning capacity of technology m in year t.

For a given technology, such as new energy generation and CCUS (carbon capture, utilization, and storage) technology, the following constraint is introduced to guide the development level:

$$\mathrm{Cap}_{t,m}^{G} \geq \mathrm{Cap}_{t,\mathrm{target}}^{G}, \quad (4)$$

where $\mathrm{Cap}_{t,\mathrm{target}}^{G}$ represents the development goal of capacity of technology m in year t.

3.1.3. Carbon Dioxide Emission Constraint. According to the China's proposed carbon dioxide emissions to peak by 2030 and achieve carbon neutrality by 2060, the constraint of country's medium- and long-term carbon dioxide emission levels is defined and the country's carbon dioxide emission constraint is decomposed into subsectors to obtain the upper limit of carbon dioxide emissions for each industry.

$$\mathrm{EM}_{t,ps} + \sum_{x\in Nps} \mathrm{EM}_{t,x} \leq \mathrm{EM}_{t,\max}. \quad (5)$$

In formula (5), $\mathrm{EM}_{t,\mathrm{ps}}$ represents the carbon dioxide emissions of the power system in the year t, Nps represents a collection of nonpower industries such as industry, commerce, transportation, and residents, $\mathrm{EM}_{t,x}$ represents the carbon dioxide emissions of industry x in the year t, and $\mathrm{EM}_{t,\max}$ represents the national carbon dioxide emission limit in the year t.

3.1.4. Energy Consumption Constraint. According to the national energy consumption control policy constraints, the total energy consumption of subsectors is limited.

$$\mathrm{EC}_{t,ps,c} + \sum_{x\in Nps} \mathrm{EC}_{t,x,c} \leq \mathrm{EC}_{t,c,\max}, \quad (6)$$

where $\mathrm{EC}_{t,ps,c}$ represents the consumption of energy product c in the power system in year t, $\mathrm{EC}_{t,x,c}$ is the consumption of energy product c in industry x in year t, and $\mathrm{EC}_{t,c,\max}$ is the upper limit of consumption of energy product c in the year t.

3.1.5. Technological Utilization Hours Constraint. In order to ensure the technical economy, the restriction of utilization hours is introduced.

$$\begin{aligned}\mathrm{Act}_{t,m} &\geq \frac{U_{t,m}}{8760}\cdot \mathrm{Cap}_{t,m}^{G}\cdot \mathrm{CAPACT}_{m},\\ \mathrm{Act}_{t,m} &= A_{t,m}\cdot \mathrm{Cap}_{t,m}^{G}\cdot \mathrm{CAPACT}_{m},\end{aligned} \quad (7)$$

where $\mathrm{Act}_{t,m}$ represents the activity level of technology m in year t, $A_{t,m}$ represents the average availability of technology m in year t, $U_{t,m}$ represents the minimum utilization hour of technology m in year t, and CAPACT_m represents the conversion coefficient between the capacity and activity level of technology m.

3.2. Power Planning Module. The power planning module is based on the results of the energy system planning, taking into account the various constraints of the power system planning and operation stage for the refined model. In order to take into account the volatility of large-scale new energy output and the seasonal differences between regions, give full play to the complementary characteristics of various power sources across time and space. Based on the historical data of new energy output in various regions, we use a clustering algorithm [34] to obtain typical new energy generation scenarios in each region and use production simulation to characterize power system operating characteristics in different scenarios, with the goal of minimizing system power supply costs.

The power planning optimization goal is as follows:

$$\mathrm{Min} \sum_{t=1}^{T} \frac{C_{\mathrm{inv},t} + C_{\mathrm{oper},t}}{(1+r)^{t-1}}. \quad (8)$$

In formula (8), $C_{\mathrm{inv},t}$ represents the investment cost of the power system in year t and $C_{\mathrm{oper},t}$ represents the operating cost of the power system in year t.

(1) Power system investment cost is as follows:

$$C_{\mathrm{inv},t} = \sum_{z=1}^{Z} \sum_{p\in\Omega} c_{z,t,p}^{\mathrm{inv}} X_{z,t,p}^{\mathrm{inv}} + \sum_{l\in L_t} C_{t,l}^{\mathrm{inv}L}. \quad (9)$$

In formula (9), the subscript z represents the region, Z is the total number of regions divided by the system, p is the power supply type, including hydropower, thermal power, and wind power, Ω represents the power supply type set, $X_{z,t,p}^{\mathrm{inv}}$ indicates the new installed capacity of power p at the region z in year t, $c_{z,t,p}^{\mathrm{inv}}$ represents the investment cost per unit capacity of power supply p, L_t represents the set of cross-region transmission channels in year t, and $C_{t,l}^{\mathrm{invL}}$ represents the new investment cost of cross-region transmission channel l in year t.

(2) System operating cost is as follows:

$$C_{\mathrm{oper},t} = \sum_{z=1}^{Z} \left(\mathrm{CM}_{z,t} + \mathrm{CF}_{z,t} + \mathrm{CR}_{z,t} + \mathrm{CC}_{z,t}\right). \quad (10)$$

In formula (10), $\mathrm{CM}_{z,t}$, $\mathrm{CF}_{z,t}$, $\mathrm{CR}_{z,t}$, and $\mathrm{CC}_{z,t}$, respectively, represent the fixed operating cost, varying operating cost, risk cost, and carbon emission cost at the region z in year t.

The fixed operating cost of the system is expressed as follows [35]:

$$\mathrm{CM}_{z,t} = \sum_{p\in\Omega} c_{z,t,p}^{\mathrm{fixed}} X_{z,t,p} + \sum_{l\in L_t} c_{l,t}^{\mathrm{fixed}L} D_l^L X_{l,t}^L. \quad (11)$$

In formula (11), $c_{z,t,p}^{\mathrm{fixed}}$ is the fixed operating cost per unit capacity of power p at the region z in year t, $c_{l,t}^{\mathrm{fixedL}}$ represents the fixed operating cost of channel l in year t, $X_{z,t,p}$ indicates the cumulative installed capacity of power p at the region z in year t, $X_{l,t}^L$ represents the cumulative capacity of transmission channel l in year t, and D_l^L is the length of the cross-region transmission channel l.

System varying operating cost is expressed as follows:

$$\mathrm{CF}_{z,t} = \sum_{p\in\Omega} X_{z,t,p} H_{z,t,p} \lambda_{z,t,p} f_{z,t,p},$$

$$H_{z,t,p} = \frac{d_t \sum_{s\in S} \pi_{z,t,s} \sum_{n=1}^{N} p_{z,t,p,s,n}}{X_{z,t,p}}, \quad (12)$$

$$\sum_{s\in S} \pi_{z,t,s} = 1.$$

In formula (12), $H_{z,t,p}$ represents the utilization hours of power p at the region z in year t, d_t represents the number of days in year t, the subscripts s and n represent the new energy generation output scenario and time period, respectively, S is the new energy output scenario set, N represents the number of time periods included in each scenario, $\pi_{z,t,s}$ indicates the probability of occurrence of scenario s at the region z in year t, $p_{z,t,p,s,n}$ is the output of power supply p of scenario s and period n at the region z in year t, $\lambda_{z,t,p}$ is the fuel consumption per kilowatt hour of power supply p at the region z in year t, and $f_{z,t,p}$ represents the unit cost of fuel p at the region z in year t. Considering the impact of local production and cross-region transportation, the average fuel cost is estimated as follows:

$$f_{z,t,p} = \frac{f_{z,t,p,\mathrm{pro}} F_{z,t,p}^{\mathrm{pro}} + f_{z,t,p,\mathrm{in}} F_{z,t,p}^{\mathrm{in}} + f_{z,t,p,\mathrm{imp}} F_{z,t,p}^{\mathrm{imp}}}{F_{z,t,p}^{\mathrm{pro}} + F_{z,t,p}^{\mathrm{in}} + F_{z,t,p}^{\mathrm{imp}}}. \quad (13)$$

In formula (3), $F_{z,t,p}^{\mathrm{pro}}$, $F_{z,t,p}^{\mathrm{in}}$, and $F_{z,t,p}^{\mathrm{imp}}$, respectively, represent the volume of local production, domestic transferred in, and foreign import of fuel p at the region z in year t; $f_{z,t,p,\mathrm{pro}}$, $f_{z,t,p,\mathrm{in}}$, and $f_{z,t,p,\mathrm{imp}}$, respectively, represent the unit production cost, domestic transfer unit cost, and foreign import unit cost of fuel p at the region z in year t.

System risk cost is expressed as follows:

$$\mathrm{CR}_{z,t} = c_{z,t}^{w} R_{z,t}^{w}, \quad (14)$$

where $c_{z,t}^{w}$ represents the penalty cost coefficient of wind and solar power curtailment at the region z in year t and $R_{z,t}^{w}$ is the amount of wind and solar power curtailment at the region z in year t.

The system carbon emission cost is expressed as follows:

$$\mathrm{CC}_{z,t} = \sum_{p\in\Omega} c_{z,t,p}^{\mathrm{carbon}} X_{z,t,p} H_{z,t,p}, \quad (15)$$

where $c_{z,t,p}^{\mathrm{carbon}}$ represents the cost of carbon emission per kilowatt hour of power supply p at the region z in year t.

We mainly consider planning constraint, power generation energy consumption constraints, system operation constraints, and carbon emission constraint in the power system planning.

3.2.1. Planning Constraint. In the planning horizon, the energy resource endowment of each region will constrain the upper limit of the installed capacity of power supply, which can be expressed as follows:

$$X_{z,t,p} \le X_{z,p}^{\max}. \quad (16)$$

In formula (16), $X_{z,p}^{\max}$ represents the upper limit of the installed capacity of power supply p at the region z.

3.2.2. Power Generation Energy Consumption Constraints

(1) Constraint on fossil energy consumption is as follows:

In order to meet the national total energy consumption constraint, the total energy consumption for power generation such as coal and natural gas shall not exceed the upper limit obtained according to the energy system planning module:

$$\sum_{z=1}^{Z} X_{z,t,p} H_{z,t,p} \lambda_{z,t,p} \le \mathrm{EC}_{t,ps,p}^{*}. \quad (17)$$

In formula (17), $\mathrm{EC}_{t,ps,p}^{*}$ represents the upper limit of fuel p in year t.

(2) Power generation energy balance constraint is as follows [36]:

$$X_{z,t,p} H_{z,t,p} \lambda_{z,t,p} \le F_{z,t,p}^{\mathrm{pro}} + F_{z,t,p}^{\mathrm{in}} - F_{z,t,p}^{\mathrm{out}} + F_{z,t,p}^{\mathrm{imp}} - F_{z,t,p}^{\mathrm{exp}} + F_{z,t,p}^{\mathrm{res}} - F_{z,t,p}^{\mathrm{Nps}}. \quad (18)$$

In formula (18), $F_{z,t,p}^{\mathrm{out}}$, $F_{z,t,p}^{\mathrm{exp}}$, and $F_{z,t,p}^{\mathrm{Nps}}$, respectively, represent the domestic transferred out volume, export volume, and nonpower industry consumption of fuel p at the region z in year t and $F_{z,t,p}^{\mathrm{res}}$ represents the initial inventory of fuel p at the region z in year t.

The import and export volume of fuel in each region should satisfy the following formula:

$$\sum_{z=1}^{Z} F_{z,t,p}^{\mathrm{imp}} = \mathrm{Ire}_{t,p,\mathrm{imp}}^{*},$$
$$\sum_{z=1}^{Z} F_{z,t,p}^{\mathrm{exp}} = \mathrm{Ire}_{t,p,\mathrm{exp}}^{*}. \quad (19)$$

In formula (19), $\mathrm{Ire}^{*}_{t,p,\mathrm{imp}}$ and $\mathrm{Ire}^{*}_{t,p,\mathrm{exp}}$, respectively, represent the national total import and export volume of fuel p in year t, which are obtained according to the energy system planning module.

The fuel consumption of nonpower industries should satisfy the following formula:

$$F^{Nps}_{z,t,p} \leq \sum_{x \in Nps} \mathrm{EC}^{*}_{t,x,p}. \tag{20}$$

In formula (20), $\mathrm{EC}^{*}_{t,x,p}$ represents the upper limit of fuel consumption in nonpower industries, which is obtained according to the energy system planning module.

The total amount of fuel transferred in and transferred out among various regions in the country should maintain an overall balance.

$$\sum_{z=1}^{Z} F^{\mathrm{in}}_{z,t,p} = \sum_{z=1}^{Z} F^{\mathrm{out}}_{z,t,p}. \tag{21}$$

3.2.3. System Operation Constraints

(1) Power balance constraints are as follows:

$$\sum_{p \in \Omega} P_{z,t,p,s,n} + \sum_{l \in L^{z}_{t}} P^{l}_{z,t,s,n} + P^{\mathrm{dis}}_{z,t,s,n} - P^{\mathrm{cha}}_{z,t,s,n} = P^{\mathrm{load}}_{z,t,s,n}. \tag{22}$$

In formula (22), $P^{\mathrm{load}}_{z,t,s,n}$ represents the load demand of scenario s period n at the region z in year t; $P^{\mathrm{dis}}_{z,t,s,n}$ and $P^{\mathrm{cha}}_{z,t,s,n}$, respectively, represent the energy storage discharge and charging power of scenario s period n at the region z in year t, L^{z}_{t} is the set of transmission channels connected to region z, and $P^{l}_{z,t,s,n}$ represents the transmission power of the transmission channel l of scenario s period n at the region z in year t and sets the inflow z to the positive direction and the outflow z to the negative direction.

(2) Energy storage charge and discharge constraints [37] are as follows:

$$\begin{aligned}
&P^{\mathrm{dis}}_{z,t,s,n} \leq g_{z,t,s,n} X_{z,t,\mathrm{sto}},\\
&P^{\mathrm{cha}}_{z,t,s,n} \leq \left(1 - g_{z,t,s,n}\right) X_{z,t,\mathrm{sto}},\\
&\mathrm{SP}_{z,t,s,n} = \mathrm{SP}_{z,t,s,n-1} + P^{\mathrm{cha}}_{z,t,s,n} \eta^{\mathrm{cha}}_{z,t} - \frac{P^{\mathrm{dis}}_{z,t,s,n}}{\eta^{\mathrm{dis}}_{z,t}},\\
&\mathrm{SP}_{z,t,\min} \leq \mathrm{SP}_{z,t,s,n} \leq \mathrm{SP}_{z,t,\max}.
\end{aligned} \tag{23}$$

In formula (23), $X_{z,t,\mathrm{sto}}$ represents the cumulative installed capacity of energy storage at the region z in year t, $g_{z,t,s,n}$ means 0-1 state variable of storage; when it is 1, it means the storage is in the state of discharging and when it is 0, it means the storage is in the state of charging. $\eta^{\mathrm{cha}}_{z,t}$ and $\eta^{\mathrm{dis}}_{z,t}$, respectively, represent energy storage charging and discharging efficiency. $\mathrm{SP}_{z,t,s,n}$ represents the energy stored of scenario s period n at the region z in year t. $\mathrm{SP}_{z,t,\max}$ and $\mathrm{SP}_{z,t,\min}$, respectively, represent the upper and lower limits of stored energy.

(3) Transmission power constraint of cross-region transmission channels is as follows:

$$P^{l,\min}_{z,t} \leq P^{l}_{z,t,s,n} \leq P^{l,\max}_{z,t}. \tag{24}$$

In formula (24), $P^{l,\max}_{z,t}$ and $P^{l,\min}_{z,t}$ are, respectively, the upper and lower limits of the transmission power of the cross-region transmission channel.

(4) Unit output constraint is as follows.

The output of conventional units such as coal power, natural gas power, and nuclear power in various regions should satisfy the following formula:

$$P^{\min}_{z,t,p} \leq P^{l}_{z,t,p,s,n} \leq P^{\max}_{z,t,p}. \tag{25}$$

In formula (25), $P^{\min}_{z,t,p}$ and $P^{\max}_{z,t,p}$, respectively, represent the lower limit and upper limit of output of power supply p at the region z in year t.

(5) New energy output constraint is as follows:

$$\begin{aligned}
&0 \leq P_{z,t,\mathrm{wind},s,n} \leq P^{*}_{z,t,\mathrm{wind},s,n},\\
&0 \leq P_{z,t,\mathrm{solar},s,n} \leq P^{*}_{z,t,\mathrm{solar},s,n}
\end{aligned} \tag{26}$$

In formula (26), $P^{*}_{z,t,\mathrm{wind},s,n}$ and $P^{*}_{z,t,\mathrm{solar},s,n}$, respectively, represent the theoretical output of wind power and solar power generation of scenario s period n at the region z in year t.

(6) Unit climbing rate constraint is as follows:

$$\begin{aligned}
&P_{z,t,p,s,n} - P_{z,t,p,s,n-1} \leq \Delta P^{\mathrm{up}}_{p},\\
&P_{z,t,p,s,n-1} - P_{z,t,p,s,n} \leq \Delta P^{\mathrm{down}}_{p}.
\end{aligned} \tag{27}$$

In formula (27), $\Delta P^{\mathrm{up}}_{p}$ and $\Delta P^{\mathrm{down}}_{p}$, respectively, represent the upward and downward climbing rate of power supply p.

(7) Other constraints are described as follows:

Other constraints mainly include system reserve constraint and curtailment rate constraint.

3.2.4. Carbon Dioxide Emission Constraint. The total carbon dioxide emissions of the power system in each year shall not exceed the upper limit obtained according to the energy system planning module in order to achieve the national carbon dioxide emission reduction target.

$$\sum_{z=1}^{Z} \sum_{p \in \Omega} X_{z,t,p} H_{z,t,p} \mu_{z,t,p} \leq \mathrm{EM}^{*}_{t,ps}. \tag{28}$$

In formula (28), $\mu_{z,t,p}$ is the carbon dioxide emission per kilowatt hour of power supply p at the region z in year t.

The energy comprehensive optimization model that we constructed is a mixed-integer linear programming model, which can be solved with mature optimization software such as GAMS. The medium- and long-term energy transition development path can be optimized by changing the upper limit of carbon emission constraint (equation (5)).

4. Simulation Analysis

4.1. Scenario Design. In order to explore the possible path for the Energy Internet to drive China's energy transition in the future, baseline scenario and carbon neutral scenario are designed considering medium- and long-term economic development and growth potential, energy development planning, carbon emission constraint, and other various uncertain factors.

Baseline Scenario. The model uses 2017 as the base year and 2060 as the target year. Assuming that the terminal energy efficiency level rises steadily, electricity is steadily replacing terminal coal, oil, and other fossil energy, and the electrification level is steadily increasing. In 2030, nonfossil energy will account for more than 25% of primary energy consumption, and the installed capacity of new energy will be expanding. It will reach over 1.2 billion kW in 2030 and over 3 billion kW in 2060.

Carbon Neutral Scenario. Considering the acceleration of the energy transition and electrification process, the substantial increase in terminal energy efficiency, and the further acceleration of the development of new energy, various carbon emission reduction technologies such as CCUS will begin to deploy on a large scale after 2030.

4.2. Simulation Results Analysis

4.2.1. Primary Energy Consumption. According to the calculation, under the baseline scenario, the total national primary energy consumption in 2025 will be about 5.7 billion tons of standard coal. In the medium and long term, the national primary energy consumption will increase first and then decrease, and it is expected to peak around 2030, with a peak value of about 6 billion tons of standard coal (see Figure 2).

Under the carbon neutral scenario, as the electrification level and energy efficiency level of the whole society are greatly improved, the peak time of total primary energy consumption is earlier than the baseline scenario. The total peak primary energy consumption is about 5.8 billion tons of standard coal, which is about 200 million tons less than that of the baseline scenario. By 2060, the total national primary energy consumption will drop to about 5.1 billion tons of standard coal (see Figure 2).

4.2.2. Carbon Dioxide Emissions. Under the carbon neutral scenario, carbon dioxide emissions from energy consumption are expected to peak between 2025 and 2030, and the peak carbon dioxide emissions are about 10.4 billion tons, which is 600 million tons less than the baseline scenario. It is estimated that by 2060, with the widespread application of

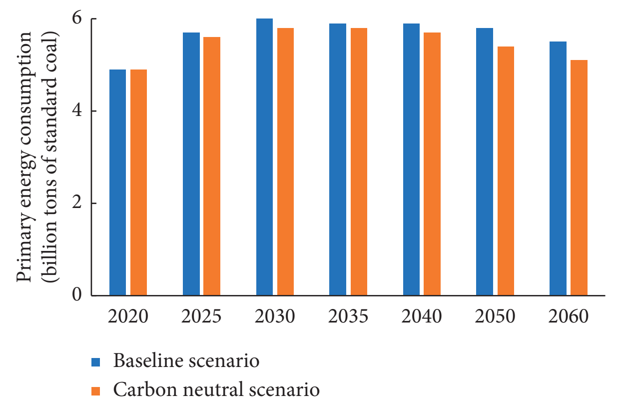

Figure 2: National primary energy consumption.

various carbon emission reduction technologies, carbon dioxide emissions will be controlled at about 300 million tons, and this part of carbon dioxide will be absorbed mainly by forest carbon sink, ocean carbon sink, soil carbon sink, and so on (see Figure 3).

The power system is the most important source of carbon dioxide emissions. According to the results predicted by the model, under the carbon neutral scenario, China's power system carbon dioxide emissions will increase from 3.8 billion tons in 2020 to 4.4 billion tons in 2030, accounting for about 44% of the total carbon dioxide emissions of the energy system. Since then, with the decline in the proportion of coal power and the large-scale application of various carbon emission reduction technologies, the carbon dioxide emissions of the power system have decreased year by year (see Figure 4).

4.2.3. Power Supply. Under the baseline scenario, it is estimated that by 2025, 2035, and 2060, the national installed power capacity will reach 3.1 billion, 4 billion, and 5.4 billion kilowatts, respectively. The installed wind and solar power capacity will surpass coal power around 2035 and become the largest power source (see Figure 5). The proportion of coal power is expected to drop from 49% in 2020 to 44%, 31%, and 11% in 2025, 2035, and 2060, while the proportion of wind and solar power will rise from 24% in 2020 to 32%, 42%, and 61%, respectively.

Under the carbon neutral scenario, it is estimated that by 2025, 2035, and 2060, the national installed power capacity will reach 3.2 billion, 4.5 billion, and 6.5 billion kilowatts, respectively (see Figure 5). Under this scenario, the peak and decommissioning progress of coal power plants will be further accelerated. It is estimated that by 2060, the proportion of coal power will drop to about 6%, while the proportion of wind and solar power will increase to about 70%.

The production simulation results of typical scenarios show that with the increase in the penetration rate of new energy, the phenomenon of wind and solar power curtailment began to appear. Take a certain region in the east as an example. Under the baseline scenario, the curtailment rate

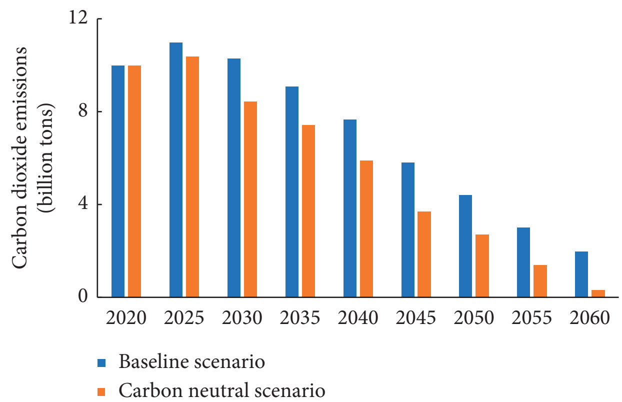

Figure 3: Carbon dioxide emissions from energy systems.

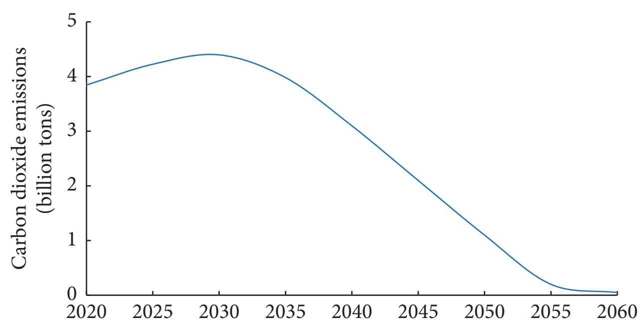

Figure 4: Carbon dioxide emissions from the power system.

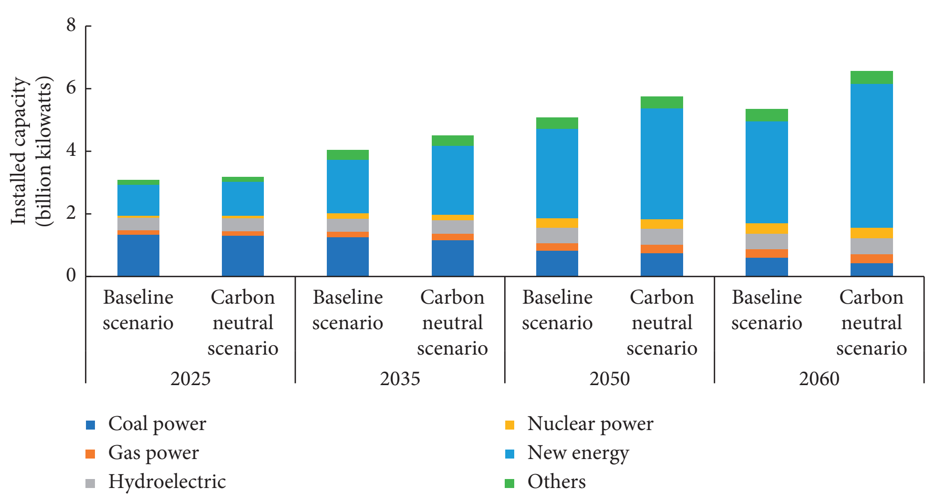

Figure 5: Installed capacity of various power sources nationwide from 2025 to 2060.

for the whole year in 2035 is about 0.25%. Under the carbon neutral scenario, as a higher proportion of new energy is connected, the amount of wind and solar power curtailment will increase exponentially. The annual curtailment rate is about 2.2%. It is necessary to coordinate and cooperate with various measures such as the development of energy storage, the improvement of thermal power flexibility, and demand side response to cope with the challenges brought by large-scale new energy.

5. Conclusions

We construct an electricity-centered energy comprehensive optimization model and conduct simulation analysis of the Energy Internet boosting energy transition by setting different development scenarios. The research results show that with the rapid progress of the energy transition and electrification process and the wide application of various carbon emission reduction technologies, the total primary energy consumption is lower than the baseline scenario and the peak time is earlier. The peaking and decommissioning of coal power generation capacity have accelerated, and the proportion of new energy has increased. Carbon emission peak value is reduced compared with the baseline scenario. It can be seen that the Energy Internet can promote clean energy to replace fossil energy, effectively improve the level of electrification of the whole society, reduce carbon emissions, and promote the development of energy transition.

Energy Internet is an important pillar of the third industrial revolution and plays an important role in the energy transition. At present, the construction of the Energy Internet still faces many challenges, such as the high proportion of fossil energy consumption and low energy utilization efficiency. The main suggestions are as follows:

(1) It is necessary to do the top-level design of the Energy Internet in the energy transition, establish a sound energy policy system, and gradually improve the power market. And it is important to building a nationwide power auxiliary service market, set up a reasonable price mechanism and effective incentive model, and guide users to replace fossil energy with clean energy. This is conducive to controlling fossil energy consumption from the source and ensuring that clean energy has sufficient development space.

(2) The construction of the Energy Internet can effectively solve the problem of unreasonable resource allocation. China has unreasonable energy allocation due to the geographical environment and uneven distribution of natural resources. Energy Internet can be fully utilized for energy allocation across time zones and regions to achieve optimal allocation of resources.

(3) The research and development of key technologies such as distributed power generation, Internet technology, energy storage technology, and intelligence technology should be actively carried out to promote the application of Energy Internet technology in the energy transition.

The development of the Energy Internet and the energy transition is very important and urgent. We establish a comprehensive energy optimization model and analyse the role of the Energy Internet in promoting the energy transition. However, there are still many issues that have not been resolved.

Energy Internet and energy transition actually interact. The construction of Energy Internet promotes the further development of energy transition. At the same time, energy transition also provides development opportunities for Energy Internet. In the future, the coupling mechanism between Energy Internet and energy transition can be further studied. And how various factors affect the development of both is also studied.

Data Availability

The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Decision-Making Optimization of Risk-Seeking Retailer Managed Inventory Model in a Water Supply Chain

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Water retailer managed inventory is a classical and inevitable inventory management mode in present economic society. Stochastic models can more clearly explain demand uncertainty and are closely related to water supply chains. Risk preferences are widely valued in behavioral operation management. Related to the risk preferences in inventory management, the research on risk aversion is dominant, while risk-seeking is insufficient. Based on the model assumptions, the risk-seeking retailer's optimal decision-making inventory model with stochastic demand in a water supply chain is studied. The risk-seeking retailer's optimal inventory quantity, optimal inventory cost, supplier profit, retailer profit, and the profit of the entire water supply chain are derived. The validity of the equations is proved. The sensitivity analysis of the risk-seeking retailer's optimal inventory decision-making is carried out. The risk level effects on the five dimensions, the retail price, wholesale price, unit shortage cost, unit inventory cost, and unit residual value, are displayed through numerical simulation. The optimal inventory quantity and optimal inventory cost of the risk-seeking retailer are obtained.

1. Introduction

1.1. Background. With the global population growth and economic development, water resources are becoming increasingly scarce. Water is a crucial business resource, but subsistent evidence suggests that the management of water resources is often poorly operated [1]. According to the United Nations World Water Development Report 2019, 45 percent of global GDP will be in the face of risk by 2050, if the natural environment and the unbearable pressures on worldwide water resources continue to degenerate at current rates. 40 percent of worldwide grain production is in the same situation. Moreover, the aggregate risk of displacement due to disasters has increased twofold since the 1970s. The exhaustion of water and other natural resources is progressively seen as the driving force behind the displacement of internal and international migration. Rogers et al. [2] considered water as an economic commodity and used prices to motivate efficiency, equity, and sustainability. In China, a series of regulations were issued to regulate water resources management. For example, "Urban Water Supply Regulations" (China State Council 2018) regulate the use of water for urban life, production, and other constructions. "Industrial Water Usage Quota for 18 Industries including Iron and Steel Industry" (Ministry of Water Resources China 2019) stipulates bound boundaries for water use in high-water-consumption industries. It is predicted that the "Industrial Water Usage Quota for 18 Industries including Iron and Steel Industry" will save 1 billion cubic meters of water annually after it is strictly implemented. Because water has commodity properties, research on water resources from the perspective of supply chain has been paid more and more attention.

In the traditional supply chain, retailers are at the end of the supply chain and directly face customers. On the one hand, the retailer keeps inventory and decides the inventory level to deal with demand uncertainty. On the other hand, the retailers also have to bear the shortage cost due to stockout. It is little motivated for upstream suppliers to reserve buffer stock to meet demand of end-users [3]. This classical inventory management mode is the retailer managed inventory (RMI) that is also known as customer managed inventory (CMI). The retailer retains the ownership of the inventory and accordingly bears the inventory cost, management cost, and some risks and responsibilities [4]. The upstream enterprise and the retailer in the supply chain are two completely independent individuals who own and manage inventory independently. The two parties transact business without cooperative management of inventory. Meanwhile, both parties bear various costs and risks caused by uncertain market demand, respectively, as shown in Figure 1.

Uncertainty is an essential feature of market. As the internal and external environments change rapidly, the uncertainty increases significantly. Several international organizations made predictions about world GDP and trade for this year and next year (Table 1). Under the influence of uncertainty, there are large gaps between pessimistic and optimistic forecasts. For water supply chains, uncertainty also means risks. Retailers' attitudes towards risks, namely, risk preferences, are unavoidable topics.

1.2. Aims. Owing to the background above, this paper focuses on the decision-making optimization of the risk-seeking retailer managed inventory mode under stochastic demand in a water supply chain, which consists of one supplier and one retailer. Based on model assumptions, the profit expressions of supplier, retailer, and the entire water supply chain are firstly provided. Then, sensitivity analyses of related factors are given through analytical equations combined with figures. The conclusions are drawn finally.

1.3. Literature Review. Based on the background discussed in the Introduction, our study involves three aspects of literature. The first stream is about the research on water supply chains, the second one is on the retailer managed inventory with stochastic demand, and the third one is on risk preferences in inventory management.

Regarding the first stream, the water footprint theory proposed by professor Hoekstra [5] provided an effective accounting and evaluation tool for the research of water security strategy, which has become one of the hot spots in the field of water resources management. Based on this theory, water was regarded as one of the evaluation indexes of a certain agricultural or industrial supply chain [6–9], instead of being regarded as a complete supply chain. There are relatively few studies on water resources as a complete supply chain. Garcia-Caceres et al. [10] considered drinking water as a supply chain. A decision support system is presented to explore an optimal plan in order to promote the efficiency and sustainability in a drinking water treatment chain. Du et al. [11] studied the efficiency of water supply chain members under two-divided contracts of pricing and wholesale price considering different competition intensities and rainfall utilization performance degrees. In the literature of Chen and Wang [12], the operational strategy and policy for internal incentives and subsidy in a water-saving service supply chain under the scenario with maximum social welfare are discussed. Chen and Chen [13] developed, analyzed, and compared four decision models of game theory in two cases of considering or without considering backlogging for the interbasin water transfer supply chain. Loss of water transport in the condition of joint pricing and stock management is considered. By reading relevant literature, we summarize and condense the following noteworthy characteristics of water supply chains:

(1) Water supply chain is characterized by high risk and multiple risks. It is obviously affected not only by climate [14] but also by human behavior [15].

(2) Water resources can form a supply chain independently [16] or a compound supply chain with other supply chains [17, 18].

(3) Because of the special form of water, it is transported in one direction through prebuilt pipes and is very dependent on the infrastructure.

(4) Water supply chain is characterized by regionalization and this characteristic is also obvious for risks in water supply chains [19, 20].

Inventory level is one of the important indicators reflecting economic benefits of enterprises. Many scholars have proved that RMI is an inevitable inventory management mode, and, in some cases, it has certain advantages. For example, Li et al. [21] through comparative studies verified that the operation efficiency of supply chains under the VMI mode is not necessarily superior to the RMI mode in any case, and the contracts that are applicable to the RMI mode are not necessarily equally applicable to the VMI mode. Anand et al. [22] proved that, in reality, retailers may hold and manage inventory in equilibrium as strategic inventory and suppliers are unable to prevent this. Hong and Park [23] compared the policies between RMI and VMI and found that the total cost of supply chain under VMI is sometimes higher than that in the traditional RMI mode. Li et al. [24] developed a scattered supply chain for two products with the retailer as Stackelberg leader. By comparing three models, the authors arrived at the conclusion that it is optimal to offer retail-sponsored gift cards in such a supply chain. Therefore, the research on the RMI mode has important practical significance.

Because of uncertainty, the assumption of stochastic demand is more practical and representative for reality than that of deterministic demand [25]. The stochastic model can more clearly explain the demand uncertainty and is closer to the present research and practice [26]. Many researches are conducted based on the stochastic demand hypothesis. A strict policy for carbon emissions considering partial backorders is explored by Ghosh et al. [27] in order to determine the optimal strategy, including order quantity, reorder point, and shipment number in a two-stage supply chain with stochastic demand. Chan et al. [28] proposed three models of synchronized cycles under stochastic customer demand and found that the total expected cost in the stochastic synchronous cycles model is better than that under the other stochastic policies. The inventory and routing decisions of supplier are studied by Onggo et al. [29] in order to minimize the costs for inventory, transportation, food-waste, and stockout of perishable products under customers'

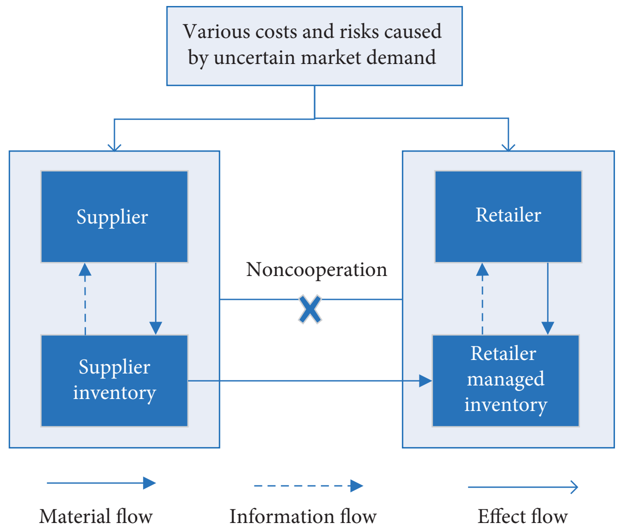

Figure 1: Schematic diagram of RMI mode.

Table 1: The recently updated forecasts for world Gross Domestic Product (GDP) and trade.

	Real GDP (% change)		Trade volume (% change)		Elasticity (ratio)	
	2020	2021	2020	2021	2020	2021
Forecast for WTO Trade (April 2020)						
Optimistic scenario	−2.5	7.4	−12.9	21.3	5.3	2.9
Pessimistic scenario	−8.8	5.9	−31.9	24.0	3.6	4.1
World Economic Prospects of the IMF (April 2020)	−3.0	5.8	−11.0	8.4	3.6	1.4
Global Economic Outlook of the World Bank (May 2020)	−5.2	4.2	−13.4	5.3	2.6	1.3
Economic Prospects of the OECD (June 2020)						
Single-hit scenario	−6.0	5.2	−9.5	6.0	1.6	1.1
Double-hit scenario	−7.6	2.8	−11.4	2.5	1.5	0.9
Memo terms						
IMF GDP set at market exchange rate	−4.2	5.4	−11.0	8.4	2.6	1.6
World Bank GDP set at purchasing power parity	−4.1	4.3	−13.4	5.3	3.3	1.2

Source: https://www.wto.org/english/news_e/pres20_e/pr858_e.htm.

stochastic demand. Chavarro et al. [30] generated and utilized 240 stochastic cases to evaluate deterministic and stochastic solution methods in the case that customer demand is considered as a normal density function. The key information for assignment decision considering customers' hierarchy is identified by Fleischmann et al. [31]. A robust and nearly optimal decentralized assignment approach is developed to fulfill the hierarchical random demand. More relevant studies can be found in the recent literature [32–34].

"Rational man" or "economic man" was assumed in the classical decision theory and caused large differences between theoretical research results and real situations. The preference and expected utility theory proposed by Von Neumann and Morgenstern [35] is the formal origin of the risk preference theory. In the inventory management area, Zanakis et al. [36] analyzed the differences between theoretical research and management practice in detail, which gradually attracted the attention of academic circles [37–39]. Related to the risk preferences in inventory management, the research on risk aversion is dominant [40–43]. For our research topic, we should also deeply explore recent literature in terms of the impact of risk preference on water supply chain. Du et al. [44] considered risk preference of water supplier and water distributor in order to study water pricing strategies in two competitive water supply chains. However, they assumed that the water supplier and water distributor were risk-neutral and acted rationally. This is the limitation of their research. Chen et al. [17] established a synthetic model system conception for a shale gas-water supply chain considering system dynamics and two-stage stochastic risk-averse programming, which generated a weight factor to measure the decision-makers' averse attitude degree towards risk. Li et al. [45], based on risk interval, proposed a stochastic optimization model aiming at many uncertainties in agricultural water resources. The application of CVaR and risk-aversion measures was considered. Fu et al. [46] contributed to the methods of water allocations by considering risk preferences of decision-makers. However, they only mentioned the level of risk-aversion. To sum up, with regard to risk preferences in water supply chain, research on risk-aversion prevails, while risk-seeking type is barely involved. The Conditional Value at Risk (CVaR) proposed by Rockafellar and Uryasev [47] is a common method to evaluate the degree of risks. Poormoaied and Atan [48] used CVaR to combine risk-averse and risk-seeking attitudes of decision-makers. The parameters of optimal policy were obtained with maximization of the weighted utility function. Xu et al. [49] introduced CVaR into a newsvendor model and came to the conclusion that the risk-averse attitude of newsvendor facing opportunity loss may more likely cause excessive orders compared to risk-seeking attitude. Kouvelis and Li [50] used VaR constraints to study integrated risk management including risk-seeking framework in a newsvendor setting using profit maximization.

Nevertheless, the research on water supply chains from the perspective of inventory mode and risk-seeking preference is rarely carried out in the present literature and practices. This article happens to be a useful supplement to this field.

2. Methods

2.1. Model Assumptions. This paper studies the inventory decision-making of a two-echelon water supply chain under the RMI mode with stochastic demand. The basic assumptions are as follows:

(1) The water supply chain is composed of one supplier and one retailer, and only the retailer is used as the main decision-making subject to study the effect of risk-seeking preference on its inventory decision. The supplier's output and inventory decisions are not controlled. Therefore, it is assumed that the supplier's ending profit is only the difference between sales revenue and production cost without supplier's inventory cost.

(2) The cost of water transportation is not considered.

(3) The retailer has only one order opportunity during the sales cycle and cannot replenish water.

(4) The wholesale price of water is determined by the supplier. The retail price of water is determined by the retailer without considering the functional relationship between price and demand.

(5) It is assumed that the market is open and there is no upper limit to the market demand. Let demand $x \in [0, +\infty)$ be a continuous random variable. Its probability density function is $f(x)$ and its cumulative distribution function is $F(x)$. $F(x)$ is a strictly monotonically increasing continuous function, and its inverse distribution exists, denoted as $F^{-1}(x)$. Since a specific functional form is required for sensitivity analysis, suppose that $F(x) = 1 - e^{-x}$, so $F^{-1}(x) = -\ln(1-x)$.

2.2. Problem Description. Based on the above assumptions, the RMI mode with stochastic demand in the water supply chain is described as follows.

In a sales cycle, the retailer orders q unit water from the supplier at wholesale price w and sells it to consumers at retail price p. Due to the uncertainty of market demand x, the best situation is that the retailer has an accurate understanding of market demand, the order quantity is exactly equal to the quantity demanded, and there is neither inventory cost nor shortage cost. But, in most cases, the deviation between the retailer's forecast of market demand and the actual market demand may lead to inventory costs (unit inventory cost is h_r) due to too many orders. At this time, at the end of the sales cycle, the retailer must deal with the remaining water at the unit residual value r_r, which is the preferential price; meanwhile, there may be shortage costs due to insufficient inventory (unit shortage cost is b).

2.3. Optimal Decision-Making of Risk-Seeking Retailer's Managed Inventory in the Water Supply Chain. Based on the above problem description, during the sales cycle, when the retailer's order quantity is q and the market demand is x, the retailer's profit function in the water supply chain is as follows:

$$\begin{aligned}\pi_r(q,x) = {} & p\min\{q,x\} - \mathrm{w}q - h_r(q-x)^+ \\ & - b(x-q)^+ + r_r(q-x)^+,\end{aligned} \tag{1}$$

where $X^+ = \max\{0, X\}$. The first term at the right end of equation (1) represents the retailer's sales revenue and therein $\min\{q, x\}$ represents the actual sales volume of the retailer, that is, the smaller one between the quantity ordered and the quantity demanded; the second item represents its order cost; the third item represents its inventory holding cost; the fourth item represents its shortage cost when demand exceeds supply; and the last item represents its income from selling surplus water when supply exceeds demand.

Since demand x is a continuous random variable, the profit described by equation (1) is also a continuous random variable. Set $Z = \pi_r(q,x)$; the distribution function of Z is the continuous function $G(z) = P\{Z \le z\}$. The probability density function of Z is the continuous function $g(z)$, and z represents the given profit level. The certain risk level $\beta \in (0, 1]$ is given, and the conditional value at risk $\mathrm{CVaRT}_\beta(Z)$ of the profit function for the risk-seeking retailer can be expressed as

$$\mathrm{CVaRT}_\beta(Z) = E\left(Z \middle| Z \ge z_\beta\right) = \frac{1}{1-\beta}\int_{Z\ge z_\beta} \mathrm{z}g(z)\mathrm{d}z. \tag{2}$$

That is, the conditional value at risk $\mathrm{CVaRT}_\beta(Z)$ of the risk-seeking retailer is used to represent the expected profit of the part, which is higher than the risk value z_β on the profit function. At this point, the retailer does not control the part below the value at risk but only makes decisions on the part above the value at risk. This is the essential difference between a risk-seeking retailer and a risk-averse retailer.

In the case of retailer managed inventory under stochastic demand, the objective function of the risk-seeking retailer is

$$\max \mathrm{CVaRT}_\beta(Z). \tag{3}$$

We have defined the distribution function of random profit Z as a continuous function $G(z) = P\{Z \le z\}$, where z

is the given profit level. Thus, in the case of the risk-seeking retailer managed inventory under stochastic demand, $G(z)$ is as follows.

(1) When $x \le q$,

$$P\{\mathrm{px} - \mathrm{wq} - h_r(q-x) + r_r(q-x) \le z\} = P\left\{x \le \frac{(w+h_r-r_r)q+z}{p+h_r-r_r}\right\}. \quad (4)$$

Let $q_1 = (w+h_r-r_r)q + z/p + h_r - r_r$ be set, denoted as

$$G_1(z) = F(q_1). \quad (5)$$

(2) When $x > q$,

$$P\{\mathrm{pq} - \mathrm{wq} - b(x-q) \le z\} = P\left\{x \ge \frac{(p-w+b)q-z}{b}\right\}. \quad (6)$$

Let $q_2 = (p-w+b)q - z/b$ be set, denoted as

$$G_2(z) = 1 - F(q_2). \quad (7)$$

Because of the target profit level $z \le (p-w)q$, $q_1 \le q$ and $q_2 \ge q$.

Now we present the relationship between the stochastic demand and profit in the case of retailer managed inventory under stochastic demand [51], as shown in Figure 2, where (a) represents the target profit level $z \le \pi_A$ and (b) represents the target profit level $z \in (\pi_A, \pi_B]$ in the water supply chain.

From Figure 2, we can visually see the relationship between the retailer's profit and the stochastic demand with the fixed order quantity q in the water supply chain. We assume that the market is open and that there is no upper limit to the market demand x. Let $x \in (0, +\infty)$ be set; therefore, the retailer's profit function is in one continuous decreasing state in the interval $(q, +\infty)$. Point A denotes the retailer's profit when the market demand $x = 0$. The retailer holds the largest inventory at this point and its corresponding profit is $\pi_A = (-w - h_r + r_r)q$. Point B represents the retailer's profit when the market demand is exactly equal to the order quantity, which is also the maximum profit $\pi_B = (p-w)q$ under the fixed order quantity. In order to further analyze the optimal inventory strategy of the risk-seeking retailer, we discuss it in the following two cases:

(1) When $z \le \pi_A$ and $z = G_2^{-1}(\beta)$, combining equation (7), the following can be obtained:

$$z_\beta = (p-w+b)q - \mathrm{bF}^{-1}(1-\beta). \quad (8)$$

Meanwhile, from $z \le \pi_A$ and equation (8), the following can be obtained:

$$q \le \frac{\mathrm{bF}^{-1}(1-\beta)}{p+b+h_r-r_r}. \quad (9)$$

(2) When $z \in (\pi_A, \pi_B]$ and $G_1(z_\beta) + G_2(z_\beta) = \beta$, combing equations (5) and (7), the following can be obtained:

$$1 + F(q_1) - F(q_2) = \beta. \quad (10)$$

We get $q > \mathrm{bF}^{-1}(1-\beta)/p + b + h_r - r_r$.

Proposition 1. *In the water supply chain under RMI mode with stochastic demand, the risk-seeking retailer takes CVaR-profit maximization as its decision-making objective and its optimal inventory quantity Q^* is as follows:*

(1) When $q \le bF^{-1}(1-\beta)/p + b + h_r - r_r$,

$$Q^* = \begin{cases} F^{-1}\left((1-\beta)\dfrac{p-w+b}{p+h_r+b-r_r}\right) - x, & q^* > x \\ 0, & q^* \le x. \end{cases} \quad (11)$$

(2) When $q > bF^{-1}(1-\beta)/p + b + h_r - r_r$ and $f(q) > b(w+h_r-r_r)^2 f(q_1) + (p+h_r-r_r)(p-w+b)^2 f(q_2) / b(p+h_r-r_r)(p+h_r+b-r_r)$,

$$Q^* = \begin{cases} (p+b+h_r-r_r)^{-1}\begin{pmatrix} (p+h_r-r_r)F^{-1}\left(F(q^*) - \dfrac{(p-w+b)(1-\beta)}{(p+h_r+b-r_r)}\right) \\ +bF^{-1}\left(F(q^*) + \dfrac{(w+h_r-r_r)(1-\beta)}{p+h_r+b-r_r}\right) \end{pmatrix} - x, & q^* > x \\ 0, & q^* \le x. \end{cases} \quad (12)$$

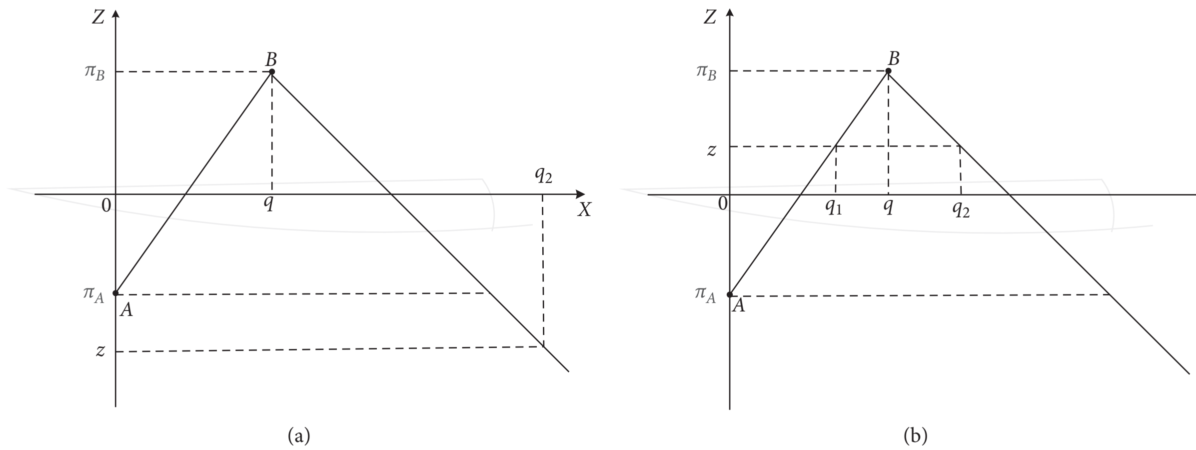

Figure 2: Schematic diagram of the relationship between stochastic demand and profit under the risk-seeking retailer managed inventory mode in the water supply chain. (a) $z \le \pi_A$. (b) $z \in (\pi_A, \pi_B]$.

Proof. Based on the groundwork mentioned above, the solution process is divided into the two following situations:

(1) When $q \le \mathrm{bF}^{-1}(1-\beta)/p+b+h_r-r_r$, $z_\beta = (p-w+b)q - \mathrm{bF}^{-1}\ (1-\beta)$. By observing Figure 2, when $z = z_\beta$, the corresponding demand is $F^{-1}(1-\beta)$. According to the definition formula (2) of the Conditional Value at Risk-seeking $\mathrm{CVaRT}_\beta(Z)$, we can draw that the retailer does not make decisions on the worst profit in the demand interval $[F^{-1}(1-\beta), +\infty]$ (the profit possibility of this part is β) but only controls the demand interval $[0, F^{-1}(1-\beta)]$ corresponding to the stochastic profit $z \ge z_\beta$. In this case, formula (2) is equivalent to

$$\mathrm{CVaRT}_\beta(Z) = \frac{1}{1-\beta}\left(\begin{array}{l}\displaystyle\int_0^q [(p+h_r-r_r)t-(w+h_r-r_r)q]\mathrm{d}F(t)\\ \displaystyle +\int_q^{F^{-1}(1-\beta)} [(p-w+b)q-bt]\mathrm{d}F(t)\end{array}\right). \tag{13}$$

Solving the first partial derivative of the above equation with respect to order quantity q, we can obtain

$$\begin{aligned}\frac{\partial \mathrm{CVaRT}_\beta(Z)}{\partial q} = &\frac{1}{1-\beta}\left(-(p+h_r+b-r_r)F(q)\right.\\ &\left.+(p-w+b)(1-\beta)\right).\end{aligned} \tag{14}$$

We have

$$\frac{\partial^2 \mathrm{CVaRT}_\beta(Z)}{\partial q^2} = \frac{1}{1-\beta}\left(-(p+h_r+b-r_r)f(q)\right) < 0. \tag{15}$$

Therefore, the maximum exists. The optimal order quantity can be obtained by setting the first-order condition equal to 0:

$$q^* = F^{-1}\left((1-\beta)\frac{p-w+b}{p+h_r+b-r_r}\right). \tag{16}$$

(2) When $q > \mathrm{bF}^{-1}(1-\beta)/p+b+h_r-r_r$, z_β satisfies $1+F(q_1)-F(q_2)=\beta$. Similarly, by observing Figure 2, we can obtain that the retailer only controls the demand segment $[q_1, q_2]$ corresponding to the stochastic profit $z \ge z_\beta$. At this point, equation (2) is equivalent to

$$\mathrm{CVaRT}_{\beta}(Z)=\frac{1}{1-\beta}\left(\begin{array}{c}\int_{q_1}^{q}[(p+h_r-r_r)t-(w+h_r-r_r)q]\mathrm{d}F(t)\\ +\int_{q}^{q_2}[(p-w+b)q-\mathrm{bt}]\mathrm{d}F(t)\end{array}\right). \tag{17}$$

Solving the first partial derivative of the above equation with respect to order quantity q, we can get

$$\frac{\partial \mathrm{CVaRT}_{\beta}(Z)}{\partial q}=\frac{1}{1-\beta}\left(-(p+h_r+b-r_r)F(q)+(w+h_r-r_r)F(q_1)+(p-w+b)F(q_2)\right). \tag{18}$$

where

$$\frac{\partial^2 \mathrm{CVaRT}_{\beta}(Z)}{\partial q^2}=\frac{1}{1-\beta}\left(-(p+h_r+b-r_r)f(q)+\frac{(w+h_r-r_r)^2}{p+h_r-r_r}f(q_1)+\frac{(p-w+b)^2}{b}f(q_2)\right). \tag{19}$$

The sign symbol of the above equation cannot be judged by the existing conditions, so we use the inverse method to solve it. Assuming that when $q>\mathrm{bF}^{-1}(1-\beta)/p+b+h_r-r_r$, the maximum exists,

$$\frac{\partial^2 CVaRT_{\beta}(Z)}{\partial q^2}<0, \tag{20}$$

that is, $f(q)>b(w+h_r-r_r)^2f(q_1)+(p+h_r-r_r)(p-w+b)^2f(q_2)/b(p+h_r-r_r)(p+h_r+b-r_r)$ holds.

Let the first-order condition be 0; combining the equation $z=(p+h_r-r_r)q_1-(w+h_r-r_r)q=(p-w+b)q-bq_2$ and equation (10), we get the optimal order quantity $\overset{*}{q}$:

$$q^*=\frac{(p+h_r-r_r)F^{-1}(F(q^*)-((p-w+b)(1-\beta)/(p+h_r+b-r_r)))+bF^{-1}(F(q^*)+((w+h_r-r_r)(1-\beta)/p+h_r+b-r_r))}{p+b+h_r-r_r}. \tag{21}$$

In conclusion, we have the following:

(1) When $q\leq \mathrm{bF}^{-1}(1-\beta)/p+b+h_r-r_r$, the optimal order quantity q^* of the risk-seeking retailer in the water supply chain is

$$q^*=F^{-1}\left((1-\beta)\frac{p-w+b}{p+h_r+b-r_r}\right). \tag{22}$$

(2) When $q>\mathrm{bF}^{-1}(1-\beta)/p+b+h_r-r_r$ and $f(q)>b(w+h_r-r_r)^2f(q_1)+(p+h_r-r_r)(p-w+b)^2f(q_2)/b(p+h_r-r_r)(p+h_r+b-r_r)$, the optimal order quantity $\overset{*}{q}$ of the risk-seeking retailer in the water supply chain is

$$q^*=\frac{(p+h_r-r_r)F^{-1}(F(q^*)-((p-w+b)(1-\beta)/(p+h_r+b-r_r)))+\mathrm{bF}^{-1}(F(q^*)+((w+h_r-r_r)(1-\beta)/p+h_r+b-r_r))}{p+b+h_r-r_r} \tag{23}$$

Thus, equations (11) and (12) of the optimal inventory quantity of the retailer in the water supply chain hold. ■ So, we can directly get Proposition 2–Proposition 5.

Proposition 2. *In the case of the risk-seeking retailer managed inventory under stochastic demand scenario in the water supply chain, the optimal inventory cost C^* of the risk-seeking retailer aiming at maximizing CVaR-profit is given by*

$$C^* = h_r\left(q^* - x\right)^+. \tag{24}$$

Proposition 3. *In the case of the risk-seeking retailer managed inventory under stochastic demand scenario in the water supply chain, the supplier's profit can be expressed by*

$$\pi_m = (w - c)q^*. \tag{25}$$

Proposition 4. *In the case of the risk-seeking retailer managed inventory under stochastic demand scenario in the water supply chain, the retailer's profit can be expressed by*

$$\pi_r = (p - w + b)q^* - \mathrm{bx} - \left(p + h_r + b - r_r\right)\left(q^* - x\right)^+. \tag{26}$$

Proposition 5. *In the case of the risk-seeking retailer managed inventory under stochastic demand scenario in the water supply chain, the profit of the entire supply chain is given by*

$$\pi_c = (p + b - c)q^* - \mathrm{bx} - \left(p + h_r + b - r_r\right)\left(q^* - x\right)^+. \tag{27}$$

3. Results and Discussion

Then, the sensitivity of the risk-seeking retailer's optimal inventory strategy is analyzed under RMI mode with stochastic demand in the water supply chain. The effects of relevant factor changes on the retailer's inventory strategy are discussed.

Since Proposition 1 gives the optimal inventory quantity under two conditions, as shown in equations (11) and (9), in this section, we only carry out sensitivity analysis on the optimal inventory strategy when $x < q^* \le \mathrm{b}F^{-1}(1-\beta)/p + b + h_r - r_r$, as shown in Corollaries 1 and 2.

Corollary 1. *In the case of the risk-seeking retailer managed inventory under stochastic demand scenario in the water supply chain, when $x < q^* \le \mathrm{b}F^{-1}(1-\beta)/p + b + h_r - r_r$, the optimal inventory quantity Q^* of the risk-seeking retailer increases monotonously with respect to the retail price p, unit shortage cost b, and unit residual value r_r, while it decreases monotonously with respect to the wholesale price w and unit inventory cost h_r.*

Proof. Solving the partial derivatives of the optimal inventory quantity Q^* with respect to the retail price p, wholesale price w, unit shortage cost b, unit inventory cost h_r and unit residual value r_r in equation (11), we can obtain

$$\begin{aligned}
\frac{\partial Q^*}{\partial p} &= \frac{1}{f\left[F^{-1}(1-\beta)\left(p - w + b/p + h_r + b - r_r\right)\right]}(1-\beta)\frac{h_r + w - r_r}{\left(p + h_r + b - r_r\right)^2} \ge 0,\\
\frac{\partial Q^*}{\partial w} &= -\frac{1}{f\left[F^{-1}(1-\beta)\left(p - w + b/p + h_r + b - r_r\right)\right]}(1-\beta)\frac{1}{p + h_r + b - r_r} \le 0,\\
\frac{\partial Q^*}{\partial b} &= \frac{1}{f\left[F^{-1}(1-\beta)\left(p - w + b/p + h_r + b - r_r\right)\right]}(1-\beta)\frac{h_r + w - r_r}{\left(p + h_r + b - r_r^2\right)} \ge 0,\\
\frac{\partial Q^*}{\partial h_r} &= -\frac{1}{f\left[F^{-1}(1-\beta)\left(p - w + b/p + h_r + b - r_r\right)\right]}(1-\beta)\frac{w - p - b}{\left(p + h_r + b - r_r\right)^2} \le 0,\\
\frac{\partial Q^*}{\partial r_r} &= \frac{1}{f\left[F^{-1}(1-\beta)\left(p - w + b/p + h_r + b - r_r\right)\right]}(1-\beta)\frac{p + b - w}{\left(p + h_r + b - r_r\right)^2} \ge 0.
\end{aligned} \tag{28}$$

To sum up, the following conclusions are valid:

$$\begin{aligned}&\frac{\partial Q^*}{\partial p}\geq 0,\\&\frac{\partial Q^*}{\partial w}\leq 0,\\&\frac{\partial Q^*}{\partial b}\geq 0,\\&\frac{\partial Q^*}{\partial h_r}\leq 0,\\&\frac{\partial Q^*}{\partial r_r}\geq 0.\end{aligned}\tag{29}$$

In other words, Corollary 1 is valid. ■

Corollary 1 shows that the risk level has no effect on the monotonicity of the optimal inventory quantity in the five dimensions of the retail price, wholesale price, unit shortage cost, unit inventory cost, and unit residual value in the water supply chain. But, from Figure 3–7, we can see that, under different risk levels, the retail price, wholesale price, unit shortage cost, unit inventory cost, and unit residual value have different effect strengths on the optimal inventory quantity. When the retail price, unit shortage cost, and unit residual value increase, the risk-seeking retailer's optimal inventory quantity also increases, as shown in Figures 3–5 and Figures 8–10. On the contrary, when the wholesale price and unit inventory cost increase, the optimal inventory quantity decreases, as shown in Figures 6, 7, 11, and 12.

Corollary 2. *In the water supply chain, when $x < q^* \leq bF^{-1}(1-\beta)/p + b + h_r - r_r$, the optimal inventory cost C^* of the risk-seeking retailer under RMI mode with stochastic demand increases monotonously with respect to the retail price p, unit shortage cost b, and unit residual value r_r, while it decreases monotonously with respect to the wholesale price w. When $0 < h_r \leq Q^*/B$, $\overset{*}{C}$ increases monotonously with respect to the unit inventory cost h_r; when $h_r > Q^*/B$, C^* decreases monotonously with respect to the unit inventory cost h_r.*

Proof. Because the proof process is similar to that of Corollary 1, we do not repeat it here and only give a brief analysis and figures. When $x < q^* \leq \mathrm{b}F^{-1}(1-\beta)/p + b + h_r - r_r$, solving the partial derivatives of the optimal inventory cost C^* with respect to the retail price p, wholesale price w, unit shortage price b, unit residual value r_r, and unit inventory cost h_r in equation (24), we can obtain

$$\begin{aligned}&\frac{\partial C^*}{\partial p}\geq 0,\\&\frac{\partial C^*}{\partial w}\leq 0,\\&\frac{\partial C^*}{\partial b}\geq 0,\\&\frac{\partial C^*}{\partial r_r}\geq 0,\\&\frac{\partial C^*}{\partial h_r}=Q^*-h_r\frac{(1-\beta)(p-w+b)}{(p+h_r+b-r_r)^2 f\left(F^{-1}\left((1-\beta)(p-w+b/p+h_r+b-r_r)\right)\right)}.\end{aligned}\tag{30}$$

Let $B = (1-\beta)(p-w+b)/(p+h_r+b-r_r)^2 f(F^{-1}((1-\beta)(p-w+b/p+h_r+b-r_r)))$ be set;

Thus, $B > 0$, where $\partial C^*/\partial h_r = Q^* - h_r B$.

Because it is not easy to judge the sign symbol on the right side of the equation, we discuss it in the two following cases:

(1) When $0 < h_r \leq Q^*/B$, it is easy to get $\partial C^*/\partial h_r \geq 0$

(2) When $h_r > Q^*/B$, it is easy to get $\partial C^*/\partial h_r < 0$

That is, Corollary 2 holds. ■

Corollary 2 shows that the risk level has no effect on the monotonicity of the optimal inventory cost in the five dimensions of the retail price, wholesale price, unit shortage cost, unit inventory cost, and unit residual value. But, from Figure 13–17, we can see that, under different risk levels, the retail price, wholesale price, unit shortage cost, unit inventory cost, and unit residual value have different effect strengths on the optimal inventory cost. When the retail price, unit shortage cost, and unit residual value increase, the risk-seeking retailer's optimal inventory cost also increases, as shown in Figures 13–15 and Figure 18–20. On the contrary, when the wholesale price increases, the optimal inventory cost decreases, as shown in Figure 16 and Figure 21. When $0 < h_r \leq Q^*/B$, the optimal inventory cost increases with the increase of the unit inventory cost; when $h_r > Q^*/B$, the optimal inventory cost decreases with the increase of the unit inventory cost, as shown in Figures 17 and 22.

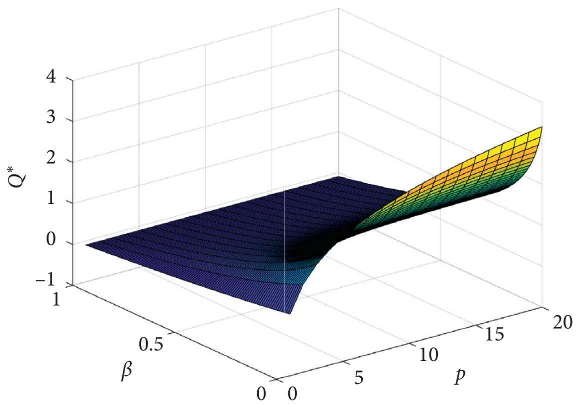

FIGURE 3: Effect of risk level β and retail price p on the optimal inventory quantity Q^* under RMI mode with stochastic demand in the water supply chain.

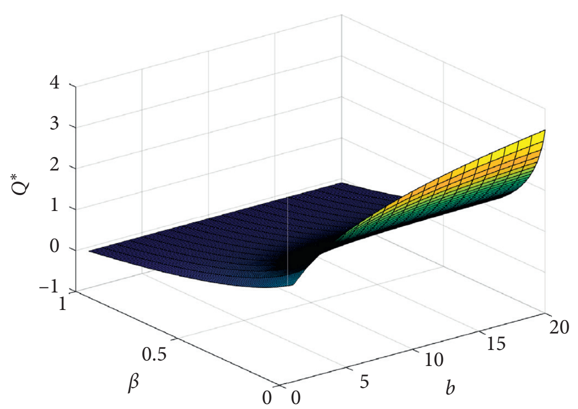

FIGURE 4: Effect of risk level β and unit shortage cost b on the optimal inventory quantity Q^* under RMI mode with stochastic demand in the water supply chain.

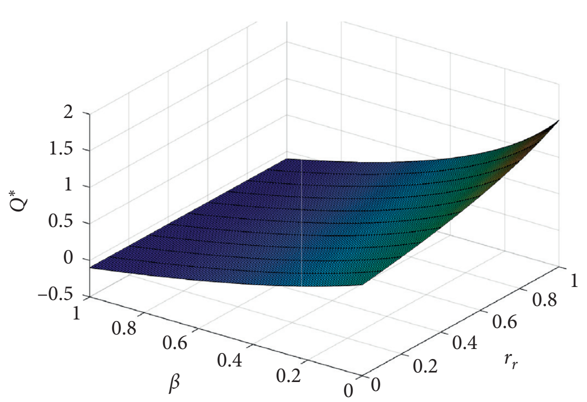

FIGURE 5: Effect of risk level β and unit residual value r_r on the optimal inventory quantity Q^* under RMI mode with stochastic demand in the water supply chain.

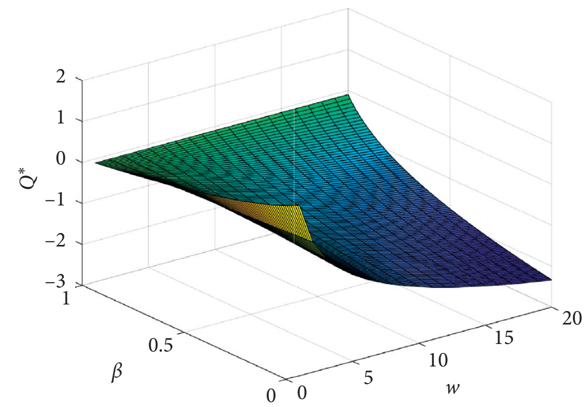

FIGURE 6: Effect of risk level β and wholesale price w on the optimal inventory quantity Q^* under RMI mode with stochastic demand in the water supply chain.

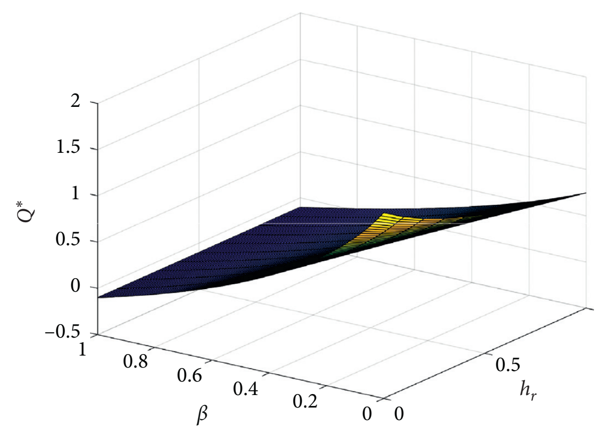

FIGURE 7: Effect of risk level β and unit inventory cost h_r on the optimal inventory quantity Q^* under RMI mode with stochastic demand in the water supply chain.

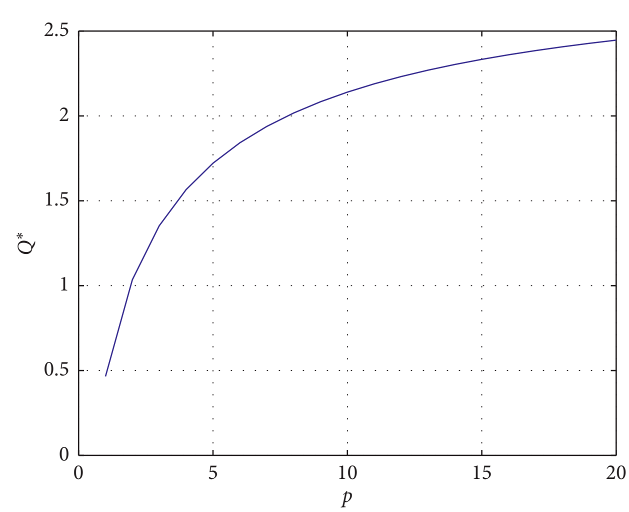

FIGURE 8: Effect of retail price p on the optimal inventory quantity Q^* under RMI mode with stochastic demand in the water supply chain.

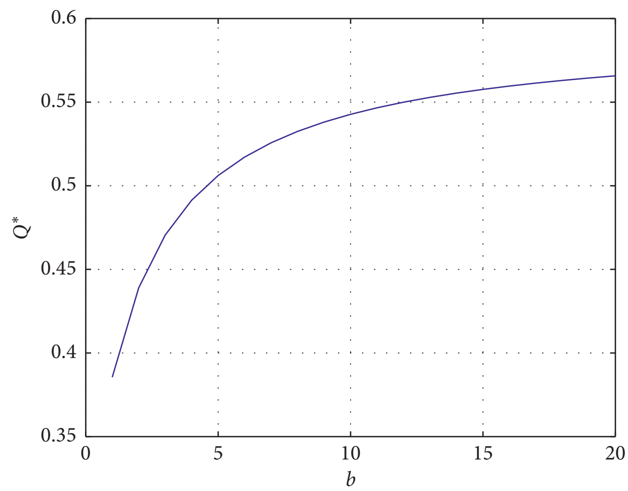

Figure 9: Effect of unit shortage cost b on the optimal inventory quantity Q^* under RMI mode with stochastic demand in the water supply chain.

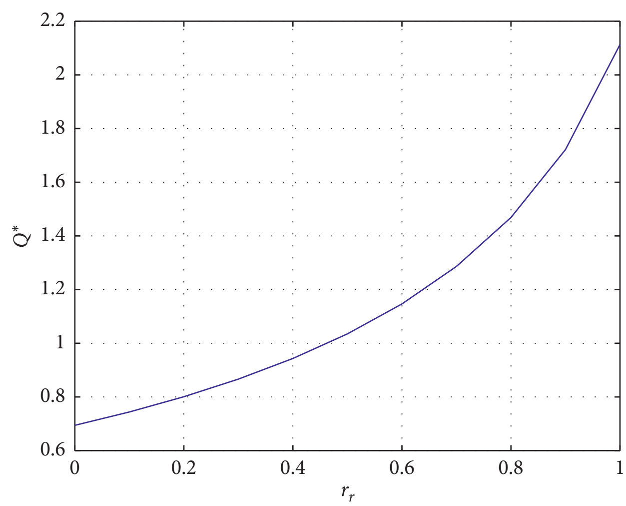

Figure 10: Effect of unit residual value r_r on the optimal inventory quantity Q^* under RMI mode with stochastic demand in the water supply chain.

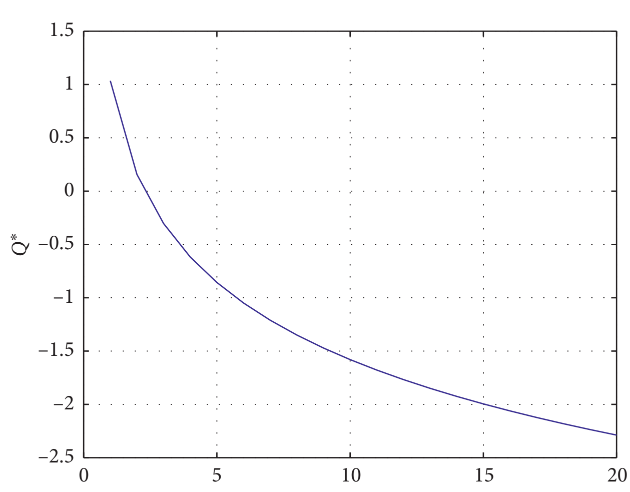

Figure 11: Effect of wholesale price w on the optimal inventory quantity Q^* under RMI mode with stochastic demand in the water supply chain.

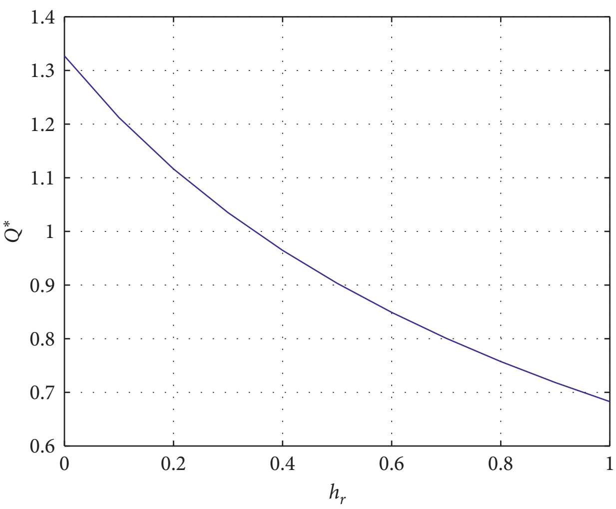

Figure 12: Effect of unit inventory cost h_r on the optimal inventory quantity Q^* under RMI mode with stochastic demand in the water supply chain.

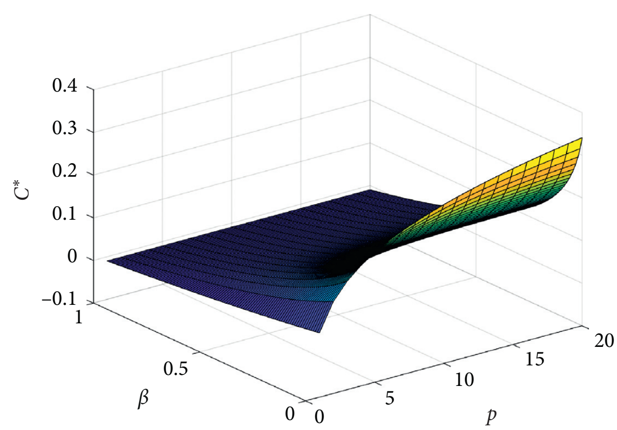

Figure 13: Effect of risk level β and retail price p on the optimal inventory cost C^* under RMI mode with stochastic demand in the water supply chain.

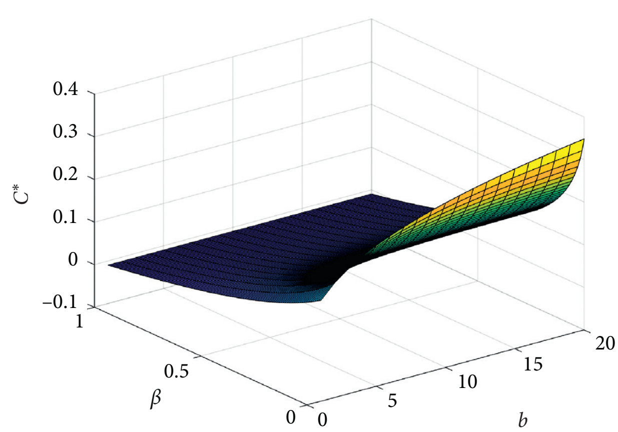

Figure 14: Effect of risk level β and unit shortage cost b on the optimal inventory cost C^* under RMI mode with stochastic demand in the water supply chain.

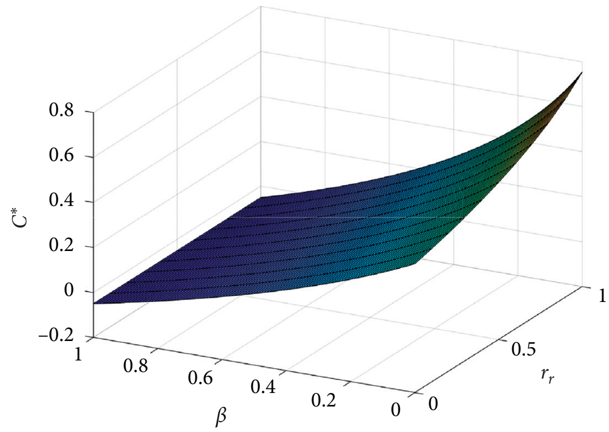

Figure 15: Effect of risk level β and unit residual value r_r on the optimal inventory cost C^* under RMI mode with stochastic demand in the water supply chain.

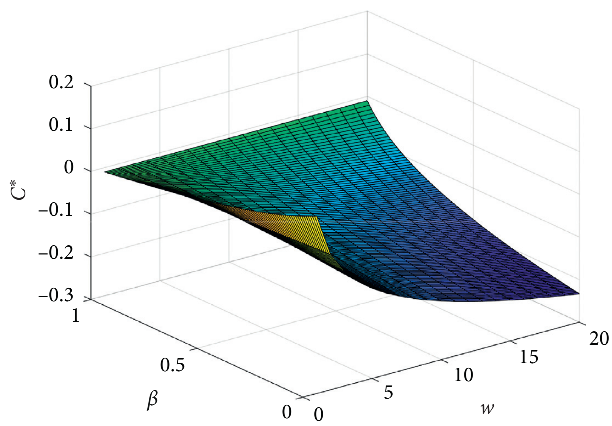

Figure 16: Effect of risk level β and wholesale price w on the optimal inventory cost C^* under RMI mode with stochastic demand in the water supply chain.

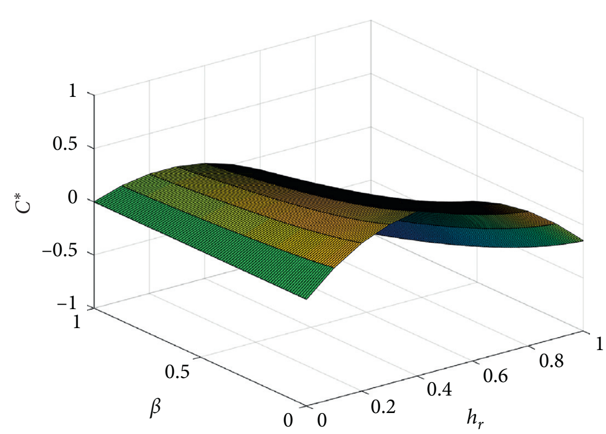

Figure 17: Effect of risk level β and unit inventory cost h_r on the optimal inventory cost C^* under RMI mode with stochastic demand in the water supply chain.

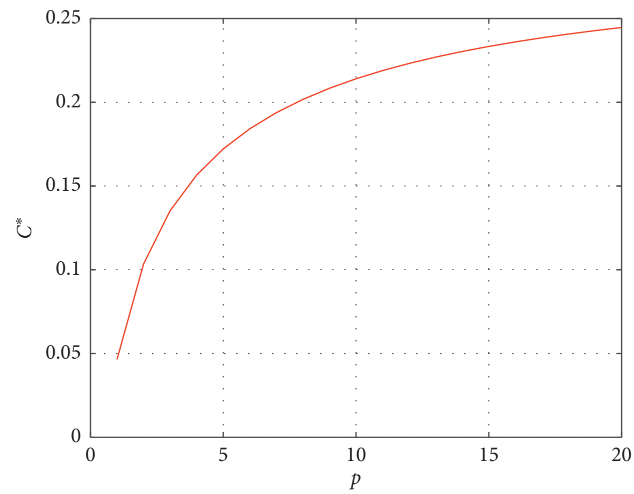

FIGURE 18: Effect of retail price p on the optimal inventory cost C^* under RMI mode with stochastic demand in the water supply chain.

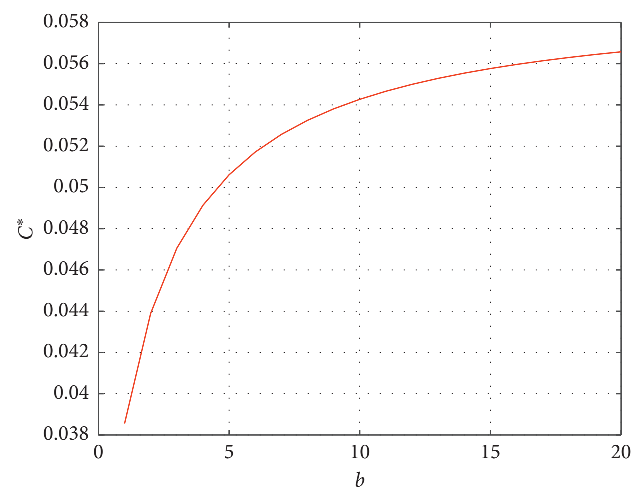

FIGURE 19: Effect of unit shortage cost b on the optimal inventory cost C^* under RMI mode with stochastic demand in the water supply chain.

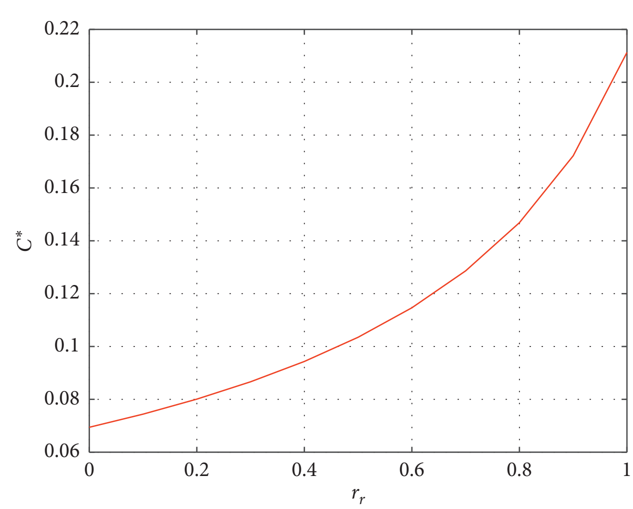

FIGURE 20: Effect of unit residual value r_r on the optimal inventory cost C^* under RMI mode with stochastic demand in the water supply chain.

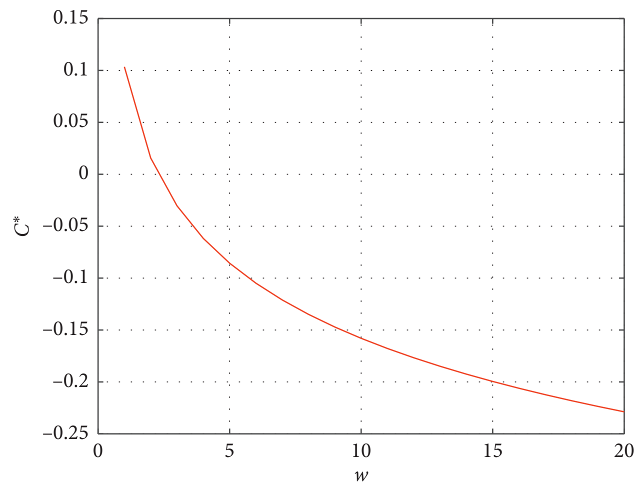

FIGURE 21: Effect of wholesale price w on the optimal inventory cost C^* RMI mode with stochastic demand under in the water supply chain.

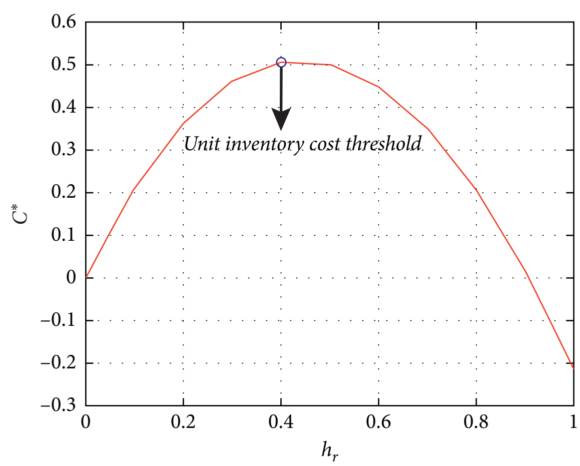

FIGURE 22: Effect of unit inventory cost h_r on the optimal inventory cost C^* under RMI mode with stochastic demand in the water supply chain.

4. Conclusions

Water supply chain is characterized by high risk and multiple risks. The decision-maker's attitude to risk is one of the important factors that affect the decision result. Uncertain demand is the most fundamental uncertainty in supply chains. So, stochastic demand is incorporated into our research hypothesis. Based on the model assumptions, we study the optimal decisions of the risk-seeking retailer under RMI mode considering stochastic demand in a water supply chain. Firstly, we discussed the relationship between stochastic demand and profit. Next, we proved the expressions of the risk-seeking retailer's optimal inventory quantity, and then the expression of the risk-seeking retailer's optimal inventory cost, the profit expressions of the supplier, retailer, and the entire supply chain are derived. Finally, through sensitivity analysis and numerical simulation, we explored the impact of risk level on the optimal inventory decisions. We get the following conclusions:

(1) In the water supply chain, the risk-seeking level has no effect on the monotonicity of the optimal inventory quantity and optimal inventory cost in the five dimensions of the retail price, wholesale price, unit shortage cost, unit inventory cost, and unit residual value. But, under different risk levels, the five dimensions generate different effect strengths on the optimal inventory strategy.

(2) With regard to the optimal inventory quantity and optimal inventory cost of the risk-seeking retailer, their monotonicities are positively associated with the retail price, unit shortage cost, and unit residual value, while they are negatively correlated with the wholesale price.

(3) The unit inventory cost has different effects on the optimal inventory quantity and optimal inventory cost. It is negatively correlated with the optimal inventory quantity. Meanwhile, there is a certain

threshold for unit inventory cost, which makes the monotonicity of the risk-seeking retailer's optimal inventory cost change before and after this threshold. We can explain this counterintuitive phenomenon. Before the unit inventory cost is less than the certain threshold, the increase in the risk-seeking retailer's inventory quantity can still increase the expected profit. At this time, the risk-seeking retailer still increases the inventory quantity, and the inventory cost increases accordingly. When the unit inventory cost exceeds the threshold, the increase in the risk-seeking retailer's inventory quantity leads to a decrease in the expected profit. At this time, the risk-seeking retailer reduces the inventory quantity, and the corresponding inventory cost also decreases.

(4) From the expressions of the supplier's optimal profit and the profit of the entire supply chain, we can obtain that the supplier's optimal profit and the profit of the entire supply chain are positively associated with the retailer's order quantity. Therefore, the risk-seeking level of the retailer also affects the supplier's profit and supply chain's profit. It is important for the supplier to pay attention to the retailer's risk preference.

(5) We considered only demand as a random variable in our research. There are also price uncertainty and cost uncertainty in practice. It makes sense to study the association of multiple random variables. Some scholars have made attempt methods to describe the relationships between various random variables [52].

Water is regarded as a crucial business resource. This correlational research is carried out from the perspective of supply chain operations and focuses on the optimal inventory strategy of the risk-seeking retailer under RMI mode considering stochastic demand, which makes the research more practical.

Data Availability

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation, to any qualified researcher.

Conflicts of Interest

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

Acknowledgments

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Research Article

Spatiotemporal Coupling Coordination Analysis of Social Economy and Resource Environment of Central Cities in the Yellow River Basin

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With the rapid economic and social development and accelerated urbanization, the negative ecological impact of major river basins worldwide has been deepening, which is gradually threatening the sustainable development of cities. This study establishes the model of the coupling coordination relationship between social economy and resources environment of nine central cities in the Yellow River Basin. Based on the evaluation index system of social economy and resource environment, we quantitatively measure the coupling coordination degree and spatiotemporal pattern of the nine central cities from 2010 to 2017. The obstacle factors of coupling coordination were then diagnosed based on the obstacle degree model. The results showed that (1) the social economy and resources environment development indices of the nine central cities in the Yellow River Basin, as well as the coupling coordination of each central city, showed an overall upward trend from 2010 to 2017. (2) Most of the central cities in the Yellow River Basin were in the coordinated coupling stage, among which Xining and Lanzhou have the highest coupling degree. (3) The obstacle factors affecting the harmonious development coupling coordination of the nine central cities were natural growth rate of population, proportion of tertiary industry in GDP and per capita investment in fixed assets in social economy system, and per capita green area of parks, per capita total amount of water resources, and per capita industrial SO_2 emissions in resources environment system. It is necessary to adopt different strategies for different cities to promote the coupling coordination development of urban social economy and resources environment in the Yellow River Basin.

1. Introduction

The Yellow River Basin is the cradle of Chinese culture, with a long history and long mainstream of 5464 km. It flows through Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shanxi, Shaanxi, Henan, and Shandong and covers 795000 km^2 [1].

The Yellow River flows through the arid and semiarid regions and undertakes the water supply task of 17.0% for cultivated land and more than 50 large- and medium-sized cities. It is an important water source for cities in the region. However, the Yellow River Basin is seriously short of water resources. In 2018, the total water resources of the Yellow River basin only accounted for 2.6% of China [2]. The Yellow River Basin plays a vital role in national economic development, and it carried 23.3% of the national population and produced 21.8% of the total economic volume. Driven by the national implementation of the Western development, the economics of cities in the Yellow River Basin have rapidly improved. However, the consequent pollution problems have seriously affected the self-cleaning capacity of the ecosystem and threatened the resources and environment. In 2017, the water quality of 692.7 km of the Yellow River was class IV and low-grade IV [3]. The extensive scale development of energy and heavy chemical industry led to the pollutants in the Yellow River. The pollution exceeded the water environment carrying capacity of its mainstream and tributaries. Therefore, it is essential to study the relationship between economy and society and resources and the environment in the Yellow River Basin.

The urban economy is composed of industry, commerce, and other nonagricultural economic sectors. Social development refers to the process of the whole human society moving forward, including the overall development of economy, humanities, politics, and other series of social existence. In recent years, the economy of the central cities in the Yellow River Basin has developed rapidly. Simultaneously, as a critical ecological functional area in China, the environmental quality of central cities in the Yellow River Basin is directly related to the national ecological security. The process of rapid economic and social development is often accompanied by problems such as heavy metal pollution of the air, water, and soil and the deterioration of the ecological environment, bringing enormous pressure on the carrying capacity of resources and the environment. In this context, the coupling coordination development of social economy with resources environment has become a strategic issue and scientific problem.

To sum up, the Yellow River Basin is an important ecological barrier and an important economic zone in China, which is of great importance for maintaining social stability and ecological security, promoting national unity, and national economic and social development. However, there is an incongruity between economic development and ecological environment development in the Yellow River Basin. This paper will take nine central cities in the Yellow River Basin as the research object, analyze the spatial and temporal trends of the coupling coordination degree of nine central cities in the Yellow River Basin from 2010 to 2017, identify the main factors affecting the development of these central cities through the barrier degree model, and finally give the corresponding evaluation and opinions on the coordinated development of economic, social, and resource environment in the central cities in the Yellow River Basin concerning the research results.

2. Literature Review

2.1. Environmental Conditions of the Yellow River Basin. The ecological foundation of the Yellow River basin is fragile. The climate of the upper reaches is dry and rainy, and desertification is a serious problem. The problem of soil erosion is serious in the middle reaches [3]. In recent years, the rapid development of various industries in the Yellow River Basin has further aggravated the environmental problems. For example, the middle reaches of the Yellow River Basin are rich in mineral resources. The extensive development of energy and minerals has increased the environmental pressure in the middle reaches, while soil erosion has increased in Shanxi and desertification has intensified in many areas [4, 5]. Zhu and Wang [6] found that environmental protection facilities of power, coking, and other industries based on coal consumption were operating at a low level. So, the SO_2 emissions seriously exceeded the standard, resulting in serious, atmospheric soot-type pollution in the region.

2.2. Urban Economic and Social Development. Many scholars have studied the high-quality economic development of the Yellow River Basin. Xu et al. [7] constructed the Yellow River Basin high-quality development evaluation index system from the two aspects of economic and social development and ecological security. They measured the level of high-quality development based on nine provinces of the Yellow River Basin from 2008 to 2017. Ma and Xu [8] evaluated the high-quality development of seven city clusters in the Yellow River Basin based on five dimensions: innovation, coordination, green, openness, and sharing. The study found significant spatial differences in the high-quality development of city clusters in the Yellow River Basin. It concluded that the role of core cities in driving the high-quality development of city clusters should be strengthened. Liu et al. [9] compared the relationship between openness and sustainable development in representative river basin economic areas in Asia, Europe, North and South America, and Africa. They found that the openness factors had a complex impact on the functioning state of river basin economic systems and led to diverse river basin economic systems and pathways of development. It was proposed that the experience of forming a positive interaction between openness and sustainable development through the combined effect of independent openness and innovation, coordination, adaptation, and sharing can provide lessons for the high-quality economic development of the Yellow River Basin.

2.3. Relationship between the Resources Environment and Social Economy for City. The coupling coordination of social economy with resources and environment has become a research hotspot in regional development in recent years. Li and Li [10] conducted a coordination analysis of the social economy and resources environmental development of Wuhan from 1988 to 2010 based on the principal component analysis method. The results show that the coupling relationship between social and economic development and the resources environment is gradually changing from severe imbalance to elemental disharmony, indicating that there is still some distance to achieve quality coordination. Sun et al. [11] studied the coupling coordination degree of social economy and resource environment with panel data from 18 cities in Henan Province. The study showed that the east-west and north-south coupling coordination approximated an inverted U curve. Wang and Wu [12] built the coupling process model of regional ecological and economic systems. They quantitatively analyzed the coupling process and trend of the regional eco-economic system in the Yellow River Delta. Li et al. [13] used the coupling coordination model to evaluate the resource environment and social economy in 19 resource-based cities in the northeast of China. This study found that the coordinated development of each city was at a low level, and the social economy development lagged far behind the development of the ecological environment. Song et al. [14] have studied the evolution law of coupling coordination development of agro-ecological environment system and agro-economic system in Ningxia of China. The result showed that the overall coordinated development of the agro-ecological system and agricultural economic system had achieved a shift from transitional development to coordinated development. Based on the data of the economic and ecological environment of Mianyang city of China on 2000–2014, Hu [15] constructed a coordination evaluation model of ecological environment and economic system. The results showed that the ecological environment and economic development are at a low level of coordination. He suggested that the proposed city should return farmland to forests, accelerate the pace of industrial restructuring, and promote clean production and the circular economy to establish a coordinated development system for the economy and the ecological environment. At present, most of the studies on the coupling and coordination of economy, society, and resources environment are based on one province or one region, and there are few studies on the cities in the River Basin.

3. Research Methods

3.1. Study Area and Data Sources. The Yellow River Basin is divided into three parts: upper, middle, and lower reaches. The upper reaches include Xining, Lanzhou, and Yinchuan; the middle reaches include Hohhot, Taiyuan, and Xi'an; and the lower reaches include Zhengzhou, Qingdao, and Jinan (see Figure 1). In terms of ecological environment, most of the cities in the upper reaches of the Yellow River Basin have good vegetation coverage and good air quality. Due to the economic development in the middle reaches, the resources and environment have deteriorated. Due to the severe water loss and soil erosion caused by the dam construction in the lower reaches of the Yellow River, a large amount of sediment was transported to the lower reaches of the Yellow River, and the silt accumulation was severe. In terms of economy and society, the upper reaches have a slower economic development, while those in the middle and lower reaches are at a more advanced level. The GDP and medical education resources in the upper Yellow River Basin cities are relatively backward compared with those in the middle and lower reaches. Xi'an, located in the middle reaches of the Yellow River Basin, is a famous historical and cultural city and a gathering area of colleges and universities. Zhengzhou, located in the Central Plains, has seen rapid growth in the manufacturing and transportation sectors in recent years. Moreover, located in the lower reaches of the Yellow River Basin, Jinan and Qingdao have distinct advantages in three areas: manufacturing, financial services, and tourism.

The quantitative indicator data used in this study are all from the China Statistical Yearbook (2010–2017), China City Statistical Yearbook (2010–2017), Provincial Water Resources Bulletin (2010–2017), National Economy and Resources Development Bulletin (2010–2017), and relevant data website of the National Bureau of Statistics (2010–2017).

3.2. Evaluation Index System. To accurately evaluate the interrelationship between social economy and resources and environment, two indicator systems for social economy and resources environment have been established, as shown in Table 1.

3.3. Model Development

3.3.1. Index Data Process. Consider

$$X_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})}, \tag{1}$$

$$X_{ij} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})}, \tag{2}$$

where x_{ij} is the original index value and X_{ij} is the normalization value. The benefit indexes are calculated by formula (1), while cost indexes are calculated by formula (2).

3.3.2. Index Weight. Consider

$$e_j = -k \sum_{i=1}^{n} \left(p_{ij} \ln p_{ij}\right), \tag{3}$$

$$w_j = \frac{1 - e_j}{\sum_{j=1}^{m} \left(1 - e_j\right)}. \tag{4}$$

In formula (3), $k = (1/\ln n)$, $p_{ij} = (y_{ij}/\sum_{i=1}^{n} y_{ij})$. If $p_{ij} = 0$, then define $\lim_{p_{ij} \longrightarrow 0} p_{ij} \ln p_{ij} = 0$. In formula (4), the weight w_j complies with the following conditions: $0 \leq w_j \leq 1$ and $\sum_{j=1}^{m} w_j = 1$.

3.3.3. Comprehensive Development Index. Consider

$$\begin{aligned} S &= \sum_{i=1}^{n} X_{ij}^{s} w_{j}^{s}, \\ E &= \sum_{i=1}^{n} X_{ij}^{e} w_{j}^{e}. \end{aligned} \tag{5}$$

where S, E are social economy level and resources environment level, respectively.w_j^s, y_{ij}^s are the weight and normalization value of index in social economy level, respectively.w_j^e, y_{ij}^e are the weight and normalization value of the index in the resources' environment level, respectively.

3.3.4. Coupling Coordination Model. This study adopts the coupling coordination model [21].

$$C = \left\{ \frac{S \cdot E}{[(S + E)/2]^2} \right\}^{1/2},$$
$$T = \alpha U + \beta E, \tag{6}$$
$$D = \sqrt{CT},$$

C is the coupling value, between 0 and 1. α and β are the coefficients to be determined, 0.5 and 0.5, respectively. T is the comprehensive coordination index of social economy and resources environment. D is the degree of coupled coordination. According to the relevant research [22], the coupling degree classification is shown in Table 2. The coupling coordination degree classification is shown in Table 3 [23].

3.3.5. Obstacle Degree Model. In order to improve the coupling coordination of the social economy and resource environment of central cities in the Yellow River Basin, it is essential to study the main reasons that hinder the social economy level and resource environment level. Barrier degree model is to filter out the factors that hinder the development of the goal. Therefore, the obstacle degree model is used for further analysis, where W_j denotes the factor contribution, which is the weight of the indicator, $1 - X_{ij}$ represents the deviation of the indicator, which is the gap between a single indicator and the desired target, and the barrier degree (Q_j) is the value of the impact of a single factor on the social and economic level and the level of resources and environment.

$$Q_j = \frac{W_j\left(1 - X_{ij}\right)}{\sum_{j=1}^{m} W_j\left(1 - X_{ij}\right)}. \tag{7}$$

4. Results and Findings

4.1. Temporal Characteristics Analysis. In this study, the collected data were used to calculate the development index, coupling degree, and coupling coordination degree of social economy and resource environment in nine central cities of the Yellow River Basin from 2010 to 2017.

The social economy development indexes of the nine central cities in the Yellow River Basin maintained an upward trend, as shown in Figure 2. The rapid social economy development of the cities from 2010 to 2015 was mainly due to the national regional development strategy from 2011, such as promoting a new round of Western development and vigorously promoting the rise of the central region. The Yellow River Basin spans the east, middle, and west of three economic zones of China, which provide a solid foundation for rapid economic development. During this period, Taiyuan rose faster, from 0.037 to 0.477. The rising of Yinchuan was the least, from 0.092 to 0.332. After 2015, the economic growth rate of the nine cities slowed down, but the economic growth momentum was still relatively stable. The main reason was that after years of rapid development, the Chinese economic development had entered a new trend of slower economic growth, continuous optimizing and upgrading of the economic structure, greening of the energy structure, and moving from rapid economic development to sustainable development. In 2017, Hohhot and Jinan had a downward trend. The social economy development index of Hohhot decreased mainly due to a 20.03% drop in per capita investment in fixed assets and the per capita general budget income of the local fiscal authorities fell by 25.29%. The growth rate in Qingdao did not slow down, with the economic and social development index increasing from 0.2985 to 0.4266.

In terms of the trend of resource and environment index in the central cities of the Yellow River Basin (Figure 3), it showed a fluctuating upward trend. Xining and Lanzhou had the largest increase. Xi'an and Taiyuan followed a steady upward trend. Due to the dry climate in Yinchuan, the total amount of water resources fluctuates wildly, resulting in a more obvious up and down fluctuation of the resource and environment index. In 2010–2014, Hohhot, Jinan, Qingdao, and Zhengzhou increased slowly. After 2015, the resource and environment development index increased significantly due to the reduction of industrial wastewater emissions and industrial sulfur dioxide emissions. In 2016–2017, the resource and environment development index of all the central cities was on an upward trend, which was related to the slow down of Chinese economic development, to construct ecological civilization and green cities.

As shown in Table 4, from 2010 to 2017, most of the cities were at the stage of coordinated coupling, among which Xining and Lanzhou had the highest coupling, indicating that the gap between the economic and social levels of these two cities and the level of resources and environment was not large. In this paper, the coupling coordination values were presented in colors, and the plots in Figure 4 indicated which values are represented by the various colors. In this paper, the coupling coordination levels were classified based on Table 3. From the change of coupling coordination degree, all nine cities were in an increasing trend of coupling coordination, but the increase varied. Yinchuan rose less, and the coordination level rose from mild coordination to primary coordination. Huhehaote rose more, with the coordination level rising from extremely disordered to primary coordination. Specifically, from 2010 to 2012, cities were mostly at the moderate and mildly dysfunctional stage. In 2013, cities were mostly on the verge of a dysfunctional stage. From 2014 to 2017, the coordination level of cities kept increasing, and all cities gradually entered the primary coordination stage. In general, the coupling coordination of cities had been rising, which indicated that the coupling coordination had been moving in a good direction. However, the coupling coordination was in the excessive type and had not yet reached the intermediate coordination stage. Due to the less stable resource and environmental development index, central cities need to reduce environmental pollution and achieve high-quality urban development along with economic development.

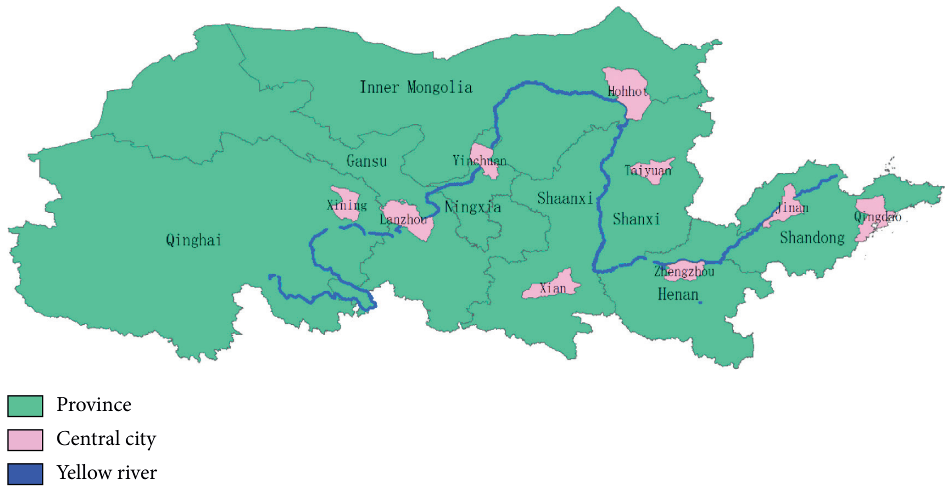

Figure 1: The research area of the central cities in the Yellow River Basin.

Table 1: Index system of social economy and resources environment.

Index system	Index (code)	Unit	Description	Index type	References
Social economy	Per capita GDP (x1)	10^4 yuan	Economic level of a city	+	Li et al. [13]
	Proportion of the tertiary industry output in GDP (x2)	%	Structure of industry	+	Hu [15]
	General local budget revenue of per capita (x3)	10^4 yuan	Level of government revenue	+	Ta and Ning [16]
	Per capita of fixed assets investment (x4)	10^4 yuan	Economic development capacity of a city	+	Zhang et al. [17]
	Urbanization rate (x5)	%	Level of urbanization	+	Zhang et al. [17]
	Population natural growth rate (x6)	%	Population growth	–	Li et al. [13]
	Per capita retail sales of social consumer goods (x7)	Yuan	Levels of people's material and cultural life	+	Li et al. [13]
	Per ten thousand people of college students (x8)	Unit	Educational attainment of the population	+	Qi et al. [18]
	Number of health facilities per ten thousand people (x9)	Unit	Reflection of medical services	+	Huang et al. [19]
Resources and environment	Per capita of park and green land (x10)	m^2	Greening of the park	+	Li et al. [13]
	Green coverage rate in city (x11)	%	Efforts on afforestation of city	+	Ta and Ning [16]
	Ratio of industrial solid wastes comprehensively utilized (x12)	%	Efforts on pollution abatement	+	Zhang et al. [17]
	Urban sewage treatment rate (x13)	%	Efforts on pollution abatement	+	Li et al. [13]
	Industrial wastewater emissions per unit of GDP (x14)	Ton	Pollutant emission in industrial production process	–	Ma and Xu [8]
	Per capita of water resources (x15)	m^3	Water resources	+	Wang and Liu [20]
	Water consumption per unit of GDP (x16)	Ton	Water use in municipal districts	–	Ta and Ning [16]
	Per capita of industrial sulfur dioxide emission (x17)	Ton	Pollutant emission in industrial production process	–	Hu [15]

4.2. Spatial Analysis of Coupling Coordination. To further study the spatial differences in coupling coordination, this study selected four years data of the cities and used ArcGIS software to plot the spatial distribution of coupling coordination levels (see Figures 5–8).

In general, the coupling coordination degrees of cities have all improved. The coupling coordination started with a distribution pattern of high in the central part and low in the west. As the coupling coordination of upstream cities increases, the middle and upper reaches of the Yellow River

Table 2: Classification of coupling degree.

Coupling degree	Coupling type	Description
0–0.29	Low coupling	The two subsystems are starting to game, and the coupling is at a low level
0.3–0.49	Antagonism stage	The interaction between the two subsystems intensifies, with the dominant subsystem beginning to occupy space in the other subsystem and the other subsystem declining
0.5–0.79	Running-in stage	The two subsystems check and coordinate with each other and exhibit positive coupling characteristics
0.8–1	Coordinated coupling stage	The benign coupling between the two subsystems becomes stronger and gradually develops in an orderly direction and is at a high level of coupling and coordination

Table 3: Coupling coordination degree classification.

Type	D	Degree	Relationship of S and E	Description
Dissonance recession	0–0.09	Profound incoordination	$S > E$	Resources and environment lag
			$S < E$	Social economy lag
			$S = E$	Coordination development
	0.1–0.19	Serious incoordination	$S > E$	Resources and environment lag
			$S < E$	Social economy lag
			$S = E$	Coordination development
	0.2–0.29	Moderate incoordination	$S > E$	Resources and environment lag
			$S < E$	Social economy lag
			$S = E$	Coordination development
Transitional category	0.3–0.39	Mild incoordination	$S > E$	Resources and environment lag
			$S < E$	Social economy lag
			$S = E$	Coordination development
	0.4–0.49	On the verge of incoordination	$S > E$	Resources and environment lag
			$S < E$	Social economy lag
			$S = E$	Coordinated development
	0.5–0.59	Reluctant coordination	$S > E$	Resources and environment lag
			$S < E$	Social economy lag
			$S = E$	Coordinated development
	0.6–0.69	Primary coordination	$S > E$	Resources and environment lag
			$S < E$	Social economy lag
			$S = E$	Coordinated development
Coordinated development	0.7–0.79	Intermediate coordination	$S > E$	Resources and environment lag
			$S < E$	Social economy lag
			$S = E$	Coordinated development
	0.8–0.89	Good coordination	$S > E$	Resources and environment lag
			$S < E$	Social economy lag
			$S = E$	Coordinated development
	0.9–1	Quality coordination	$S > E$	Resources and environment lag
			$S < E$	Social economy lag
			$S = E$	Coordinated development

had a higher coordination level than the lower reaches. Finally, the pattern of the same coordination level was reached uniformly. In 2010, only the cities of Yinchuan, Zhengzhou, and Xi'an in the middle of the Yellow River Basin were at the stage of mild dissonance, while the rest were at the stage of extreme and moderate dissonance. In 2012, Taiyuan and Hohhot in the middle reaches of the Yellow River Basin and Xining in the upper reaches had a significant increase in coupling coordination. In 2015, only Qingdao, which is in the lower reaches of the Yellow River Basin, was at the near-dissonance stage, while the rest of the cities were at the barely coordinated stage. In 2017, all cities reached primary coordination.

The development types of cities were also different. Most cities changed their development type from economic and social lagging to resource and environmental lagging, and some cities reached synchronous type. In 2010, the central cities were economic and social lagging type. In 2012, with the development of economic level, the economic and social indexes of Zhengzhou, Xining, and Hohhot cities began to be larger than the resource and environment indexes, and the development type changed to resource and environment lagging type. The development type of Lanzhou and Xi'an basically reached the synchronous type of economic society and resource environment. In 2015, the economic and social indexes of the central cities in the Yellow River Basin further increased, and the development type of the cities was resource-environment lagging type. In 2017, as China began to slow down its economic growth after years of high-speed development, it began to promote the green development of

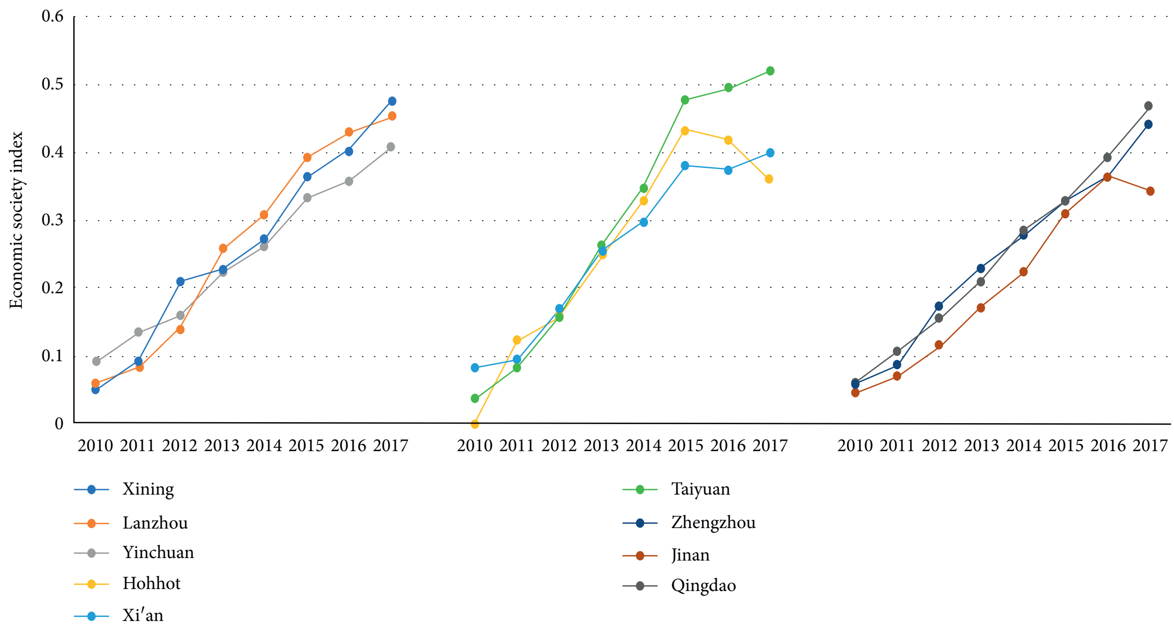

Figure 2: Change trend of comprehensive level social economy.

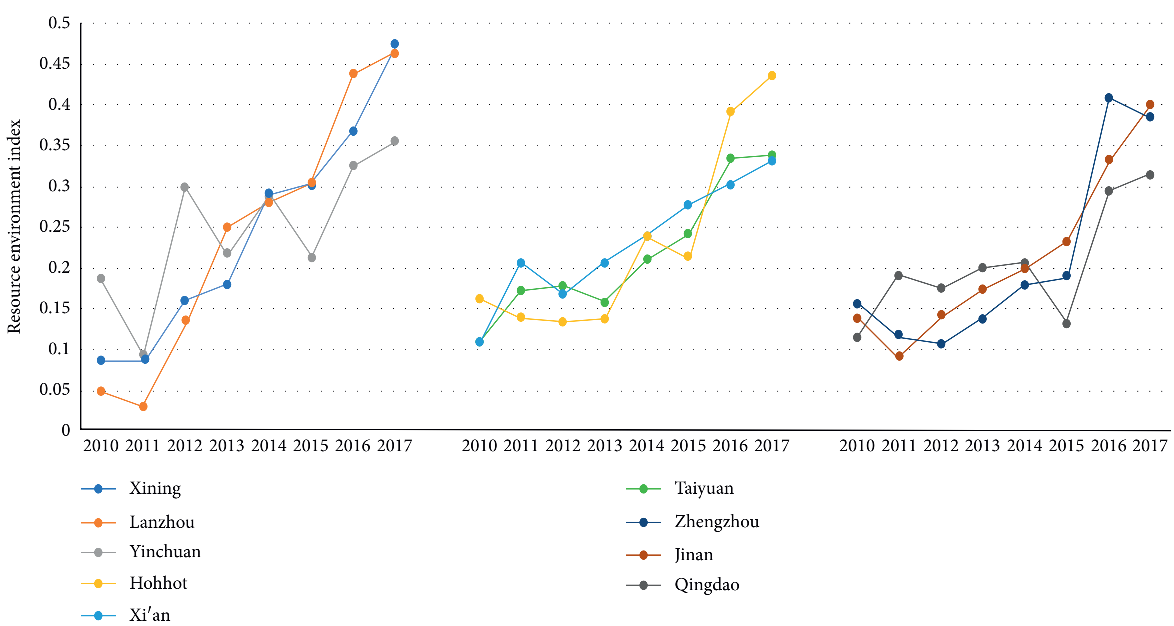

Figure 3: Change trend of the comprehensive level of resources environment.

Table 4: Coupling degree of social economy and resources environment.

Years	Taiyuan	Jinan	Qingdao	Zhengzhou	Lanzhou	Hohhot	Xi'an	Xining	Yinchuan
2010	0.871	0.867	0.951	0.885	0.993	0.000	0.993	0.965	0.941
2011	0.940	0.992	0.960	0.989	0.865	0.998	0.931	0.999	0.981
2012	0.998	0.995	0.999	0.968	1.000	0.997	1.000	0.990	0.952
2013	0.967	1.000	1.000	0.967	1.000	0.955	0.994	0.993	1.000
2014	0.969	0.998	0.987	0.975	0.999	0.987	0.994	1.000	0.999
2015	0.943	0.989	0.901	0.962	0.992	0.940	0.988	0.995	0.975
2016	0.981	0.999	0.990	0.998	1.000	0.999	0.994	0.999	0.999
2017	0.977	0.997	0.981	0.998	1.000	0.996	0.996	1.000	0.997

Figure 4: Coupling coordination of social economy and resources environment.

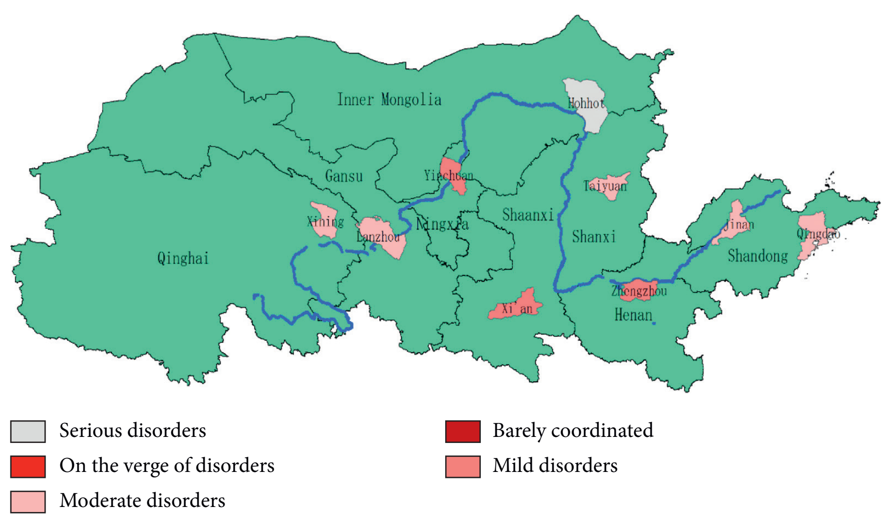

Figure 5: Coupling coordination level of central cities in the Yellow River Basin in 2010.

energy structure. The rise of resource and environment indexes in Jinan and Lanzhou increased significantly, and the type of urban development changed to economic and social lagging type. Xining had the highest coupling degree and coupling coordination degree and was in the primary coordination stage, and the city development type basically reached the synchronous type of economic society and resources and environment.

4.3. Obstacle Factors Analysis. According to equation (7), the barrier degree value of each central city indicator can be calculated, and finally the average value is obtained to arrive at the combined barrier degree value of each factor from 2010 to 2017, as shown in Figure 9. From 2010 to 2017, the average obstacle degree of resource environment was 6.19%, slightly higher than the social economy obstacle degree of 5.61%, indicating that the resource environment was an essential obstacle factor that restricts the coupling coordination development of the central cities of the Yellow River Basin. All the cities should improve the local resource and environmental conditions while achieving substantial social economy development in the future. In terms of the annual average obstacle level, among the social economy indicators, the natural population growth rate, the share of tertiary industry in the GDP, and the per capita fixed asset

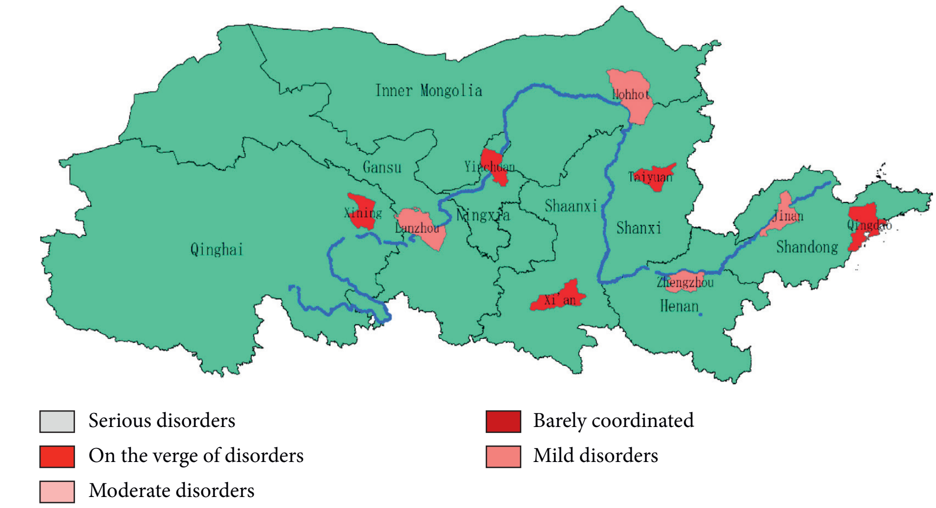

Figure 6: Coupling coordination level of central cities in the Yellow River Basin in 2012.

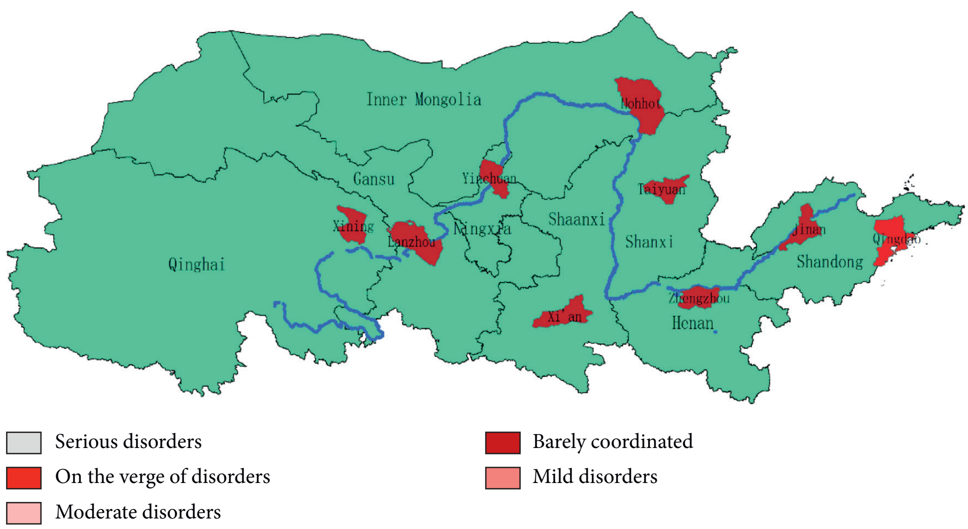

Figure 7: Coupling coordination level of central cities in the Yellow River Basin in 2015.

investment are the most crucial obstacle factors, with the multiyear average obstacle degree of 9.86%, 8.73%, and 5.65%, respectively. As to the resource and environment indicators, the per capita green park area, the per capita total water resources, and the per capita industrial SO_2 emissions are the most critical obstacle factors, with the average obstacle degree of with multiyear average barrier factors of 9.19%, 7.95%, and 8.28%, respectively.

In terms of obstacle factors, population natural growth rate, per capita green park area, the proportion of tertiary industry in GDP, per capita industrial SO_2 emissions, and per capita total water resources are the top five obstacle factors, with two factors in the social economy system and three factors in the resources and environment system. It was demonstrated that there is a need to maintain a balanced development while focusing on resources and environmental protection. From 2010 to 2017, the proportion of the tertiary industry in the GDP, per capita green park area, and per capita industrial SO^2 emissions are in the top five obstacle factors for accumulated six times. The indicator of total water resources per capita ranked the top five obstacle degrees five times in the past five years. The obstacle degree of this factor was greater than 10% in the past three years. The obstacle degree of total water resources per capita reached a peak of 16.10% in 2016, indicating that this indicator will be an essential obstacle factor for the coupling coordination development of the region in the future. The indicator of natural population growth rate ranked at the top of five obstacles' degrees in the past three years, with the obstacle degree being more significant than 10%. In 2016 and 2017, it even reached 19.78% and 33.82%. There is no doubt that the high natural population growth rate will become one of the primary factors that hinder the coupling coordination of economic–social and resource environment. From 2010 to 2016, three indicators: per capita local budget revenue, general industrial solid waste utilization rate, and centralized wastewater treatment rate did not appear in the top five obstacles, but

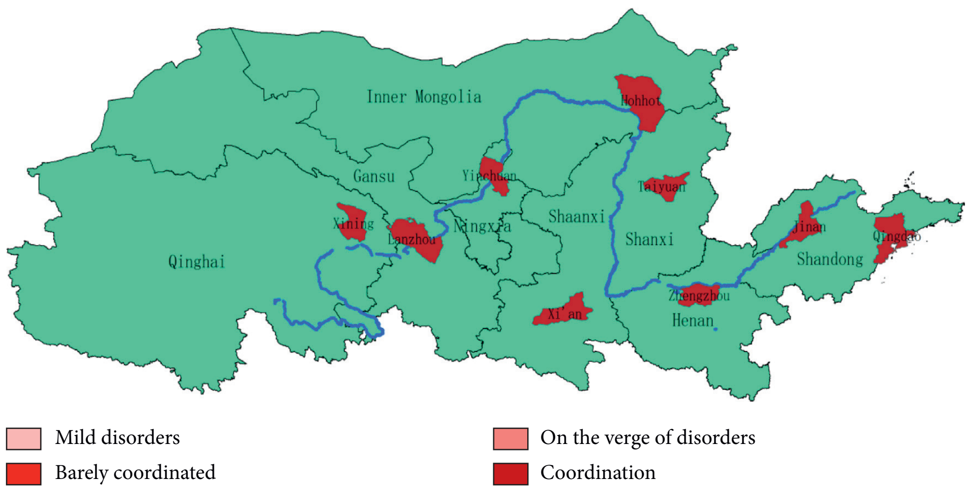

Figure 8: Coupling coordination level of central cities in the Yellow River Basin in 2017.

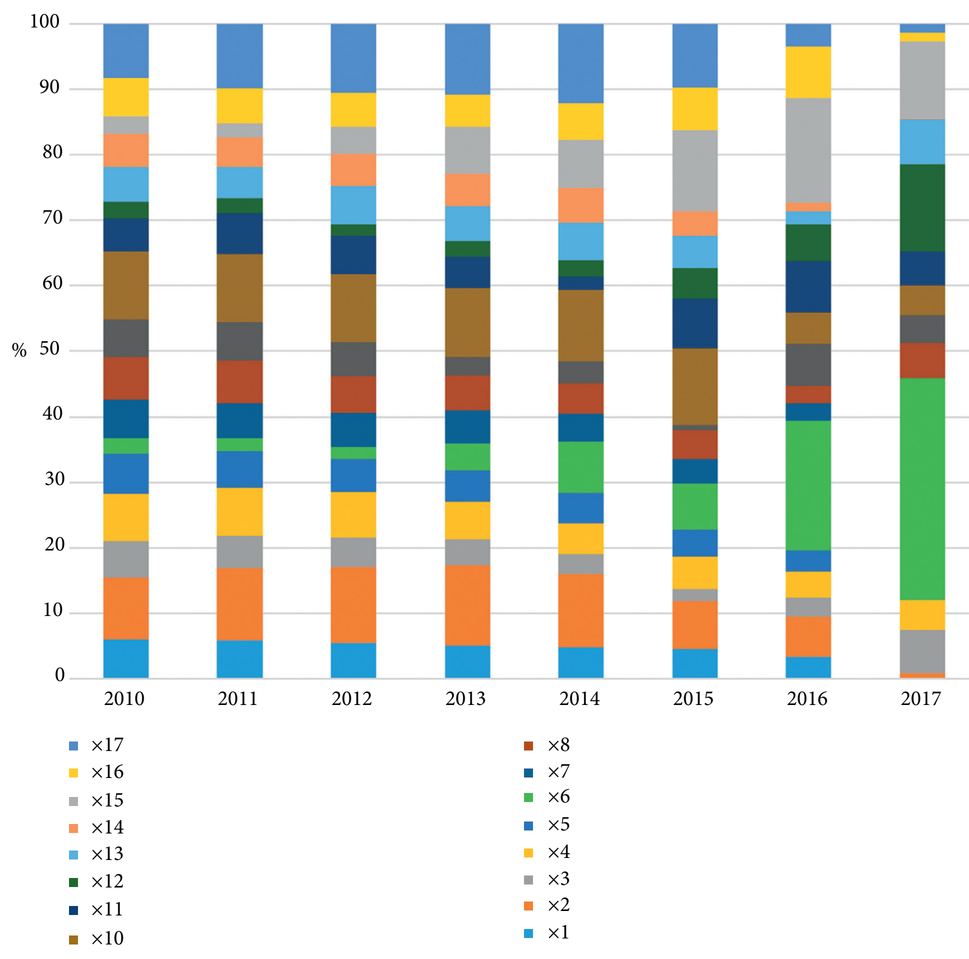

Figure 9: The degree of obstacle factors for coupling coordination development of central cities in the Yellow River Basin. X1–X17 presented factors in the index system in Table 1.

the three indicators were in the top five in 2017. The general industrial solid waste utilization rate of the obstacles even reached 13.35%, indicating that the three indicators are likely to become the main obstacle to coupling coordination development of central cities in the Yellow River Basin.

5. Discussion

The economic level of the nine central cities in the Yellow River Basin has developed rapidly because of the improvement of education level, health, and other public services infrastructure. Although Chinese economic strength has been improving and strengthening, there are still problems such as energy consumption and short industrial chains [3]. The Yellow River Basin is rich in energy and mineral resources. The cities in the middle and upper reaches of the river mainly focus on resource-based industries such as energy mining and processing. But the shortage of water resources in the Yellow River Basin and uneven spatial and temporal distribution limited the development of industries. The development of industrialization further increases the pressure on the environment [24]. Therefore, the promotion of new industrialization is of great significance to the sustainable development of cities. With the implementation of the 13th Five-Year Plan policies, the country has begun to focus on adjusting the economic structure, increasing environmental protection, and reducing pollutant emissions [25]. From the above results, since 2016, the economic development in the central cities of the Yellow River Basin has begun to slow down. The economic development model has begun to change. So, the environmental situation has improved significantly. In 2019, China proposed to strengthen ecological and environmental protection and promote high-quality urban development [26]. The importance of the development of the Yellow River Basin in China was emphasized once again. If only the coordinated development of the economy and resources and environment would be adequately handled, can we ensure the healthy development of the Yellow River Basin and improve people's living standards.

The coupling coordination degree of the central cities in the Yellow River Basin was on the rise as a whole, from the social economy lag to the resource and environment lag type. However, due to geographical location differences, the degree of coupling coordination also differs. In order to achieve high-quality urban development, it is necessary to fully consider the natural resources, culture, and other differences between the central cities of the Yellow River Basin and find a suitable development model. Cities in the middle and upper reaches of the Yellow River can improve the construction of new energy industries such as wind energy and solar energy, promote the extension of the nonferrous metal industry chain, speed up the technological transformation of the industry, and improve the market competitiveness of heavy industry. Cities in the lower reaches of the Yellow River can focus on developing electronic information, food, automotive, and other service industries to the high end of the value chain and expand biomedicine, real estate for the elderly, modern logistics, and other emerging industries. Central cities can also develop cultural tourism and ecotourism according to local characteristics and improve the high-quality development of agricultural storage products.

The obstacle factors should be investigated to improve the coupling coordination development. As to the natural population growth rate, the population cannot be increased significantly due to the fragile resources and environment of the local cities. The proportion of tertiary industry to GDP reflects the level of development of the service industry in the city area. To improve the level of coordinated development of the city, we need to pay attention to the development of the service industry in the city and ensure the rationalization of the industrial layout. The per capita green space area reflects the per capita occupancy of green space in cities and towns, indicating that the central cities in the Yellow River Basin need to improve the environmental carrying capacity of each city. The urban can better carry the economic and social development and the pressure of population and resources. The per capita industrial SO_2 emissions reflect the amount of sulfur dioxide emitted into the air by enterprises in the process of fuel combustion and production process, indicating that the government needs to adjust industrial policy, reduce the number of enterprises with high energy consumption, vigorously promote the development of energy-saving enterprises, and promote the implementation of various environmental protection measures. The per capita water resource reflects the regional water resources level, indicating the need to vigorously promote water conservation in all industries and improve overall water use efficiency. Besides, more investment and construction of urban wastewater treatment plants are needed to increase the centralized wastewater treatment rate. A significant measure is to increase the amount of investment in the solid waste disposal and to improve the promotion, popularization, and implementation of waste utilization to increase the overall utilization rate of general industrial solid waste. The city administration should increase the attractiveness of the city, intensify the introduction of foreign capital, and improve the per capita local budget revenue by increasing taxes.

6. Conclusion

In recent years, the rapid economic and social development of China has led to a series of resource and environmental problems, such as air pollution, water shortage, etc. Coordinating the relationship between social economy development and resources environment has become a hot topic of concern. Therefore, it is of great significance to study the coupling coordination relationship between social economy development and resources environment in order to achieve sustainable development. This study firstly constructed the evaluation system of social economy and resource environment and adopted the coupling coordination degree model to study the changes of coupling coordination degree of social economy and resource environment in nine central cities in the Yellow River Basin from 2010 to 2017. Moreover, based on the changes of the coupling coordination degree of the central cities in the Yellow River Basin in 2010, 2012, 2015, and 2017, the spatial differences of the nine central cities were compared and analyzed. The study showed that (1) the social economy development index of central cities in the Yellow River Basin maintained an upward trend from 2010 to 2017. The economic development was faster in 2010–2015 and slowed down after 2015, but still in an upward trend. (2) The resource and environment development index of the central cities of the Yellow River Basin showed a fluctuating upward trend. After 2015, the growth rate of the resource and environment index of most cities begun to accelerate. (3) The overall coupling coordination of central cities in the Yellow River Basin is on an upward trend, with most cities rising from moderate dissonance to primary coordination stage. (4) In 2010, the coupling coordination of Xining and Lanzhou was generally lower than that of other central cities except for Hohhot. In the following years, the coupling coordination degree of Xining and Lanzhou increased significantly, indicating that the central cities in the upper Yellow River Basin have great potential for development.

This study makes three research contributions as follows: (1) this study conducts an evaluation index system of social economy and resource and environment to investigate the coupling coordination of them. The social economy subsystem includes social, economic, educational, and medical, involving all aspects of human activities. The resource and environment subsystem index system reflects the development level of the resource and environment from the state of the resource and environment, pressure, and governance aspects. (2) In this study, the coupling coordination degree model was used to calculate the coupling degree and coupling coordination degree of social economy and resource environment for nine central cities in the Yellow River Basin from 2010 to 2017. The changes in the social economy and resource environment of the central cities of the Yellow River Basin were analyzed in spatial and temporal dimensions, respectively. (3) To explore the obstacle degree of the coupled coordination in central cities of the Yellow River Basin, this study introduced the obstacle degree model. The results obtained can provide a targeted reference for policy decision-making in the central cities of the Yellow River Basin, which is conducive to promoting the high-quality development of the relevant cities.

The present study still has research limitations. The first is that the urban social economy and resource environment are two very complex systems. Future studies will focus on the interactive coercive relationship between the two systems. Second, this study only collected several years of data, which is a short time series. In the future, more years of data can be collected and panel data analysis can be conducted to produce more reliable results.

Data Availability

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

Conflicts of Interest

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

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Research Article

Environmental Risk Assessment of Subway Station Construction to Achieve Sustainability Using the Intuitionistic Fuzzy Analytic Hierarchy Process and Set Pair Analysis

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Environmental risks have a significant impact on the sustainability of subway station construction projects. This paper proposes an environmental risk assessment model based on the intuitionistic fuzzy analytic hierarchy process (IFAHP) and set pair analysis (SPA) to deal with the ambiguity and uncertainty in the assessment. An index system for environmental risk assessment is established based on a literature review and the rough set method. Subsequently, the IFAHP is used to calculate the indicator weights to describe the certainty, uncertainty, and hesitation degree of expert decisions in the weighting calculation by means of affiliation, nonaffiliation, and hesitation. Finally, SPA, which can deal with the randomness, uncertainty, and ambiguity of the indicators, is used to assess environmental risk. A case study of two typical stations (Lushan Avenue Station and Huilong Road West Station) of Metro Line 11 in Chengdu, China, is conducted. The case study results are consistent with field surveys. The evaluation results of the proposed model are more objective and reasonable than those of the traditional analytic hierarchy process, the entropy weight method, fuzzy comprehensive evaluation, grey correlation analysis, and technique for order of preference by similarity to an ideal solution (TOPSIS). The research results prove the scientific validity and superiority of the proposed model.

1. Introduction

A subway station is a large, multilayered underground structure and an important component in subway construction projects [1]. Due to the large construction scale and open construction site, subway station engineering is susceptible to environmental influences during construction, which may affect the sustainability of subway station construction projects [2]. The environmental risks of metro station engineering are related to the external environment, such as geological conditions [3], the hydrological environment [4], and many other factors. These factors could easily lead to construction safety accidents, construction efficiency decline, and other adverse events. Then, these adverse events presumably disrupt the sustainability of subway station construction projects and cause the loss of life and property in the construction site. The research on environmental risks is an important way and guarantee to achieve the sustainability of subway station construction projects.

At present, engineering practice uses on-site investigation and verification of major hazard sources in subway station construction to identify and evaluate environmental risks. However, these qualitative and passive methods may be unable to deal with the challenges of numerous risk factors and the randomness, vagueness, and uncertainty. Therefore, to achieve sustainability of subway station construction projects, this paper proposes an environmental risk assessment of subway station engineering based on the intuitionistic fuzzy analytic hierarchy process (IFAHP) and the set pair analysis (SPA) to deal with the ambiguity and uncertainty of environmental risk assessment of subway station construction.

Scholars often assess environmental risks as part of construction risks or construction safety risks. Shen et al. [1] discussed five dimensions of environmental risks, that is, foundation pit construction risks, structural construction risks, ancillary facilities and equipment risks, environmental risks, and geological and natural risks. The risks of subway pit construction were assessed, but the environmental risk was considered part of the construction risk. Pan et al. [5] analyzed the main risk factors that might cause accidents in the construction of subway shield tunnels regarding human, mechanical equipment, environmental, and management factors. The definition of environmental risk was similar to that used in this study. Wu et al. [6] analyzed the influence of geological environment risk factors on the cost of the Fangshan subway line project. Hu and Duan [7] adopted a fuzzy evaluation method to assess and classify the risk sources for a metro tunnel crossing an existing highway; the study considered the impact of the geological environment on the construction of a metro tunnel as a construction risk. Niu et al. [8] introduced the Kent method to evaluate the safety risk in a new subway tunnel that was close to an existing tunnel. In that paper, environmental risk was a part of safety risk. Luo et al. [9] developed a safety risk assessment model using the analytic hierarchy process (AHP) and fuzzy matter-element method (FMEM). To the best of the authors' knowledge, no research has been reported to date on environmental risk assessment of subway station construction.

The weight calculation of the evaluation indicators is a key task in risk assessment, directly affecting the scientific validity of the evaluation results. Traditional methods for calculating the risk factor weights include the AHP [10–12], the Delphi method [13], and the fuzzy analytic hierarchy process (FAHP) [14, 15]. These subjective weighting methods rely heavily on the experts' empirical decisions and do not represent an accurate weighting approach. The inability to define the hesitation factor and vagueness in the expert's description regarding the importance of the indicator may be the main source of the highly subjective nature of these methods. Objective calculation methods, such as the entropy weighting method [3], are often used to calculate the weights of construction risks in metro projects. However, these objective weighting methods often have two shortcomings: they do not use expert knowledge, and the results are difficult to interpret [16]. Intuitionistic fuzzy analysis, which takes into account the subjective decisions and choices of decision-makers and the influence of the fuzzy nature of preferences on the weighting process, has been increasingly used for the weighting of indicators in recent years. Intuitionistic fuzzy analysis integrates not only expert knowledge but also minimizes subjective decisions through accurate and objective processing. Ohta et al. [17] introduced four kinds of AHP: classical AHP, FAHP, IFAHP, and hesitant fuzzy AHP (HFAHP) in the actual factory maintenance management application. It provides a reference for the application of related theories in management, engineering, and other fields of social sciences. Yu et al. [18] considered the hesitation and consistency test of the evaluation experts in the index comparison process in the index evaluation process. The use of IFAHP does not need to invite experts to repeat the score, reducing human intervention, and the evaluation process is simpler and more objective. Xu et al. [19] used IFAHP to comprehensively evaluate the development performance of GVCGF. The results show that the development performance of GVCGF is at a "relatively high" level. Compared with the traditional analytic hierarchy process, IFAHP effectively avoids the false expansion of the impact caused by the subjectivity of the data and the uncertainty of the evaluation.

The choice of risk assessment model is another crucial task in the environmental risk assessment of metro station construction projects. Luo et al. [9] used the FMEM to calculate the correlation between the geo-environmental risk indicators and classify the risk level of the indicators to determine the project's risk level. Since it is difficult to obtain accurate engineering data in construction engineering, Wang & Chen [20] proposed a systematic decision support method based on a fuzzy integrated Bayesian network (FCBN), which combines the fuzzy integrated evaluation method (FCEM) and Bayesian network (BN), to analyze the safety risk of subway construction projects under uncertain conditions. Wu et al. [21] proposed a fuzzy analytic network process comprehensive evaluation (FANPCE) model for risk assessment of subway station construction. Qin et al. [22] proposed a new decision model combining an interval type-2 fuzzy set and the TOPSIS method to assess the dynamic risks of metro stations. Huang et al. [23] used the AHP and grey theory to analyze construction safety risk in China's construction industry. The results of this method are better than the safety checklist method, which is one of the most commonly used methods in engineering practice but has the shortcoming of not accurately portraying the experience and decision of experts, resulting in highly subjective calculation results. Sun et al. [24] emphasized that important tools for handling uncertain and fuzzy information such as hesitant fuzzy sets should be introduced into classic evaluation methods, which can significantly improve the accuracy and reliability of traditional evaluation methods. At present, the methods of subway construction environmental risk assessment mostly use fuzzy evaluation. However, due to different risk factors in different subway projects, the risk factors are often random and complex, and the factors influencing construction risk factors have both certainty and uncertainty information. Therefore, the description of the general evaluation method is not adequate, and it is difficult to evaluate the deterministic and uncertain characteristics of the risk influencing factors comprehensively.

The SPA can accurately depict the relationship between certainty and uncertainty and provides a new method to assess the environmental risk of metro construction. The SPA has been widely applied in many fields. Wang [2] used the SPA for risk assessment of karst tunnel flooding. X. F. Chen and W. T. Chen [25] argued that most blasting safety evaluation studies only considered the vagueness of the influencing factors of blasting safety. Thus, they proposed an assessment model of blasting safety based on the SPA. Wang et al. [26] considered the uncertainty of the risks caused by subway construction to nearby buildings and proposed the use of SPA to evaluate the safety of cultural relics adjacent to subway construction. The results show that the effectiveness of the model provides decision support for controlling the risks of similar projects.

The main contributions of this study are as follows. (1) We conduct a literature review to determine an initial and common index system for the evaluation of environmental risk in subway station construction. Subsequently, we propose an indicator system for environmental risk assessment of a typical subway station project for the first time, using the rough set method for indicator approximation. (2) An environmental risk assessment model for subway station construction based on the IFAHP and SPA is established. The certainty, uncertainty, and hesitation factor of expert decisions in the weight calculation are considered by determining the degree of affiliation, non-affiliation, and hesitation in the IFAHP. The SPA is selected to deal with the randomness, ambiguity, and incompleteness in the environmental risk assessment of subway station construction. (3) The Lushan Avenue Station and Huilong Road West Station of the Chengdu Metro Line 11 in Chengdu, Sichuan Province, China, are selected as case studies. The results of the case studies show that the frequency of natural disasters has the largest weight (0.183) and is the most important factor affecting the environmental risk of the subway station. The Lushan Avenue Station has a risk level of V (extreme risk) and Huilong Road West Station has a risk level of III (moderate risk). In addition, this paper provides the measures to improve the sustainability of them, based on the calculation results of weights and environmental risks.

The remaining sections of this paper are arranged as follows. Section 2 describes the materials and methods, including the establishment of an environmental risk assessment index system for the metro station and an assessment model based on the IFAHP and the SPA. Section 3 describes the case study and provides the measures to improve the sustainability of the Lushan Avenue Station and Huilong Road West Station of Line 11 of the Chengdu Metro in China. Section 4 is a discussion of the results of different weighting methods and evaluation method calculations to highlight the superiority of the proposed models. Section 5 provides the conclusion, summarizing the findings and suggesting future research directions.

2. Materials and Methods

2.1. Environmental Risk Assessment Index System of Subway Station Engineering

2.1.1. Preliminary Selection of Environmental Risk Assessment Index for Subway Station Engineering. The establishment of an evaluation index system is the basis for an environmental risk assessment of subway station construction. The scientific validity and rationality of the index system affect the accuracy of the evaluation results. At present, there is little research on the environmental risk of subway station construction and a lack of a unified and general environmental risk assessment index system. Therefore, we conduct a literature review to obtain information on the construction risks, environmental risks, and the sustainable development of subway station engineering. Subsequently, an initial index system of environmental risk assessment of subway station engineering is established, as shown in Table 1.

2.1.2. Index System Establishment Based on the Rough Set Method. The index system in Table 1 is based on subway construction safety risk and environmental risk in other disciplines; thus, it may not be suitable for subway station engineering. We selected 38 typical subway station projects in China for index screening and developed an index system conforming to the construction characteristics of subway station projects. The 38 subway stations are 17 stations of the Chengdu Metro Line 11, 9 stations of the Wuhan Metro Line 8, and 12 stations of the Wuhan Metro Line 21.

Commonly used index screening methods are divided into two categories: qualitative screening [34, 35] and quantitative screening [36–38]. Qualitative screening relies entirely on expert experience, resulting in highly subjective results. Quantitative screening does not consider expert opinion and experience, and the screening results are difficult to interpret. The rough set does not only avoid the lack of qualitative screening relying on expert experience but also considers the practical experience of industry experts. Therefore, we use the rough set method to screen the environmental risk indices of subway station engineering.

We selected 20 experienced experts who worked in the subway industry for many years. The details of the selected experts are shown in Figures 1–3. Twenty experts scored the importance degree of the indices in Table 1 and reduced the number of indices using Rosetta, a commonly used rough set software.

Rough sets theory is a mathematical method proposed by Polish scientist Z. Pawlak to deal with inaccurate, uncertain, and incomplete data [39]. In the process of rough set reduction, the relationship between evaluation indicators and decision indicators can be established according to methods such as self-information and mutual information, so as to determine the importance of conditional attributes and calculate weights [39]. The basic principle of the rough set method and the index reduction process using the Rosetta software has been described in [39]. Finally, seven indicators were selected to comprise the evaluation index system of the subway station environment. The interpretation of the indices is shown in Table 2.

It should be emphasized that the index system in Table 3 was designed for the 38 typical metro station projects in China. The proposed method can be used to obtain a targeted index system using the information in Table 1 to conduct an environmental risk assessment of other subway station projects.

2.1.3. Environmental Risk Assessment Standards for Metro Station Construction. The environmental risk level is divided into five levels, according to the needs of subway station project management: no risk (I), low risk (II), medium risk (III), high risk (IV), and extreme risk (V). No risk (I) means that the environmental risk is negligible, the sustainability is perfect, and no measures are needed. Low risk (II) means that the potential adverse impacts of

Table 1: Initial index system of environmental risk assessment for subway station engineering.

Indicator	References	Screening results
Harsh hydrological conditions	[27]	Retained
Rainfall	[28]	Deleted
Complex groundwater conditions	[29]	Deleted
Frequency of geological disasters	[30]	Deleted
Adverse geological conditions	[31]	Retained
Adverse geomorphological conditions	[27]	Retained
Distance from a river	[31]	Deleted
Stability of foundation of nearby buildings	[20]	Deleted
Number of obstacles in underground construction	[32]	Deleted
Frequency of natural disasters	[1]	Retained
Frequency of earthquake disasters	[1]	Deleted
Frequency of flood disasters	[1]	Deleted
Frequency of severe weather	[33]	Retained
Abnormal load	[21]	Deleted
Confined construction space	[21]	Deleted
Density of underground pipelines	[30]	Retained
Layout of pipelines	[20]	Deleted
Surrounding roads and traffic conditions	[5]	Deleted
Density of surrounding buildings	[1]	Retained

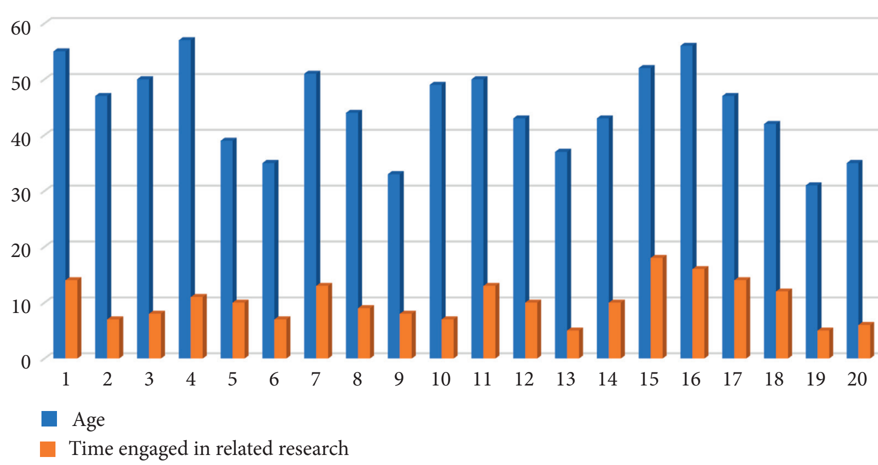

Figure 1: Distribution of age and working years of review experts participating in this project.

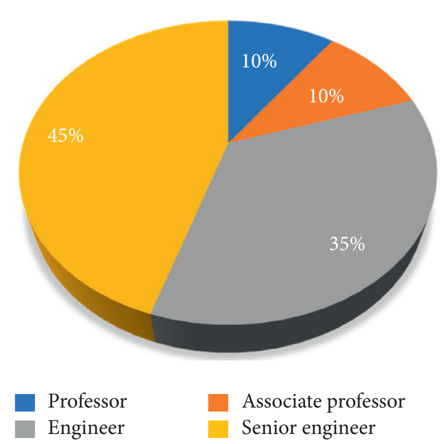

Figure 2: Distribution of expert title.

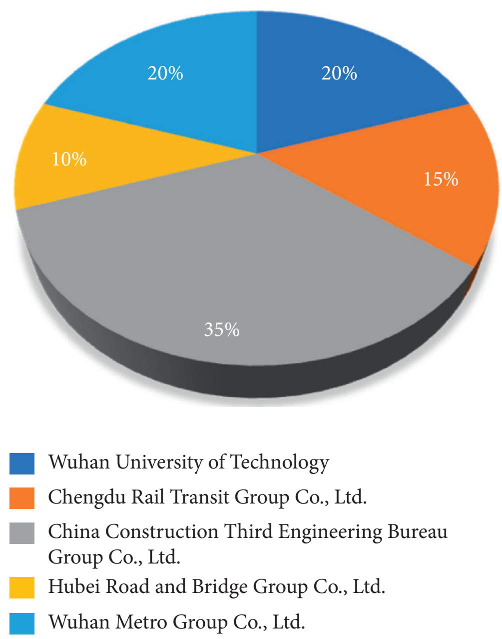

FIGURE 3: Distribution of expert work units.

TABLE 2: Classification standard for environmental risk assessment.

Index	No.	Unit	I	II	III	IV	V
Harsh hydrological conditions	E1	—	No [0, 20)	Few [20, 40)	Moderate [40, 60)	Many [60, 80)	Excess [80, 100]
Adverse geological conditions	E2	—	No [0, 20)	Few [20, 40)	Moderate [40, 60)	Many [60, 80)	Excess [80, 100]
Adverse geomorphological conditions	E3	—	No [0, 20)	Few [20, 40)	Moderate [40, 60)	Many [60, 80)	Excess [80, 100]
Frequency of natural disasters	E4	times/year	[0, 0.1)	[0.1, 0.5)	[0.5, 1)	[1, 2)	[2, +∞)
Frequency of severe weather	E5	times/year	[0, 3)	[3, 6)	[6, 12)	[12, 24)	[24, +∞)
Density of underground pipelines	E6	km/km^2	[0, 1)	[1, 2)	[2, 4)	[4, 8)	[8, +∞)
Density of surrounding buildings	E7	/km^2	[0, 1)	[1, 2)	[2, 4)	[4, 8)	[8, +∞)

environmental risk are acceptable, but project managers should check the implementation of existing environmental management measures in order to maintain the sustainability. Medium risk (III) means that project managers need to decide whether to take further environmental risk response measures to maintain the sustainability. High risk (IV) means that environmental risks are high and the sustainability has been destroyed. If risk is IV, the project management personnel are advised to stop the construction work and take targeted risk response measures, according to the environmental risk assessment results. Extreme risk (V) means that the adverse impact of environmental risk factors is unacceptable. Project management personnel must immediately stop the construction of subway station engineering and take decisive measures to reduce the level of environmental risk.

The opinions of 20 experts were used in accordance with China's national codes (Code for Design of Metro, GB 50157-2013; Technical Guidelines for Environmental Risk Assessment on Projects, HJ 169-2018; standard for sustainability assessment of building project, JGJ/T 222-2011) to develop a classification standard for environmental risk assessment for subway station construction, considering the 38 subway stations (Table 2). E1, E2, and E3 are qualitative indicators, and the risk level description is divided into qualitative descriptions and a quantitative score range. For example, the "no risk" risk level of E1 is described as "no [0, 20)," where "no" is the qualitative description, and [0, 20) is the quantitative score range. If the experts have determined that the risk level E1 is none from their own experience, it means that the index score is between 0 and 20. It must be pointed out that the upper limit of the quantitative indices E4, E5, E6, and E7 has not been determined. Therefore, the upper limit of these indicators is "+∞" in Table 4. When these indicators are used for a case analysis, the upper limit value should be in line with the needs of project management of metro station engineering.

2.2. Environmental Risk Assessment Model of Subway Station Engineering

2.2.1. Introduction to the Intuitionistic Fuzzy Analytic Hierarchy Process. The concept of intuitionistic fuzzy sets was proposed by Bulgarian scholar Atanassov in 1983 [40]; it is an extension of the traditional fuzzy set theory proposed by Zadeh [41]. The traditional fuzzy sets, which only consider the membership, are extended to intuitionistic fuzzy sets that

Table 3: Index system and interpretation of environmental risk assessment for metro stations.

Indicator	No.	Indicator interpretation
Harsh hydrological conditions	E1	Metro stations are usually constructed underground and are substantially affected by hydrological conditions. When the groundwater table is high, measures are required to deal with water inflow, which increases the structural requirements and prolongs the construction period. After lowering the groundwater level, uneven settlement of the surrounding buildings may occur, and the main structure of the station may experience “floating.” Harsh hydrological conditions also adversely affect the stability of the foundation pit support.
Adverse geological conditions	E2	Adverse geological conditions will increase the difficulty of subway station excavation, increase the cost, and prolong the construction period. The worse the geological environment, the more complex the foundation pit support has to be, and the worse the stability is. The supporting structure may not adapt adequately to adverse geological conditions, resulting in geological disasters, such as landslides.
Adverse geomorphological conditions	E3	Adverse geomorphic conditions may cause landslides, waterlogging, and other natural disasters. If the stability of the deep foundation pit of the station project is poor, additional measures are required during project construction, affecting the project cost and the construction period.
Frequency of natural disasters	E4	Typhoons, earthquakes, tsunamis, landslides, mudslides, and other natural disasters may have a devastating impact on the subway station project, and people, materials, and equipment at the construction site may be damaged.
Frequency of severe weather	E5	Low or high temperatures, heavy snow, strong wind (blowing sand), heavy rainfall, and other severe weather does not only reduce the safety of construction workers but also causes accidents and adversely affects the construction cost and construction period.
Density of underground pipelines	E6	Underground pipeline protection is an important aspect of subway station construction. The denser the underground pipelines are, the more difficult the construction is, and the more likely it is that the construction period and cost are affected. Underground pipelines are often municipal pipelines. Once damaged, people, materials, and equipment at the construction site may be seriously damaged, and the daily life of residents may be affected.
Density of surrounding buildings	E7	The greater the density of buildings around the station, the greater the difficulty of construction is, and the more likely it is that the construction period and cost will be affected. The greater the density of the buildings around the foundation pit, the more complex the supporting structure of the foundation pit has to be, and the worse the stability is.

consider membership, nonmembership, and hesitation. Therefore, the intuitionistic fuzzy set method is more flexible and practical than traditional fuzzy sets in dealing with fuzziness and uncertainty. Xu nd Liao developed the IFAHP based on Zadeh’s fuzzy set theory [42].

The basic steps of the IFAHP to calculate the weight of the environmental risk assessment indices of subway station are as follows.

Step 1. Construct intuitionistic fuzzy decision matrix

It is necessary to establish the intuitionistic fuzzy decision matrix to describe the information comprehensively and objectively:

$$\mathbf{Z} = \left(z_{ij}\right)_{n\times n}, \tag{1}$$

where $z_{ij} = (\mu_{ij}, \nu_{ij})$, $i, j = 1, 2, \ldots, n$ represents the evaluation result of the decision-maker after comparing the importance of the two indicators. μ_{ij} denotes the degree of membership, which is the degree of importance of the i index over the j index. ν_{ij} represents the degree of hesitation $\pi_{ij} = 1 - \mu_{ij} - \nu_{ij}$. The evaluation scale used in [43] is used in this study to quantify the importance of the evaluation indicators, as shown in Table 4.

Step 2. Consistency test.

In the IFAHP, it is necessary to test the consistency of the intuitionistic decision matrix to prevent unreliable results or errors. The consistency of the intuitionistic decision matrix is defined as [42]

$$\overline{Z} = \left(\overline{z}_{ij}\right)_{n\times n}, \tag{2}$$

when $j > i + 1$, $\overline{z}_{ij} = (\overline{\mu}_{ij}, \overline{\nu}_{ij})$. Consider

$$\overline{\mu}_{ij} = \sqrt[j-i-1]{\frac{\prod_{t=i+1}^{j-1} \mu_{it}\mu_{tj}}{\sqrt[j-i-1]{\prod_{t=i+1}^{j-1} \mu_{it}\mu_{tj}}\ \sqrt[j-i-1]{\prod_{t=i+1}^{j-1} \left(1-\mu_{it}\right)\left(1-\mu_{tj}\right)}}}, \tag{3}$$

$$\overline{\nu}_{ij} = \sqrt[j-i-1]{\frac{\prod_{t=i+1}^{j-1} \nu_{it}\nu_{tj}}{\sqrt[j-i-1]{\prod_{t=i+1}^{j-1} \nu_{it}\nu_{tj}}\ \sqrt[j-i-1]{\prod_{t=i+1}^{j-1} \left(1-\nu_{it}\right)\left(1-\nu_{tj}\right)}}}, \tag{4}$$

Table 4: The relationship between the evaluation results and the intuitionistic fuzzy number.

Evaluation result	Intuitionistic fuzzy number	Evaluation result	Intuitionistic fuzzy number
Extremely important	(0.90, 0.10)	Less important	(0.40, 0.45)
Very important	(0.80, 0.15)	Unimportant	(0.30, 0.60)
Important	(0.70, 0.20)	Very unimportant	(0.20, 0.75)
More important	(0.60, 0.25)	Extremely unimportant	(0.10, 0.90)
Equally important	(0.50, 0.30)	—	—

when $j = i + 1$ or $j = i$, $\overline{z}_{ij} = z_{ij}$. When $j < i$, $\overline{z}_{ij} = (\overline{v}_{ji}, \overline{v}_{ji})$.

If the distance measure d between $\mathbf{Z}$ and $\overline{Z}$ satisfies $d(\mathbf{Z}, \overline{Z}) < \tau$, the intuitionistic decision matrix meets the consistency requirement. τ is the consistency index threshold, and the value used here is 0.1.

$$d(\overline{Z}, \mathbf{Z}) = \frac{1}{2(n-1)(n-2)} \sum_{i=1}^{n} \sum_{j=1}^{n} \left(\left| \overline{\mu}_{ij} - \mu_{ij} \right| + \left| \overline{v}_{ij} - v_{ij} \right| + \left| \overline{\pi}_{ij} - \pi_{ij} \right| \right). \tag{5}$$

In contrast, when $(\overline{Z}, tZ) \geq \tau$, it is assumed that the consistency of the intuitionistic decision matrix has to be adjusted. The iteration parameter σ is input, and σ is adjusted to change the intuitionistic fuzzy decision matrix until it passes the consistency test. The range of the parameter σ in this study is $\sigma \in [0, 1]$, and an iterative test is performed starting with 1 with a step length of -0.01. The conversion process is as follows [37]:

$$\widetilde{\mu}_{ij} = \frac{\left(\mu_{ij}\right)^{1-\sigma} \left(\overline{\mu}_{ij}\right)^{\sigma}}{\left(\mu_{ij}\right)^{1-\sigma} \left(\overline{\mu}_{ij}\right)^{\sigma} + \left(1 - \mu_{ij}\right)^{1-\sigma} \left(1 - \overline{\mu}_{ij}\right)^{\sigma}}, \tag{6}$$

$$\widetilde{v}_{ij} = \frac{\left(v_{ij}\right)^{1-\sigma} \left(\overline{v}_{ij}\right)^{\sigma}}{\left(v_{ij}\right)^{1-\sigma} \left(\overline{v}_{ij}\right)^{\sigma} + \left(1 - v_{ij}\right)^{1-\sigma} \left(1 - \overline{v}_{ij}\right)^{\sigma}}, \tag{7}$$

$$d(\widetilde{Z}, \mathbf{Z}) = \frac{1}{2(n-1)(n-2)} \sum_{i=1}^{n} \sum_{j=1}^{n} \left(\left| \widetilde{\mu}_{ij} - \mu_{ij} \right| + \left| \widetilde{v}_{ij} - v_{ij} \right| + \left| \widetilde{\pi}_{ij} - \pi_{ij} \right| \right). \tag{8}$$

In this step, the IFAHP shows another advantage. When the consistency test fails, in the traditional AHP or the FAHP, the expert opinions have to be obtained again, and the test has to be repeated. However, this is not required in the IFAHP, and the parameters in the consistency test can be adjusted.

Step 3. Determination of weights.

After obtaining the matrix that satisfies the consistency test, the matrix is simplified using

$$\omega_i = \left(\frac{\sum_{j=1}^{n} \overline{\mu}_{ij}}{\sum_{i=1}^{n} \sum_{j=1}^{n} \left(1 - \overline{v}_{ij}\right)}, 1 - \frac{\sum_{j=1}^{n} \left(1 - \overline{v}_{ij}\right)}{\sum_{i=1}^{n} \sum_{j=1}^{n} \overline{\mu}_{ij}} \right). \tag{9}$$

We calculate the score of the index weight:

$$H(\omega_i) = \frac{1 - v_i}{1 + \pi_i}. \tag{10}$$

After normalization, the index weight is obtained:

$$\sigma_i = \frac{H(\omega_i)}{\sum_{j=1}^{n} H(\omega_i)}. \tag{11}$$

2.2.2. Introduction to Set Pair Analysis. SPA is a quantitative analysis theory that considers certainty and uncertainty as an integrated system and describes them as identity, discrepancy, and contrary relationships. SPA was proposed by the Chinese scholar Zhao [44]. Certainty includes identity and contrary relationships, whereas uncertainty only refers to the discrepancy relationship.

In the SPA, the connection degree is used to describe the certainty and uncertainty of the system and their mutual transformation rules. The expression of the connection degree is [44]

$$\mu = a + bi + cj, \tag{12}$$

where a, b, and c are the identity degree, discrepancy degree, and contrary degree of the set pair under certain conditions background. i and j are the uncertainty coefficient of the discrepancy term and the uncertainty coefficient of the contradictory term, respectively.

Each index and the risk level standard constitute a set pair, and the connection degree between the actual state value of each index and the risk level standard is calculated. Considering the index weight, (12) can be expressed as follows:

$$\mu = \sum_{l=1}^{m} \omega_l a_l + \sum_{l=1}^{m} \omega_l b_{l,1} i_1 + \cdots + \sum_{l=1}^{m} \omega_l b_{l,K-2} i_{K-2} + \sum_{l=1}^{m} \omega_l c_l j, \tag{13}$$

where ω_m is the index m ($m = 1, 2, \ldots, n$).

The degree of connection between the index x_l, which should be as small as possible, and the index level standard is [45]

$$\mu_l = \begin{cases} 1 + 0i_1 + 0i_2 + \cdots + 0i_{k-2} + 0j, & x_l \le s_1, \\[2ex] \dfrac{s_1 + s_2 - 2x_l}{s_2 - s_1} + \dfrac{2x_l - s_1}{s_2 - s_1} i_1 + 0i_2 + \cdots + 0i_{K-2} + 0j, & s_1 < x_l \le \dfrac{s_1 + s_2}{2}, \\[2ex] 0 + \dfrac{s_2 + s_3 - 2x_l}{s_3 - s_1} i_1 + \dfrac{2x_l - s_1 - s_2}{s_3 - s_1} i_2 + \cdots + 0i_{K-2} + 0j, & \dfrac{s_1 + s_2}{2} < x_l \le \dfrac{s_2 + s_3}{2}, \\[2ex] \vdots \\[2ex] 0 + 0i_1 + 0i_2 + \cdots + \dfrac{s_{K-1} - 2x_l}{s_{K-1} - s_{K-2}} i_{K-2} + \dfrac{2x_l - s_{K-2} - s_{K-1}}{s_{K-1} - s_{K-2}} j, & \dfrac{s_{K-2} + s_{K-1}}{2} < x_l \le s_{K-1}, \\[2ex] 0 + 0i_1 + 0i_2 + \cdots + 0i_{K-2} + 1j, & x_l > s_{K-1}, \end{cases} \tag{14}$$

where $s_1 \le s_2 \le \cdots \le s_{K-1} \le s_K$.

The degree of connection between the index x_l, which should be as large as possible, and the index level standard is [45]

$$\mu_l = \begin{cases} 1 + 0i_1 + 0i_2 + \cdots + 0i_{k-2} + 0j, & x_l \ge s_1, \\[2ex] \dfrac{2x_l - s_1 - s_2}{s_1 - s_2} + \dfrac{2s_1 - 2x_l}{s_1 - s_2} i_1 + 0i_2 + \cdots + 0i_{K-2} + 0j, & \dfrac{s_1 + s_2}{2} \le x_l < s_1, \\[2ex] 0 + \dfrac{2x_l - s_2 - s_3}{s_1 - s_3} i_1 + \dfrac{s_1 + s_2 - 2x_l}{s_1 - s_3} i_2 + \cdots + 0i_{K-2} + 0j, & \dfrac{s_2 + s_3}{2} \le x_l < \dfrac{s_1 + s_2}{2} \\[2ex] \vdots \\[2ex] 0 + 0i_1 + 0i_2 + \cdots + \dfrac{2x_l - 2s_{K-1}}{s_{K-2} - s_{K-1}} i_{K-2} + \dfrac{s_{K-2} + s_{K-1} - 2x_l}{s_{K-2} - s_{K-1}} j, & s_{K-1} \le x_l < \dfrac{s_{K-2} + s_{K-1}}{2} \\[2ex] 0 + 0i_1 + 0i_2 + \cdots + 0i_{K-2} + 1j, & x_l < s_{K-1}, \end{cases} \tag{15}$$

where $s_1 \ge s_2 \ge \cdots \ge s_{K-1} \ge s_K$.

The confidence degree is used to evaluate the risk level of each factor.

$$h_k = (f_1 + f_2 + \cdots + f_k) > \lambda, \tag{16}$$

where $f_1 = \sum_{l=1}^{m} \omega_l a_l$, $f_2 = \sum_{l=1}^{m} \omega_l \quad b_{l,1}$, $f_3 = \sum_{l=1}^{m} \omega_l b_{l,2}$, $\ldots$, $f_{k-1} = \sum_{l=1}^{m} \omega_l b_{l,K-2}$, $f_k = \sum_{l=1}^{m} \omega_l c_l$.

λ is the confidence level, which is generally [0.50, 0.70]. The larger the value is, the more conservative the result is.

2.3. Environmental Risk Assessment Model of Subway Station Engineering Based on the IFAHP and SPA. The flowchart of the environmental risk assessment of subway station engineering is shown in Figure 4. The detailed steps of the environmental risk assessment model are as follows.

Step 1. Field investigations and expert interviews are used to determine the indicators of the index system and their relative importance. According to the relation in Table 5, the intuitionistic fuzzy decision matrix $\mathbf{Z} = (z_{ij})_{n\times n}$ is obtained.

Step 2. The consistency of the intuitionistic decision matrix $\mathbf{Z}$ is tested. After the consistency test and adjustment, a satisfactory consistency matrix is obtained. Using (9)–(11), the weights of the indices $\mathbf{W} = (\sigma_1, \sigma_2, \ldots, \sigma_n)$ are obtained.

Step 3. The measured values of the sample evaluation indices are recorded as set $\mathbf{A}$, and the corresponding evaluation criteria are recorded as set $\mathbf{B}$. Sets $\mathbf{A}$ and $\mathbf{B}$ form a set pair $\mathbf{H}(\mathbf{A}, \mathbf{B})$. For example, (13) uses the five-element connection degree μ to describe the relationship between the set pairs.

Step 4. The score of each rating index is used in (14) and (15) to determine the connection degree of a single index.

Step 5. We obtain the connection degree of the index grade standard and index weight vector $\mathbf{W} = (\sigma_1, \sigma_2, \ldots, \sigma_n)$ and calculate the overall connection degree.

Step 6. According to (16), the environmental risk level of the subway station project is determined using the confidence degree.

3. Case Study

3.1. Case Background and Data Sources. The Chengdu Metro Line 11 is located in Chengdu, Sichuan Province, China. It spans the High-Tech Zone, the Tianfu New District, and the Shuangliu District in Chengdu. The project is 22.0 km long, with a total investment of about 16.5 billion RMB and 17 new subway stations. Chengdu is close to the active seismic zone of the Longmen Mountains, where seismic activities of different levels occur frequently. The terrain along the Chengdu Metro Line 11 is mostly shallow and hilly, which complicates the construction. Chengdu has a subtropical monsoon climate with abundant rainfall and a low number of sunshine hours, resulting in abundant groundwater. According to the Chengdu Metropolis Almanac, floods and droughts are frequent in Chengdu.

Lushan Avenue Station is an underground two-story frame structure and it uses an underground two-story island platform. The standard section width is 22.5 m, the station length is 260.900 m, and the total construction area is 15153 m^2. The station is located at the intersection of planned Zhongbai Avenue and Lushan Avenue and is arranged along the north-south direction of Zhongbai Avenue. It is the interchange station between Metro Line 11 and the planned Metro Line 14. There are Wan'an Town Heyun Community and Chengfeng Driving School to the northeast, Donglin Spring Phase II community to the northwest, Yunxi Terrace of Lushan International Community to the southwest, and China Mobile to the southeast. The enclosure structure of the station adopts the form of bored piles with internal supports.

Huilong Road West Station also adopts an underground two-story island platform. The total length of the station is 511.55 m, the total width of the standard section is 21.10 m, the effective platform length is 186 m, and the total construction area of the station is 27296.22 m^2. Huilong Road West Station is adjacent to the Huilong Parking Lot of Line 5 and is arranged along the east-west direction on the south side of the planned Sanchahu Expressway. The planned road has not been implemented. The station crosses the Qinglan Gully. The surrounding area of the station is mostly farmland and wasteland. There is a driving school on the northwest side of the station and the parking lot of Line 5 on the south side. The existing roads are Shuanghuang Road and Langou Road. The retaining structure of the station adopts the form of bored piles with internal support and the form of slope excavation with soil nail wall spray anchor.

We use Lushan Avenue Station and Huilong Road West Station as a case study. The two stations have the following characteristics, which was the reason for their selection.

(1) Lushan Avenue station is surrounded by a suburban development zone with complex underground pipelines. Suburban rural area of Chengdu is around Huilong Road West Station. The common surrounding environments of subway station construction are included in these two stations.

(2) The construction company for the Huilong Road West Station was China Construction Third Bureau Infrastructure Construction Investment Co., Ltd. The construction company for the Lushan Avenue station was China Construction Railway Investment and Construction Group Co., Ltd. These two construction units include almost all construction units of the Chengdu Metro Line 11. In addition, the management level and technical level of these construction enterprises are quite different.

(3) The geological conditions of Lushan Avenue Station and Huilong Road West Station are different and include typical geological conditions of subway stations in Chengdu.

The detailed information on the Chengdu Metro Line 11 and the Lushan Avenue and Huilong Road West stations was compiled and provided to the scoring experts. The details of the 20 experts invited to participate in the interviews are shown in Table 3. According to the risk classification criteria and their professional experience, the experts scored the harsh hydrological conditions, adverse geological conditions, and adverse geomorphological conditions from [0,100]. The average of the scores was used as the final score of the indicators.

The rest are quantitative indicators, and the data were obtained from measurements performed by professional

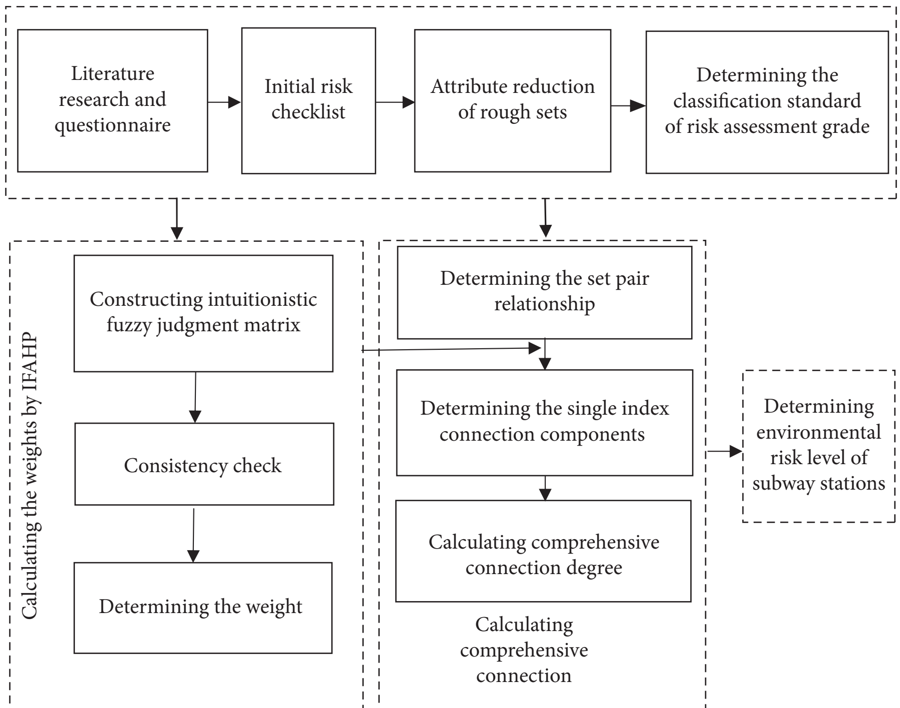

Figure 4: Flowchart of environmental risk assessment for subway station construction.

Table 5: Comparative results of the importance of the evaluation indicators.

Indicator	E1	E2	E3	E4	E5	E6	E7
E1	(0.50, 0.30)	(0.40, 0.45)	(0.20, 0.75)	(0.20, 0.75)	(0.30, 0.60)	(0.40, 0.45)	(0.70, 0.20)
E2	(0.60, 0.25)	(0.50, 0.30)	(0.30, 0.60)	(0.30, 0.60)	(0.40, 0.45)	(0.60, 0.25)	(0.70, 0.20)
E3	(0.80, 0.15)	(0.70, 0.20)	(0.50, 0.30)	(0.40, 0.45)	(0.60, 0.25)	(0.70, 0.20)	(0.90, 0.10)
E4	(0.80, 0.15)	(0.70, 0.20)	(0.60, 0.25)	(0.50, 0.30)	(0.60, 0.25)	(0.70, 0.20)	(0.90, 0.10)
E5	(0.70, 0.20)	(0.60, 0.25)	(0.40, 0.45)	(0.40, 0.45)	(0.50, 0.30)	(0.60, 0.25)	(0.80, 0.15)
E6	(0.60, 0.25)	(0.40, 0.45)	(0.30, 0.60)	(0.30, 0.60)	(0.40, 0.45)	(0.50, 0.30)	(0.70, 0.20)
E7	(0.30, 0.60)	(0.30, 0.60)	(0.10, 0.90)	(0.10, 0.90)	(0.20, 0.75)	(0.30, 0.60)	(0.50, 0.30)

engineers at the project site. The frequency of natural disasters is the average number of natural disasters per year in the Chengdu area according to the national natural disaster statistics released by the Ministry of Emergency Management of the People's Republic of China in the past 10 years. The frequency of severe weather events is the average number of severe weather occurrences per year for the past 5 years as published on the website of the Chengdu Meteorological Bureau. The density of underground pipelines was determined by the available data from Lushan Avenue Station and Huilong Road West Station and survey data per square kilometer of the construction area. Density of surrounding buildings is the average number of buildings per square kilometer within 500 m of the construction area of Lushan Avenue Station and Huilong Road West Station. The scores of all indicators were averaged. It is important to note that the upper limits of the quantitative indicators E4, E5, E6, and E7 are 20, 240, 80, and 80, respectively, as required by the project management practices for the Foothill Avenue Station and the Huilong Road West Station.

The scores of the indicators for Lushan Avenue Station and Huilong Road West Station are shown in Table 6.

3.2. Indicator Weights. The results of the comparison of the importance of the evaluation indicators are shown in Table 5. These results are based on the data in Table 4, previous studies on environmental risk assessment in metro station projects, and the data from the questionnaire data on the importance of all the indicators in Table 2.

The consistency test results (see (2)–(5)) indicate that the distance measure $d(\overline{Z}, tZ) = 0.172 > 0.1$ between $\mathbf{Z}$ and $\overline{\mathbf{Z}}$ does not meet the requirement of $\mathbf{Z}$ of the intuitionistic decision matrix. Thus, the results are corrected by (6)–(8). When $\delta = 0.56$, $d(\widetilde{Z}, \mathbf{Z}) = 0.0987 < 0.1$. The intuitionistic decision matrix passes the one-time test; the importance levels of the corrected evaluation indicators and the weighting results of the indicators are shown in Table 7.

The maximum weight of the E4 (frequency of natural disasters) is 0.183; thus, E4 is the most important factor

Table 6: The results of seven indicators' five-element contact numbers by the SPA.

Index	Lushan avenue station						Huilong road west station					
	Score	a	b1	b2	b3	c	Score	a	b1	b2	b3	c
E1	76.5	0	0	0	0.35	0.65	71.5	0	0	0	0.85	0.15
E2	86.5	0	0	0	0	1	84.5	0	0	0	0	1
E3	78.5	0	0	0	0.15	0.85	25	0.5	0.5	0	0	0
E4	0.625	0	0.28	0.72	0	0	0.625	0	0.28	0.72	0	0
E5	5.7	0	0.6	0.4	0	0	5.7	0	0.6	0.4	0	0
E6	1.5	0	1	0	0	0	0	1	0	0	0	0
E7	7	0	0	0	0.5	0.5	0	1	0	0	0	0

Table 7: The importance levels of the corrected evaluation indicators and weighting results.

Indicator	E1	E2	E3	E4	E5	E6	E7
E1	(0.500, 0.300)	(0.400, 0.450)	(0.212, 0.645)	(0.188, 0.688)	(0.291, 0.526)	(0.403, 0.390)	(0.678, 0.190)
E2	(0.517, 0.329)	(0.500, 0.300)	(0.300, 0.600)	(0.255, 0.573)	(0.395, 0.383)	(0.544, 0.251)	(0.743, 0.151)
E3	(0.673, 0.187)	(0.646, 0.253)	(0.500, 0.300)	(0.400, 0.450)	(0.544, 0.230)	(0.673, 0.158)	(0.876, 0.079)
E4	(0.713, 0.166)	(0.619, 0.211)	(0.517, 0.329)	(0.500, 0.300)	(0.600, 0.250)	(0.696, 0.137)	(0.875, 0.073)
E5	(0.576, 0.243)	(0.446, 0.324)	(0.285, 0.478)	(0.311, 0.535)	(0.500, 0.300)	(0.600, 0.250)	(0.788, 0.104)
E6	(0.452, 0.335)	(0.311, 0.478)	(0.192, 0.628)	(0.168, 0.652)	(0.311, 0.535)	(0.500, 0.300)	(0.700, 0.200)
E7	(0.228, 0.634)	(0.184, 0.702)	(0.075, 0.874)	(0.075, 0.874)	(0.122, 0.767)	(0.241, 0.658)	(0.500, 0.300)
ω_i	(0.0893, 0.829)	(0.109, 0.802)	(0.145, 0.761)	(0.151, 0.752)	(0.117, 0.787)	(0.088, 0.827)	(0.048, 0.902)
$H(\omega_i)$	0.158	0.182	0.219	0.226	0.195	0.160	0.093
σ_i	0.128	0.148	0.178	0.183	0.158	0.130	0.075
Ranking	6	4	2	1	3	5	7

affecting the environmental risk of metro station engineering. The second- and third-largest weights of are E3 (adverse geomorphic conditions) and E5 (frequency of severe weather). The minimum weight (0.075) occurred for E7 (density of surrounding buildings).

According to Chinese code (standard for sustainability assessment of building project, JGJ/T 222-2011), the investigation results of the construction site of two stations are as follows. Chengdu is relatively close to the Longmenshan seismic belt in Sichuan, which has been active in recent years, with frequent seismic activity of varying degrees. Therefore, the frequency of natural disasters has the maximum weight. The Chengdu Metro Line 11 between Guandong Road Station and Huilong Avenue Station and between Diaoyuzui Station and Huilong Road Station is the high terrace, and the area between Huilong Avenue Station and Diaoyuzui Station has shallow, hilly, and variable terrain. These conditions make construction difficult. Thus, the adverse geomorphological conditions have great weight. Chengdu has a subtropical monsoon climate characterized by abundant rainfall and low sunshine hours, resulting in abundant groundwater. The area has abundant rainfall, and the flood season is May to September. The excavation of the foundation pit of this project occurred mostly in the rainy season. Continuous rainfall caused an increase in groundwater, affecting the surrounding environment and increasing the uncertainty of metro construction. The frequency of severe weather had a considerable impact on the Chengdu Metro Line 11. Density of surrounding buildings had a negligible influence, with the minimum weight. An appropriate construction plan can reduce the influence of the density of the surrounding buildings on the construction safety. These results indicate that the weighting results are in agreement with the actual conditions of the construction of the Chengdu Metro Line 11 station.

The following recommendations to achieve sustainability and manage environmental risks can be provided to the subway station construction workers and managers. The project managers should focus on the frequency of natural disasters (E4) and adverse geomorphological conditions (E3) when dealing with environmental risks. The majority of resources and energy should be focused on preventing natural disasters and reducing adverse geomorphic conditions around the construction site. During a natural disaster, construction should be stopped, and the building site should be reinforced to ensure construction safety. Before construction, the topography around the subway station should be surveyed, and an appropriate construction plan should be developed to reduce the influence of topographic conditions on the construction safety of the subway station. The construction company should formulate response plans, implement countermeasures, and, where possible, conduct test drills to minimize construction risks of the metro station. The frequency of severe weather (E5), adverse geological conditions (E2), the density of underground pipelines (E6), and the harsh hydrological conditions (E1) should be weighted moderately high, and the project manager should decide if implementation measures are required. The density of the surrounding buildings (E7) had the least impact on environmental risk; thus, the project manager should not invest many resources in E1 and E7.

3.3. Results of the Environmental Risk Assessment of the Subway Station Project. The scores of the environmental risk assessment indicators were used in (14) and (15) to obtain the results (Table 6).

Table 8 shows the results of combining the weights with the five environmental risk levels.

According to (13)–(15), the calculation result of five-element connection number of two stations can be calculated, as shown in Table 9. The risk level for $\lambda = 0.6$ is determined by (16). The influence of the value of λ on the calculation results will be discussed in Section 4.3.

Lushan Avenue Station has a risk level of V (extreme risk), and Huilong Road West Station has a risk level of III (moderate risk). According to Chinese code (Standard for sustainability assessment of building project, JGJ/T 222-2011), the investigation results of the construction site of two stations are as follows. Lushan Avenue Station is located at the planned intersection of Zhongbai Avenue and Lushan Avenue. Zhongbai Avenue is oriented north-south. Wanan Town, rhyme community, and the Chengfeng Driving School are located in the northeast, Donglin Spring Phase II community is located in the northwest, Lushan International Community Yunxi Terrace is located in the southwest, and China Mobile is located in the southeast. The surrounding environment is complex, with a high building density. Surveys have shown that the station has complex hydrogeological conditions and high pipeline density. The evaluation results indicate that Lushan Avenue Station has an extreme risk, which is consistent with actual conditions. Extreme risk (V) means that the risk level is unacceptable, and the project manager must immediately stop construction and take measures to reduce the risk level to ensure the safety of project construction. Huilong Road West Station is close to the car park of Huilong of Line 5, which is oriented east-west on the south side of the planned Sancha Lake Expressway. The station has complex hydrogeological conditions, flat terrain, and few underground pipelines, and the actual conditions are consistent with the evaluation results of moderate risk. Moderate risk (III) indicates that the project manager needs to inspect the project and decide whether further risk response measures are required.

3.4. Response Strategy of Subway Station Project Environmental Risk. For the extreme risks of Lushan Avenue Station, we must attach great importance to and avoid them. Otherwise we must reduce the risks to an acceptable level at least at any cost. According to the actual situation of Lushan Avenue Station, in view of the poor hydrogeological conditions of the station, the stratum in the affected area should be reinforced to improve the antideformation ability of the stratum. Considering the high density of buildings around the excavation of the station, the most appropriate building reinforcement protection should be selected according to the structural form, building size, building quality, and expected uneven deformation of the existing buildings within the scope of the excavation measures.

The density of underground pipelines in this station is high, so the most suitable pipeline protection measures are comprehensively considered in combination with many factors such as site construction conditions, underground pipeline properties, and construction period. When risks are evaded or reduced to an acceptable range, the monitoring of construction site risks should be strengthened, and risk events caused by deformation of surrounding buildings and pipelines should be detected as early as possible, and a series of measures should be taken immediately to avoid risk events.

Although the landform condition of Huilong Road West Station is good, and there are no underground pipelines and surrounding buildings near the station, the hydrogeological condition of the station is poor, and the construction may cause large surface settlement and damage the retaining structure of foundation pit. Monitoring should be strengthened during construction, and monitoring should be focused on surface settlement and settlement speed. Determine different warning values in different construction stages and determine different monitoring frequencies at the same time. The foundation pit engineering is divided into before excavation, excavation, and after excavation. Each stage has its corresponding frequency and corresponding warning value. When the monitored data is abnormal, risk control measures should be taken according to the actual situation, and all parties of the company should be coordinated to deal with it to reduce the risk loss.

4. Discussion

Different methods were used to compare the environmental risk assessment results to demonstrate the superiority of the proposed method. The AHP and entropy power method were selected for weight calculation, and a fuzzy assessment, the grey correlation method, and the technique for order of preference by similarity to an ideal solution (TOPSIS) were used.

4.1. Comparison of Calculation Results Obtained from Different Weighting Methods. The comparison results of the importance of the evaluation indicators in Table 4 were transformed into a range of 1–9 for comparison with the AHP [35], as shown in Table 10. The indicator weights were $\omega = (0.046, 0.094, 0.266, 0.368, 0.156, 0.071, 0.021)$ and $CR = 0.090 < 0.1$. Table 11 shows the weight calculation results obtained from the AHP.

The 20 experts were given questionnaires to score the seven indicators according to their importance from 1 to 9, and the entropy weights of the indicators were evaluated according to the returned questionnaires. The weights of the corresponding indicators were $\omega = (0.034, 0.141, 0.104, 0.267, 0.245, 0.186, 0.022)$, as shown in Table 11. The results of the weights for the density of underground pipelines and adverse geomorphological conditions obtained from the IFAHP and AHP differed significantly. The weight of the

Table 8: The combination of the weights and the five environmental risk levels of the indicators.

Index	Lushan avenue station					Huilong road west station				
	a	b1	b2	b3	c	a	b1	b2	b3	c
E1	0.0000	0.0000	0.0000	0.0448	0.0833	0.0000	0.0000	0.0000	0.1089	0.0192
E2	0.0000	0.0000	0.0000	0.0000	0.1474	0.0000	0.0000	0.0000	0.0000	0.1474
E3	0.0000	0.0000	0.0000	0.0266	0.1508	0.0887	0.0887	0.0000	0.0000	0.0000
E4	0.0000	0.0514	0.1321	0.0000	0.0000	0.0000	0.0514	0.1321	0.0000	0.0000
E5	0.0000	0.0949	0.0632	0.0000	0.0000	0.0000	0.0949	0.0632	0.0000	0.0000
E6	0.0000	0.1297	0.0000	0.0000	0.0000	0.1297	0.0000	0.0000	0.0000	0.0000
E7	0.0000	0.0000	0.0000	0.0379	0.0379	0.0758	0.0000	0.0000	0.0000	0.0000
f_k	0.0000	0.2759	0.1953	0.1094	0.4194	0.2943	0.2349	0.1953	0.1089	0.1666

Table 9: The environmental risk levels of the two stations.

Case objects	f_1	f_2	f_3	f_4	f_5	Level
Lushan avenue station	0.0000	0.2759	0.1953	0.1094	0.4194	V
Huilong road west station	0.2943	0.2349	0.1953	0.1089	0.1666	III

density of underground pipelines was 0.186 (third place). The weight of adverse geomorphological conditions was 0.104, ranking fifth.

Therefore, the results show that the IFAHP accurately describes the opinions of decision-makers if incomplete information is available and considers the certainty and uncertainty of environmental risk in subway station construction and the hesitation of the experts in the weight calculation.

A comparison of the results of the weights between the IFAHP and the AHP shows that the order of importance of the indicators has not changed, and only the weights have changed. The AHP failed to pass the one-time test, unlike the IFAHP. In the AHP, a new test had to be performed for the decision matrix that failed the consistency test, whereas the IFAHP adjusted the matrix by setting parameters, which did not require the participation of decision-makers and was faster and more accurate than the AHP.

The environmental survey showed that the area around the station of Chengdu Metro Line 11 is mostly open, and the density of underground pipelines at most of the stations is relatively low. The area of the Chengdu Metro Line 11 contains terraces and shallow hills, and the topography and geomorphology are relatively complex. Therefore, there is a significant discrepancy between the weight ranking obtained from the entropy weighting method and actual conditions.

Therefore, the results show that the IFAHP accurately describes the opinions of decision-makers if incomplete information is available and considers the certainty and uncertainty of environmental risk in subway station construction and the hesitation of the experts in the weight calculation.

4.2. Comparison of the Results Obtained from Different Evaluation Methods. We used the weighting results of the IFAHP and the results of the scores of the qualitative indicators and quantitative indicators to conduct an environmental risk evaluation of Lushan Avenue Station and Huilong Road West Station using a fuzzy evaluation. The evaluation result for Lushan Avenue Station was [0.000, 0.288, 0.183, 0.301, 0.228]. The risk level of Lushan Avenue Station was IV. The evaluation result of the Huilong Road West Station was [0.205, 0.336, 0.183, 0.128, 0.148], and the risk level of the Huilong Road West Station was II. These results demonstrate that the two evaluation models provide similar results for the environmental risks of the subway stations.

The grey correlation degree is used to evaluate the environmental risks of subway stations. Based on the average of the risk index scores of Lushan Avenue Station and Huilong Road West Station, the grey correlations of the two stations are derived. The grey correlation degree of Lushan Avenue Station is 0.4156 (risk level IV), and the grey correlation degree of Huilong Road West Station is 0.6514 (risk level II). The evaluation results are similar to those of the SPA. The grey relational analysis prevents the ambiguity of the indicators, but it requires the determination of the optimal value of each indicator, which is subjective and challenging. The SPA does not have the disadvantages of grey relational analysis and has better reliability.

TOPSIS is used to evaluate the environmental risks of subway stations. The relative closeness for Lushan Avenue Station is 0.4515 (risk level IV). The relative closeness of Huilong Road West Station is 0.5700 (risk level III). The evaluation results are consistent with those obtained from the other evaluation methods. TOPSIS is a straightforward method but, similar to the grey relational analysis, it is difficult to determine the optimal value of the indices. When the index values of two indicators are the same for the best and worst scheme, accurate results cannot be obtained.

The extension matter-element method is used to evaluate the environmental risks of subway station projects. According to the classification standards of the risk factors of each risk factor and the average number of the scores of each index, the classic domain matter element, the node domain matter element, and the pending evaluation of the evaluation model are determined. Matter element calculates the correlation function value of each evaluation index with respect to the evaluation grade and combines the weight calculation result of IFAHP to calculate the correlation degree of the evaluation grade between Lushan Avenue Station and Huilong Road West Station, as shown in the table.

Table 10: Correspondence between the 1–9 scale and the intuitionistic fuzzy values.

Intuitive ambiguity	(0.90, 0.10)	(0.80, 0.15)	(0.70, 0.20)	(0.60, 0.25)	(0.50, 0.30)	(0.40, 0.45)	(0.30, 0.60)	(0.20, 0.75)	(0.10, 0.90)
1–9 scale	9	7	5	3	1	1/3	1/5	1/7	1/9

Table 11: Calculation results of different weighting methods.

Index	IFAHP		AHP		Entropy weighting method	
	Weight	Order	Weight	Order	Weight	Order
E1	0.128	6	0.046	6	0.034	6
E2	0.148	4	0.094	4	0.141	4
E3	0.178	2	0.266	2	0.104	5
E4	0.183	1	0.368	1	0.267	1
E5	0.158	3	0.156	3	0.245	2
E6	0.130	5	0.071	5	0.186	3
E7	0.075	7	0.021	7	0.022	7

According to the principle of maximum subordination, the environmental risk levels of the two subway station projects are determined: $\max\{k_{\mathrm{I}}(L); k_{\mathrm{II}}(L); k_{\mathrm{III}}(L); k_{\mathrm{IV}}(L); k_{\mathrm{V}}(L)\} = k_{\mathrm{V}}(L) = 0.0605$, that is, the risk level of Lushan Avenue Station is V; $\max\{k_{\mathrm{I}}(H); k_{\mathrm{II}}(H); k_{\mathrm{III}}(H); k_{\mathrm{IV}}(H); k_{\mathrm{V}}(H)\} = k_{\mathrm{III}}(H) = 0.2734$, that is, the risk level of Huilong Road West Station is III.

The evaluation results of each evaluation method are shown in Table 12.

When performing fuzzy comprehensive evaluation on Lushan Avenue Station, the risk levels of II and IV are relatively close, and the weighting of some indicators has a considerable impact on the evaluation results, resulting in inaccuracies. The SPA provides more accurate results because it analyzes the interaction between certainty and uncertainty from a systems perspective.

The grey correlation model effectively resolves the ambiguity of indicators, but it is necessary to determine the optimal value of each indicator currently, which is too subjective, and it is difficult to determine the optimal value of some indicators in the calculation process. In the process of calculating the grey correlation degree in this paper, because the data of $+\infty$ appears in the evaluation standard, the calculation result has a certain deviation. The data analysis of the generated deviation shows that when parameter adjustments are made to the optimal value of the index, a slight numerical change can make a large change in the level interval. It can be seen that in the evaluation process, once an overly subjective expert opinion appears, it can have an irreversible impact on the final result. And the overall degree of relevance is obtained by adding the correlation coefficients, and the overall degree of relevance is determined by the large correlation coefficient, which causes partial relevance tendencies and biases the analysis results. SPA does not need to determine the optimal value of indicators, which avoids the disadvantages of grey correlation degree. At the same time, considering the fuzziness of grade standard boundary, it does not need to determine the optimal value of each indicator, which avoids the difficult problem of directly determining the difference uncertainty (component) coefficient in the correlation degree and has good reliability and operability.

TOPSIS is to construct a two-dimensional data space of the distance between the evaluation index and the optimal solution and the worst solution by seeking the optimal solution and the worst solution in each index and, on this basis, the evaluation index and the optimal solution. We compare with the worst solution. If it is the closest to the optimal solution and the farthest away from the worst solution, then the plan is the best plan among the plans to be evaluated. Conversely, if it is the closest to the worst solution and the farthest away from the optimal solution, then the plan is the worst plan among the plans to be evaluated. When using this method to evaluate the subway station environment, $+\infty$ also appears in the worst solution, which leads to a certain error between the calculation result and the actual situation. The most prominent feature of TOPSIS algorithm lies in the forward module calculation of indicators. The uncertain indicators of risk factors have been analyzed and quantified in the projects relied on in this paper, and there are inaccuracies in the quantification of some natural disaster indicators; it is impossible to describe the impact of indicators perfectly. Therefore, TOPSIS is not suitable for risk assessment of this project.

When the extension matter element is used for evaluation, the distance function in the matter-element extension does not take into account the interval and the relative position relationship between the midpoint of the interval and the variable. SPA adopts interval segmentation, which can avoid this problem well. At the same time, the degree of relevance is the basis for determining the level of the evaluation object. When the relevance of each index for each evaluation level is negative, according to the meaning of the degree of relevance, it is impossible to judge the evaluation

Table 12: Evaluation results of different evaluation methods.

Station	SPA	Fuzzy comprehensive evaluation	Grey relational degree	TOPSIS	Extension matter element
Lushan avenue station	V	IV	IV	IV	V
Huilong road west station	III	II	II	II	III

Table 13: Calculation results for different values of λ.

Value of λ	Lushan avenue station	Huilong road west station
0.5	IV	II
0.55	IV	III
0.6	V	III
0.65	V	III
0.7	V	III

level of each indicator. When using set pair analysis to calculate the connection components of each indicator, normalizing the indicators can avoid the occurrence of this situation.

4.3. Comparison of the Results of Different Lambda Calculations. Different values of λ indicate different attitudes of the decision-makers; the larger the value of $\lambda$is, the more conservative the results are. In this study, the value of lambda is 0.6. In previous studies, the value of λ was usually 0.5–0.7; thus, we calculate the environmental risk levels of Lushan Avenue Station and Huilong Road West Station in this range of λ.

λ represents the probability of the analysis results being in a certain range and the degree of confidence in the decision. A small value of λ is unlikely. Table 13 shows the confidence level for the different risk levels. If the confidence level is very low, the risk level is low, and the probability of an evaluation error is high. If the confidence level is very high and the risk level is high, the probability of an evaluation error is low, but the practical significance is small. When $\lambda = 0.5$, relatively low risk levels are obtained; the risk level of Lushan Avenue Station is IV, and the risk level of Huilong Road West Station is II. When $\lambda = 0.7$, higher risk levels are obtained; that is, the risk level of Lushan Avenue Station is V, and that of Huilong Road West Station is III. As the risk attitude shifts from low to high, the risk level increases. This calculation is consistent with the results of previous research [46–48].

5. Conclusions

To achieve sustainability of subway station construction projects, this paper proposes an environmental risk assessment of subway station engineering based on the IFAHP and the SPA. We established an initial and general index system for an environmental risk assessment of subway station construction and used 19 index factors. A typical subway station project was used as an example, and the rough set method was used to reduce the number of indices, resulting in an index system for an environmental risk assessment of subway station construction using seven indicators. The IFAHP was used to calculate the index weights to avoid having to obtain expert opinions again when the consistency test failed, as is required in the subjective AHP method. The fuzziness of expert decisions in the weight calculation was considered, and the disadvantage of poor interpretability of the calculation results in objective weight calculation methods, such as the entropy weight method, was avoided. The SPA was used to evaluate the risk level since it considers certainty and uncertainty as an integrated system and describes them as identity, discrepancy, and contrary relationships. The evaluation results are also compared with fuzzy comprehensive evaluation, grey relational degree, TOPSIS, and matter-element extension method to illustrate the superiority of the proposed method. The results of the case study showed that the dominant environmental risks of subway station construction included the frequency of natural disasters and adverse geomorphological conditions, and the majority of resources and energy should focus on these types of disasters. The risk level of Lushan Avenue Station was extreme, and the project manager should immediately stop construction and take measures to reduce the risk level. The risk level of Huilong Road West Station was moderate, and the project manager should decide whether further risk response measures are necessary. The proposed method provided better performance than the traditional AHP, the entropy weight method, the fuzzy evaluation, the grey correlation analysis, and the TOPSIS.

Although the IFAHP and the SPA provided satisfactory results for the environmental risk assessment of subway station projects, this study has the following limitations. (1) The index system for the environmental risk assessment of metro station projects was based on 38 typical metro station projects in China. The index system and risk assessment results will likely be different for different metro stations. (2) The weight results did not provide an accurate and complete representation of the opinions of different experts. A future study will focus on a unified and universal environmental risk assessment index system, or fully.

Data Availability

The case analysis 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

Efficiency Measurement and Determinant Factors of Marine Economy in China: Based on the Belt and Road Perspective

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Analyzing the evolution characteristics and influencing factors of marine economic efficiency is the foundation to improve the quality of marine economic development. A super-efficiency Slacks-Based Measure (SBM) model is applied to measure the marine economic efficiency of 11 coastal provinces between 2006 and 2017 in China. Time series and standard deviation ellipse methods are used to analyze its temporal and spatial characteristics. The influencing factors of efficiency are analyzed using the Bayesian model averaging (BMA) method based on the indicator system constructed on the relationship between the *Belt and Road* and marine economic efficiency. The research found that (1) the average change of marine economic efficiency is not large, and the efficiency values among most provinces are relatively stable. (2) The center of gravity of marine economic efficiency gradually shifts from the northeast to the southwest; the spatial scope continues to shrink, the level of flatness indicates increase at first followed by decrease, and the direction angle shows a fluctuating trend. (3) The compliance rate of industrial wastewater discharge and the diversification of the marine industry structure have strong explanatory capacity in marine economic efficiency in the coastal areas. This research proposed the specific path to improve the efficiency of marine economy and facilitate quality development under the "Belt and Road" initiative from the aspects of the optimization of the marine industry structure, the integrated construction of transportation, the development of opening to the outside world, the progress of marine science and technology, and the improvement of the marine ecological environment.

1. Introduction

The eastern coast of China carries 40% of the population with 13% of the land area and creates more than 65% of the GDP. However, the gross marine economic output accounts for only 9% of GDP, which shows a significant gap compared with 15% of GDP, the highest marine economy among the world marine powers.

In response to changes in the global situation, taking into account the strategic direction of land and sea and coordinating the overall international and domestic situation, China proposed *the Belt and Road Initiative* in 2013. In 2017, the national policy emphasized on focusing on the construction of *the Belt and Road*, insisting on both importing and exporting, forming an open pattern of land-sea domestic and foreign linkages and east-west mutual assistance, and setting the new requirements and a higher starting point for the development of the marine economy in coastal areas. In 2019, China proposed at *the Second Belt and Road International Cooperation Summit Forum* that the promotion of *the Belt and Road Initiative* is inseparable from the construction of a global connectivity partnership. It can be seen that *the Belt and Road Initiative* has brought China the dual opportunities of a large international land channel as well as a large maritime transportation channel, which provided China with strong support for accelerating the development of the marine economy in coastal areas. As a "great bridge" for the Chinese economy to the world, the marine economy is an important part of the coastal economy, and its position in national development strategy has steadily improved. It is becoming a new growth point for Chinese economic development.

However, the rapid development of the marine economy has inevitably increased people's intervention in the ocean, and marine resources, environment, and ecology have been severely damaged. Under the background of the new normal of the marine economy, there is a need for scientific and quantitative research on the efficiency of the marine economy, exploring the ineffective links of its marine efficiency and seeking effective ways to improve the quality of marine economic development, in order to strengthen the Chinese marine economy and maritime power construction.

Therefore, in the context of the significant imbalance between the input and output of marine production factors, starting from the role of the *Belt and Road Initiative* on the marine economy, there is a need to accurately grasp the key influencing factors of the changes in marine economic efficiency and analyze the direction and extent of their influence. It is of great significance for improving the quality of marine economic development, speeding up achieving the strategic goal of maritime power, and ensuring the smooth implementation of the *Belt and Road Initiative*.

This study intends to select a super-efficiency Slacks-Based Measure (SBM) model to measure marine economic efficiency and analyze its temporal and spatial pattern evolution characteristics. Based on the influence mechanism of the *Belt and Road* on marine economic efficiency, a marine economic efficiency impact index system is established to analyze the factors influencing efficiency and contributing causes by application of the Bayesian model averaging (BMA) approach. It aims to provide a theoretical basis to identify the influencing factors of marine economic efficiency, improve the construction of the *Belt and Road*, and realize the high-quality development of the marine economy.

2. Literature Review

2.1. The Belt and Road and the Marine Economy. Since the *Belt and Road* was put forward, it has had a significant impact on the Chinese national economy from many aspects. Studies have found that the political connection of leaders can affect the infrastructure investment, industrial structure changes, and economic growth of the source or related regions through the implementation of fiscal, monetary, financial, and foreign trade policies [1, 2]. The improvement of transportation infrastructure and traffic density along the *New Silk Road* economic belt will help play a positive role in promoting trade and boost the integrated development of the regional economy [3]. The strong cooperation with the infrastructure construction of the countries along the *Belt and Road* can effectively promote the reconstruction of the global value chain [4].

The smooth implementation of the *Belt and Road Initiative* will not only promote the overall balance of the Chinese eastern, central, and western regions of the economy but also provide a diversified medium of cooperation for facilitating and liberalizing the world economy and trade [5]. It can strengthen appropriate trade policy communication with countries along the route and enhance the stability of bilateral trade settlement. The initiative will help China and the countries along the route to jointly construct a mutually beneficial and win-win trade growth pattern and effectively promote economic cooperation among the countries along the route [6]. From the current point of view, the intensive marginal expansion has shown a significant promotion effect on the investment of the *Belt and Road Initiative* [7]. The leading role of finance in the *Belt and Road Initiative* must be fully exerted. Attention must be paid to improving the efficiency and quality of finance in countries along the route and deepening the financial cooperation between China and countries along the route [8]. It can be seen that *the Belt and Road* construction has laid a solid foundation for regional economic development to shift from quantity growth to quality improvement.

With the development of research, scholars have introduced relevant theories about the impact of the *Belt and Road Initiative* on economic development in the marine field and researched the impact of the *Belt and Road Initiative* on the marine economy. It was pointed out that the *Belt and Road*, as China caters to the deepening of reform and opening-up, advocated the reconstruction of ocean awareness and encourages people to actively develop and utilize the ocean and breakthrough geographical barriers to walk into the world economic network [9].

It was emphasized that the implementation of the *Belt and Road Initiative* was a manifestation of the arrival of the land-sea economy era and provides an essential platform for China and countries along the route to carry out blue economic cooperation and construct "blue partnership" [10]. Some other scholars pointed out that the *Belt and Road* is intended to adhere to land-sea coordination and mutual benefit, and the key to its smooth implementation lies in the promotion of the status and role of the marine economy [11]. The *Belt and Road* is applied to develop the marine economy and achieve land-sea overall planning which is the core means of Chinese progressive geostrategic [12]. By analyzing the economic development of coastal node cities and the coordinated development of port and city, it is found that, after removing the influence of common trends and impacts, the net effect of the policy of the *Belt and Road* is negative [13]. The expansion of development levels, transportation infrastructure construction, and optimization and upgrading of the marine industry structure are the main aspects of marine economy development under the *Belt and Road* [14]. It can be seen that the continuous advancement of the *Belt and Road* initiative is conducive to the maritime economic cooperation between China and countries or regions along the route. The continuous strengthening of maritime economic cooperation between countries has also pointed out the direction for China to better plan the construction of the *Belt and Road* and then attract more maritime countries to participate.

2.2. Marine Economic Efficiency. The intensity of marine resource consumption and the pressure on the marine ecological environment continue to increase, which has seriously affected the output benefits of marine production factors [15]. Theories of economic efficiency are gradually introduced into the marine field. Evaluation methods mainly include DEA, SFA, SBM, and Malmquist. The research content mainly focuses on the efficiency of single marine industry and the overall efficiency of the marine economy.

At the efficiency level of the single marine industry, it was found that the growth rate of comprehensive technical efficiency of the fishery industry was significantly lower than that of fishery GDP and was mainly contributed by scale efficiency [16, 17]. Through methods such as the transformation of production and output constraints, it can effectively improve scale efficiency and increase the output efficiency of marine fisheries. Some scholars have gradually extended the efficiency theory to industries such as marine transportation, marine shipping, and coastal tourism. Talley [18] and Pablo et al. [19] analyzed the economic efficiency of ports and found that there is a negative relationship between port scale and economic efficiency. Pang [20] and Sun and Xiao [21] further found that the key to reducing port scale efficiency was caused by redundant input and low output efficiency. Yu and Pan [22] and Zhou and Guan [23] analyzed the efficiency values of the marine transportation industry, marine shipping industry, and coastal tourism and found that pure technical inefficiency was a reduction in overall technical efficiency, which is the direct cause that leads to regional differences.

The research results on the overall efficiency of the marine economy are mostly domestic. Scholars mainly combined their research themes and used models such as data envelopment analysis (DEA) and SBM to select marine employees, marine capital stock, port cargo throughput, etc., as input variables, and the added value of the marine economy as output variables. The efficiency is measured and calculated to obtain the changing rules of efficiency accurately. Marine industrial structure, resource environment, science and technology, and regional openness are the key to the formation of marine economic efficiency [24–26]. Due to the in-depth research, some scholars classified environmental factors into the evaluation system of marine economic efficiency. The green efficiency and ecological efficiency of the marine economy became research hotspots [27, 28].

By sorting out the existing literature, it is found that the research on the development of the marine economy by the *Belt and Road* is also relatively wealthy, but further improvement is needed in the following two aspects. On the one hand, the research on the impact of the *Belt and Road Initiative* on marine economic efficiency is blank. On the other hand, the efficiency-influencing factors selected by different scholars are different, and the conclusions drawn by different analytical frameworks are quite biased and lack specific theoretical support.

The review of existing literature found that scholars are relatively mature in the research on the influencing factors of marine economic efficiency and affirmed the important impact of the *Belt and Road* on the development of the marine economy, and the research on the development of the marine economy in the context of the *Belt and Road* is relatively rich. But it was mainly concentrated on the impact of the *Belt and Road* on the regional economy and marine economic efficiency. There were few studies on the impact of the *Belt and Road Initiative* on the efficiency of the marine economy.

Given this, this study applies the super-efficiency SBM model to measure the marine economic efficiency of coastal provinces and uses time series and standard deviation ellipses to analyze the characteristics of temporal and spatial patterns. A marine economy efficiency impact index system is constructed based on the relationship between the *Belt and Road* and marine economic efficiency. The research not only provides a theoretical basis for choosing a suitable coastal area marine economic development model, formulating macroeconomic policies for the marine economy, and promoting the construction of the marine economy but also pointing out the direction for coastal areas to use the *Belt and Road Initiative* to achieve high-quality marine economic development goals.

3. Research Method

3.1. Theoretical Framework. The construction of the *Belt and Road* will promote the all-round development strategy of countries along the route, promote the free flow and optimal allocation of production factors such as talents, technology, and capital, improve the output efficiency of factors, and improve the quality of economic development. Marine economic efficiency is a measure of the ability of marine labor and capital to transform into the gross marine product and an essential manifestation of the output benefits of production factors. The *Belt and Road Initiative* brings significant opportunities to the eastern region. It is necessary for coastal areas to establish the relationship between the *Belt and Road* construction and marine economic efficiency from multiple perspectives such as industry, transportation, trade, technology, and environment to seek a double-win cooperation path. The specific relationship is shown in Figure 1.

The detailed description is as follows.

(1) With the continuous advancement of the *Belt and Road* construction, the “One Road” regional development platform will be completed, and the regional integrated development pattern of the coastal marine economy will gradually be shaped [11]. The advantages of the marine industry foundation, labor force, and market in the eastern region will be highlighted. They promote the upgrading and transformation of the marine industry structure, thereby realizing reasonable allocation of marine production factors and improving the output efficiency of the marine economy.

(2) The key to constructing *the Belt and Road* lies in constructing infrastructure such as aviation, high-speed rail, and ports [13]. It is necessary to build a comprehensive transportation network as a guide,

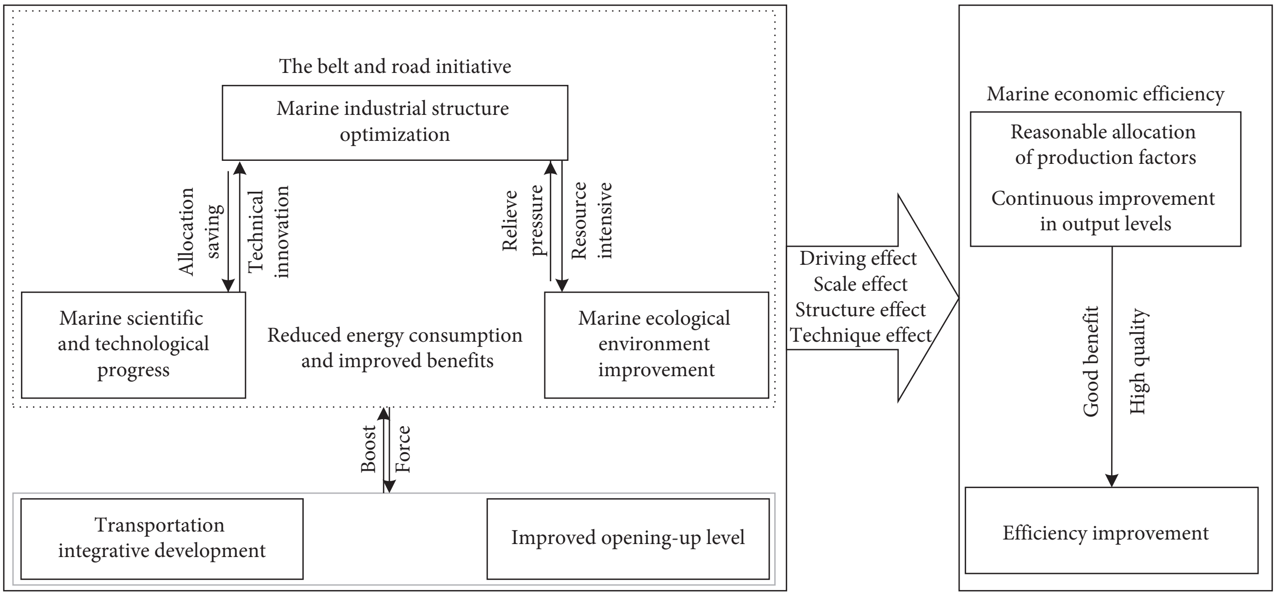

Figure 1: The mechanism of the *Belt and Road Initiative* on marine economic efficiency.

plan the interconnection layout of the countries along the route, and form a diversified, multilevel international cooperation channel. The network will deepen international cooperation in transportation, promote the facilitation of investment and trade, and maximize the social welfare of humankind.

(3) Trade opening-up and investment opening-up are the two main aspects of opening to the outside world. The promotion of the *Belt and Road* strategy will not only help open up the logistics, trade, and investment channels between the eastern region and southeast Asia but also accelerate the exploration of open economic development. The pace of system reform also laid the foundation for Chinese participation in the future development model of economic globalization and international division of labor [7].

(4) Relying on the major strategic opportunities of the *Belt and Road*, China will actively cooperate with countries along the route to build marine science and technology parks and jointly cultivate high-tech marine science and technology talents, gradually establishing a stable long-term partnership [9]. China would take advantage of the favorable conditions for international exchange and cooperation of marine science and technology and give full play to marine science and technology to the marine economy.

(5) The intensity of marine environmental protection and marine pollution control and the rational use of marine resources are the prerequisites for transforming the marine economy to quality and efficiency. The concept of the 21^{st} Century Maritime Silk Road emphasizes the green development path and promotes organic integration with the construction of marine ecological civilization [10]. The Chinese government proposes to participate in the global marine ecological environment governance system actively and jointly implement marine ecological environmental protection actions with countries along the route. It will provide high-quality marine ecological services, ensure the ecological safety of global oceans, and reduce the marine economy's undesired output through strong ecological constraints.

3.2. Model Development

3.2.1. Super Efficiency SBM Model. The DEA model is a commonly used method for efficiency estimation. Its basic idea is to obtain more output with minimal input. It is mainly measured from radial and angular perspectives. There is no need for the preset production function. It can effectively avoid the bias of function form setting. Due to insufficient consideration of the slackness of input and output, the accuracy of the measured efficiency value is insufficient. Tone proposed the SBM model in 2001, which effectively solved the traditional DEA model [29]. The model made the efficiency value conform to the strictly monotonous decreasing law by changing the level of relaxation. Besides, the traditional DEA model analysis method will cause multiple decision-making units to be useful simultaneously, and the resulting efficiency values are not greater than 1, while the effective decision-making units on the frontier are all at 1. It is difficult to distinguish further and the problem of sorting. Andersen and Petersen proposed a super-efficiency DEA model in 1993 [30]. The core idea is to remove the evaluated decision-making unit from the reference set. The efficiency value of the invalid decision-making unit remains unchanged, and the efficiency value of the effective decision-making unit refers to other decision-making units. The efficiency of the composition is obtained along the surface, which effectively solves the problem of sorting the efficiency values of the traditional DEA model. Tone combined the SBM model and super-efficiency DEA model to construct a super-efficiency SBM model [31], distinguishing effective decision-making units based on slack variables.

3.2.2. Bayesian Model Averaging Method. In 1978, the Bayesian model averaging (BMA) method was an effective method to solve model uncertainty [32]. An average model is obtained mainly by setting prior information and probability of explanatory variables, and it calculates the posterior inclusion probability of potential explanatory variables with the assistance of relevant information of the dataset to judge the relative importance of each explanatory variable. The details are as follows.

Consider the general multiple linear regression model $y = \alpha + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k + \varepsilon$. In the model, y is the marine economic efficiency, x is the explanatory variable set that affects marine economic efficiency, k is the number of explanatory variables, α is the constant, β is the coefficient, and ε is the error term $\varepsilon \sim N(0, \sigma^2)$. If $M = \{M_1, M_2, \ldots, M_N\}$ is a model space that is arbitrarily constructed by k explanatory variables, there are models of $N = 2^k$. The BMA method is employed to estimate each model to obtain the posterior probability and statistical coefficient indicators of each explanatory variable and mark M_j as one model in M, and the prior probability of M_j is $P(M_j)$, and based on Bayesian theory, calculate the posterior probability of the model M_j:

$$P\left(M_j|y, X\right) = \frac{P\left(y|M_j, X\right)P\left(M_j\right)}{P(y|X)} = \frac{P\left(y|M_j, X\right)P\left(M_j\right)}{\sum_{i=1}^{2^k} P\left(y|M_i, X\right)P\left(M_i\right)}. \tag{1}$$

In the above formula, X is a matrix of explanatory variables of k, and $j = 1, 2, \ldots, N$. It can be seen that the weighted average of the prior probability of the model is the posterior probability of the model. So the relevant statistical indicators of regression coefficients of each explanatory variable can be obtained [33], including posterior inclusion probability (PIP), posterior mean (PM), and posterior variance (PV). Among them, the value of PIP indicates the relative importance of each explanatory variable, the sign of the PM value reflects the direction of action of the explanatory variable, and the absolute number of the ratio of PM to posterior standard deviation reflects the explanatory ability of the explanatory variable. Besides, it should be emphasized that different models, prior parameter probabilities, and model space sampling methods will all affect the final result of BMA estimation.

3.3. Data Source and Variable Description. The research takes the panel data from 11 provinces along the coast of China between 2006 and 2017 as the research object. The data involved are drawn from the Chinese Marine Statistical Yearbook, Chinese Statistical Yearbook, and Statistical Yearbooks of coastal areas.

3.3.1. Selection of Variables for Ocean Economic Efficiency Measurement.

(1) Input variables: comprehensively, considering the availability and scalability of the data and referring to the research by Wang and Zhai [24] and Zhao et al. [26], maritime-related employees and marine capital stock are regarded as labor and quantitative capital indicators, which are used as super-efficiency SBM model input variables. Regarding the data on maritime-related employees, since the statistics in the Marine Statistical Yearbook have been the number of maritime-related employees in coastal areas since 2006, it can be obtained directly from the Yearbook. The marine economic capital stock draws on the method proposed by He et al. [34], which uses the ratio of GOP to GDP in coastal areas to convert the capital stock in coastal areas. As for the capital stock of coastal areas, the method proposed by Zhang et al. [35] is applied. Based on the perpetual inventory method, the current capital stock of coastal provinces in 2005 is calculated with a depreciation rate of 10.96%. Then, it is combined with the total fixed asset in each region to calculate in turn the current capital stock between 2006 and 2017. Finally, the fixed asset price index is applied to convert the capital stock of each period into a comparable capital stock with the year of 2006 as the base period.

(2) Output variables: corresponding to the Gross Domestic Product (GDP), the Marine Economic Gross Ocean Product (GOP) is a total indicator that reflects the level of regional marine economic development. Referring to the practice of Ji and Wang [36], the added value of marine economy in coastal provinces is applied as the output variable in the super-efficiency SBM model, and the constant price in 2006 is adopted to deflate it to remove the effect of price factors.

3.3.2. Selection of Influencing Factors for Marine Economic Efficiency. Based on the analysis of the mechanism of the *Belt and Road Initiative* on the efficiency of the marine economy, the influencing factors of the marine economy under the *Belt and Road Initiative* are selected in line with the principles of scientificity, operability, and comparability of the evaluation indicators (see Table 1).

(1) Marine industry structure: based on the research by [37, 38], the rationalization, diversification, and advancement of the marine industrial structure are selected to reflect the optimization of the industrial structure. Among them, rationalization is obtained by quantifying the proportion of each industry as an entropy coefficient, diversification is obtained by the weighted average of the proportions of the tertiary industry, and advancement is obtained by the ratio of the added value of marine tertiary and secondary industries.

Table 1: Drivers of marine economic efficiency under the *Belt and Road Initiative*.

Variable category	Variable name	Variable code
Marine industrial structure	Marine Industrial Structure	*MISI*
	Marine Industrial Structure Diversification	*MISD*
	Marine Industrial Structure Upgrading	*MISU*
Transportation integration	Transport Network Density	*TND*
	Transportation Investment Scale	*TIS*
Level of opening-up	Import and Export Trade Proportion	*IETP*
	Outward Foreign Direct Investment Proportion	*OFDIP*
	Foreign Direct Investment Proportion	*FDIP*
Marine science and technology	Marine Scientific and Technological Achievements Conversion Rate	*MSTACR*
	Marine High-level Talents Reserve	*MHTR*
	Marine Research Institutions Density	*MRID*
	Marine Scientific and Technological Innovation Level	*MSTIL*
Marine ecological environment	Industrial Wastewater Discharge Control Rate	*IWDCR*
	Industrial Solid Waste Comprehensive Utilization Rate	*ISWCUR*

(2) Transportation integration: combined with the research of [3, 4], the density of transportation network and investment are selected to determine the space-time cost of transportation and the utilization of regional industrial advantages, reflecting the development of integrated transportation. Among them, the density of the transportation network is obtained by the weighted average of the density of roads, railways, inland rivers, and aviation, and the scale of transportation investment is measured by the proportion of transportation expenditures in public financial expenditures.

(3) The level of opening-up: based on the research by Pei [39], trade opening and investment development are selected to reflect the level of opening-up. Trade opening is measured by the proportion of total import and export trade in GDP. Investment opening selects foreign direct investment as a percentage of GDP. The proportion is measured.

(4) Marine science and technology: based on the research of [40, 41], indicators such as the conversion rate of marine scientific and technological achievements, the reserve of high-level talents, the density of scientific research institutions, and the level of scientific and technological innovation are selected to reflect the development of marine science and technology. The innovation level of marine science and technology here is calculated by the weighted average of the number of topics, patents, and articles undertaken by marine science and technology institutions, and the reserve of marine high-level talents is measured by the proportion of marine postgraduates in school.

(5) Marine ecological environment: more than 80% of total marine pollution in China comes from the land. Industrial wastewater that does not meet the set standards or industrial solid waste that has not been effectively treated is the source of sea pollution. Concerning the practices of [27, 42], the rate of compliance of industrial wastewater discharge and the rate of comprehensive utilization of solid waste were selected to measure marine ecological environmental protection.

4. Result and Discussion

4.1. Time Characteristics of Marine Economic Efficiency. With the assistance of MaxDEA software, a variable return to scale, nonoriented super-efficiency SBM model is selected to calculate the marine economic efficiency values of 11 coastal provinces in China between 2006 and 2017, and the change trends of efficiency across the country and provinces are plotted, as shown in Figure 2.

It is easy to see that the national average of marine economic efficiency has not changed much between 2006 and 2017, and they are all on an effective frontier. From the perspective of the changes in the marine economic efficiency of the province, Tianjin and Jiangsu have become highly efficient in 2008 and 2009, respectively, after the low efficiency in the initial years. The efficiency value of Fujian Province has shown high efficiency since 2014. Zhejiang Province has always been in a state of low efficiency, and the efficiency values of other regions have always been on an effective frontier. The reason is that, from 2006 to 2008, China actively advocated the construction of a "resource-saving and environment-friendly" society, and the eastern coastal areas successively introduced relevant measures for energy saving and emission reduction. However, the export-oriented marine economy was hit by a financial crisis that suffered strong impact, by which the intensive effect of marine economic development has been hindered.

From 2009 to 2012, China was transitioning from the "Eleventh Five-Year" period to the "Twelfth Five-Year" period. The "National Science and Technology Support Plan," "863," and "973" plans were launched one after another. The scale effect and supporting the capacity of marine science and technology have been releasing continuously. "Transformation and structural adjustment" has become the focus of marine economic growth. However, the foam effect caused by mandatory investment in the marine industry, while accelerating the optimization and upgrading of the marine industry, harms marine resources and ecological environment, which hindered the development of the

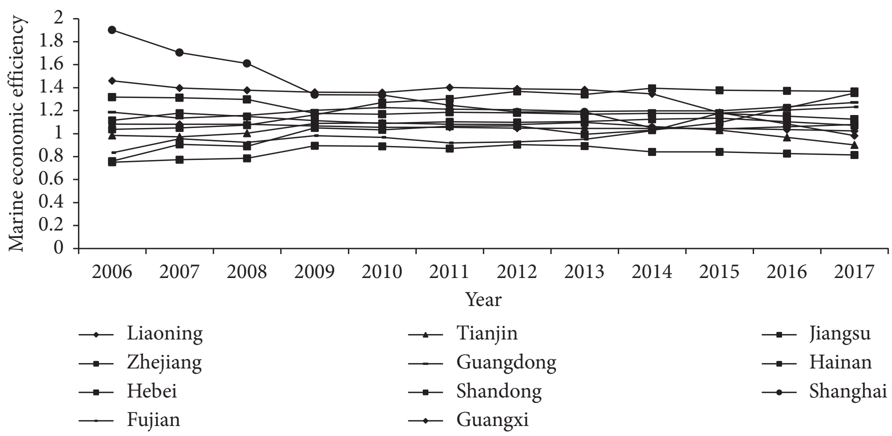

Figure 2: The changing trend of marine economic efficiency in coastal provinces between 2006 and 2017.

marine economy. Thus, the efficiency of the marine economy experienced several slight fluctuations during the period between 2006 and 2012. Between 2013 and 2017, the efficiency value showed a slightly negative growth trend, mainly due to the continuous advancement of maritime power strategy and the *Belt and Road Initiative*. Coastal areas have regarded the marine economy as the focus of regional development, and three major marine economic circles have gradually formed. The radiation-influencing effect of the economy on coastal and hinterland has become increasingly prominent. It should be noted that the previous "reclamation of sea and land" project has caused severe damage to marine resources and the ecological environment and has a certain negative effect on marine economic efficiency during this period.

4.2. Spatial Features. ArcGIS 10.5 software is used to calculate the basic parameters of the standard deviation ellipse of marine economic efficiency in coastal provinces from 2006 to 2017. The spatial pattern characteristics of marine economic efficiency are analyzed in terms of center of gravity, scope, shape, and direction.

From the changes in the center of gravity in Figures 3 and 4, from 2006 to 2017, except for a few years, the overall marine economic efficiency gradually moved from northeast to southwest with overall movement of 142.6 km. It showed an east-west movement of 83.9 km and a north-south movement of 97.34 km. Among them, during 2006–2010 and 2013-2014, it mainly moved to the southwest. During 2014–2017, it moved south, indicating that the output efficiency of marine production factors in the Yangtze River Delta and Pan-Pearl River Delta has been steadily improving. From the perspective of the range and shape changes in Figure 5(a), the overall spatial range of marine economic efficiency shows a shrinking trend. Compared with 2006, the range of efficiency distribution in 2017 decreased by about 4.07%, indicating that the growth rate of regional marine economic efficiency in the interior ellipse is significantly faster than that of the outer ellipse. The shape change is characterized by the degree of flatness, showing a changing trend of "increasing first and then decreasing." Among them, the flatness index dropped from 0.332 in 2006 to 0.318 in 2009. It then quickly increased to 0.349 in 2017, which shows that the efficiency value growth rate of the area distributed in the long axis direction of the ellipse is higher than that of the short axis direction. The higher efficiency growth rate in the Pan-Pearl River Delta region drives the efficiency standard deviation ellipse to expand southward. From the perspective of the change in the direction in Figure 5(b), the spatial direction angle of marine economic efficiency in China during the observation period increased from 23.04° in 2006 to 23.18° in 2017, showing overall fluctuating characteristics.

The abovementioned spatial pattern changes are strongly related to geographic location, marine industrial structure, and policy environment. For example, Liaoning Province in Bohai Rim is relatively backward in terms of environmental protection and resource optimization, and its comprehensive utilization rate of industrial solid waste is only 38%. Hebei Province, dominated by mineral resources and steel industry, suffers severe marine resources and environmental problems. Shandong Province, where the fishery is the leading industry, consumes lots of marine biological resources, which has severely affected the marine economic efficiency of the Bohai Rim. The Yangtze River Delta region has benefited from better geographical location advantages and land economic foundation. With the continuous advancement of national strategies such as the *Belt and Road* and the *Yangtze River Economic Belt*, the development of the green marine economy has been significantly accelerated. The efficiency of the marine economy has been significantly improved. Fujian Province in the Pan-Pearl River Delta region has always had preferential policies given by the state and has an excellent marine economic foundation. During *the* Eleventh Five-Year Plan and Twelfth Five-Year Plan period, it pays more attention to the development of marine emerging industries and has good marine resources and environmental benefits. Hainan Province has abundant marine resources and is dominated by the "high-yield, low-polluting" marine tertiary industry. However, due to the impact of marine disasters and disputes of rights, efficiency improvement is slow. The improvement of marine economic efficiency in other regions

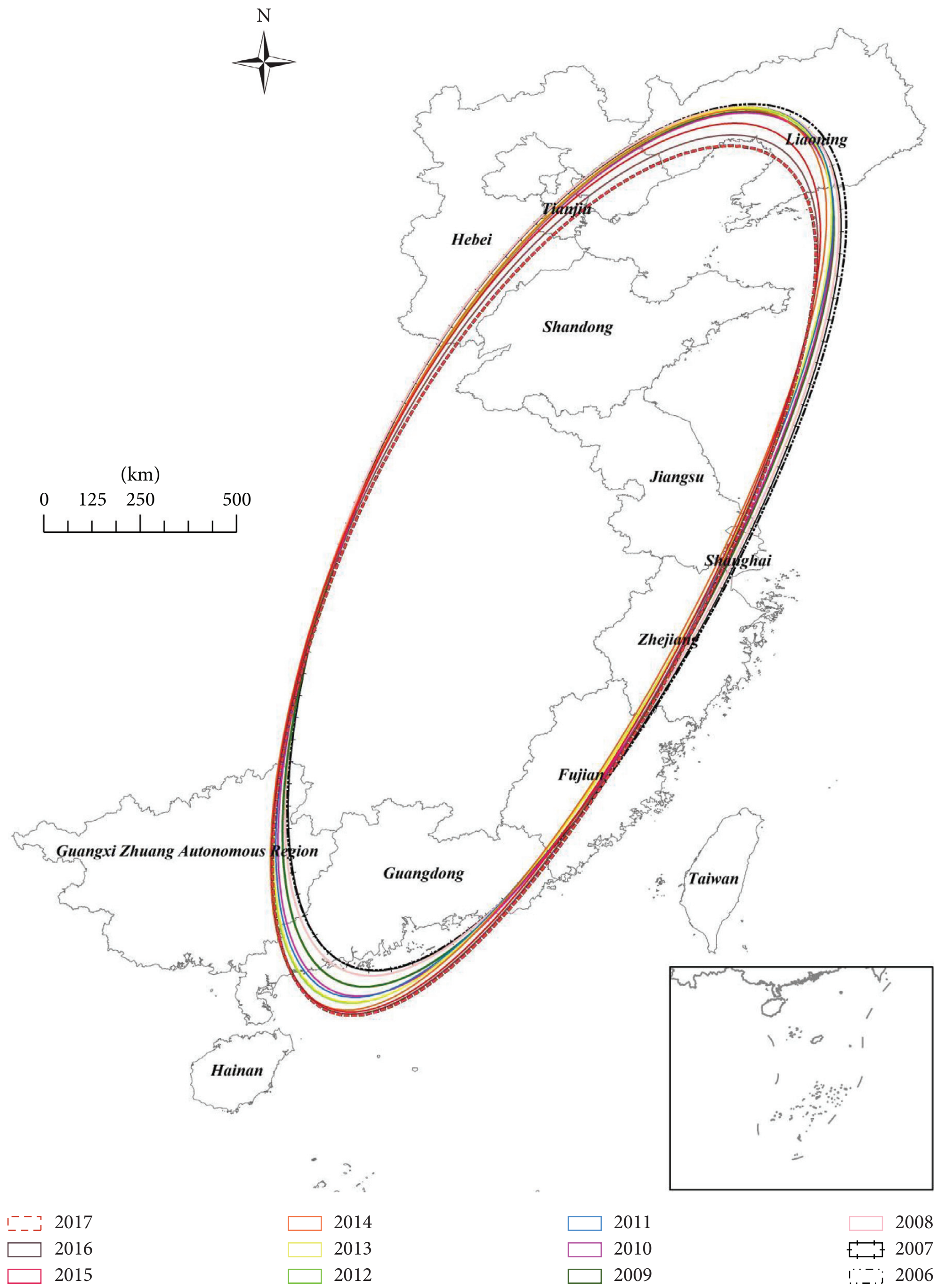

Figure 3: The spatial change of the center of gravity of marine economic efficiency between 2006 and 2017: ellipse distribution.

such as Zhejiang and Guangdong has benefited from the superior marine industrial structure and the scale effect and technology-induced effect brought by the input of marine production factors such as the number of sea employees and marine capital stock.

4.3. Drivers of Marine Economic Efficiency. Given the regional differences in natural resource endowments, land economic foundations, industrial development policies, and spatial interactions, the unbalanced development of the coastal marine economy is more prominent. The same explanatory variable produces a different-level impact on the efficiency of each regional marine economy. Concerning geographical locations of the South (including Fujian Province, Guangdong Province, Guangxi Zhuang Autonomous Region, and Hainan Province), Centre (including Shanghai, Jiangsu Province, and Zhejiang Province), and North (including Hebei Province, Liaoning Province, Tianjin City, and Shandong Province), the observation objects are divided into regions. From regional perspectives, the marine economy's efficiency is estimated by BMA to

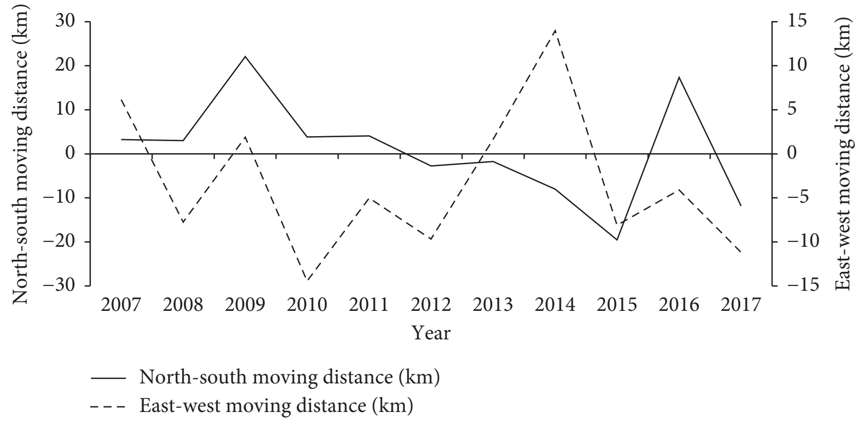

Figure 4: The offset distance of the center of gravity of marine economic efficiency between 2007 and 2017.

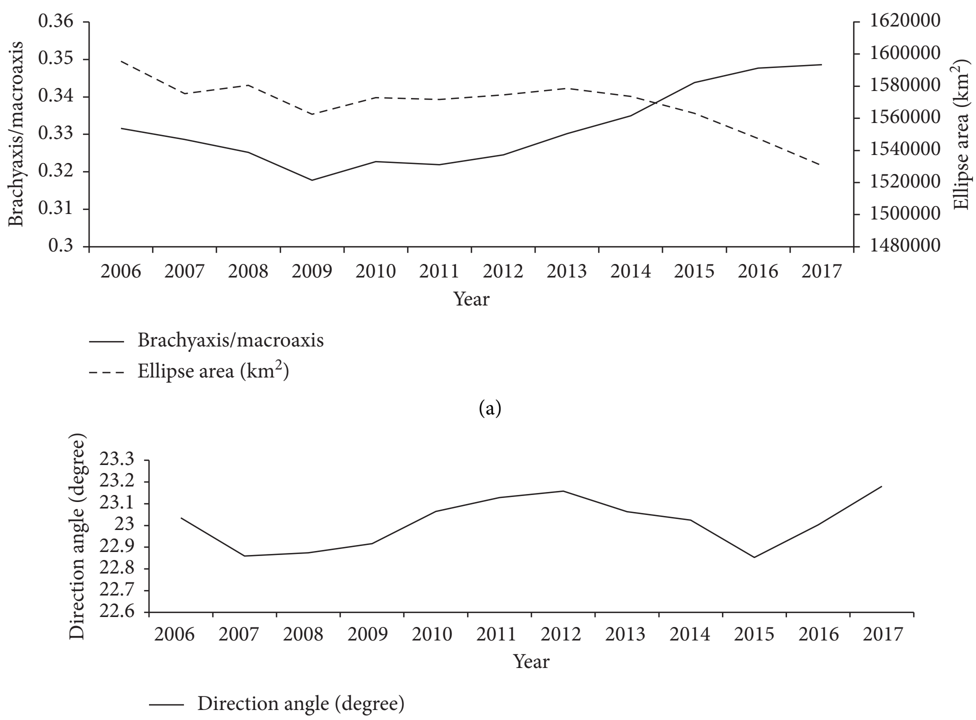

Figure 5: Change trends of marine economic efficiency between 2006 and 2017. (a) Changes in range and shape. (b) Changes in direction angle.

formulate developmental policies by local governments based on local conditions.

Regarding marine economic efficiency as the explained variable, the influencing factors mentioned above act as an explanatory variable, and a total of 16,384 candidate models are formed. The R software is used to call the BMS software package that integrates the BMA method and MC^3 sampling technology. In the premise of the model obeying random prior probability and hyperparameters, the BMA estimation results of the determinant factors of regional marine economic efficiency are obtained, as shown in Table 2.

(1) From the perspective of marine industry structure variables, the efficiency of the marine economy in the southern and central regions is hugely dependent on diversification, advancement, and rationalization of the marine industry structure and a strong positive effect. The northern region is strongly dependent on the diversification of the industrial structure. The proposal of the *Belt and Road Initiative* has fully released the advantages of marine resources, geographical location, and economic foundation of core coastal cities. It has a strong effect on improving the

Table 2: BMA regression results of influencing factors of regional marine economic efficiency.

Variate	South part			Middle part			North part		
	PIP	PM	PV	PIP	PM	PV	PIP	PM	PV
ISWCUR	99.67%	−0.323 6	0.085 7	7.20%	0.000 3	0.023 8	19.96%	−0.030 4	0.081 3
MISD	100%	−2.048 4	0.229 0	94.35%	−6.52	2.741 9	79.15%	0.259 3	0.041 9
MSTIL	98.24%	0.008 0	0.086 7	12.89%	0.011 2	0.047 1	12.30%	0.002 1	0.042 3
MISI	99.91%	−1.644 2	0.363 3	93.82%	−1.397 5	0.627 9	11.69%	0.001 5	0.051
MISU	99.90%	1.051 9	0.244 0	97.46%	2.771 7	1.266 6	14.47%	−0.019 8	0.071
MHTR	97.66%	0.489 0	0.148 8	0.67%	0.000 1	0.011 4	2.52%	0.006	0.04
IETP	99.99%	−1.192 1	0.253 5	13.27%	−0.021 8	0.100 9	93.23%	−0.517 9	0.199 6
TND	71.57%	0.170 5	0.147 6	17.93%	0.080 3	0.232 2	11.11%	0.002 9	0.057 2
FDIP	58.23%	−0.118 8	0.144 8	14.71%	−0.021 8	0.079 6	93.06%	0.448 7	0.178 6
TIS	30.36%	−0.012 9	0.051 6	84.88%	−0.311	0.183 8	9.19%	0.002 7	0.034 5
IWDCR	99.90%	−0.359 9	0.082 8	77.78%	−0.150 8	0.013 4	99.36%	−0.437 8	0.150 2
OFDIP	60.14%	0.092 8	0.104 7	10.31%	0.005 7	0.044 3	66.58%	−0.140 5	0.121 3
MRID	0.61%	0.000 7	0.024 0	27.94%	−0.069 5	0.148 3	14.65%	−0.012 9	0.091
MSTACR	0.75%	0.000 6	0.011 5	16.20%	0.022 1	0.068 8	9.33%	0.006 9	0.045

Note: PIP, PM, and PV represent posterior inclusion probability, posterior mean, and posterior variance.

efficiency of the marine economy. Further analysis found that, except for Guangdong and Shandong, other neighboring provinces with close GDPs have a small gap in marine economic GDP, but the industrial structure difference is noticeable. For example, Zhejiang and Fujian have a higher level of advanced industrial structure. The industrial structure has been formed earlier, making the southern and central regions have similar effects on the efficiency of the marine industrial structure. The northern region is overly dependent on the pull of marine primary and secondary industries, and the problem of overexploitation of marine resources is serious. The level of rationalization and advancement of the industrial structure is relatively backward, and the ability to explain efficiency is unobvious.

(2) From the perspective of transportation integration variables, the density of the transportation network promotes the efficiency of the three major regions to varying levels. The southern region has the most substantial dependence on the density of transportation network; the scale of transportation investment in the central region reflects strong explanatory ability (84.88%) and adverse effect (−0.311). The reason for this is that most of the southern cities are located in Guangdong Province, where the intercity traffic correlation is relatively strong and the spatial spillover effect of the marine economy is more significant. Lianyungang and Yancheng in the middle and Cangzhou, Dandong, Binzhou, and other cities in the north have transportation infrastructure, and the level of its interconnection and interoperability is low. The regional transportation master plan still needs to be improved, resulting in a weaker influencing force for radiation from Tianjin and Shanghai. The *Belt and Road Initiative* has increased investment in transportation projects in coastal areas, especially the Yangtze River Delta and Guangdong. However, public finances cannot afford the long-term, high-investment, and high-risk transportation infrastructure construction. Private participation in the investment and financing model gradually dominates. The substantial investment competitiveness of the central region is the main reason for its strong negative effect on marine economic efficiency.

(3) From the perspective of variables such as the level of opening to the outside world, the explanatory capacity of all variables on the efficiency of the marine economy in the central region is between 10% and 20%. The explanatory capacity and adverse effects of trade opening on the efficiency of the southern and northern regions are more significant. The explanatory capacity of foreign direct investment in the northern region is relatively strong. The explanatory capacity of foreign direct investment in the southern and northern regions is between 60% and 70%. In the early stage of reform and opening-up, foreign investment in China was mostly concentrated on the southeast coast. With the development of Pudong, the policy advantages enjoyed by the Pearl River Delta gradually disappeared, and the foreign direct investment performance index in coastal areas gradually declined. The central region thoroughly enjoyed the dividends brought by Shanghai constructing an international economic, trade, financial, and shipping center. The past export experience will help increase eastern coastal area investment in countries along the *Belt and Road.* Besides, the Chinese economic structure and growth model have inherent shortcomings, making the development of the marine industry not keep pace with the level of trade and investment, leading to traditional industries dominating the foreign investment industry. The degree of integration with the world economy still needs to be improved. Thus, the positive effect of marine economic efficiency needs to be further explored.

(4) From the perspective of marine science and technology variables, the southern marine scientific and technological innovation level and high-level talent reserves have a substantial impact on marine economic efficiency. The central and northern parts are similar, and all variables have less than 30% explanatory capacity for marine economic efficiency. The reason is that the layout of Chinese marine scientific research institutions is characterized by the spatial pattern of the North being more important than the South. Since the *Belt and Road Initiative* was put forward, China has paid more attention to the growth of the total marine economy in the short term, which has led the marine industry sector to commit to scaling expansion. More than half of the institutions engaged in marine basic scientific research are different from the actual needs of the regional marine industry. Among them, the southern region is more obviously driven by the radiation of central cities such as Shanghai and Guangzhou, enjoying a higher level of marine technology and a complete platform for transforming scientific and technological achievements, and most regions have high technical efficiency. The cities such as Tangshan, Qinhuangdao, Qinhuangdao, Panjin, and Yancheng in the central and northern regions lack government support and intervention. The lack of investment in scientific research and innovation motivation weakened the marine technology spillover effect in core cities, and the overall technical efficiency level was not prominent.

(5) From the perspective of marine ecological environment variables, the industrial wastewater discharge compliance rate has a strong explanatory capacity and negative effect on the marine economic efficiency of the three major regions. The comprehensive utilization rate of industrial solid waste has a high explanatory capacity of 99.67% for the efficiency of the southern region. The northern and central regions do not exceed 20%, and both show adverse effects. The *Belt and Road* construction has promoted the rapid development of the coastal industrial economy. Although the growth rate of industrial wastewater and solid waste discharge in various regions has been declining year by year, but affected by the environmental governance model of the heavy end, light source, and weak cycle, land-source sewage is discharged into the sea. The phenomenon of excessive discharge and substandard monitoring has become severe, and nearly 40% of solid waste cannot be effectively used. For example, the discharge of industrial wastewater and solid waste per GOP in Liaoning, Hebei, Jiangsu, Guangxi, and other places has been above average. The total solid waste utilization rate in Hebei, Guangxi, Hainan, and Fujian is less than 80%. The Pearl River Delta region with better industrial bases actively introduces advanced foreign capital technology and management to promote industries with high technological content and low environmental pollution.

It can be seen that, during the study period, the industrial wastewater discharge compliance rate and the PIP of the marine industrial structure diversification were both greater than 77%, and the corresponding absolute numbers of the posterior mean and standard deviation ratios were both greater than 1.1. Both have the strong explanatory capacity in marine economic efficiency. Further analysis of the variables that have a strong negative effect on the efficiency value found that the southern region needs to tap the potential of the transformation rate of marine scientific and technological achievements and the density of marine scientific research institutions. The central region needs to pay attention to the impact of the marine high-level talent pool. The northern region needs to focus on stimulating the effect of the marine tertiary industry on the marine economy.

5. Conclusions and Recommendations

This study takes the panel data of 11 coastal provinces in China as a sample between 2006 and 2017. It applies the super-efficiency SBM model to measure the marine economic efficiency and analyzes its temporal and spatial pattern evolutionary characteristics. Then, the marine economic efficiency-influencing indicator system is established based on the impact of the *Belt and Road* mechanism on marine economic efficiency. At last, it adopts the BMA method to analyze efficiency-influencing factors and causes. It provides a theoretical basis for advancing the construction of the *Belt and Road* and achieving the goal of high-quality marine economic development, also it provides advice on promoting marine economic efficiency in coastal areas, choosing appropriate development models, and formulating macroeconomic policies for the marine economy. The results show the following:

(1) The average change of the national marine economic efficiency during the observation period is not large. The efficiency values of most provinces are relatively stable. The overall efficiency center of gravity is gradually shifting from the northeast to southwest, and the spatial scope was in shrinking trends. The flatness level shows “increase at first followed by decrease,” and the direction angle indicates a fluctuating trend.

(2) The compliance rate of industrial wastewater discharge and the diversification of the marine industry structure have a robust explanatory capacity in marine economic efficiency in the three major regions. The southern region needs to tap the potential of the transformation rate of marine scientific and technological achievements and the density of marine scientific research institutions. The central region needs to pay attention to the role of the marine high-level talent pool. The northern region needs to

focus on the role of the marine tertiary industry in pulling the marine economy.

In specific practice, it is necessary to start from various factors that affect the efficiency of the marine economy and combine the level of impact and the direction of action to comprehensively improve the quality of marine economic development. The specific approaches are as follows:

(1) Facilitating the optimization of the marine industry structure: based on the characteristics of rationalization, diversification, and advanced nation of the marine industrial structure of each province, appropriate marine industry development goals will be formulated. With the development trend of the world's marine fisheries, the marine aquaculture industry should be developed to reduce the contribution of traditional marine fisheries to marine economic growth. With the progressing of technology and achievement transformation of the marine industry, the marine industry would be built with strong brands and excellent technology, to improve the added value and efficiency of the marine secondary, grasp the "service" function of the marine tertiary industry, scientifically determine the development scale of the marine tertiary industry, and avoid blindly pursuing the increase in the value of the industrial proportion. For example, for Tianjin, Shanghai, and Guangdong, there is a need to break the trend of centralized development of a single marine industry; for Liaoning, Shandong, Jiangsu, Zhejiang, and Fujian, there is a need to focus on the diversified development of marine industries, and for Hebei and Guangxi, there is a need to focus on increasing marine labor productivity.

(2) Strengthening the construction of integrated transportation: based on the *Belt and Road* policy guarantee function, there is a need to fully release the advantages in the prioritized areas of facility connectivity, attach importance to the investment and construction of transportation infrastructure, accelerate the realization of international interconnection in the transportation field of coastal areas, and enhance the radiation and driving capacity of the marine industry to achieve marine production factors to effectively flow around the world. Regarding the transportation industry as the basic industry and tourism and port industry as advantageous industries, gradually build the eastern port industry cluster, resource development industry belt, and tourism industry belt to strengthen the dominant position of the marine industry. For example, for the coastal areas of Liaoning, Hebei, and Jiangsu, there is a must to continuously improve the overall transportation planning, increase investment, fully play the leading role of the surrounding areas with higher accessibility, and strive to improve the connectivity of the eastern coastal transportation infrastructure.

(3) Improving the opening-up level of the marine economy: in order to promote the construction of the *Belt and Road* as the top-level design of China's economic diplomacy and a key guideline for opening-up, we should focus on alleviating the shortage of land resources, breaking through resource bottlenecks, and expanding development space. We should also make full use of the advantages of coasts opening to the outside world and absorb optimized allocation methods for marine economic production factors and advanced ocean management concepts from other countries or regions. Under the new development pattern of "circulation," we should match the cooperation for the double win with the essential connotation of "opening," take the matching and reform of both supply and demand sides as the starting point to cater to the market demand for marine high-tech and high value-added market, and change the traditional labor-intensive, primary product marine industry supply model. Besides, we also need to optimize the structure of marine foreign trade and cultivate new momentum for marine trade, continue to enhance the status of maritime foreign trade in services, and finally achieve the purpose of enhancing the positive impact of opening-up on the growth of marine economic efficiency.

(4) Promoting the progress of marine science and technology: combined with the short-, medium-, and long-term development plan of marine science and technology, we should allocate the national marine science and technology resources scientifically, improve the unreasonable layout of marine scientific research institutions, and pay attention to the problems of obvious regional advantages and weak scientific research force. The coastal regions should be encouraged to strengthen human capital investment, improve the induction system of high-level marine talents, train high-quality marine scientific and technological personnel, enhance the cooperation between "politics, industry, university, and research" in coastal cities, which aims to change the current unitary marine technological research and developmental model, encourage enterprises and universities or scientific research institutions to jointly establish marine technology research and development centers, and share scientific and technological patent dividends employing capital or technology shares. Also, it needs to fully exert the radiative and driving function of the three major coastal city clusters, relies on the flow of talents and technology transfer, promotes the effective application of marine scientific and technological resources, improves the efficiency of the marine economy, and builds the eastern coastal zone full of modern science and technology vitality.

(5) Contributing to the improvement of the marine ecological environment: it is advocated to use the *Belt and Road* to strengthen marine cooperation with other countries in the field of marine environmental protection and restoration, marine endangered species protection, marine environmental pollution prevention, marine acidification, etc., adhere to the principle of "jointly protecting and avoiding large-scale development" to formulate a sustainable marine development strategy from the overall situation, strengthen the development of marine economic management and planning, and ensure the coordinated development of marine economy, society, and ecology with the "large-scale, paid, and orderly" marine industry. We should also need to establish a land-sea linkage pollution prevention mechanism to strictly control the increase in pollution sources and improve the ecological carrying capacity of shorelines and beaches. Besides, there is a need to participate in global marine environmental governance action actively, relying on the idea of systematic governance and multiple forces to improve the efficiency of marine ecological environment governance and force the efficient development of marine resources through ecological environmental constraints and promote the marine economy to take quality and benefit-oriented development path.

Data Availability

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

Conflicts of Interest

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

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Research Article

The Influence Study on Environmental Regulation and Green Total Factor Productivity of China's Manufacturing Industry

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Green development is the theme of the current era. Environmental regulation is an essential means to achieve environmental benefits and improve the total green factor productivity of manufacturing facing a series of problems brought by the development model of "high investment, high pollution, and high consumption." Appropriate environmental regulations need to be implemented to achieve economic and environmental harvest. Based on the panel data of 25 manufacturing industries from 2003 to 2016 in China, this thesis constructs a comprehensive indicator of environmental regulation and calculates the green total factor productivity, and its decomposition applied SBM directional distance function and Malmquist–Luenberger productivity index. Besides, this thesis conducts an empirical analysis of environmental regulation's effect on green productivity in China. The main conclusions showed that the green total factor productivity of China's manufacturing industry maintains an upward trend on the whole, and the growth of GTFP mainly depends on technological progress rather than the improvement of technical efficiency. The great differences have significant industrial heterogeneity characteristics of GTFP. A single threshold in the whole manufacturing industry, environmental regulation, and GTFP of industries are shown to be "U shape," and the left of the inflection point is not significant. Environmental regulations and GTFP of moderation and slightly pollution industries are "U shape," and there is no nonlinear relationship between environmental regulation intensity and GTFP in light pollution industries. Therefore, the government's optimal environmental regulation intensity should be implemented according to the industry's heterogeneity to prevent the phenomenon of "ineffective regulation;" it is necessary to pay attention to both technological innovation and technical efficiency.

1. Introduction

Since the reform and opening up, the economy has continued to develop at a high speed. Material and spiritual conditions have been greatly improved and enriched. The industrialization process has been gradually accelerated and has developed into the largest country in the manufacturing industry. The manufacturing industry is the lifeblood of China's development and the top priority of economic revitalization and has been given high priority to national security. However, along with the continuous enhancement of competitiveness, the manufacturing industry is facing the dual pressure of excessive consumption of energy and resources [1]. China is still an extensive growth model driven by factor input [2]. Excessive consumption of resources and energy and negative environmental impacts have become essential factors restricting the economy's sustainable green development. Therefore, comprehensively improving the manufacturing industry's green total factor productivity and reducing environmental pollution are the fundamental ways to achieve economic growth and sustainable development. Some scholars point out that the improvement of environmental regulation intensity will impose mandatory "fine cleaning" on the industry and then affect the green total factor productivity (GTFP) of the industry [3]. Therefore, it is necessary to deeply research the impact of environmental regulations on green total factor productivity in manufacturing, and it is of great practical significance for implementing good environmental regulation intensity to promote the improvement of green total factor productivity in the context of "green development" as the central theme in China.

This thesis has the following marginal contributions. First, consider the measurement method of the intensity of environmental regulations (wastewater and waste gas discharge fees) comprehensively and use the entropy method to construct a comprehensive index. Second, the manufacturing industry is divided into heavy, moderate, and light polluting industries according to the pollution intensity, and the industrial heterogeneity of green total factor productivity caused by environmental regulation is analyzed. Third, the manufacturing industry's environmental regulation threshold value and each subindustry are empirically tested, and a threshold model with environmental regulation as the threshold variable was established. The internal relationship between environmental regulation and GTFP in the manufacturing industry is analyzed from a practical and theoretical aspect. Fourth, taking the panel data of Chinese manufacturing industries as the sample, this study focuses the impact of environmental regulation on GTFP of the manufacturing industry, which complements the existing literature.

2. Literature Review

Scholars have presented three different views on environmental regulation and green total factor productivity for the past. First, environmental regulation is an additional cost imposed by the government on enterprises, which will reduce enterprises' competitiveness, implement environmental regulations hurt enterprises, and indirectly hinder green total factor productivity. For example, Li and Wei [4] investigated the GTFP in China's manufacturing industry by using ML productivity index during the period 2000–2008 and decomposed, and they found that the increase in the intensity of environmental regulations would weaken the total factor productivity of industries. He and An [5] demonstrated that insufficient environmental regulation due to competition is not conducive to the improvement of green development efficiency. Lei and Yu [6] analyzed the factors influencing the growth of total factor productivity of carbon cycle and found that environmental regulation indicators significantly inhibited the growth of green total factor productivity. Sun et al. [7] tested the impact of environmental regulations on total factor productivity by establishing a long-term equilibrium model and showed that the appropriate improvement of environmental regulation standards failed to improve total factor productivity. Yuan and Xie [8] pointed out a negative linear relationship between investment-oriented environmental regulations and green industrial productivity. Chintrakarn [9] explored the relationship between environmental regulations and technological inefficiency that used the manufacturing data of 48 United States from 1982 to 1994, and their finding indicated that the relationship between environmental regulations and technological innovation is significantly negative. Filbeck and Raymond [10] found that the increase in the intensity of environmental regulation makes a negative correlation between financial return and environmental regulation. Paul et al. [11] made an empirical analysis on the data of manufacturing industry in eastern Canada from 1996 to 2008, and the study showed that environmental regulation was detrimental to the improvement of total factor productivity.

The second view is that reasonable environmental regulatory policies can stimulate enterprises' competitiveness in the long term, which will positively impact enterprises and improve green total factor productivity. Many scholars verified the view subsequently, and instead, the conclusion is heterogeneous depending on the indicators, data, and models. For example, Fu et al. [12] used SBM directional distance function and Luenberger productivity index to measure green total factor productivity in China's provinces and found that environmental regulations can effectively improve green total factor productivity through FDI. Yana et al. [13] employed a panel data of 17 European manufacturing, positing that implementing environmental regulations can enhance enterprise technology innovation and strongly support the "Porter Innovation Hypothesis." Wu and Zhang [14] measured the total factor productivity of 28 manufacturing industries from 2001 to 2013, and the results showed that environmental regulation promoted the growth of overall total factor productivity of the manufacturing industry. Use the panel data of manufacturing industry in 29 provinces in China except for Xinjiang and Chongqing; Li and Liu [15] found that environmental regulations can significantly promote green economic efficiency in the long run, and strengthening environmental regulations can achieve a win-win situation for both the economy and the environment. Feng et al. [16] used the ML index to measure China's provincial green total factor productivity and found that environmental regulation and innovation drive have a synergistic effect in promoting the total green factor production rate. Debnath [17] proposed that environmental regulation could promote technological innovation. He also confirmed that environmental regulation effectively promoted GTFP by the compensation effect. Hamamoto [18] found that strict environmental regulation policies will stimulate enterprises' innovation activities actively, thereby promoting total factor productivity. Wu and Wang [19] used the ML productivity index to measure the green total factor productivity of 17 countries and regions APEC from 1980 to 2004. The results showed that environmental regulation was proportional to GTFP. Liu and Yang [20] confirmed that ERI effectively promoted GTFP by overseas technology introduction and domestic technology introduction.

With the deepening of green development, some research shows a nonlinear relationship between environmental regulations and green total factor productivity of the manufacturing industry. Li and Tao [21] applied microdata at the Chinese manufacturing industry's enterprise level and found that the influence of environmental regulations on green total factor productivity presented an inverted U-shaped relationship. Chen et al.' [22] finding indicated the existence of a significant "inverted U" relationship between them. Liu and Tang [23] found that environmental regulations positively affected China's GTFP growth using the DEA Malmquist index technique. Wang et al. [24] believed that environmental regulation promotes environmental quality and increases GTFP of the service industry. Yin [25] applied the SBM model to investigate GTFP in China and found that the relationship between GTFP and environmental regulation intensity is a “U” type. Brannlund [26] empirically tested the impact of environmental regulation on the productivity of manufacturing enterprises in Sweden. The study showed no significant relationship between the two. Ravetti et al. [27] believed that it is difficult for environmental regulation to improve enterprise technological innovation and further prove that the effect of environmental regulation on enterprise technological innovation is almost negligible.

The above literature provides a solid foundation for studying environmental regulation’s impact on green total factor productivity, but there are still the following shortcomings. First, most of the construction of environmental regulation intensity is based on a single index or a single dimension, and the measurement of environmental regulations is not sufficient. Second, existing research studies primarily focus on the provincial and industrial sectors, which fails to provide a more abundant theoretical and practical basis for the manufacturing industry. Therefore, this study adopts the Malmquist–Luenberger productivity index to estimate the GTFP change of China’s 25 manufacturing industrial subsectors covering the period 2003–2016. Subsequently, a threshold effect model is applied to analyze the heterogeneous effects of ERI on GTFP in China. It is hoped to provide a realistic basis for the green and sustainable development of China’s economy.

3. Mechanism Analysis

Reasonable environmental regulations can effectively correct system failures and promote the efficient allocation of environmental resources [28]. In general, environmental regulations impact green total factor productivity by technological innovation, industrial structure, and FDI. Figure 1 shows the analysis framework of environmental regulation mechanism on green total factor productivity in manufacturing.

Technological innovation: environmental regulations impact green total factor productivity by technological innovation. The “Porter Hypothesis” [29] believes that reasonable environmental regulation policies can reduce innovation compensation effects by stimulating enterprise technological innovation and environmental protection technology upgrades, making up or exceeding the costs of environmental regulations, thereby enabling green total factor productivity to increase and achieve green development [30–35].

Industrial structure: industrial structure and environmental regulation affect industrial structure upgrading, changing the market structure through industrial behavior [36], which acts on GTFP. Liu et al. [37] found the decline in GTFP mainly derived from optimization and upgrading of the industrial structure rather than energy efficiency. The impact of environmental regulation on the industrial structure can be categorized into the following three aspects. First, environmental regulations can affect green total factor productivity changing the industrial structure by affecting investment and consumption demand. On the one hand, the costs of enterprises will be increased if implemented environmental regulations; squeeze the funds used by enterprises to expand reproduction, and there are higher thresholds for enterprises with high energy consumption and high pollution, which will change the investment direction more willing to invest in the clean industry. On the other hand, consumers will buy more green products with less pollution and high technology with the increased income and the environmental awareness, which will change demand structure and promote the development of the tertiary industry, and thus promote the greening of industrial structure [38]. Second, environmental regulations can affect green total factor productivity changing the industrial structure through interindustry competition and entry and exit barriers [39]. Environmental regulations will put pressure on heavy industry companies in terms of environmental governance costs and technology. Companies will be eliminated if they cannot afford higher costs. Companies with environment friendly products have more advantages than other companies with the enhancement of living and awareness, and enterprise’s profit rate has risen to achieve scale expansion and industrial structure upgrading and optimization. The main change in the industrial structure is the transfer of production factors such as labor, capital, and land to the tertiary industry. There are differences in output efficiency between different industries before reaching equilibrium economic growth. When production factors are transferred from lower to higher, it will promote economic growth. Chanary calls it the “total allocation effect,” which is considered to be a fundamental reason for the growth for green total factor productivity [40], and some scholars have also confirmed the positive impact [41–44].

FDI, environmental regulations have raised the environmental threshold of foreign-funded enterprises through market access, pollution taxes, and fees [45]. Advanced green technology and environmental protection technology were brought to the country by high-quality foreign-funded enterprises, which stimulated technological innovation and technology upgrades of enterprises, and promoted green total factor productivity [32]).

4. Empirical Test of the Influence of Environmental Regulations on the GTFP

4.1. Measuring the ERI. Given that the current investigation object was the ERI of manufacturing sectors, special requirements were imposed on manufacturing data availability and industry statistics’ caliber. Therefore, 31 manufacturing industries need to be classified according to the national economic industry classification standard (GB/T4754-2002). Considering the absence of data on individual industry segments, six segments (manufacture of rubber and manufacture of plastics, manufacture of textile and manufacture of textile wearing apparel, footwear, and caps are a combined industry. Manufacture of transport equipment still includes manufacture of automobiles. Besides, other manufactures*, utilization of waste resources, repair service

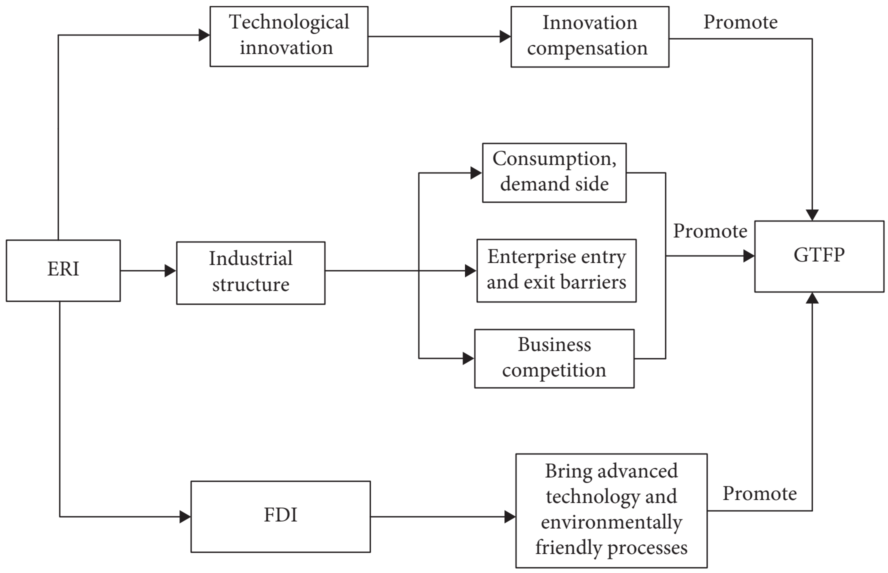

Figure 1: An analysis framework of the mechanism of ERI on GTFP of manufacturing.

of metal products, machinery, and equipment have incomplete data in the sample range studied) were removed and combined from the existing 31 industry segments to yield the final 25. The study samples drew on panel data on 25 segments of the Chinese manufacturing industry in 2003–2016. The original data were taken from the China Statistical Yearbook, China Economic Census Yearbook, China Urban Life And Price Yearbook, Development Research Center Of The State Council, China Industry Economy Statistical Yearbook, China Energy Statistical Yearbook, and China Statistical Yearbook on the Environment for the relevant years, as well as from relevant data released by the National Bureau of Statistics.

To further reflect the influence of environmental regulations on the GTFP and industry differences in environmental regulations and green total factor productivity, the 25 manufacturing industries will be divided according to pollution emissions. Given the method of Li [46], an industry's pollution intensity is determined by summing up various pollution emissions. Linear standardization and equal weight sum average of various pollutant emission data are carried out to calculate each industry's pollution emission intensity. First, calculate the pollution emission value of each industrial pollutant unit output value, and it can be expressed as

$$\mathrm{UE}_{ij} = \frac{E_{ij}}{O_i}, \tag{1}$$

where UE_{ij} represents the pollution emission, where i represents each industry, j represents the pollutant source, O_i represents the total industrial output, and E_{ij} is the emission of each pollutant.

Second, the standardized pollution emission value is defined as

$$\mathrm{UE}_{ij}^{s} = \frac{\left[\mathrm{UE}_{ij} - \min\left(\mathrm{UE}_j\right)\right]}{\left[\max\left(\mathrm{UE}_j\right) - \min\left(\mathrm{UE}_j\right)\right]}, \tag{2}$$

where $\min(\mathrm{UE}_j)$ and $\max(\mathrm{UE}_j)$ represent the maximum emission and minimum emission of each pollutant, respectively, UE_{ij} represents the current year emission of each pollutant in each industry, and UE_{ij}^{s} represents the standardization value.

Third, weighted and averaged the above pollutant emission scores, the average scores of waste water, waste gas, and solid waste were calculated, and it can be described using the following equation.

$$\mathrm{NUE}_{ij} = \sum_{j=1}^{n} \frac{\mathrm{UE}_{ij}^{s}}{n}, \tag{3}$$

where NUE_{ij} represents the pollution emission intensity index of the industry.

Finally, the average score is summarized to get the average of the total pollution emission intensity coefficient γ of the industry over the years.

The pollution emission intensity is calculated according to the above method and formulas (1)–(3) as given in Table 1. This study classifies industries based on the intensity of total pollution emissions. If $\gamma > 0.125$, the industry is heavy pollution industry; if $0.125<\gamma<0.0225$, the industry is moderate pollution industries; if $\gamma<0.0225$, the industry is slight pollution industry.

From Table 1, we can find that the main characteristics of heavy pollution industries composed of capital-intensive industries and traditional heavy chemical industries are high energy consumption and strong pollution emissions. The moderate pollution industries are mainly slight, and the energy consumption and pollution emission intensity are lower than those of heavy industries. The slight pollution industries are mainly high-tech industries and clean industries which have technical advantages, the high added value of products, low energy consumption, and low pollution emissions that make the lowest energy consumption and pollution emission intensity. It can be found that the

Table 1: Industry classifications based on pollution emission intensity.

Pollution emission intensity index	Group	Industry
γ>0.125	Heavy pollution industries	Manufacture of liquor, beverages, and refined tea; papermaking and paper products; processing of petroleum; coking and processing of nuclear fuel; raw chemical materials and chemical products; manufacture of chemical fibers; nonmetal mineral products; smelting and pressing of ferrous metals; smelting and pressing of nonferrous metals
0.125<γ<0.0225	Moderate pollution industries	Farm products processing; food manufacturing; leather, furs, down, and related products, timber processing; medical and pharmaceutical products; metal products; textile industrial and garments; shoes and hats manufacturing
γ<0.0225	Slight pollution industries	Tobacco products; furniture manufacturing; printing and record medium reproduction; manufacture of general purpose machinery; special purpose equipment manufacturing; manufacture of transport equipment; manufacture of computers; communication and other electronic equipment; manufacture of measuring instruments and machinery

heavy pollution industries are showing a stable and rising trend, the moderate pollution industries are on the rise, and the slight pollution industries remain stable, as shown in Figure 2. Table 2 provides the pollution emission intensity values of various industries.

There is no consistent conclusion for the influence of environmental regulation on GTFP due to the difference in ERI measurement by reviewing past literature. There are mainly the following methods: (1) use sewage charges to measure ERI [47, 48]; (2) measure the ERI by the proportion of pollution costs in total industrial output value or sales output value [46–49]; and (3) use a comprehensive pollutant index to measure the ERI [50]. We used the comprehensive indicators to measure the ERI [51], constituting the waste water pollutant discharge fee and exhaust pollutant discharge fee. Due to the lack of public statistical data, this study adopted the "levy standards and calculation methods for pollutant discharge fee" specified in both the Administrative Regulations on Levy and Use of Pollutant Discharge Fee (hereinafter referred to as "the Regulations"), issued by the State Council, and the Circular on Adjusting the Levy Standards for Pollutant Discharge Fee and Other Issues (hereinafter referred to as "the Circular"), issued by the National Development, estimating the pollutant discharge fee except a solid waste of 25 segments of the Chinese manufacturing industry in 2003–2016. First, the emissions of the main pollutants of various industries were calculated. Second, the calculation of each type of pollutant's pollution equivalent was undertaken (as shown in Formula (4)). Step three involved identifying the top three (≤3) representative fee factors according to the pollution equivalent sequence of various pollutants (from high to low). Finally, the pollutant discharge fees of waste water and exhaust in various industries were calculated according to the "levy standards for pollutant discharge fee" specified in the circular (formulas (5) and (6)). Last, the objective weight-based entropy method was adopted to derive the comprehensive index of ERI.

$$\mathrm{PEP} = \frac{\mathrm{EP}}{\mathrm{EVA}}, \tag{4}$$

where PEP represents the pollution equivalent of a pollutant, EP represents the pollutant's emission, and EVA represents the pollutant's equivalent value.

$$\mathrm{WPDF} = 1.4 \cdot \sum \left(\mathrm{PEPW}_i\right), \quad i = 1, 2, 3. \tag{5}$$

where WPDF represents the waste water pollutant discharge fee, and PEPW represents the pollution equivalents of pollutants in waste water.

$$\mathrm{EPDF} = 1.2 \cdot \sum \left(\mathrm{PEPE}_i\right), \quad i = 1, 2, 3. \tag{6}$$

where EPDF represents the exhaust pollutant discharge fee, and PEPE represents the pollution equivalents of pollutants in the exhaust.

Following these steps, the objective weight-based entropy method was adopted to derive the comprehensive index of ERI.

We plot the average value of the three major industries' environmental regulation intensity over the years in Figure 3. ERI of heavy pollution industries was the highest, followed by moderate pollution industries, with ERI of slight polluting industries being the lowest from 2003 to 2016, as shown in Figure 3. It shows that industries dominated by traditional heavy industries have always been the national pollution control targets, and the overall intensity of environmental regulations is on the rise. However, the ERI of heavy pollution industries has declined from 2008 to 2010. It can be attributed primarily to the financial crisis, with lower profit margins and lower output, which reduces the environment's impact. ERI of moderate pollution industries has also shown an upward trend, indicating that the moderate pollution industries' regulation was paid more attention, and the slight polluting industries have been maintained at a low level with minimal fluctuations. In general, the ERI of the three categories of industries is consistent with the conclusions obtained from pollution intensity.

4.2. Measuring the ETFP of Chinese Manufacturing Industries

4.2.1. Measurement Methods. This study uses the production frontier analysis tool, SBM directional distance function, and Luenberger productivity index proposed by Chung et al. [52], which incorporate energy consumption and environmental pollution into a TFP unified analysis framework, using a comprehensive approach to measure the TFP of manufacturing and its decomposition in the Chinese

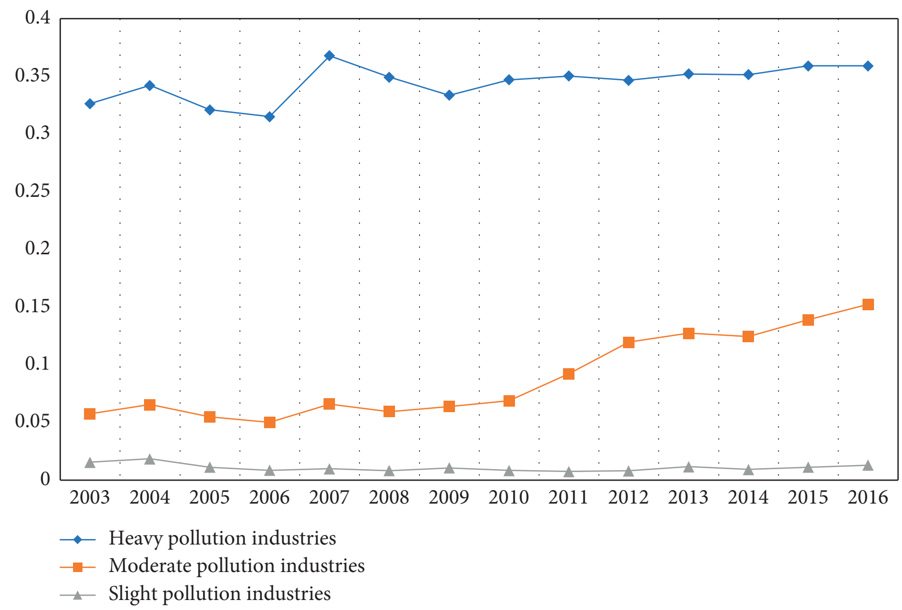

Figure 2: Changes in the average pollution intensity of the three pollution industries.

Table 2: Pollutant emission intensity values of various industries.

Groups	Industries	Index value
Heavy pollution industries	Manufacture of liquor, beverages, and refined tea	0.1245
	Papermaking and paper products	0.4759
	Processing of petroleum	0.2334
	Coking and processing of nuclear fuel	0.3475
	Manufacture of chemical fibers	0.1606
	Nonmetal mineral products	0.4136
	Smelting and pressing of ferrous metals	0.6614
	Smelting and pressing of nonferrous metals	0.3367
Slight pollution industries	Tobacco products	0.0136
	Furniture manufacturing	0.0076
	Printing and record medium reproduction	0.0059
	Manufacture of general purpose machinery	0.0108
	Special purpose equipment manufacturing	0.0126
	Manufacture of transport equipment	0.0225
	Manufacture of computers	0.0036
	Communication and other electronic equipment	0.0081
	Measuring instruments and machinery	0.0118
Moderate pollution industries	Farm products processing	0.1017
	Food manufacturing	0.0862
	Leather, furs, down, and related products	0.0324
	Timber processing	0.0529
	Medical and pharmaceutical products	0.0624
	Metal products	0.0383
	Textile industrial and garments	0.1202
	Shoes and hats manufacturing	0.1241

manufacturing industry from 2003 to 2016. Provide objective data for the empirical test, and provide objective data for the later empirical test. Put each industry as the decision-making unit, construct the best production frontier in each period, using N types of inputs, $x = (x_1, \ldots, x_n) \in \mathrm{Rn}^+$, to produce M types of desirable outputs $y = (y_1, \ldots, y_m) \in \mathrm{Rm}^+$ and i types of undesirable outputs $b = (b_1, \ldots, b_i) \in \mathrm{Ri}^+$ at the same time, where the superscripts n, m, t denote periods n, m, $t = 1, 2, \ldots, T$. Environmental technology can be described as

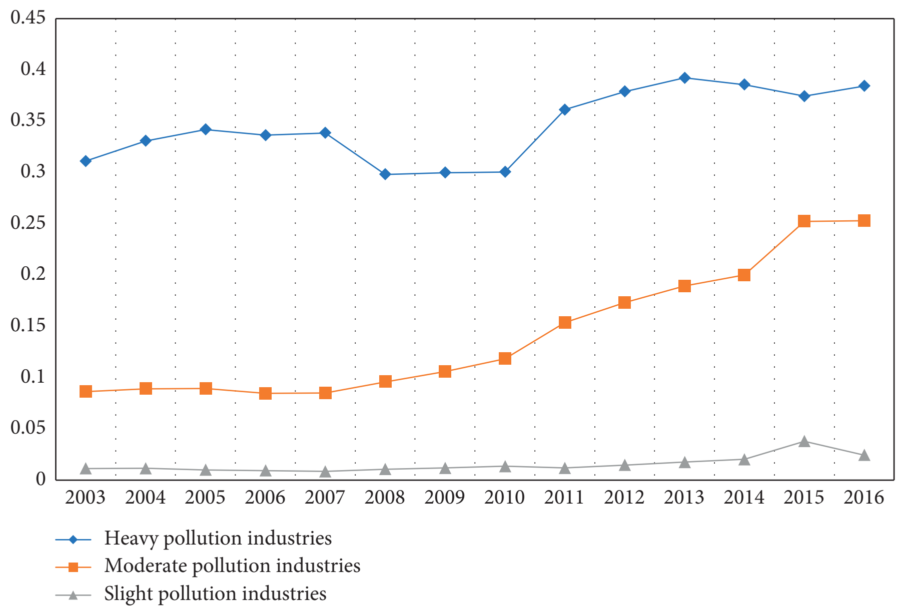

Figure 3: Changes in the intensity of environmental regulations in the three major categories of industries.

$$p^t(x^t) = \left\{ (y_t, b_t) \sum_{k=1}^{K} \alpha_k^t y_{km}^t \geq y_{km}^t, \quad \forall m; \sum_{k=1}^{K} \alpha_k^t b_{ki}^t = b_{ki}^t, \quad \forall i; \sum_{k=1}^{K} \alpha_k^t y_{kn}^t \leq x_{kn}^t, \quad \forall n; \sum_{k=1}^{K} \alpha_k^t = 1, \alpha_k^t \geq 0, \quad \forall k \right\}. \tag{7}$$

According to SBM directional distance function of energy environment proposed by Tone [53],

$$\begin{aligned} \overrightarrow{S^{G,k}} &= \left(x^{G,k}, y^{G,k}, b^{G,k}, g^{G,k,x}, g^{G,k,y}, g^{G,k,b}\right) \\ &= \max \frac{1/N \sum_{n=1}^{N} S_n^{G,k,x}/g_n^{G,k,x} + 1/M + I\left(\sum_{m=1}^{M} s_m^{G,k,y}/g_m^{G,k,y} + \sum_{i=1}^{I} s_i^{G,k,b}/g_i^{G,k,b}\right)}{2}, \\ \text{s.t.} & \sum_{k=1}^{K} \alpha^{t,k} x_n^{t,k} + s_n^{G,k,x} = x_n^{t,k}, \quad \forall n; \sum_{k=1}^{K} z^{t,k} b_i^{t,k} + s_i^{G,k,b} = b_m^{t,k}, \quad \forall i; s_n^{G,k,x} \geq 0, \forall n; s_m^{G,k,y} \geq 0, \forall m; s_i^{G,k,b} \geq 0, \forall i, \end{aligned} \tag{8}$$

where $\overrightarrow{S^{G,k}}$ represents the global directional distance function, $x^{G,k}, y^{G,k}, b^{G,k}$ is the factor input vector, desirable output vector, and undesirable output vector for each industry, respectively, $g^{G,k,x}, g^{G,k,y}, g^{G,k,b}$ is the input shrinking direction vector, expected output expansion direction vector, and directional vector for shrinking direction vector, respectively, $s_n^{G,k,x}$, $s_m^{G,k,y}$, $s_i^{G,k,b}$ represents the input slacks, desirable outputs slacks, and undesirable output slacks, respectively, slacks vector refers to the distance from the best production frontier, $s_n^{G,k,x}$ stands for the investment redundancy, $s_m^{G,k,y}$ is the insufficient expected output, and $s_i^{G,k,b}$ is the undesired output redundancy. When the slacks scalar is a zero, the SBM directional distance function is equal to the traditional directional distance function. The larger the value, the lower the efficiency level. Luenberger productivity index of period t and period $t+1$ (GTFP_t^{t+1}) is proposed by Chambers et al. [54]:

$$\text{GTFP}_t^{t+1} = \frac{1}{2}\left\{\left[s_c^t\left(x^t, y^t, b^t, g\right) - s_c^t\left(x^{t+1}, y^{t+1}, b^{t+1}, g\right)\right] + \left[s_c^{t+1}\left(x^t, y^t, b^t, g\right) - s_c^{t+1}\left(x^{t+1}, y^{t+1}, b^{t+1}, g\right)\right]\right\}. \tag{9}$$

Green total factor productivity index (GTFP) can be further broken down into technological efficiency change (GEC) and technical progress (GTC) [55]. Changes in factors such as system innovation, experience accumulation, and economies of scale in production can be expressed by technical efficiency changes (GEC). The innovation and improvement of technology can be expressed by technological progress (GTC). If GTFP > 1, it indicates that GTFP improves; otherwise, it decreases. If GEC > 1 is equivalent to technological efficiency progress, it deteriorates. If GTC > 1, it indicates green technological progress; otherwise, it regresses.

4.2.2. Related Data Processing. To measure the ETFP, calculated by a data envelopment analysis method, we first need to define input, desirable output, and undesirable output [56].

(1) Input variables. Labor input: this index is measured by the annual average number of persons employed by manufacturing enterprises above industry scale. Capital stock (K_t): the perpetual inventory method is generally used to calculate manufacturing capital stock [57, 58]. The calculation formula is as follows:

$$K_{\mathrm{t}} = (M_t - M_{t-1}) + \{1 - [(M_t - N_t) - (M_{t-1} - N_{t-1})]/M_{t-1}\} \cdot K_{t-1}. \quad (10)$$

Among them, $(M_t{-}M_{t-1})$ represents the current investment, $[(M_t{-}N_t){-}(M_{t-1}{-}N_{t-1})]/M_{t-1}$ represents the depreciation rate, K_t represents the current capital stock, and K_{t-1} represents the previous capital stock. At the same time, we use the fixed asset price index to deflate the investment in fixed assets (the base year is 2003) to obtain the manufacturing capital stock. Energy consumption: this index is measured by industrial enterprises' total energy consumption above the industry scale.

(2) Output variables. desirable output: this study selected the total industrial output value instead of the industrial added value as the desired output and use the industrial producer price index to deflate the total industrial output value (the base year is 2003) Undesirable output: we use waste water, exhaust, solid waste discharge, and CO_2 emissions to express undesirable output for the respective sector [51, 59]. The formula for the total amount of CO_2 emissions is as follows:

$$C_t = \sum_{i=1}^{3} C_{i,t} = \sum_{i=1}^{3} E_{i,t} \cdot \mathrm{NCV}_i {\cdot} \mathrm{CEF}_i \cdot \mathrm{COF}_i \cdot \left(\frac{44}{12}\right). \quad (11)$$

Among them, C denotes the CO_2 emissions, i denotes the energy type, E denotes the energy consumption, NCV represents the average lower heating value of various energy sources, CEF denotes the CO_2 emission factor of the energy, and COF indicates the energy's carbon oxidation rate. Energy types include coal, crude oil, and natural gas. The coefficients of different energy types are given in Table 3.

4.2.3. Calculation Results and Analysis. This study uses MaxDEA software to measure the GTFP of the manufacturing industry considering energy consumption and undesired output; it is decomposed into the following: technical efficiency index (GEC) and technological progress index (GTC). Table 4 reveals the industry differences in GTFP and the decomposition of the manufacturing sectors. The average value of China's GTFP of manufacturing was 1.0555 from 2003 to 2016, green TFP in overall manufacturing shows an upward trend, and the average annual growth rate of GTFP in Chinese manufacturing is 5.6%. In terms of decomposition, the technical progress index has the largest contribution to GTFP. The average annual growth rate of GEC is 1.3% and GTC is 4.3% from 2003 to 2016. Figure 4 shows the steady trend of the overall GTFP of the manufacturing industry and its decomposition items. GTFP and GTC show simultaneous changes and are higher than GEC. We can see that the GTFP is featured by a declining trend and is affected by the deterioration of technical efficiency and weak technological progress, especially in the period 2007-2008. The GTFP declined from 1.1% to 0.95%. Considering its external factors may be that in the 2008 global financial crisis, the global economy fell into a trough, which harmed the manufacturing industry.

In terms of the industry type, both slightly polluting and moderate pollution industries presented relatively significant regression on GTFP. However, only heavy pollution industries have achieved a slight increase. In the sample period, the GTFP of heavy, moderate, and slightly polluting industries increased 1.3%, −0.2%, and −0.5%, respectively; this means that there is a positive effect of the country's environmental regulation policy on heavy pollution industries and slight and moderate pollution industries should be strengthened. Heavy pollution industries have the highest average value of GTFP, second only to GTFP of the whole industry, and the growth during the study period is positive, followed by moderate polluted industries and slight polluted industries. However, the green total factor productivity growth is negative. Compared with GEC, GTC is a more important reason for the increase of GTFP in China's manufacturing industry from the perspective of its decomposition term. Therefore, we can see that the GTFP of the heavily polluting industries has been dramatically improved due to the "energy," imposed by the government. Therefore, the government's attention should be shifted to the promotion of GTFP in the moderately and slight pollution industry.

Further analysis from (Figure 4) fluctuation trends of GTFP and its decomposition in the industries are consistent. In terms of heavy pollution industry, there is a significant decline during the period 2007-2008, and the possible reason is that the outbreak of the financial crisis in 2008 hurt the

Table 3: Coefficients of different energy.

Energy type	Net heat value (kJ/kg)	Carbon emission factor (kg C/GJ)	Carbon oxidation rate
Raw coal	0.7143	2.763	0.99
Crude oil	1.4286	2.145	1
Natural gas	1.3300	1.642	1

Table 4: Average GTFP and its decomposition in the industry from 2003 to 2016.

Groups	Industry	Green total factor productivity (GTFP)	Technical efficiency (GEC)	Technological progress (GTC)
Heavy pollution industries	Manufacture of liquor, beverages, and refined tea	0.9570	0.9336	0.9626
	Manufacture of paper and paper products	1.0299	0.9654	0.9887
	Processing of petroleum, coking, and processing of nuclear fuel	0.9971	0.9286	0.9971
	Manufacture of raw chemical materials and chemical products	1.0575	0.9629	1.0218
	Manufacture of chemical fibers	0.9679	0.9790	0.9117
	Manufacture of nonmetallic mineral products	1.0541	0.9846	0.9860
	Smelting and pressing of ferrous metals	1.0434	0.9595	1.0103
	Smelting and pressing of nonferrous metals	0.9985	0.9475	0.9815
	Average	1.0131	0.9576	0.9824
Moderate pollution industries	Processing of food from agricultural products	0.9639	0.9256	0.9673
	Manufacture of foods	0.9468	0.9350	0.9446
	Manufacture of leather, fur, feather and related products, and footwear	1.0823	0.9290	1.0829
	Processing of timber and manufacture of wood, bamboo, rattan, palm, and straw products	0.9884	0.9148	1.0082
	Manufacture of medicines	0.9744	0.9438	0.9618
	Manufacture of metal products	0.9118	0.9269	0.9188
	Manufacture of textile, wearing apparel, and accessories	0.9690	0.9448	0.9593
	Manufacture of rubber and plastics products	0.9391	0.9180	0.9495
	Average	0.9720	0.9297	0.9740
Slight pollution industries	Manufacture of tobacco	0.8850	0.9286	0.8850
	Manufacture of furniture	1.0232	0.9289	1.0232
	Printing and reproduction of recording media	0.8819	0.9286	0.8819
	Manufacture of general purpose machinery	0.9646	0.9403	0.9520
	Manufacture of special purpose machinery	0.9722	0.9471	0.9542
	Manufacture of transport equipment	0.9958	0.9437	0.9791
	Manufacture of electrical machinery and apparatus	0.9205	0.9286	0.9205
	Manufacture of computers, communication, and other electronic equipment	1.0025	0.9286	1.0025
	Manufacture of measuring instruments and machinery	0.9767	0.9286	0.9767
	Average	0.9580	0.9336	0.9528
Manufacturing industry	Overall average	1.0555	1.0135	1.0436

manufacturing industry. With regard to moderate pollution industries, there is a significant increase during the period 2009-2010, and GTC has the same change. However, GEC is the opposite, proving that the changes in GTFP mentioned above are mainly from technological progress.

4.3. Model Testing and Estimation Results

4.3.1. Model Introduction. Using the panel threshold model proposed by Hansen [60], individual observations can be divided into classes based on an observed variable's value, called the threshold variable [61]. As the value of the threshold variable changes, the relationship between the dependent and independent variables varies nonlinearly. The threshold effect model with a single variable here is

$$y_{it} = \partial_0 + x_{it}\partial_1 + \varepsilon_{it}, q_{it} \le \gamma, \tag{12}$$

$$y_{it} = \partial_0 + x_{it}\partial_2 + \varepsilon_{it}, q_{it} > \gamma, \tag{13}$$

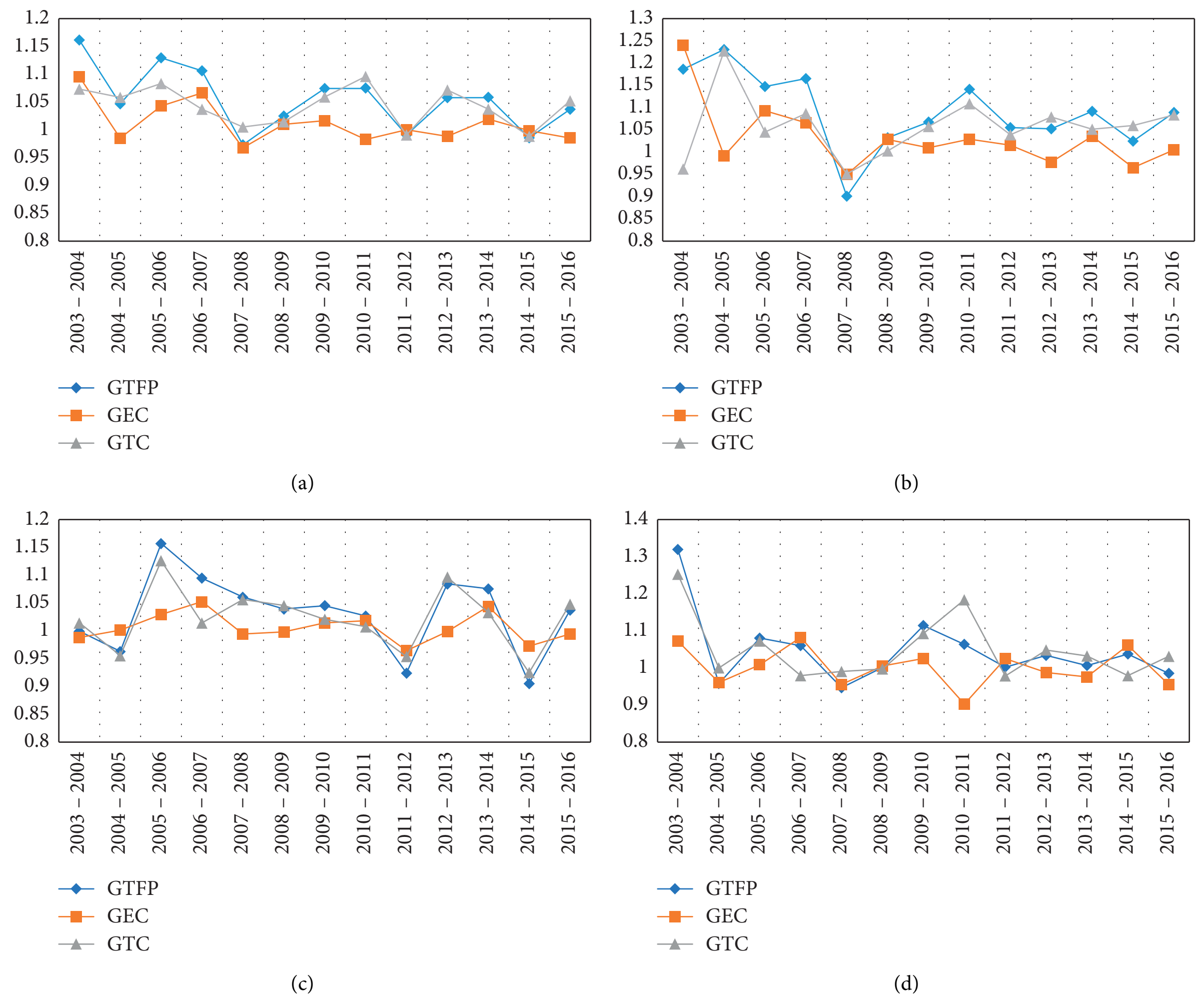

FIGURE 4: Industrial green total factor productivity and its decomposition. Manufacturing industry (a), heavy pollution industry (b), slight pollution industry (c), and moderate pollution industry (d).

where q_{it} is the threshold variable, γ is the threshold value of q, i and t denote the geographical units and years, respectively, ∂_0 andε_{it} represent the constant term and stochastic error term, respectively, and ∂_i is the coefficient. Set the following panel model according to the basic model:

$$\begin{aligned}\mathrm{GTFP}_{it} = {} & \partial_0 + \partial_1 \mathrm{ERI}_{it} \cdot I\left(\mathrm{ERI}_{it} \leq \gamma\right) + \partial_2 \mathrm{ERI}_{it} \cdot \left(\mathrm{ERI}_{it} > \gamma\right) \\ & + \partial_3 \mathrm{SS}_{it} + \partial_4 \mathrm{FDI}_{it} + \partial_5 CP_{it} + \partial_6 \mathrm{ES}_{it} + \varepsilon_{it},\end{aligned} \tag{14}$$

where GTFP_{it} represents the green total factor productivity, as explained variable; ERI_{it} represents the environmental regulation, as explanatory variable; i represents the industry; t represents the year; SS_{it} represents the scale structure; FDI_{it} represents the foreign direct investment; CP_{it} represents the capital per; ES_{it} represents the energy structure; ∂_i is the coefficient; andε_{it} represents the stochastic error term.

4.3.2. Index Selections

(1) Explained variable: green total factor productivity (GTFP)

(2) Core explanatory variable: environmental regulations intensity (ERI)

(3) Control variables: scale structure and the economic proportions of multiple ownership within the industry tend to be reasonable if the manufacturing's scale structure is reasonable, and this will optimize the allocation of resources and have a positive impact on environmental protection. Therefore, select the proportion of the total industrial output value of state-owned and state-controlled enterprises in various industries in the total industrial output value of all industries above designated size as the proxy variable. FDI, the flow of transnational capital, is the external driving force for green economic growth. The proportion of all industries' total industrial output value above the designated size invested by foreign investors and Hong Kong, Macao, and Taiwan will be selected as a proxy variable [57]. Capital per, the development of a green economy will be affected by capital per capita through technological innovation and personal pollution emissions. Therefore, each industry's capital-labor ratio is

selected as the proxy variable of per capita capital in this study. The capital stock mentioned above and the average number of employees in each industry are used for labor [62]. Energy structure, introducing energy consumption into green total factor productivity, will inevitably impact green economic growth. On the one hand, the overuse of energy will affect the input factors. On the other hand, excessive energy emissions will indirectly affect undesired output, and the proportion of primary energy has gradually decreased, and clean energy such as natural gas and hydropower has increased with the development of the economy. Referring to Chen et al. [22], this study chooses the proportion of total electric power consumption in total industrial energy consumption in each industry as the proxy variable. Table 5 presents the indexes selected.

4.3.3. Model Testing and Estimation Results. In line with the threshold model-based estimation method, the value of environmental regulation was adopted as the threshold variable. The self-sampling frequency was set at 300 times, and the bootstrap method was used to calculate the critical value of the F-statistics and thus determine the number of thresholds.

Table 6 provides the test results of the number of thresholds of the four industry groups; there is one threshold in the manufacturing industry, heavy pollution industries, and moderate pollution industries, thus indicating a nonlinear effect between ERI and GTFP. The three threshold values are 60.63%, 62.95%, and 3.86%, respectively, and all are significant at the 1% level. There is no threshold in the slight pollution industries.

Table 7 summarizes the estimation results of the panel threshold models. With regard to manufacturing, there was a "U-shaped" relationship between the environmental regulation and the GTFP, but insignificance left of the inflection point. Although the intensity of environmental regulation will have not a significant impact on the GTFP in the short term, it will increase the additional burden of enterprises with the intensity of environmental regulation increases, forcing enterprises to carry out technological innovation, which in turn produces an "innovation compensation effect" and improve the GTFP. It shows that the GTFP of the manufacturing industry has been significantly improved under the high environmental regulations, aching a win-win situation for the environment and benefits. To heavy pollution industries, environmental regulations are different and significant in two stages. Environmental regulation and green total factor productivity present a significant "U"-shaped relationship that will first decrease and then increase the impact on green total factor productivity as environmental regulation changes. Specifically, when ERI is less than 0.6295, the coefficient value is −1.4467, which is significant at the 1% significance level, which means every 1% increase in ERI, the impact on GTFP decreases by 1.4467%. When ERI is greater than 0.6295, the coefficient value rises back to 1.7550, which means every 1% increase in ERI, and the impact on GTFP increases by 1.755%. Enhancing environmental regulations will promote the increase of green total factor productivity. The reason may be that companies often only spend a small amount of money on governance when the intensity of environmental regulations is weak. As the intensity of environmental regulations increases to the "inflection point" level, companies will face more significant pollution control, affecting corporate profit. It will pay attention to protecting the environment and improving technology to reduce energy consumption and pollutant emissions, thereby increasing green total factor productivity. For moderately polluting industries, the relationship between the intensity of environmental regulations and green total factor productivity is "U"-shaped, but it is not significant on the right side of the inflection point. The results above explanations are as follows: with the increase of environmental regulation intensity, green total factor productivity is impeded. In moderately polluted industries that are dominated by means of living manufacturing and some heavy industries with relatively weak technological foundations, the high environmental regulation intensity will squeeze out enterprises' R&D input, affecting technological innovation and R&D, and not conducive to the improvement of green total factor productivity. In terms of slight polluting industries, environmental regulations' coefficient is different in two stages and not significant, indicating that there is no nonlinear relationship between environmental regulation and green total factor productivity in lightly polluted industries. In analysis of other control variables, in terms of the FDI, the latter's effect on the GTFP was found to be negative. This outcome supports the Pollution Haven Hypothesis. We must pay attention to the quality of foreign capital introduction, strengthen the capital introduction environment's supervision, and prohibit western enterprises from shifting their high pollution industries to China and prohibit the transfer of some foreign high energy consumption and polluting industries to my country through foreign capital, thereby restricting the green development of the manufacturing industry. The energy structure's regression coefficients were significantly positive, which shows that the energy structure has been improved and more reasonable. The source of energy consumption has been transformed from the primary energy sources based on coal and oil to clean energy based on electricity, which reduces the emission and undesired output, and realized the optimizing effect of energy structure and promotes the improvement of GTFP in the manufacturing industry indirectly. The capital per worker's coefficient performed relatively well among heavy and slight pollution industries but was nonsignificant among moderate pollution industries. This indicates that per capita capital positively impacts the GTFP of the heavy pollution industries and proves that capital deepening and heavy industrialization are synchronized. Traditional heavy industries are characterized by high energy consumption and large emissions under unchanged technical conditions, but capital deepening will have technological progress and promote productivity, which is conducive to improving green total factor productivity. The coefficient of scale structure is negative in the manufacturing industry,

Table 5: Explanatory variable selection and definitions.

Variable	Abbreviation	Index definition
Scale structure	SS	The total output value of state holding industrial enterprises above the designated size/total output value of industrial enterprises above the designated size
Foreign direct investment	FDI	Total output value of foreign-funded and HK/Macao/Taiwan-funded industrial enterprises above the designated size/total industrial output value of industrial enterprises above the designated size
Capital per	CP	Total assets of the industry/year-end number of persons employed in the industry
Energy structure	ES	Power consumption/total energy consumption in each industry

Table 6: Threshold effect test.

Industry type	Threshold	F value	P value	F-critical value			Critical value
				10%	5%	1%	
Manufacturing industry	Single	64.81***	0.0067	32.1869	38.7840	53.8896	0.6063
Heavy pollution industries	Single	41.80***	0.0000	19.1182	22.9038	23.1817	0.6295
Moderate pollution industries	Single	62.07***	0.01	33.4110	41.0916	58.8345	0.0386
Slight pollution industries	No	12.86	0.1800	16.4522	19.9639	23.0009	0.0001

*, **, and *** are significant at the levels of 10%, 5%, and 1%, respectively.

Table 7: Test results for the threshold effects of manufacturing and sectors.

Variables	ERI is threshold variable			
	Manufacturing industry	Heavy pollution industries	Moderate pollution industries	Slight pollution industries
One step	−0.6440963	−1.44666***	−28.64005***	−17679.08
Two-step	1.683985***	1.754965***	0.0115814	1.457588
SS	−0.011081	−1.434119***	−2.535244***	0.0477941
FDI	−0.2118817	−1.545412	0.004708	−1.040166***
CP	0.0198497***	0.0226288***	−0.0132586	−0.0178023***
ES	3.609595***	2.998984	4.011365***	7.740971***
Cons	0.74884	2.13412	1.277074	0.2564002
F value	34.62	25.45	20.25	14.28
R2	0.3944	0.6091	0.5536	0.4356

*, **, and *** are significant at the levels of 10%, 5%, and 1%, respectively.

moderately pollution industries, and heavy pollution industries and is significant in the moderate and heavy pollution industries and nonsignificant in the slight pollution industries. It shows that state-owned enterprises' vitality has not been further released in the manufacturing industry, and the effect on GTFP is not apparent. The reform of state-owned enterprises should be further strengthened. The development of state-owned enterprises and other ownership enterprises should be coordinated to promote factor flow, market competition, and optimal allocation of resources to promote the improvement of GTFP.

5. Conclusions and Prospects

This study uses the entropy method to construct a comprehensive environmental regulation index including wastewater and waste gas discharge fees and also calculated the GTFP of 25 manufacturing industries and subsectors in China from 2003 to 2016 through MaxDEA software. On this basis is an empirical analysis of the impact and heterogeneity of environmental regulations on the manufacturing industry's overall green total factor productivity and subsectors.

The main conclusions are as follows: (1) ERI presented a pattern of progressive decrease going from heavy pollution industries to moderate pollution industries and finally to slight pollution industries; (2) China's overall manufacturing industry GTFP exhibited an increasing trend during the study period; technological progress rather than efficiency promotion was the main contributor to the improvement of industrial GTFP in China; the effects are heterogeneous in GTFP across different types of industries, heavily polluting industries grow relatively fast, while moderate and light polluting industries are regressive; it shows that the economic development model of the heavily pollution industries is gradually shifting to the technology innovation-driven mode, while the moderate and light industries still have room for improvement in the technological innovation, and there is a problem of low technical efficiency; (3) the overall manufacturing industry and the moderately polluting industries have a single threshold, but the threshold is significant on one side. There is a single threshold in the manufacturing industry, and the relationship between environmental regulation and GTFP presents a "U" shape. It means that environmental regulations have a negative inhibitory effect on the growth of the green total factor productivity in manufacturing and exceeding the critical value; it will positively affect the GTFP of the heavily polluting industry. There is no nonlinear relationship between environmental regulations in lightly polluting industries and green total factor productivity.

Given the above conclusions, this study proposes the following countermeasures.

First, the industry heterogeneity of environmental regulation should be fully considered to implement environmental regulation's optimal intensity, to maintain the intensity of environmental regulation in heavily polluting industries, and to appropriately elevate environmental regulation intensity in moderate and light polluting industries within a reasonable range. The "extensive" environmental regulations adopted by China before are mainly aimed at high pollution, high energy consumption in heavily polluting industries. According to the research results, environmental policies have achieved positive results but still pose a threat to the environment for moderate and slight pollution industries. Therefore, based on the existing environmental regulatory intensity, it is necessary to increase further the medium and light polluting industries' regulatory intensity, stimulating the industry's green innovation power and increasing total factor productivity.

Second, focus on technological innovation while improving technical efficiency. Technical efficiency is an important factor restricting the promotion of green total factor productivity in the manufacturing industry. Therefore, we should pay more attention to the accumulation of experience in the production process, build a management sharing platform, integrate interindustry technical resources, improve the level of comprehensive technical efficiency, play the role of scale economy, and realize the joint development of technological efficiency and technological innovation.

Third, pay attention to the implementation of environmental regulations, control the intensity of environmental regulations to the "right side of the turning point," and prevent the phenomenon of "ineffective regulations." Establish a real-time monitoring mechanism for environmental regulations, conduct regular comprehensive evaluations of the company's implementation effects, and adjust the intensity of regulations based on the results to ensure the rationality and effectiveness of environmental regulations. Simultaneously, the company conducts satisfaction surveys, actively receives feedback, and makes appropriate adjustments based on them to ensure its green production enthusiasm.

This study empirically tests the impact of environmental regulations on green total factor productivity based on measuring the overall and subdivided industry green total factor productivity and its decomposition from 2003 to 2016. However, several limitations of this study should be considered. First, the comprehensive index of wastewater and waste gas discharge fee is adopted to select environmental regulation indicators, which cannot fully reflect the intensity of environmental regulation and has the problem of incomplete consideration. Second, in the decomposition of green total factor productivity, it is only decomposed into technological progress and technical efficiency, which may cause incomplete analysis of the change of green total factor productivity. Therefore, there may be some errors. Given the above shortcomings, the author believes that comprehensive indicators can be constructed from a more multidimensional perspective when selecting environmental regulation indicators, and the regulatory policies can be quantified into the index system. The limitations of this study need to be considered and improved in future research.

However, there are some limitations in this study that should be pointed out. First, the GTFP can be further divided into several aspects; only decomposing it into technical progress and technical efficiency may not comprehensively analyze for changes in green total factor productivity. Second, more comprehensive indicators can be used to measure environmental regulations intensity, since changes in the intensity of environmental regulations in various industries can be more fully reflected. Therefore, comprehensive indicators can be constructed from more dimensions when selecting environmental regulatory indicators, considering to include the quantification of indicators implemented by the government into the indicator system. GTFP can be decomposed into technical efficiency, technological progress, and scale efficiency to improve the accuracy of problems.

Data Availability

The original data used to support the findings of this study are available in the China Statistical Yearbook, China Economic Census Yearbook, China Urban Life and Price Yearbook, Development Research Center Of The State Council, China Industry Economy Statistical Yearbook, China Energy Statistical Yearbook, and China Statistical Yearbook on the Environment for the relevant years, as well as from relevant data released by the National Bureau of Statistics.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Understanding Disabilities among the Elderly in China: Important Factors, Current Situation, and Future Perspective

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The physiological functions of various organs and tissues of the elderly begin to decline with the growth of age, and the body is more and more affected by various degenerative diseases, resulting in the decline of the overall sports ability. As a result, some elderly people even become unable to live independently. This paper describes the current situation of the elderly in China by using the data of the elderly over 60 years of age in the 2015 China Health and Retirement Longitudinal Survey. In addition, Activities of Daily Living scale was used to determine the degree of disability, and Stata 13.0 software was used for multiple regression analysis, focusing on the analysis of the factors affecting the disability of the elderly. According to the research results, the paper puts forward the future trend from multiple perspectives and puts forward specific countermeasures and suggestions to alleviate the disability of the elderly or reduce its adverse effects. This will help China become an aging friendly country.

1. Introduction

1.1. Literature Review. At present, there is relatively little research on the elderly with disabilities in China; however, this issue has gradually received more attention from scholars. Most of the existing studies have focused on providing elderly care services in the context of population aging. Furthermore, most of them used small-sample-size questionnaire surveys to analyze the regional long-term care situation of the elderly who were disabled and its influencing factors, or to analyze the sharing of social and family responsibilities from the perspective of caregivers. In China, some studies have assessed the self-care ability of the elderly, with most of them following evaluation metrics used internationally. Examples include the Sample Survey of the Aged Population in Urban/Rural China (SSAPUR), the Chinese Longitudinal Healthy Longevity Survey (CLHLS), and the China Health and Retirement Longitudinal Survey (CHARLS). Gao pointed out that government-provided care services are more readily accepted by the elderly living in rural areas than other forms of care. In addition, this population has great potential demand for daily life care services, but it is difficult to implement these services effectively [1]. Liu argues that, in general, the current elderly care system focuses on daily life care and does not provide enough spiritual comfort. In addition, by examining relevant literature [2], Wang and Zheng found that an increase in the number of the elderly in China who are disabled is an inevitable trend, especially considering China's aging population [3]. The current imbalance in the supply and demand of care for the elderly with disabilities requires urgent attention. Many factors influence the deterioration of human bodily functions. The deterioration of the elderly people's ability to take care of themselves, to some extent, stems from the bodily deterioration that occurs over time. Exercise can reduce the chance of death and has a positive effect on reducing the impairment of self-care ability [4]. The activity of the elderly gradually decreases as they age, with females being less active than males. A decline in physical function accompanies a decrease in the frequency of activity. However, some scholars have reached different conclusions. Thus, Bauman et al. argues that people's mobility is significantly correlated with age and gender. Through analysis and comparison of data from several countries, it was found that young men had a higher capacity for physical activities than women. At the same time, for the elderly, there were no any significant differences in their capacity for activities between genders [5]. Zhao believes that there is a nonlinear relationship between gender, age, and health, and that gender has a significant impact on health. The age of 30 is taken as a critical indicator as it has been found that this is the point when health starts declining. However, men's health starts deteriorating at an earlier age than women's [6].

Huang pointed out that there was a clear positive correlation between nursing needs and age. In other words, the nursing needs and nursing time of the elderly are greater than those of younger people [7]. According to Yao also argued that disabilities increased the elderly people's dependence on family [8]. Zhou [9] argued that there was a strong correlation between the socioeconomic status of the elderly in urban and rural China and the loss rate of the Activities of Daily Living (ADL) scale. Moreover, Zhuang et al. found that the group aged ≥80 years accounted for 93% of the elderly with disabilities and that the number of females was twice that of their male counterparts [10].

For research purposes, different scholars use different instruments to measure and gauge self-care abilities in daily life. The most widely used instruments are the Katz Activities of Daily Living (ADL) and the Lawton Instrumental Activities of Daily Living (IADL) scales [11–13]. The ADL includes the ability to dress, bath, eat, get in and out of bed, stand/squat when using the toilet, and maintain continence. The IADL includes doing chores, cooking, shopping, making phone calls, managing finances, using different modes of transportation, and doing laundry [14]. Scholars combined the ADL and IADL scales to study the self-care ability of the elderly and found that there were differences in bathing, dressing, toilet use, and manual activities between genders. People older than 80 experience more difficulty in bathing themselves compared to those younger than 80. Except for eating, all other activities included under the ADL and IADL scales will gradually decline with age. The difference between genders is mainly reflected in the difference in muscle mass between men and women [15]. For the elderly living independently, gender differences in ADL are largely influenced by cultural and environmental factors, chronic disease risk factors, and health conditions [16–18]. The cumulative effect brought about by differences in social roles is that older women are more severely impaired in their ability to care for themselves than their male counterparts. Although older women have longer life expectancy than men, they face worse health conditions later in life. In addition, studies have shown that women have higher rates of obesity, muscle weakness, and contracting chronic diseases that affect their ability to take care of themselves as compared to men [19]. Muscle strength and function are higher in men than in women of all ages. The decline in muscle strength and function is more pronounced with age in women, which is a major cause of differences between genders considering self-care abilities.

1.2. Significance of the Study. Considering the many challenges posed by aging, how healthy aging can be achieved has become an important topic for the Chinese government and society. Under the combined effects of population aging, elderly population, and low birth rates, the burden of supporting China's working population is increasing, and the problem of caring for the disabled elderly is gradually emerging. Although the proportion of severely disabled elderly people is declining as the medical and health technology improves, it is still necessary to pay attention to the elderly who are disabled and improve their quality of life.

A serious consequence of aging is an increased prevalence of diseases, especially chronic diseases. With an increase in age, there is likewise an increase in the incidence of diseases and functional disorders. The types of diseases that the elderly contract become more complex as the population ages. There is a higher risk of physical limitations and disabilities among those with multiple chronic diseases. Furthermore, there is a strong association between chronic diseases, disabilities, and long-term care needs. The aging of the elderly population accompanies the aging of the Chinese population, and the rate of aging among this subset is faster than the rate of total population aging. The number of individuals aged ≥80 years will reach 43 million in 2030. The percentage of people aged ≥60 years will increase to 12.07% in 2030 from 10.44% in 2000, and it will reach 100 million in 2050, accounting for 22.91% of the population of those aged ≥60. On October 9, 2016, the National Committee on Aging, the Ministry of Civil Affairs, and the Ministry of Finance jointly released the results of the "Fourth Sample Survey on the Living Conditions of China's Urban and Rural Older Persons," [20] showing that, in 2015, the total number of disabled and semidisabled elderly nationwide reached 40.63 million, accounting for 18.3% of the elderly population. Among them, the percentage of elderly people who are totally disabled is higher in urban areas (6.9%) than in rural areas (5.0%). In addition, 84.3% of disabled elderly are mildly disabled, followed by 5.1% moderately disabled and 10.6% severely disabled. The Zhongmin Social Assistance Institute under the Ministry of Civil Affairs has also released, for the first time, the "Status Report on the Loss of China's Elderly," [21] showing that approximately 500,000 elderly people are lost nationwide every year, with an average of 1,370 people lost per day. In an investigation on the causes of this trend, it was found that dementia and a lack of care were the main causes. In terms of regional distribution, most of them were the elderly left behind in rural areas. The problem of disablement among the elderly population cannot be ignored and must be addressed urgently.

Due to apparent differences in the level of socioeconomic development in various parts of the country, the overall picture of the ADL impairment among the elderly in China remains to be clarified. The elderly people's ADL is influenced by a variety of factors, including individual demographic characteristics (e.g., gender, age, way of living), personal medical conditions, socioeconomic status, lifestyle (e.g., exercise or smoking), cognitive and emotional status (e.g., depression), and even geographical location. There have also been investigations that obtained different results;

for example, some studies have concluded that self-rated sleep status and loneliness have no significant effect on ADL. This paper attempts to use the 2015 CHARLS, conducted in 28 provinces across China, to analyze the current status of disabilities and its influencing factors in the elderly aged ≥60 years. The paper uses the ADL scale to measure the self-care ability of elderly people aged ≥60 years.

From the findings of the study, age and education level can predict the disability level of the elderly, while disease and marriage have a significant impact on the disability level of the elderly. Based on the data of CHARLS 2011, the proportion of the elderly who are over 60 years old will continue to increase. Continuous research on the influencing factors and current situation of the disabled elderly can continuously assess the disability status of the elderly in China, help to improve the long-term care security system in China, pay attention to prevention and healthcare, and prevent the elderly from weakening, and it can be gradually included in the scope of long-term care assessment and healthcare.

2. Research Design

2.1. Sources. Data used in this paper are from the CHARLS follow-up survey released in 2015. The survey was organized and implemented by the National School of Development at Peking University, with a baseline survey conducted in 2011, a follow-up survey conducted in 2013 based on the 2011 survey, and another follow-up survey conducted in 2015 based on the 2013 survey. It is currently the only large-scale household survey in China that focuses on middle-aged and elderly people, with a wide geographical representation and large sample size. This study used survey data collected in the summer of 2015 and released on November 18, 2015, targeting middle-aged adults over the age of 45. From there, elderly people over age 60 were selected, and samples with missing key variables were removed, resulting in a total of 1,293 samples. CHARLS questionnaire design refers to international experience, including the United States Health and Retirement Survey (HRS) and the European Health, Aging and Retirement Survey (SHARE). The project adopts multistage sampling, and PPS sampling method is adopted in county and village sampling stages. CHARLS first created the electronic mapping software (CHARLS-GIS) technology, using map method to make village level sampling frame. CHARLS questionnaire includes basic personal information, family structure and financial support, health status, physical measurement, medical service utilization and medical insurance, work, retirement and pension, income, consumption, assets, and community basic information. The access response rate and data quality of CHARLS are in the forefront of similar projects in the world, and the data has been widely used and recognized in academic circles. China's elderly health and pension tracking survey project covers the most complete provinces, but the sample number of the elderly aged 60 and above is the lowest. It is necessary to control the age group to analyze the stability of disability rate.

2.2. Determining Disabilities. The ADL scale developed by Katz evaluates daily activities of elderly people. It represents the self-care ability required by an individual to maintain basic daily activities, which includes the following six activities: eating, bathing, dressing, toileting, continence, and ambulating. In this study, the ADL scale was used to determine whether the elderly were disabled, which included the six indicators of eating, dressing, getting in and out of bed, bathing, toileting, and continence. Each of these indicators comes with four levels: no difficulty, able to complete with some difficulty, needs help due to difficulty, and unable to complete. If any one of them is indicated as "needs help due to difficulty" or "unable to complete," it indicates disability; otherwise, it is not disability [22]. Activities of Daily Living are basic tasks of daily life that most people are used to doing without assistance. The ability to perform ADL is used to help determine medical status for health coverage and long-term care decisions. Assisted living facilities, in-home care providers, and nursing homes specialize in providing care and services to those who cannot perform ADL for themselves. Although the self-care ability scale decomposes the independent living ability into the ability to complete several basic daily activities, there are still some differences in the process of analyzing the specific information collected by the scale and what kind of norms to follow. What is the status of self-care ability to be judged as disability? How to define basic self-care ability (BADL) or instrumental self-care ability (IADL) in the specific operational measurement? In the clinical rehabilitation nursing work, the number of patients who were damaged was usually calculated according to the basic daily self-care activities included in Katz scale, such as bathing, dressing, going to the toilet, transferring, controlling defecation, and eating. The subjects' self-care ability was divided into seven grades, and the requirements of six items for physical fitness were different. The above order was from difficult to easy. When we use this scale to measure the disabled state of the elderly in China, we also refer to this idea, but there are some differences in the setting of specific measurement activities.

Functional independence measurement (FIM) is more detailed, accurate, and sensitive index in reflecting the level of disability or the amount of help needed. It is a powerful index to analyze and judge the rehabilitation effect. FIM not only assesses ADL dysfunction caused by motor impairment, but also evaluates the impact of cognitive impairment on daily life.

FIM includes 6 aspects, including 18 items, including 13 sports ADL and 5 cognitive ADL.

The scoring system is 7 points; that is, the highest score is 7 points, and the lowest score is 1 point. The highest total score is 126 points, and the lowest score is 18 points. The score is based on the degree of independence of patients, the need for assistive devices or assistive devices, and the amount of help given by others. When applying FIM to assessment, the assessor should first make the content and action points of each activity clear. Only by following the specific content defined by each activity can the result be objective and accurate. Pay attention to the observation of the actual operation ability of patients in the evaluation, not only relying on their oral statement. When evaluating the ADL of the disabled, do not evaluate what they should be able to do or what they may be able to do under certain conditions. What should be examined is the actual state.

When the patient can complete a certain activity with help, the method and amount of help should be recorded in detail. The assessment should be conducted at an appropriate time and place. Usually, occupational therapists should go to the ward to observe the patients' self-care activities such as dressing, washing, shaving, or wearing make-up when they get up in the morning, so as to show the reality. If the occupational therapy department has ADL assessment settings, it must be as close to the actual living environment as possible. In order to avoid inaccuracy due to fatigue, the assessment can be completed in several times if necessary, but it should be carried out in the same place.

The purpose of reassessment of ADL is to observe the curative effect, test the treatment method, provide the basis for timely adjustment of treatment plan, and judge the prognosis. Therefore, the time for reevaluation should be arranged at the end of a course of treatment and before discharge. New dysfunction should be evaluated at any time. For items that cannot be completed independently, the therapist should further examine the factors that affect the completion of these activities, such as joint range of motion, muscle strength, balance, coordination, and sensation. ADL level is closely related to cognitive function. Therefore, for patients with ADL disorder, cognitive and perceptual functions should be further evaluated.

2.3. Research Methodology. The survey questions and answer choices related to the respondents' basic information such as gender, age, marital status, and educational background were extracted from the basic information and family module sections of the CHARLS database. Questions and answer choices related to the respondents' mobility, self-care, and daily activities were extracted from the health status and function sections of the database. Based on those two extractions, elderly people aged ≥60 years were selected, which resulted in 1,293 subjects out of 2,378 that fit the requirements. The SPSS 24.0 was used for descriptive statistics and multifactor analysis of variance, after which Stata 13 was employed for multiple linear regression equations for multifactor analysis.

2.4. Variable Selection and Description. In this paper, the dependent variable was whether the elderly aged ≥60 years were disabled, as indicated by (Y) (valuation: no = 0, yes = 1). The ADL scale was used to determine whether a person was disabled. The ADL difficulty variable is a measure of the elderly people's ability to perform daily activities, which includes the six ADL of dressing, bathing, eating, waking up, toileting, and continence. The values of these variables were summed up in the questionnaire, which asked about the difficulty in performing the ADL. These specific values were of practical significance. A value of 0 was assigned to variables deemed not difficult or difficult to complete. In contrast, a value of 1 was assigned to variables deemed difficult, needing help to complete, and that cannot be completed.

The main explanatory variables in this paper were age, gender, educational background, marital status, presence of chronic illness, and presence of any disabilities. The following six variables were used as control variables for the model: (1) the age of the respondents at the time of the survey; (2) gender (assigned a value of 1 for men and 2 for women); (3) educational background (primary school and below, secondary school, and university and higher, assigned a value of 1, 2, and 3, respectively); (4) marital status (assigned a value of 1 for married and 0 for not married); (5) whether the respondents had chronic diseases: if the respondent answers yes to one of the choices, it was considered a chronic disease and assigned a value of 1, but if the respondent answered no to both, it was not considered a chronic disease and was assigned a value of 2; (6) whether they were disabled: if the respondent answers yes, they were considered disabled and assigned a value of 1, but if they answer no, they were not considered disabled and were assigned a value of 0. Since the paper only analyzed whether the explanatory variables had an effect and the direction of influence, the specific values of disability, chronic illness, and marital status had no effect on the results of this regression analysis.

3. Empirical Findings and Analysis

3.1. Descriptive Analysis. This paper uses the multiple linear regression method for regression analysis. Considering the significance level, setting it too high will result in too few variables entering the model, which will directly affect the model's accuracy. Therefore, the significance level $p = 0.05$ was set to ensure the correctness of the model. Automatically, we set the p value, which is the probability that the test statistic calculated according to the sample observation results falls into the rejection domain when the original hypothesis is true. If the p value is very small, this means that the probability of this situation is very small. If this happens, according to the principle of small probability, we have a reason to reject the original hypothesis. The smaller the p value is, the more sufficient the reason for rejecting the original hypothesis is. Secondly, the significance level usually has two values (0.01 and 0.05). If $p < 0.01$, this means that it is a strong judgment result and the original hypothesis is rejected. If $0.01 < p$ value <0.05, this means that the judgment result is weak and the original hypothesis condition is rejected. If $p > 0.05$, the results cannot reject the original hypothesis.

3.1.1. Results of the Multivariate Analysis of Variance. According to the regression results in Table 1, the F-test value of the whole model was 3.725, and the p value was 0, which passed the test. All variables passed the significance test with a confidence level of 95%, proving that the respective variables had a significant effect on the dependent variable. Based on the regression results in Table 2, the whole model passed the test with an F-test value of 3.625 and a p value of 0. All variables passed the significance test with a confidence level of 95%, proving that the respective variables had a significant effect on the dependent variable.

Table 1: Results from the multifactor analysis of variance.

Dependent variable: disabled or not						
Variable	Sum of squares of deviation from mean	Degree of freedom	Mean-square value	F	Statistical significance	Partial eta-squared
Correction model	14.651a	68	0.215	3.725	0.000	0.171
Age	2.320	35	0.066	1.146	0.258	0.032
Educational background	0.648	8	0.081	1.399	0.192	0.009
Marital status	0.052	5	0.010	0.179	0.970	0.001
Gender	0.201	1	0.201	3.468	0.063	0.003
Physical disability	1.442	1	1.442	24.929	0.000	0.020
Brain damage/intellectual disability	0.306	1	0.306	5.293	0.022	0.004
Blindness or partial blindness	0.254	1	0.254	4.395	0.036	0.004
Deafness or partial deafness	0.326	1	0.326	5.637	0.018	0.005
Stuttering or severe stuttering	0.007	1	0.007	0.114	0.736	0.000
Hypertension	0.029	1	0.029	0.509	0.476	0.000
Dyslipidemia	0.056	1	0.056	0.963	0.327	0.001
Diabetes	0.169	1	0.169	2.930	0.087	0.002
Cancer	0.122	1	0.122	2.111	0.147	0.002
Chronic lung disease	0.051	1	0.051	0.883	0.348	0.001
Liver diseases	0.083	1	0.083	1.431	0.232	0.001
Heart disease	0.197	1	0.197	3.412	0.065	0.003
Stroke	1.188	1	1.188	20.537	0.000	0.017
Kidney disease	0.003	1	0.003	0.049	0.825	0.000
Stomach or digestive system disease	0.116	1	0.116	2.001	0.157	0.002
Emotional and mental problems	0.010	1	0.010	0.172	0.679	0.000
Memory-related disorders	0.781	1	0.781	13.500	0.000	0.011
Arthritis or rheumatism	0.233	1	0.233	4.019	0.045	0.003
Asthma	0.532	1	0.532	9.201	0.002	0.007
Errors	70.803	1224	0.058			
Aggregate	92.000	1293				
Revised total	85.454	1292				

3.1.2. Results of the Multiple Regression Analysis. The data for the variables previously described were entered into Stata 13.0, and a multiple linear regression analysis was performed. The results are shown in Table 3.

By observing the regression results from Table 3, it is evident that the F value of the model is $F(6, 1323) = 14.64$. Prob $> F = 0.000$ indicates that the model, as a whole, is very significant. In these regression results, age, marital status, presence of disability-related issues, and presence of chronic diseases are highly significant at the 95% significance level. In contrast, educational background and being retired were not significant. The univariate analysis showed that there were statistically significant differences in mobility scores for gender, educational background, marital status, children's income level, chronic disease status, and alcohol consumption.

3.1.3. Stepwise Multiple Regression. According to the regression results in Table 4, both F and p values of the model indicate that the model, as a whole, is statistically significant. The p value for all variables is <0.05 at the 95% significance level, indicating that all variables are statistically significant. An expansion of the variables as to whether there were disability problems and chronic diseases is shown in Table 5. Thus, among disability problems, physical disability, brain damage/intellectual disability, blindness and partial blindness, and deafness/partial deafness have a significant impact on the disabilities of the elderly. Among chronic diseases, having a stroke, memory-related diseases, arthritis/rheumatism, and asthma had a significant impact on the disabilities of the elderly.

3.2. Analysis of the Multiple Regression Model Results. There are significant differences in the inference results of disability rates from different source databases. In this paper, the disability rate was 9.25%, which is significantly different from the study results by Zhang and Wei (10.48%~13.31%) and Yang et al. (8.18%). Zhang and Wei's research makes full use of the completed survey data; the CLHLS, SSAPUR, and CHARLS special survey data of the same period are combined in the assessment of the disability level of the elderly, so as to overcome the size of the sample population to the greatest extent and the problem of low modulus. Although this method can increase the sample size of data and improve the accuracy of research, it will also make the structural differences between databases become a problem. We think that the comparison of continuous data based on CHARLS is also an important perspective, so it is valuable to make a comparison with the failure rate of 11.25% based on CHARLS analysis. From the intuitive data, with the improvement of medical level and personal quality, the disability rate of the same age dimension has a downward trend. This may be related to the sample composition of the data, the survey timing, and the assessment of disabilities [23, 24].

Table 2: Results from the multifactor analysis of variance.

Dependent variable: disabled or not					
Variable	Sum of squares of deviation from mean	Degree of freedom	Mean-square value	F	Statistical significance
Correction model	14.692a	70	0.210	3.625	0.000
Age	2.329	35	0.067	1.149	0.254
Gender	0.645	8	0.081	1.393	0.195
Educational background	0.053	5	0.011	0.183	0.969
Marital status	0.202	1	0.202	3.494	0.062
Presence of disability-related issues	0.021	1	0.021	0.367	0.545
Suffering from chronic illnesses	0.018	1	0.018	0.314	0.575
Errors	70.762	1222	0.058		
Aggregate	92.000	1293			
Revised total	85.454	1292			

Table 3: Results of the multiple regression analysis on being disabled or not.

Disabled or not	Coefficient	Standard deviation	t	$p > \|t\|$	(95% confidence interval)	
Age	0.0023967	0.0010061	2.38	0.017	0.0004229	0.0043706
Gender	0.0052931	0.0044926	1.16	0.248	−0.00362	0.0140063
Educational background	0.0002336	0.00429929	0.06	0.957	−0.008188	0.0086553
Marital status	0.313562	0.148443	2.11	0.035	0.0022352	0.604772
Presence of disability-related issues	−0.1244832	−0.168741	−7.38	0.0001	−0.1575861	−0.913803
Suffering from chronic illnesses	−0.617708	0.0161676	−3.82	0.0001	−0.934878	−0.300539
Cons	0.1476852	0.843754	1.76	0.080	−0.017839	0.3132093
$F(6,1323) = 14.64$						
Prob > $F = 0.000$						
R-squared = 0.0623						
Adj R-squared = 0.580						
Root MSE = 0.25366						

Table 4: Results of the stepwise multiple regression.

Disabled or not	Coefficient	Standard deviation	t	$p > \|t\|$	(95% confidence interval)	
Age	0.0023967	0.0010061	2.38	0.017	0.0003938	0.3644116
Marital status	0.313562	0.148443	2.11	0.035	0.0022352	0.604772
Presence of disability issues	−0.1244832	−0.168741	−7.38	0.0001	−0.1575861	−0.913803
Chronic illnesses	−0.617708	0.0161676	−3.82	0.0001	−0.934878	−0.300539
Cons	0.1476852	0.843754	2.79	0.005	0.0637036	0.3644116
$F(6,1323) = 27.64$						
Prob > $F = 0.000$						
R-squared = 0.0589						
Adj R-squared = 0.567						
Root MSE = 0.25383						

Both age and educational background have clear impacts on the ADL, with many studies showing that health differs between genders such that women are often at a disadvantage. However, when other factors are considered, gender differences in ADL are not significant. Gender may be strongly correlated with other factors, such as age (longer life expectancy for women) and educational background (lower educational attainment for women). There are significant age differences in ADL as well. Zhang and Wei evaluated the level of disabilities in China's urban and rural elderly population using data from three Chinese surveys on the elderly (CLHLS, CHARLS, and SSAPUR). The results showed that the disability rate in China's urban and rural elderly population fluctuates due to age, gender, and urban-rural distribution of the samples [23], which is consistent with previous findings. As age increases, the prevalence of chronic disease increases, physical function decreases, and ADL levels decline among older adults. With regard to the impact of educational background, the study leans toward the conclusion that higher educational attainment leads to less ADL impairment. Older adults who are better educated tend to have better work environments, economic status,

Table 5: Multiple regression results for the individual variables of the disabled.

Disabled	Coefficient	Standard deviation	t	$p > \|t\|$	(95% confidence interval)	
Age	0.0023769	0.0009777	2.43	0.015	0.0004577	0.004294
Educational background	0.0002456	0.0043722	0.56	0.574	−0.0061215	0.0110335
Marital status	0.0002278	0.0041569	0.05	0.956	−0.0079275	0.008383
Gender	0.0248379	0.0143658	1.73	0.084	−0.0033454	0.0530211
Physical disability	−0.2177461	0.0413576	−5.26	0.0001	−0.2988828	−0.1366093
Brain damage/intellectual disability	−0.105346	0.0438723.	−2.40	0.016	−0.1914162	−0.0192759
Blindness or partial blindness	−0.0579315	0.0279862	−2.07	0.039	−0.1128358	−0.0030272
Deafness or partial deafness	−0.0475304	0.0204548	−2.32	0.020	−0.0876594	−0.0074014
Stuttering or severe stuttering	−0.0636656	0.105319	−0.60	0.546	−0.2702841	0.1429529
Hypertension	−0.0130158	0.0145785	−0.89	0.372	−0.0416165	0.0155849
Dyslipidemia	0.0220961	0.0236721	0.93	0.351	−0.0243446	0.0685368
Diabetes	−0.0422556	0.0260122	−1.62	0.105	−0.0932872	0.0087759
Cancer	−0.0752628	0.0533932	−1.41	0.159	−0.1800114	0.0294857
Chronic lung disease	−0.0229355	0.022411	−1.02	0.306	−0.0669022	0.0210313
Liver diseases	0.0235449	0.0295659	0.80	0.426	−0.0344586	0.0815483
Heart disease	−0.0279454	0.0194356	−1.44	0.151	−0.0660749	0.0101841
Stroke	−0.1752278	0.0372891	−4.70	0.0001	−0.2483829	−0.1020728
Kidney disease	−0.0080584	0.0289459	−0.28	0.781	−0.0648455	0.0487287
Stomach or digestive system disease	−0.0204425	0.0164599	−1.24	0.214	−0.0527342	0.0118491
Emotional and mental problems	0. 0191352	0.061465	0.31	0.756	−0.101449	0.1397194
Memory-related disorders	−0.2007915	0.0563144	−3.57	0.0001	−0.311271	−0.0903119
Arthritis or rheumatism	−0.0312724	−0.014733	−2.12	0.034	−0.0601762	−0.0023687
Asthma	−0.1116816	0.0351583	−3.18	0.002	−0.1806563	−0.0427069
cons	2.112104	0.3026871	6.98	0.0001	1.518282	2.705926

lifestyle habits, cognitive functions, and therefore lower rates of disability impairments.

Many factors affect disabilities among the elderly. Studies have found that diseases (especially chronic diseases) are key factors behind disabilities among the elderly. The number and types of diseases that affect the elderly show a tendency to increase gradually with age. These diseases affect the ability to see, hear, think, and react [25]. Marital status is also a key factor behind disabilities among the elderly. Generally speaking, elderly people who are unmarried, widowed, and divorced are more likely to experience negative emotions such as loneliness, repression, and depression, all of which will invariably pose a hidden danger to their physical health and will affect their daily self-care ability [26]. A study by Yang et al. [24] found that chronic disease is an important factor affecting disability. Older adults with chronic diseases have a greater risk of being disable 1.43 times greater than those without chronic diseases. Those with three or more chronic diseases have a 2.47 times greater risk than those without. The disability rate among the elderly increases significantly with age. Risk factors, such as chronic illnesses and mental health problems, also influence the continued ability of older adults to care for themselves. This finding is consistent with the results of this study.

4. Discussion and Conclusion

This study found that the disability rate among the elderly increases significantly with age. Risk factors such as having chronic diseases and disability-related problems also affect the continued ability of the elderly to take care of themselves. This suggests that the state should continue to strengthen prevention and control measures to address the factors affecting the disablement of the elderly, such as reducing the prevalence of chronic diseases, strengthening mental health education for the elderly, and raising awareness of self-health management among the elderly to improve their self-care ability and control the disability rate. Furthermore, as the population's median age and the number of disabled elderly people continue to increase, the demand for long-term care for the elderly will continue to increase. However, presently in China, care for the elderly who are disabled mainly comes from their family as there is a relative shortage of welfare resources for their long-term care along with a slow development of social care. Therefore, the government should establish a comprehensive long-term care service system and improve the quality of long-term care services for the elderly.

Emphasis should be placed on the physical and mental health of the disadvantaged elderly, and they should be supported by both their family and society. Families and society should pay closer attention to the physical and mental health of the disadvantaged elderly people, such as those who are female, old, or disabled. For disadvantaged elderly people, their traditional attitudes still favor home or community-based care, so family members, especially their children, should take responsibility for the daily care of disadvantaged elderly people, especially those who are ill or disabled. Children of the disadvantaged elderly should try to live with them, or close to them, to provide daily care and spiritual companionship. The government should also provide professional services for the elderly in their homes, establish even more standardized and professional institutions, and provide social groups for spiritual comfort. All these could help to reduce the suffering that the disadvantaged elderly experience from physical illness or pain and could promptly resolve their negative psychological anxiety and depression so that they can lead a more positive and healthy life in their old age.

The massive number of disabled elderly people in China has put tremendous pressure on the country's elderly service system in addressing the challenges posed by aging. The country must recognize that healthy aging is the key to alleviating the pressures of an aging population. The insidious onset, long duration, and persistence of chronic diseases must be addressed; there is a need to innovate the prevention and control functions of the health service system for chronic diseases. The incidence of chronic diseases can be effectively reduced by disseminating information on health and healthcare, developing preventive health programs, and investing resources in maternal and child healthcare. Additionally, physical exercise and regular medical check-ups are important ways to reduce the risk of disabilities from diseases, while also maintaining health capital. Optimization of rural sports infrastructure and arrangements for regular medical check-ups for the elderly can promote the maintenance of their health capital.

Strengthening health management for the elderly and focusing on the prevention and control of chronic diseases are necessary. Chronic diseases are a major factor in the lives and health of the elderly in China, causing physical pain, inhibiting mobility and self-care abilities, and seriously affecting every-day activities. Moreover, the financial pressure and mental burden caused by chronic pain and medication make them vulnerable to anxiety, depression, despair, and other psychological problems, which further aggravate their illnesses, negatively impacting their health. Departments related to the physical and mental health of the elderly should conduct regular quality-of-life measurements of both healthy and sick elderly people. They should also conduct a comprehensive analysis based on the data derived from the health examinations so they could provide data basis and scientific guidance for community health services, thereby reducing the negative impact of chronic diseases on the quality of life. The most effective way to reduce the damage of chronic diseases is to carry out health literacy education. Only through long-term and persistent education can the elderly people's health awareness and sensitivity to chronic disease symptoms be improved. They can gradually develop positive daily healthcare awareness and behavioral habits. In carrying out health literacy education, the concept that must be adhered to is "teaching considering the individual and teaching considering the disease"; different health conditions stem from individual characteristics of the elderly. Different methods of teaching and awareness raising must be adopted for those with different health conditions, occupations, and educational background.

4.1. Theoretical Contribution. The first theoretical contribution is using new data to verify the research conclusions of Zhang and Wei, and Yang et al. on disability of the elderly in China and discussing the possibility of different research results [23, 24].

The second theoretical contribution is concluding that gender has no significant effect on ADL of the elderly in China. It corrects the conclusion of many studies that gender health is unfair.

The third contribution is to verify the predictability of age and education level to ADL level through new data. The prevalence of chronic diseases in the elderly is increased, the body function is decreased, and the ADL level of the elderly will be decreased. Regarding the influence of education level, the research is close to the conclusion of "higher education level, lower ADL damage." The elderly with higher education often have better working environment, economic status, living habits, and cognitive function, so the disability rate is lower.

The fourth theoretical contribution is to reverify that disease, marriage, and other factors have a significant impact on disability of the elderly in China.

4.2. Practical Contribution and Policy Suggestions. With the aging of the population and the change of family structure, the care of the disabled elderly has gradually evolved from family responsibility to the whole society. It is necessary to take appropriate preventive measures and public policies to deal with it. Based on the concept of "active aging" and "healthy aging," this study aims to maintain and enhance the feasible ability and function of the elderly through the improvement of care resources and care environment for the elderly in China, improve their social participation opportunities and subjective well-being, and help build an aging friendly country and sustainable society.

The first practical contribution: The research on the situation and affecting factors of the disabled elderly in China is conducive to the construction of the evaluation system for the disabled elderly. By learning from the international long-term care needs assessment indicators, a composite evaluation index system is established to comprehensively assess the physical and mental functions, care resources, social environment, and personal will of the disabled elderly, so as to enhance their feasible ability and function. The assessment system of the disabled elderly is the basis of long-term care insurance system. Combined with the theory of feasible ability and international experience, the assessment index of care needs (disability assessment index) should include physical structure, ADL, IADL, cognitive and behavioral problems, action ability, family care resources, social participation ability, and psychological status. However, the current care needs assessment in China's pilot areas fails to reflect the needs of the cognitive disabled. With the continuous expansion of pilot areas in China, the scientific assessment tools for long-term care rating have been promoted. Firstly, based on the concept of maintaining and restoring the feasible ability of disabled elderly people, a composite disability assessment scale was established. Secondly, using the method of dividing the degree of disability by care time in advanced countries for reference, the research on care time of disabled care projects was gradually carried out, and the evaluation information of China was collected. The objective is to evaluate the consumption of nursing resources and to classify the disability level more scientifically. The establishment of needs assessment level and care level matching, through the scientific and objective division of disability level and corresponding care level service, is conducive to the rational allocation of long-term care resources for the disabled elderly in China. In order to better estimate the number of potential long-term care needs and the demand for care services and manpower and to plan the care level, payment standard, and human resource development strategy for long-term care insurance, which is limited by the existing database, it is suggested that the responsible units of long-term care insurance should design relevant questionnaires according to the multidimensional evaluation system and conduct national long-term care demand surveys regularly, which can be used as a reference for long-term care policy planning.

The second practical contribution: The research on the situation and affecting factors of the disabled elderly in China is conducive to improving the long-term care security system and establishing the care management system. Referring to the care management system established in developed countries and regions, after the assessment of disability level by assessors, the care management specialist, in combination with the care level, formulates the most appropriate care plan according to the multiple needs of the caregivers within the scope of insurance benefits, integrates and connects the care resources, and regularly modifies them according to the changes of individual needs, so as to effectively build the disabled persons and long-term care resources bridge. As the "gatekeeper" of the long-term care insurance fund, in order to maintain the public welfare and fairness, the long-term care management department, a subsidiary of the health and health management committee, should be responsible for the assessment and care plan arrangement. The care administrators should cooperate closely with community service resources (designated institutions) and informal care resources (family members) to integrate the resources of formal care and informal care, respect the choice of the elderly, and link and coordinate the arrangement of long-term care services to respond to their care needs.

The current long-term care insurance system in China has not yet set up a care management link. In actual operation, some pilot areas, such as Guangzhou, provide care service packages, which are selected by the personnel who have passed the disability assessment; or those who choose to provide for the aged who are cared by institutions, the care managers will assess the disability status and draw up care plans.Although the former retains the autonomy of the caregivers, the information asymmetry exists in the demander, which may not match the supply and demand scientifically; in the latter, the institutional staff are often considered by the business performance and overestimate the level of the need for care, so as to obtain higher insurance benefits. The construction of long-term care system needs not only care insurance and service institutions, but also a sound care management system and human resources system.

The third practical contribution: The research on the situation and affecting factors of the disabled elderly in China is conducive to the national level to pay attention to the prevention and treatment of elderly weakness and gradually bring them into the scope of long-term radiation assessment and healthcare. In Japan, we attach great importance to the need to support level 1 and level 2 prevention and care work. In particular, 3% of the nursing insurance premium is allocated to the high-risk elderly for preventive care services. At the same time, Taiwan has also added the elderly frailty assessment (SOF) in the disability assessment scale to identify the high-risk disabled elderly, and the relevant expenses are included in the long-term care fund payment scope. Therefore, this paper suggests that, at the initial stage of long-term care insurance in China, we should not only focus on the care needs of the elderly with moderate or severe disability, but also include preventive healthcare measures, such as setting up community-based care stations to provide health promotion and health examination for the elderly and encourage social participation of the elderly, so as to prevent the occurrence of and deepen the degree of disability of the elderly.

The fourth practical contribution: The research on the situation and affecting factors of disabled elderly in China is conducive to strengthening the support of caregivers and improving their skills.

In the assessment of care needs, it is necessary to assess the degree of physical dependence and family care ability and willingness and further assess the demand for formal services. The assessment of long-term care needs in many countries and regions covers the assessment of the care burden and ability of family caregivers. Family caregivers are included in the target of long-term care services, and corresponding support is provided for family caregivers in long-term care service projects, including the provision of care resources, long-term care knowledge and skills training, breathing service, family care service, and community volunteers. We should build special consultation service line, interactive network platform, volunteer service platform, and emergency placement system to provide more care and support for family caregivers from both software and hardware levels.

Data Availability

The data of the study can be obtained after the website is registered, http://charls.pku.edu.cn/.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Analyzing the Formation Mechanism of Cross-City Transportation Network Resilience

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The formation mechanism of cross-city transportation network resilience occupies an important position in cross-city transportation network resilience management. This study analyzes the constituent elements of the cross-city transportation network and their interrelationships, and the connotation of cross-city transportation network resilience is defined from the general meaning of system resilience. Combining with the connotation of cross-city transportation network resilience, the specific formation process of cross-city transportation network resilience is analyzed and summarized from three stages, including resisting disturbance, absorbing disturbance, and function recovery. Taking cross-city transportation network nodes and systems as specific objects, the static and dynamic formation path of cross-city transportation network resilience is condensed. Based on the standard linear solid model, a theoretical model is constructed and solved for revealing the formation mechanism of cross-city transportation network resilience. Finally, the theoretical model of cross-city transportation network resilience proposed in this study is used for analyzing the China railway network resilience.

1. Introduction

With the continuous advancement of urbanization, cities and transportation infrastructure between cities form a huge cross-city transportation network in the form of nodes and links [1, 2]. Local disturbances faced by a single city will be amplified through cross-city transportation networks and become common disturbances in the region or even the entire cross-city transportation network [3, 4]. As an important part of the socio-technical system, cross-city transportation network should show resilience in the face of disturbances, which means cross-city transportation network can resist external disturbances and maintain certain network performance, and quickly recover to the original equilibrium state after disturbances disappearing or adjust itself to a new state according to the external environment [5, 6].

With the increasingly frequent exchanges and interactions between cities, the concept of resilience needs to be applied on multiple scales, such as communities, cities, and regions, and cross-city transportation network resilience research, which has become an inevitable trend [7–9]. Related research studies on the formation mechanism of cross-city transportation network resilience can enhance the self-recovery ability of network nodes and links in the cross-city transportation network, which is beneficial for cities to mobilize resources from the network level during emergencies and reduce losses and quickly recover after disturbance occurring [10–12]. Therefore, the resilience management of cross-city transportation network has gradually become a new research paradigm.

Existing research studies on resilience management of cross-city transportation networks have found that local disturbances faced by regional transportation network will be amplified and become common disturbances by cross-city transportation [3, 13]. Due to the difficulty of data acquisition, the research object of cross-city transportation network resilience management is mainly a single category of cross-city transportation, such as railway network and highway network [14–18]. Some studies have studied the resilience of different cross-city transportation networks from a static perspective, such as air transportation network [19–21] and water transportation networks [22–24]. However, most of the related research studies focus on the assessment and comparative analysis of resilience for different types of cross-city transportation networks [14, 15, 22, 25]. Research contents of previous research studies are mainly based on the assessment methods of cross-city transportation network resilience [26]. The formation mechanism of cross-city transportation network resilience has not received enough attention in previous research studies [13, 27]. There is a lack of research studies on the optimization and improvement of cross-city transportation network resilience from a system perspective [28, 29].

Besides, few research studies on the formation mechanism of the cross-city transportation network resilience focus on the changing of network scale and structure influencing cross-city transportation network resilience [22, 30, 31]. For example, Miller-Hooks et al. used the Monte Carlo simulation method to measure the resilience of the American railroad network and found that the resilience can be improved by optimizing the topological structure of the transportation network and other intrinsic properties [32]. Ip and Wang constructed a China railway network with cities as nodes and railways as links, and the results showed that city nodes with higher resilience were mainly located in the core part of the network [30]. Osei-Asamoah and and Lownes used simulation methods to study the resilience of the railroad network in Connecticut and Indiana, and the analysis results pointed out that the railroad network exhibited biological network characteristics and had the resilience properties such as redundancy and robustness [16]. Bhatia et al. also used simulation methods to study the impact of the 2004 Indian Ocean tsunami and the 2012 North India blackout on the resilience of the Indian railway network, and the quantitative analysis results showed that the improvement of network centrality could improve the recovery speed and efficiency of railway network after disasters [31]. Ouyang Min analyzed the resilience of the China railway network from the perspective of vulnerability and found that the weighted shortest path model was more suitable for the resilience analysis of the China railway network [17].

In general, the existing research studies on the formation mechanism of cross-city transportation network resilience were limited to qualitative theoretical descriptions. The connotation of cross-city transportation network resilience was not clear, and existing research studies also did not establish a quantitative model for analyzing the cross-city transportation network resilience considering the network structure characteristics. Thus, it is necessary to analyze the formation mechanism of cross-city transportation network resilience from a systematic perspective.

Based on the practical needs of cross-city transportation network resilience management, this study takes cross-city transportation network resilience as the research object and aims to reveal the formation mechanism of cross-city transportation network resilience by complex network analysis methods. The following research questions will be answered in this study. (1) What is the connotation of cross-city transportation network resilience? (2) How is cross-city transportation network resilience formed? (3) How to theoretically describe and solve cross-city transportation network resilience?

The remainder of this paper is structured as follows. Section 2 describes the connotation of cross-city transportation network resilience considering the specific response processes of the cross-city transportation network to external disturbances. Section 3 analyzes the formation process and path of cross-city transportation network resilience. In Section 4, the theoretical model of cross-city transportation network resilience is constructed and solved. China railway network is selected as a case study in Section 5. Finally, Section 6 summarizes the research contents of this study and explores future research directions.

2. Connotation of Cross-City Transportation Network Resilience

Resilience comes from the Latin word "resilio," its original meaning is "to jump back" [33, 34]. The initial definition of resilience refers to the ability of a material to absorb energy when elastically deformed and release energy when unloaded [35, 36]. The first definition of resilience was proposed by Holling in the field of social ecosystems in 1973, which focused on the ability of the system to absorb and adapt to various unexpected disturbances in the future through system design [37]. The widely accepted definition of resilience is the ability of the system to recover from an unfavorable state to a normal state or adjust itself to a new state according to new needs or circumstances. Thus, resilience reflects the adaptability and survivability of the system [38]. Generally, resilience is still a relatively new concept. Different disciplines have different cognitions and understandings, and the connotation of resilience is still continuously developed and improved in the development process of resilience science.

A cross-city transportation network is constituted by nodes and links which are cities and transportation infrastructure between cities, respectively. The nodes and links of cross-city transportation network present an evolution process, and the coupling relationship between the nodes and links of cross-city transportation network shows dynamic characteristics [2, 39]. The system performance of a cross-city transportation network can be calculated by the cumulative degree of nodes. Thus, the system performance of cross-city transportation network reflects the maximum actual transportation demand that can be met between different cites, which determines the impact of cross-city transportation network on human social and economic activities [40, 41]. Based on the dynamic evolution characteristics of the cross-city transportation network, cross-city transportation network resilience is defined in this study as cross-city transportation network adopts its network topology and evolution characteristics to resist external disturbances and maintain a certain system performance and quickly restore the ability to balance after the disturbance disappears. According to the above definition of cross-city transportation network resilience, this study divides the conceptual connotation of cross-city transportation network resilience into three different stages: resistance stage, absorption stage, and recovery stage, which are shown in Figure 1.

Figure 1 describes the three stages of cross-city transportation network resilience. Before disturbances occur, the system performance of the cross-city transportation network is in an equilibrium state. After disturbances occur, cross-city transportation network resilience is firstly reflected by the resistance ability of cross-city transportation networks to external disturbances. When cross-city transportation network can resist external disturbances, cross-city transportation network maintains original equilibrium state, or external disturbances have a negligible impact on the system performance of cross-city transportation network. When cross-city transportation network cannot resist external disturbances, cross-city transportation network resilience is reflected by the absorption ability of cross-city transportation network to external disturbances. At the absorption stage, the cross-city transportation network can maintain a certain system performance to meet the basic transportation needs between cities. After disturbances disappear, cross-city transportation network resilience is reflected by the system performance recovery of the cross-city transportation network. At the recovery stage, the system performance of the cross-city transportation network is recovered to its original equilibrium state, or a new equilibrium state by adjusting its network characteristics to adapt to the external environment, which reflects the adaptive characteristics of the cross-city transportation network.

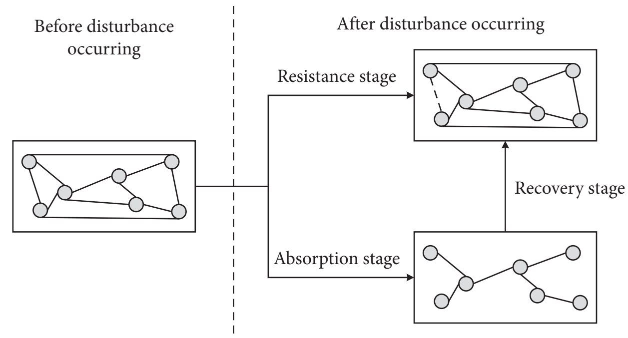

Figure 1: Stages division of cross-city transportation network resilience.

3. Formation Process and Path of Cross-City Transportation Network Resilience

3.1. Formation Process of Cross-City Transportation Network Resilience. By defining the connotation of cross-city transportation network resilience in Section 2, the formation process of cross-city transportation network resilience is divided into three stages: resistance stage, absorption stage, and recovery stage. Before disturbances occur, the cross-city transportation network is in a static equilibrium state, and its network state is described by static model SM:

$$\mathrm{SM} = \mathrm{SM}(N, L, d). \tag{1}$$

The static model of the cross-city transportation network in equation (1) includes three types of elements: nodes, links, and degree. In equation (1), $N = \{n_1, n_2, \ldots, n_i\}$ is the set of city nodes in cross-city transportation network and $L = \{l_1, l_2, \ldots, l_j\}$ is the set of transportation infrastructure links between different city nodes in cross-city transportation network. The degree of link $l_i \in L$ is d_i; $d = \{d_1, d_2, \ldots, d_j\}$ is the set of all degree d_i in the cross-city transportation network. The degree of link l_i is d_i, which is determined by the number of transportation infrastructure links between two city nodes. The static model of the cross-city transportation network defines links between nodes as undirected links:

$$l = l(n_a, n_b) = l(n_b, n_a). \tag{2}$$

In equation (2), n_a and n_b are the starting point (ending point) and ending point (starting point) of link l, respectively, where $n_a, n_b \in N$, and $n_a \neq n_b$.

When cross-city transportation network can resist external disturbances, cross-city transportation network maintains the original equilibrium state or the external disturbances have negligible impacts on the system performance of cross-city transportation network. The network state of the cross-city transportation network is still described by equation (1). When cross-city transportation network cannot resist external disturbances, cross-city transportation network resilience is reflected by the absorption ability of cross-city transportation network to external disturbances. At the absorption stage, the cross-city transportation network can maintain a certain system performance to meet the basic transportation needs between cities, and the network state of the cross-city transportation network is described by the dynamic model SDM:

$$\mathrm{SDM} = \mathrm{SDM}(N(t), L(t), d(t)). \tag{3}$$

In equation (3), node N and link L in the cross-city transportation network show dynamic evolution characteristics over time, where $N(t)$ and $L(t)$ are the numbers of city nodes and the number of links between city nodes in cross-city transportation network at time t, respectively. The changes of city nodes $N(t)$ and links $L(t)$ between city nodes will lead to the dynamic evolution of cross-city transportation network structure. In general, the change of city nodes $N(t)$ and links $L(t)$ between city nodes will cause a change in degree d of the cross-city transportation network, which means that the degree of cross-city transportation network will change from d to $d(t)$. Dynamic model $S\,DM$ describes the dynamic changes of network structure and degree of the cross-city transportation network, which reflects the random characteristics of the cross-city transportation network and the changes of the transportation state. Therefore, the dynamic model $S\,DM$ explains the dynamic evolution characteristics of the cross-city transportation network from a macroperspective.

After disturbances disappear, cross-city transportation network resilience is reflected by the system performance recovery of the cross-city transportation network. At the recovery stage, the system performance of the cross-city transportation network is recovered to its original equilibrium state or a new equilibrium state by adjusting the network characteristics to adapt to the external environment. At the recovery stage, the state of the cross-city transportation network is described by new static model SM_n:

$$SM_n = SM_n(N_n, L_n, d_n). \quad (4)$$

In equation (4), N_n is the set of city nodes in cross-city transportation network after the recovery stage is completed, L_n is the set of links between different city nodes in cross-city transportation network after the recovery stage is completed, and d_n is the set of all degrees in the cross-city transportation network after the recovery stage is completed. In the formation process of cross-city transportation network resilience, the logical relationship between the three stages is summarized in Figure 2.

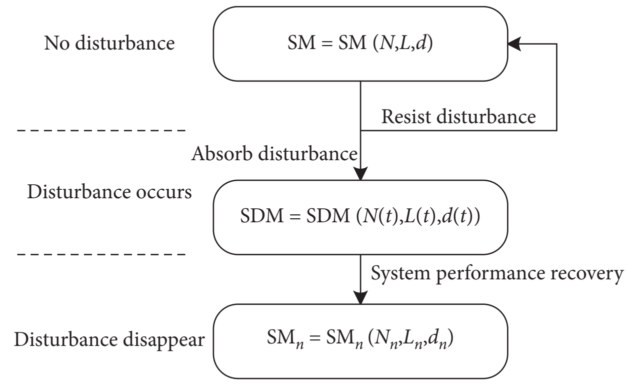

Figure 2: Logical relationship between three stages.

3.2. Formation Path of Cross-City Transportation Network Resilience. The formation process of cross-city transportation network resilience can be divided into resistance stage, absorption stage, and recovery stage, which form different resilience characteristics at different stages. After disturbances occur, cross-city transportation network firstly resists the impacts of external disturbances [42, 43]. When cross-city transportation network cannot resist external disturbances, cross-city transportation network absorbs the impacts of external disturbances [44, 45]. After disturbances disappear, the cross-city transportation network recovers its system performance [46, 47]. The above three stages, respectively, reflect the resistance ability, absorption ability, and recovery ability of the cross-city transportation network to external disturbances. Therefore, cross-city transportation network resilience has different formation paths at different stages, as shown in Figure 3.

Figure 3 summarizes the formation path of cross-city transportation network resilience. Different formation paths are divided by the time points of the horizontal axis and labeled with different line types. Point b in Figure 3 is the threshold point of external disturbances impacts on the cross-city transportation network. Before point b, cross-city transportation network statically resists external disturbances. After point b, the cross-city transportation network dynamically absorbs external disturbances and recovers to a balanced state after disturbances disappear. Therefore, the formation paths of cross-city transportation network resilience are divided into static formation path and dynamic formation path. In the static formation path, cross-city transportation network resilience is formed by the static resistance of city nodes to external disturbance, which reflects the nodes' resilience of the cross-city transportation network. In the dynamic formation path, cross-city transportation network resilience is formed by the dynamic absorption and recovery of the network system to external disturbances, which reflects the system resilience of cross-city transportation network.

3.2.1. Static Formation Path of Cross-City Transportation Network Resilience. The static formation path is the solid line ab in Figure 3, and cross-city transportation network resilience reflects the static resistance of city nodes to external disturbances. This study defines $[t_0, t_1)$ period as the resistance stage. At the resistance stage, the external disturbance faced by the cross-city transportation network is less than or equal to the resistance ability of the cross-city transportation network. Thus, the cross-city transportation network maintains the original static equilibrium state, and its state is described by the static model $SM = SM(N, L, d)$. At the resistance stage, network nodes' resilience is reflected by the resistance ability of city nodes to external disturbances, which is essentially the resilience of cities in the cross-city transportation network to external disturbances [42].

Point b is the threshold point of external disturbances impact on the cross-city transportation network, and static formation path may be transformed into a dynamic formation path at point b. If cross-city transportation network can still resist external disturbances in period $[t_1, t4]$, which means that external disturbance is less than or equal to the resistance ability of city nodes in the cross-city transportation network, then cross-city transportation network resilience will be manifested as the static resistance of the city nodes to external disturbances in period $[t_1, t4]$. The static formation path will not be converted into a dynamic formation path, as shown by the extended broken line of the solid line ab in Figure 3. When the external disturbance is less than or equal to the resilience resistance of city nodes in cross-city transportation network, cross-city transportation network resilience is manifested as the static resistance path of city nodes to the external disturbance in the period $[t_1, t4]$.

If cross-city transportation network cannot continue to resist external disturbances at point b, which means that external disturbance is larger than the resistance ability of city nodes in the cross-city transportation network. Then, the static formation path will be transformed into a dynamic formation path at point b, which is shown by the broken line

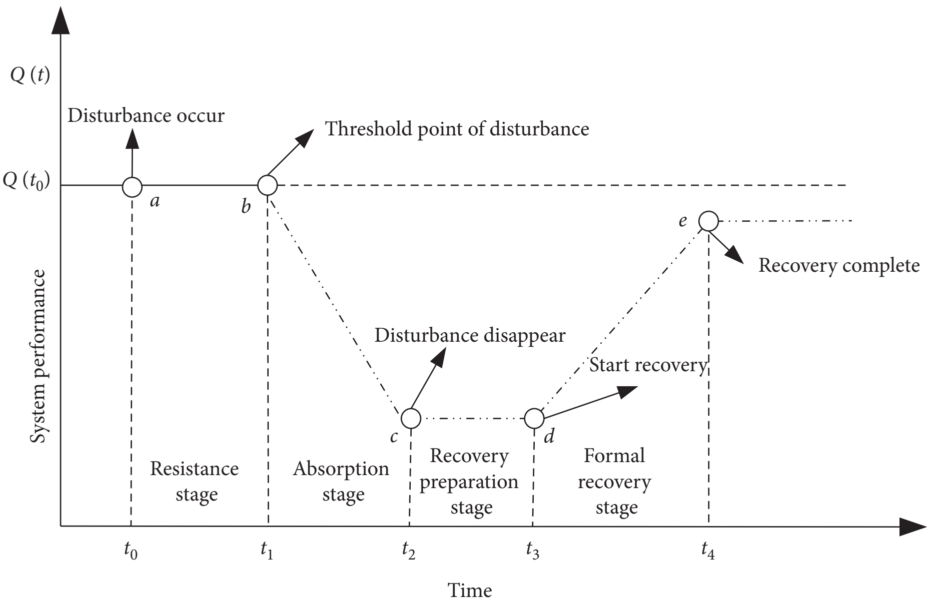

Figure 3: Formation path of cross-city transportation network resilience.

bc de in Figure 3. Dynamic formation path is the dynamic continuation of static formation path at the threshold point*b*, which reflects the system resilience of cross-city transportation network.

3.2.2. Dynamic Formation Path of Cross-City Transportation Network Resilience. When an external disturbance at the threshold point b is larger than the resistance ability of cross-city transportation network, cross-city transportation network resilience will change from a static formation path at resistance stage to a dynamic formation path. Disturbance disappearing point b divides the dynamic formation path into the absorption stage and recovery stage. As shown in Figure 3, the absorption stage is the dashed line *bc* in period $[t_1, t_2]$, and the recovery stage is the broken line cde in the period $(t_2, t_4]$.

In dynamic formation path, cross-city transportation network resilience is firstly reflected by the dynamic absorption ability of cross-city transportation network to external disturbance. At the absorption stage, the network state of the cross-city transportation network changes under the external disturbance. The absorption ability of the cross-city transportation network is finally manifested as the network performance level that can be maintained when external disturbance disappears. At the absorption stage, cross-city transportation network resilience reflects the network performance loss Q_L of the cross-city transportation network, $Q_L = Q(t_0) - Q(t_2)$, as shown in Figure 3.

After external disturbance disappears at point c, the dynamic formation path of cross-city transportation network resilience is reflected by the dynamic recovery of system performance in period $(t_2, t_4]$, which means dynamic formation path transfer to the recovery stage. The recovery stage can be further divided into the recovery preparation stage and the formal recovery stage. As shown in Figure 3, the dynamic formation path of the recovery preparation stage is described by the dotted line cd in period (t_2, t_3). The dynamic formation path of the formal recovery stage is described by the dotted line de in period $[t_3, t_4]$. Different recovery plans are selected at the recovery preparation stage, and the final recovery plan is determined as the dynamic path point d at time t_3. At the formal recovery stage, the system performance of cross-city transportation network recovers in period $[t_3, t_4]$. The system performance of cross-city transportation network recovers along the dynamic formation path dotted line de in Figure 3 and returns to a new equilibrium state $Q(t_4)$ at time t_4.

4. Theoretical Model of Cross-City Transportation Network Resilience

This study divides the formation process of cross-city transportation network resilience into resistance stage, absorption stage, and recovery stage. At different stages, the cross-city transportation network shows different resilience characteristics. Based on the analysis results of the formation process and formation path of cross-city transportation network resilience, the standard linear solid model [44, 46, 48, 49] is used to qualitatively describe the formation process of cross-city transportation network resilience. The qualitative model of cross-city transportation network resilience is summarized in Figure 4.

Figure 4 is the qualitative model of cross-city transportation network resilience. The left side of the qualitative model is the external disturbance input $D(t)$, and the right side is the internal constraint boundary of the cross-city transportation network. The qualitative model consists of two series units, namely, resistance unit C_1 and absorption unit C_2. Resistance unit C_1 is an elastic unit, which works in the process of cross-city transportation network resisting

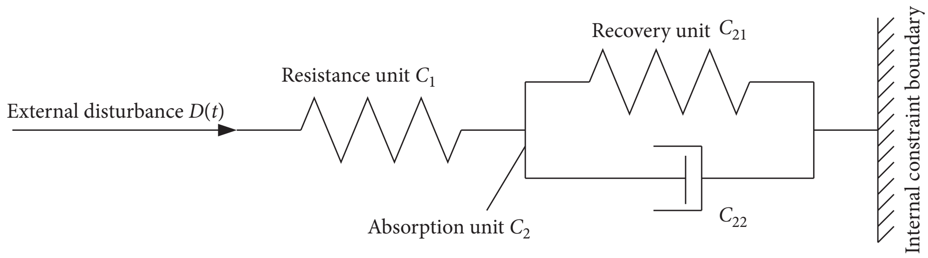

Figure 4: Qualitative model of cross-city transportation network resilience.

external disturbance $D(t)$. When resistance unit C_1 cannot resist external disturbance $D(t)$, the absorption unit C_2 begin to work. Absorption unit C_2 is composed of two parallel subunits C_{21} and C_{22}, where the subunit C_{21} is an elastic unit and the subunit C_{22} is a damping unit. The subunits C_{21} and C_{22} jointly absorb the impacts of external disturbance $D(t)$ on the system performance of cross-city transportation network. When external disturbance $D(t)$ disappears, subunit C_{21} in the absorption unit C_2 is converted into a recovery unit, and the recovery unit C_{21} restores cross-city transportation network to a new equilibrium state. The system performance $Q(t)$ of the cross-city transportation network is determined by absorption unit C_2, and resistance unit C_1 does not affect the system performance $Q(t)$ of the cross-city transportation network.

4.1. Theoretical Model Construction. External disturbance $D(t)$ has the same influence on all parts of the cross-city transportation network, which means that the external disturbance influence function received by the resistance unit C_1 and the absorption unit C_2 is the same. The influence functions of external disturbance $D(t)$ on the resistance unit C_1 and the absorption unit C_2 are described as follows:

$$D_1(t) = D_2(t) = D(t). \tag{5}$$

In equation (5), $D_1(t)$ and $D_2(t)$ are the influence functions of external disturbance $D(t)$ on absorption unit C_1 and resistance unit C_2, respectively. At the resistance stage, external disturbance $D(t)$ firstly influences the resistance unit C_1, and the performance of resistance unit C_1 produces a loss $\varepsilon_1(t)$. When external disturbance $D(t)$ is less than or equal to the resistance ability of cross-city transportation network, the performance loss $\varepsilon_1(t)$ of resistance unit C_1 is within the elastic limit of the resistance unit C_1. Thus, the resistance unit C_1 can completely resist the negative impact of external disturbance $D(t)$ on the system performance of cross-city transportation network. The performance loss $\varepsilon_1(t)$ of resistance unit C_1 can be calculated by equation (6).

$$\varepsilon_1(t) = \frac{D_1(t)}{k_1}. \tag{6}$$

In equation (6), k_1 is the elastic coefficient of the resistance unit C_1 which reflects the resistance ability dimension of the cross-city transportation network to external disturbance $D(t)$. When external disturbance $D(t)$ is larger than the resistance ability of cross-city transportation network, the performance loss $\varepsilon_1(t)$ reaches the elastic limit of the resistance unit C_1. Then, the cross-city transportation network enters the absorption to external disturbance $D(t)$.

At the absorption stage, the absorption unit C_2 is composed of two parallel subunits C_{21} and C_{22}. The absorption unit C_2 and two parallel subunits C_{21} and C_{22} have the same external disturbance influence function, which are $D_2(t)$, $D_{21}(t)$, and $D_{22}(t)$, respectively. The absorption unit C_2 decomposes the performance loss $\varepsilon_2(t)$ caused by external disturbance influence function $D_2(t)$ into two parallel subunits C_{21} and C_{22}, which are named as $\varepsilon_{21}(t)$ and$\varepsilon_{22}(t)$, respectively. At the absorption stage, the relationship between external disturbance influence function and performance loss of absorption unit C_2, subunits C_{21} and C_{22}, is shown in equations (7) and (8):

$$D_2(t) = D_{21}(t) = D_{22}(t), \tag{7}$$

$$\varepsilon_2(t) = \varepsilon_{21}(t) + \varepsilon_{22}(t). \tag{8}$$

The subunit C_{21} is an elastic unit, and its elastic coefficient is k_2. Under the action of external disturbance $D_{21}(t)$, the performance loss $\varepsilon_{21}(t)$ of subunit C_{21} can be calculated by the following equation:

$$\varepsilon_{21}(t) = \frac{D_{21}(t)}{k_2}. \tag{9}$$

The subunit C_{22} is a damping unit, and its absorption function to external disturbances is a cumulative process. The performance loss $\varepsilon_{22}(t)$ is affected by external disturbance $D_{22}(t)$ and damping coefficient μ, which can be calculated by the following equation:

$$\varepsilon_{22}(t) = \int_{t_1}^{t} \frac{D_{22}(t)}{\mu} \mathrm{d}t. \tag{10}$$

In equation (10), t_1 is the time corresponding to the external disturbance threshold point in Figure 3. The elastic coefficient k_2 of subunit C_{21} and the damping coefficient μ of subunit C_{22} jointly determine the absorption capacity of the absorbing unit C_2 to external disturbance $D_2(t)$. According to equations (7)–(10), the performance loss $\varepsilon_2(t)$ of absorption unit C_2 can be calculated by external disturbance influence function $D_2(t)$, the elastic coefficient k_2 of subunit C_{21}, and the damping coefficient μ of subunit C_{22} together:

$$\varepsilon_2(t) = \frac{D_2(t)}{k_2} + \int_{t_1}^{t} \frac{D_2(t)}{\mu} \mathrm{d}t. \tag{11}$$

When external disturbance $D(t)$ disappears at time t_2, cross-city transportation network enters the recovery preparation stage. At the recovery preparation stage, the system performance of cross-city transportation network will be kept unchanged and the system performance of cross-city transportation network is $Q(t_2)$. Different recovery plans are compared at the recovery preparation stage, and the final recovery plan is determined at time t_3. At time t_3, cross-city transportation network enters the formal recovery stage.

At the formal recovery stage, the subunit C_{21} of absorption unit C_2 is converted into a recovery unit and the performance loss of subunit C_{21} at the absorption stage is recovered. At time t_4, the system performance of the cross-city transportation network is recovered to a new equilibrium state. Recovery unit C_{21} recovers to its original performance and the final recovery performance is ε_{21}^r which can be determined by

$$\varepsilon_{21}^r = \frac{D_2(t_2)}{k_2}. \tag{12}$$

4.2. Theoretical Model Solution. The theoretical model of cross-city transportation network resilience indicates that the system performance of the cross-city transportation network shows different evolution trends at different stages. Thus, the theoretical model of cross-city transportation network resilience needs to be solved in different stages. At the resistance stage, cross-city transportation network can completely resist the influence of external disturbance $D(t)$ on the system performance $Q(t)$ of cross-city transportation network through resistance unit C_1, and the system performance of cross-city transportation network remains as the initial performance $Q(t_0)$. External disturbance $D(t)$ reaches threshold point b at time t_1, and cross-city transportation network enters the absorption stage to external disturbance $D(t)$. During the period $[t_1, t_2]$, the system performance $Q(t)$ of cross-city transportation network gradually decreases under the action of external disturbance $D(t)$:

$$Q(t) = Q(t_0) - \varepsilon_2(t). \tag{13}$$

In equation (13), ε_2 is the real-time system performance loss of cross-city transportation network at absorption stage, which can be calculated by equation (11). External disturbance $D(t)$ disappears at t_2, and cross-city transportation network enters the recovery preparation stage. The system performance of cross-city transportation network is kept as $Q(t_2)$ at the recovery preparation stage. According to equation (13), $Q(t_2)$ can be described as

$$Q(t_2) = Q(t_0) - \varepsilon_2(t_2). \tag{14}$$

Cross-city transportation network enters the formal recovery stage at time t_3, and the system performance of cross-city transportation network recovers to a new equilibrium state at t_4 through the performance recovery of the recovery unit C_{21}. This study assumes that the system performance of the cross-city transportation network shows linear recovery characteristics at the formal recovery stage. The system performance of cross-city transportation network increases by ε_{21}^r at time t_4 compared with the system performance at time t_3. Thus, the system performance $Q(t_4)$ of cross-city transportation network at time t_4 is described as

$$Q(t_4) = Q(t_0) - \varepsilon_2(t_2) + \varepsilon_{21}^r. \tag{15}$$

Through the above analysis, the system performance of the cross-city transportation network at different stages can be obtained. The system performance of cross-city transportation network $Q(t)$ at each stage is shown as

$$Q(t) = \begin{cases} Q(t_0), & t_0 \le t < t_1, \\ Q(t_0) - \varepsilon_2(t), & t_1 \le t \le t_2, \\ Q(t_0) - \varepsilon_2(t_2), & t_2 < t < t_3, \\ Q(t_0) - \varepsilon_2(t_2) + \dfrac{\varepsilon_{21}^r}{(t_4 - t_3)}(t - t_3), & t_3 \le t \le t_4. \end{cases} \tag{16}$$

Equations (5), (11), and (12) are incorporated into equation (16), and the final quantified system performance of cross-city transportation network under external disturbance $D(t)$ at each stage is shown as

$$Q(t) = \begin{cases} Q(t_0), & t_0 \le t < t_1, \\ Q(t_0) - \dfrac{D(t)}{k_2} - \displaystyle\int_{t_1}^{t} \frac{D(t)}{\mu} \mathrm{d}t, & t_1 \le t \le t_2, \\ Q(t_0) - \dfrac{D(t_2)}{k_2} - \displaystyle\int_{t_1}^{t_2} \frac{D(t)}{\mu} \mathrm{d}t, & t_2 < t < t_3, \\ Q(t_0) - \dfrac{D(t_2)}{k_2} - \displaystyle\int_{t_1}^{t_2} \frac{D(t)}{\mu} \mathrm{d}t + \frac{D(t_2)}{(t_4 - t_3)k_2}(t - t_3), & t_3 \le t \le t_4. \end{cases} \tag{17}$$

5. Case Study of China Railway Network Resilience

5.1. China Railway Network Resilience Construction. As a typical cross-city transportation network, China railway network nodes represent different cities and links manifest the railway links between cities. In this section, China railway network is selected as a case study for testing formation mechanism of cross-city transportation network resilience proposed in this study. China railway network is constructed according to the following rules [13, 50]:

(1) Network nodes: network nodes are prefecture-level cities that have railway passenger access.

(2) Network links: links are the railway links between different prefecture-level cities.

(3) Weighted network: the degree of one city node is defined as the accumulative number of links from this city to the other cities of China railway network.

(4) Undirected network: not all railway links between the different cities of China railway network appear in pairs. Thus, the degrees between two cities are not completely symmetrical. Here, each network is simplified as an undirected network.

This study constructs China railway network in 1957, 1985, 1987, 1997, 1998, 2000, 2007, 2008, 2009, 2014, 2015, 2016, and 2017, respectively. Most prefecture-level cities have been connected to China railway network after 2017, and the scale characteristics of China railway network between 2018 and 2020 are consistent compared with 2017. Thus, the data of China railway network from 2018 to 2020 are not collected for analyzing the resilience characteristics of China railway network. Table 1 summarizes the scale characteristic indicators of the China railway network.

As shown in Table 1, the China railway network presents dynamic evolution characteristics. The network scale of the China railway network is getting larger and larger, which is manifested by the increase of city nodes number and degree strength between city nodes. According to the analysis results on the formation process and path of cross-city transportation network resilience in Section 3, the dynamic evolution of the China railway network scale will lead to corresponding evolution on China railway network nodes' resilience and system resilience. Thus, this section selects the above China railway network as the research object, and the theoretical model of cross-city transportation network resilience established in Section 4 is used to conduct a case study for analyzing the evolution characteristics of China railway network nodes' resilience and system resilience.

Table 1: Scale characteristic indicators of China railway network.

Year	N	D	AD
1957	114	8560	75
1985	164	14166	86
1987	174	17760	102
1997	219	32626	149
1998	216	35684	165
2000	230	55230	240
2007	242	70724	292
2008	243	77440	319
2009	245	88314	360
2014	268	133633	499
2015	269	268047	996
2016	273	288823	1058
2017	274	300946	1098

Note. N is nodes' number; D is degree; $\mathrm{AD} = D/N$, which is the average degree.

5.2. Evolution Characteristics of Nodes' Resilience. This section selects 96 city nodes that have always existed in the China railway network as the research object, and the evolution characteristics of these 96 city nodes resilience are analyzed in 13 years. The evolution characteristics of China railway network nodes' resilience essentially reveal the evolution characteristics of city resistance ability to external disturbances in the China railway network. The evolution characteristics of 96 city nodes' resilience in the China railway network are calculated by the theoretical model proposed in Section 4 and shown in Figure 5.

Figure 5 summarizes the evolution characteristics of 96 city nodes' resilience in the China railway network. The point line is the evolution curve of 96 city nodes' resilience, and the evolution curve of the 96 city nodes' average resilience is described by the thick black line. Figure 5 shows that 96 city nodes' resilience in the China railway network generally increases over time, but the evolution characteristics of 96 city nodes' resilience show certain differences in different time intervals. According to the differences of city nodes' resilience in different time intervals, the period from 1957 to 2017 is divided into four evolution stages: (1) volatile growth stage (1957–1987), city nodes' resilience showed volatility with time, (2) gentle growth stage (1987–2009), city nodes' resilience increased slowly with time, (3) rapid growth stage (2009–2014), city nodes' resilience increased rapidly over time, and (4) stable stage (2014–2017), city nodes' resilience tended to stabilize over time.

As shown in Figure 5, the resilience values of most city nodes are greater than the average value of 96 city nodes' resilience. The resilience values of few city nodes are significantly lower than the average value of 96 city nodes' resilience, which results in the resilience values of 96 city nodes at a relatively low level. Although the resilience value of different city nodes present differences, these differences have gradually decreased over time and have been in a convergence trend after 2014. From 1987 to 2014, there are some city nodes, such as Beijing and Zhengzhou, the resilience values of these city nodes are significantly higher than that of other city nodes. Except for very few city nodes, such as Jixi and Yichun, the differences of resilience values between city nodes have converged and stabilized after 2014. The above analysis results show that the opening of high-speed railways after 2007 has reduced differences in the resilience values of different city nodes. City node Jixi does not open high-speed rails from 2014 to 2017, and city node Yichun has a small number of high-speed rails from 2014 to

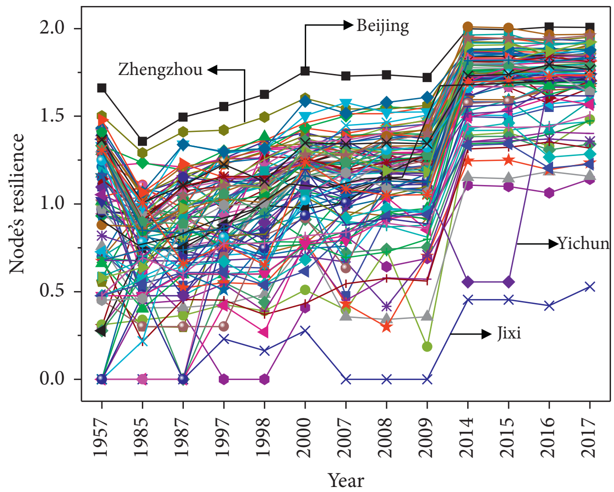

Figure 5: Evolution characteristics of city node resilience.

2015. Thus, the resilience values of Jixi and Yichun are still significantly lower than other 94 city nodes.

5.3. Evolution Characteristics of System Resilience. The system resilience of the China railway network is the cumulative result of absorption ability and recovery ability at the absorption stage and recovery stage. According to the analysis results on the formation process and path of cross-city transportation network resilience, the China railway network will compare and select different recovery plans at the recovery preparation stage, which is affected by the network characteristics of the China railway network. This section uses the theoretical model of cross-city transportation network resilience to quantify the formation path of China railway network system resilience in different years, which is shown in Figure 6.

Figure 6 describes the formation path curve of China railway network system resilience in different years. The decreasing curves on the left side of the formation path curve reflects the absorption path of China railway network system resilience to external disturbances, and the absorption path ends at the common threshold point of different absorption scenarios. The horizontal straight lines in the middle of the formation path curve reflect the time length of the recovery preparation stage. This study simplifies the time length of the recovery preparation stage as 10-time units. The incremental curves on the right side of the formation path curve reflect the recovery path of China railway network system resilience, and the recovery path ends at the common threshold point of recovery behavior iterative ending under different recovery scenarios. The quantitative results of the enclosed area size of the formation path curve are shown in Figure 7.

The enclosed area size of the formation path curve in Figure 7 presents the dimension of China railway network system resilience. The larger enclosed area size of the formation path curve reflects that the China railway network presents lower system resilience to external disturbances. In contrast, the smaller enclosed area size of the formation path curve reflects that the China railway network presents higher

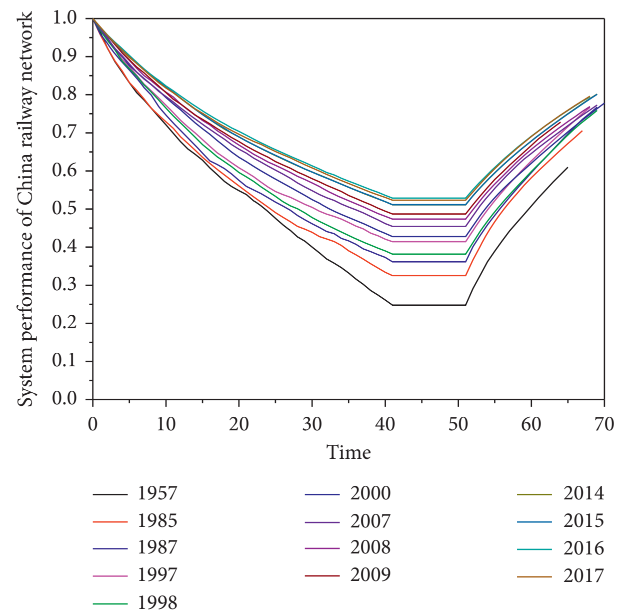

Figure 6: Formation path of China railway network system resilience.

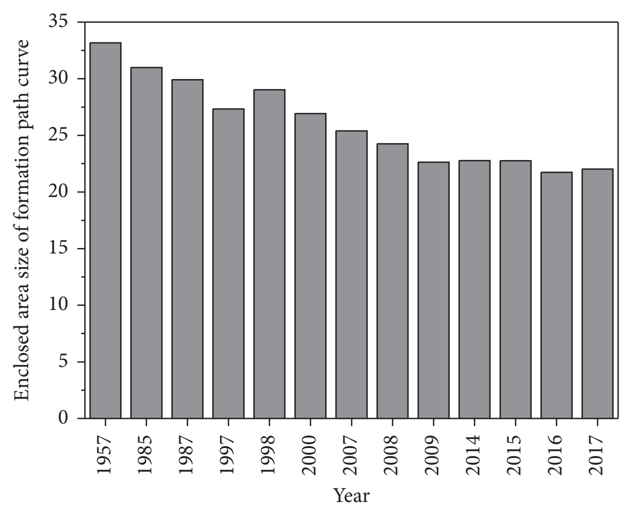

Figure 7: Enclosed area size of the formation path curve.

system resilience to external disturbances. As shown in Figure 7, except for 1997, the size of the formation path curve generally shows a decreasing trend overtime in the process of China railway network absorbing and recovering from external disturbances. Thus, the system resilience of the China railway network system gradually increases over time. After 2014, the number of city nodes approached the limit value of the potential city nodes' number and the system resilience of the China railway network gradually stabilized state.

6. Conclusions

In this study, the connotation of cross-city transportation network resilience is defined. The specific formation process of cross-city transportation network resilience is analyzed and summarized. Finally, a theoretical model is constructed and solved for revealing the formation mechanism of cross-city transportation network resilience. The research results show that the formation process of cross-city transportation network resilience includes three stages: resisting disturbance, absorbing disturbance, and function recovery. In the process of resisting disturbance, absorbing disturbance, and recovering functions, cross-city transportation network adjusts the network scale and structural characteristics to adapt to external disturbances and achieve a new equilibrium state, which reflects the connotation of cross-city transportation network resilience. The formation path of cross-city transportation network resilience includes the static formation path and dynamic formation path. In the static formation path, cross-city transportation network resilience is formed by the static resistance of city nodes to external disturbance. In the dynamic formation path, cross-city transportation network resilience is formed by the dynamic absorption and recovery of the network system to external disturbances.

This study constructs and solves the theoretical model of formation mechanism for cross-city transportation network resilience, which provides a qualitative and quantitative integrated research method for the resilience management of cross-city transportation network. The research results of this study can be systematically applied to resilience management practices for the different types of cross-city transportation networks, which is very important for the improvement of cross-city transportation network resilience. In general, this study systematically reveals the formation mechanism of cross-city transportation network resilience from qualitative and quantitative perspectives, which help to enhance and improve the city nodes' resilience and system resilience of the cross-city transportation network to external disturbances. Although the research object of this study is cross-city transportation network, the theoretical model proposed in this study is also suitable for the resilience analysis of transportation network in the urban area. The research results of this study provide development strategies for promoting the collaborative planning and construction of cross-city transportation network and transportation network in the urban area from the perspective of resilience.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

The Causal Model of Public Acceptance of Genetically Modified Food: An Invariance Analysis

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Measurement invariance refers to the equivalence of measurement instrument in different groups. Research on social science often involves comparing different groups, such as whether the relationship between two variables is the same in male and female groups. Measurement invariance is a prerequisite of these studies because if the measurement tools are not equivalent, we cannot distinguish the difference between the degree of measurement tools and the empirical results. The causal model proposed by Michael Siegrist is one of the baseline models for studying public acceptance of genetically modified food, but only a few studies have tested the invariance of the causal model. Thus, it is difficult for researchers to judge the reliability of some conclusions about group comparison, such as whether the risk perception of men is lower than that of women. In this study, we use sample data about China ($N = 1091$) to test the invariance of the causal model among groups with different genders and knowledge levels. The test results show that the model has full invariance across gender, and only factor loading invariance has no measurement error invariance across knowledge levels. The results of this study show that the conclusion about group comparison on gender in previous studies is credible, but the reliability of the measurement of the differences between knowledge level groups needs to improve before meaningful comparison can be made.

1. Introduction

Measurement invariance (equivalence) means that measurement instruments, such as scales, used in the study are identical across relevant groups [1]. In social science research, research objects often come from different subpopulations, such as male and female. Thus, determining measurement invariance is a logical prerequisite to evaluating substantive hypotheses about differences in groups, regardless of whether the comparison is as simple as between-group mean differences test or as complex as testing whether some theoretical structural model is invariant across groups [2]. Moreover, it is impossible to determine whether the relationship between variables observed in the study reflects the hypothetical relationship proposed in the study or it reflects an artificial relationship caused by differences in the measurement instruments [3].

If the variables used in the study are directly observable, such as income and education, then measurement invariance is easy to judge. However, if the variable is not directly observable, such as perceived benefit, it is often measured indirectly by manifest (i.e., observed) variables, and the measurement instruments are mostly scales. In this study, the measurement invariance needs to be tested using statistical techniques. Testing the equivalence of measurement instruments is called invariance analysis [4].

Genetically modified food (GMF) is an emerging food technology with multiple social and environmental benefits [5]. Like any other new food technology in history, public acceptance of GMF was low in the early stage of its development [6–9]. What factors influence public acceptance of GMF? This question has an important impact on the decision-making of stakeholders of food industries, such as policymakers, farmers, and agrobiotechnology enterprises

[10–12]. Many studies have examined this question [13–17]. Some studies have shown that trust, perceived risk, and perceived benefit are the three most important factors that affect public acceptance [10, 13]. Siegrist examined these three factors and proposed a causal model to explain public acceptance of GMF. He found that perceived risk has a direct negative effect on public acceptance; perceived benefit has a direct positive effect on public acceptance, and trust indirectly affects public acceptance through perceived risk and benefit. In addition, perceived benefit has a negative direct effect on perceived risk [18, 19]. Owing to its explanatory power and simplicity, this causal model has been widely used to explain public acceptance in a variety of technological research, such as gene technology [15, 20, 21], financial technology [22, 23], nanotechnology [24–27], renewable energy [28–30], unmanned aircraft [31], and automated driving technology [32, 33]. The samples used in these studies are made up of individuals with different demographic characteristics, such as sex, education, and income. Therefore, for research about social science to be credible, it is essential to conduct invariance analysis of the measurement instruments. Unfortunately, only a few studies have explored the invariance of the causal model. In the existing literature, only Siegrist has tested the invariance of the gender group in this model [18].

Because it is impossible to test the invariance of all the possible individual features, the features that have a greater impact on the core variables of the model are tested [34]. Perceived risk is the core explanatory variable in the causal model [35]. Previous studies have found that gender and relevant knowledge level are important factors that affect an individual's perceived risk [36–41]. Therefore, this study analyzes the invariance of the model across gender and knowledge level variables.

This study complements previous studies in three aspects. First, the above discussion shows that invariance analysis is very important, but only a few studies have tested this aspect, so this study supplements the current research. Second, although Siegrist explored this issue, the data used in his study are about the United Kingdom. The data in this study are from China. Since China is quite different from most western countries in terms of culture, politics, and economic system, this study supplements Siegrist's model. Finally, Siegrist tested only the measurement invariance of the causal model across gender, but this study considers both gender and relevant knowledge level, so this study is also an extension of the study of Siegrist.

The remainder of the study is organized as follows. The next section introduces the basic concepts, testing principles, and testing methods of the invariance analysis. The statistical hypothesis section briefly introduces the causal model of public acceptance of GMF and the statistical hypothesis (null hypothesis) used in the invariance test. The research method section introduces the measurement scales, samples, and data analysis methods used in this research. The results section shows the analysis results of the invariance test. The final section discusses the results, mainly the theoretical and policy implications, as well as the limitations.

2. Invariance Analysis

Measurement invariance (equivalence) was first proposed by Drasgow and Fritz: "Measurement equivalence holds when individuals with equal standing on the trait measured by the test but sampled from different subpopulations have equal expected observed test scores." In particular, "individuals with equal standings on the latent trait, say verbal aptitude, but sampled from different subpopulations, say male and female, should have the same expected observed score" ([42], p. 134). Measurement invariance analysis helps to ensure that any comparisons made represent the true differences in the constructs being studied [43].

There are, essentially, four levels of measurement invariance, which are configural, metric, scalar, and strict invariances (for more details, the reader is referred to [2, 4]). Among them, the first two levels, configural and metric invariances, are collectively referred to as conceptual invariance, whereas the last two levels, scalar and strict invariances, are called psychometric invariance [44]. These levels are hierarchical: higher levels impose more restrictions on the measurement parameters while allowing a higher degree of comparability (see Figure 1) [45–48]. The following paragraphs explain the four levels of measurement invariance in detail.

Configural invariance (the invariance of configuration) is also commonly referred to as pattern invariance. At this level, the focus is solely on testing whether the same items measure the given construct across multiple groups. To test this, both factor models are estimated simultaneously. Since this is the baseline model, it is only necessary to assess the overall model fit to test whether configural invariance holds.

Metric invariance is also commonly referred to as weak invariance. Metric invariance builds upon configural invariance; it requires that, in addition to the constructs being measured by the same items, the factor loadings of those items must be equivalent across multiple groups. The factor loadings reflect the degree to which differences in the responses of the participants to an item are due to differences in their levels of understanding of the underlying construct that is being assessed by that item. Thus, the invariance of the factor loadings suggests that the construct has the same meaning for participants across different groups. This is because if a construct has the same meaning across multiple groups, then there are identical relationships between the construct and participants' responses to the items used to measure that construct.

Scalar invariance builds upon metric invariance; it requires that the item intercepts should also be equivalent across multiple groups. Item intercepts are the origin or starting value of the scale that a given factor is based on. Thus, participants who have the same value of the latent construct should have equal values for the items that the construct is based on.

The final level of invariance is called strict factorial invariance. Strict invariance refers to the invariance of the error terms of an individual indicator variable, representing the unique error of that indicator variable. Thus, when

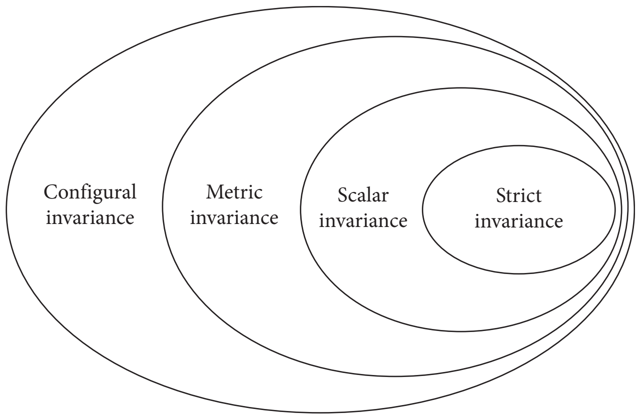

Figure 1: The relationship between the four levels of measurement invariance.

testing strict invariance, what is essentially being tested is whether the residual error is equivalent across groups.

Several methods have been proposed for testing measurement invariance. Vijver and Harsveld proposed that the factor parameters of the unconstrained model should be examined and those with the largest between-group differences should be classified as noninvariant [49]. Marsh and Hocevar suggested that the modification indices in the fully constrained model should be examined, and the large modification indices of the associated items that are indicators of noninvariance should be interpreted [50]. However, among all the potential methods, the method proposed by Byrne et al. and Byrne (2004) is the most widely used because of its rationality and rigor. In this method, multi-group confirmatory factor analysis (MGCFA) is used to estimate the unconstrained measurement model and a series of constrained measurement models; then the fitting indices of these models are obtained and compared to test the invariability of the scale [51, 52]. Since the constraints of the four levels of measurement invariance are progressively enhanced, the order of testing measurement invariance is generally the same as that of the four levels of measurement invariance; that is, testing is conducted in turn from configural invariance, metric invariance, and scalar invariance to strict invariance.

Based on the method of Byrne et al. and Byrne, measurement invariance analysis starts with configural invariance. Configural invariance is an unconstrained model and is used as the baseline model for subsequent tests. The null hypothesis of the test is "the same factor structure among groups." If the unconstrained model fits well, it indicates that the measurement model has configural invariance, and a series of subsequent constrained model estimates can be conducted. If the fitting index of the unconstrained model is not up to the corresponding critical value, it implies that there is no configural invariance and subsequent invariance tests are not conducted [2].

The second model analyzed is the metric invariance model. Based on the configural invariance, intergroup equivalence restriction is applied to the factor loading to test whether there is invariance between each measurement item and its representative factor across groups. Metric invariance is the basis of measurement invariance. On the one hand, from the perspective of the moderate replication strategy, if the metric invariance is met, it has measurement invariance [52]. On the other hand, it is not possible to vary with higher-order invariance until metric invariance is met. Finally, the structural invariance analysis is based on the metric invariance [43].

The third model analyzed is the scalar invariance model. Based on the metric invariance, the intergroup equivalence restriction is applied to the regression intercept between each measurement item and its representative factor (latent factor) to test whether there is invariance in the intercept of the measurement item across groups. If a mild test strategy is adopted at this stage, the measurement model is said to be invariant [53].

The fourth model analyzed is the strict invariance model. Based on the scalar invariance, an intergroup equivalent restriction is applied to the variances of each measurement error to test whether there is cross-group invariance in the variance of the measurement error.

Figure 2 summarizes the sequence of these invariance tests.

3. Statistical Hypothesis

Our statistical test model of invariance is shown in Figure 3. It is based on Siegrist's causal model. In our model, perceived risk has a negative and direct impact on public acceptance; perceived benefit has a positive and direct impact on public acceptance of GMF, and perceived benefit has a negative and direct impact on perceived risk. Trust indirectly affects public acceptance of GMF through perceived benefits and perceived risks; trust has a positive impact on perceived benefits and a negative impact on perceived risks [18]. Since the objective of this study is to examine the measurement equivalence of the causal model, the focus of the model is to determine whether gender and individual knowledge level affect the causal model.

Based on Section 2, we propose the following statistical hypotheses for the invariance analysis of the model; it is shown in Table 1.

4. Research Method

4.1. Measurement. Knowledge was measured using eight true/false statements (see Table 2). These statements covered areas of knowledge about gene technology. Content validity was established by having three independent experts in the field of biology and genetics review the questions. The goal was to assess the respondents' knowledge of biology objectively. The response options were "true" and "false."

The measurement scale used in this study comprised of four constructs and 15 items, which are based on several scales used in relevant studies (see Table 3 for specific studies) that demonstrate high reliability and validity. The idiosyncrasies of the Chinese language and culture were considered throughout the translation process, so minor modifications were made in the wording to suit these idiosyncrasies. The subjects were asked to indicate their

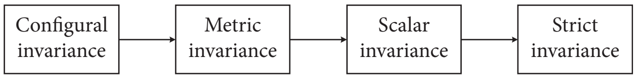

Figure 2: Flowchart of invariance tests.

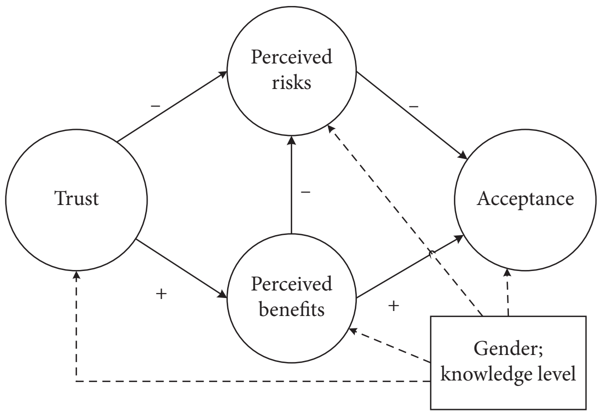

Figure 3: Statistical test model of invariance.

agreement or disagreement with the statements provided, using a seven-point Likert scale (1 = strongly disagree and 7 = strongly agree). Table 3 shows the detailed scale items of the construct variables.

To assess perceived risks of GMF, we asked the respondents to indicate their agreement with the four items developed by Sjöberg, Chen, Ghoochani et al., and Sjöberg et al. [54–57]. Two items reflect the possible harmful effect of GMF on human health, and the other two reflect its possible harmful effect on the environment. Examples of the items are "Eating genetically modified food will lead to infertility" and "The production of genetically modified food will destroy the diversity of animals and plants."

Regarding social trust, although previous studies have shown that this aspect comprises multiple components, Lang and Hallman showed that these components are highly correlated and converge on a common factor [58]. Therefore, the public's social trust of different objects can be measured holistically. Based on this argument, in this study, social trust was measured as the public's trust in various institutions [18, 59]. Specifically, the participants were asked, "How much trust do you have in the following institutions: (1) regulatory agencies, (2) agricultural corporations, and (3) public research institutions in the GMF domain?" Participants had to indicate their level of trust on a 7-point scale, ranging from "no trust at all" (1) to "a very high level of trust" (7).

4.2. Sample. The data were collected through self-reported, structured questionnaires. The questionnaire was developed in Chinese and submitted to a panel of five experts at one of the key universities in Central China to evaluate the validity of the content. Two of these experts work at the Department of Biology and the rest work at the School of Public Management in this university. The panel approved both the initial list and question format and suggested revisions to clarify certain questions for the general public to fully understand and respond accordingly. Prior to the formal survey, a pilot test was conducted. During the pilot test, respondents were asked whether they could clearly understand the questions and felt comfortable answering them. Based on their feedback, changes were made about the wording, expressions, and grammar to improve the questionnaire's clarity, accuracy, flow, and validity. In the pilot test, 50 individual participants, 20 undergraduates and 30 ordinary people, that were randomly selected to represent the public were interviewed individually.

The questionnaire was comprised of four parts. The first section screened the question, "Have you heard of genetically modified food?" The respondent did not need to continue if his or her answer was "no." The second section requested sociodemographic information, including gender, age, educational background, income, and knowledge about gene technology. The third section focused on the public's acceptance of GMF. The final section inquired about perceived risks or benefits of GMF and social trust in different objects.

The survey used stratified sampling. First, to account for geographical differences and maximize representativeness, eight provinces from the east (Zhejiang), south (Guangdong), west (Sichuan, Xizang, and Xinjiang), north (Hebei), northeast (Jilin), and central (Hubei) regions of China were selected. Two high-income and two lower-income counties were randomly selected from each province, resulting in 32 counties. Then, four to six city communities or villages were randomly selected from each county, resulting in 150 city communities or villages. Finally, seven to ten households were randomly approached in each of these city communities or villages, resulting in a total sample of 1200 observations. In June 2019, through public recruitment, 100 university students were recruited as interviewers (3-4 interviewers per county) from Central China Normal University. The students were selected according to their home addresses, which had to be located in the 32 selected counties. The student interviewers then conducted face-to-face interviews from July to September 2019.

A total of 1200 paper questionnaires were distributed, with 1168 recovery and 1091 valid questionnaires after eliminating those with clerical errors or contradictions. The effective recovery rate was 93.41%.

4.3. Data Analysis. The data were analyzed using Statistical Package for the Social Sciences (SPSS) 24 and AMOS 24. The analysis was comprised of three steps, which are measurement model analysis for the full sample (full sample analysis), measurement model analysis for subgroups (subgroup analysis), and measurement invariance analysis. The aim of the full sample and subgroup analyses is to test whether the data support the measurement model. If the data do not support the model, it would be meaningless to conduct a subsequent measurement invariance analysis.

The full sample and subgroup analyses have the same idea. The method used to conduct the analysis is confirmatory factor analysis (CFA). Several fit indices, such as

Table 1: Statistical hypotheses for the invariance analysis.

Model (M)	Test	Null hypothesis ($H0$)	Reference model
M0	Configural invariance	For two groups: $H_{\mathbf{form}}$: $\Lambda_{form}^{(1)} = \Lambda_{form}^{(2)}$	—
M1	Metric invariance	For all i, j in the model of two groups: H_{Λ}: $\lambda_{ij}^{(1)} = \lambda_{ij}^{(2)}$	M0
M2	Scalar invariance	For all i items in the model of two groups: $H_{\Lambda,\lambda}$: $\tau_i^{(1)} = \tau_i^{(2)}$	M1
M3	Strict invariance	For all i items in the model of two groups: $H_{\Lambda,\lambda,\Theta}$: $\delta_{ii}^{(1)} = \delta_{ii}^{(2)}$	M2

Table 2: Knowledge about gene technology.

Questions
(1) Normal tomatoes do not have genes, but genetically modified ones do
(2) If a person eats genetically modified fruit, the genes of this person will also be modified
(3) Genetically modified animals are always bigger than normal animals
(4) It is currently impossible to transfer genes from animals into plants
(5) The sex of a child is determined by the mother's genes
(6) More than half of human genes are identical to those of chimpanzees
(7) The first transgenic plant in the world was successfully cultivated in China
(8) Transgenic technology refers to transferring the gene of one organism to the genome of another

Table 3: Measures used in the study.

Construct	Items	Source
Public acceptance (ACC)	(ACC1) Would you buy genetically modified food (GMF)? (ACC2) Would you buy this kind of food if the product trademark indicated that it contained genetically modified ingredients? (ACC3) Whenever possible, I avoid buying GMF (reversed scoring). (ACC4) Compared with ordinary food, GMF has a longer shelf life. Would you choose to buy because of this?	[18, 19, 60]
Perceived benefits (PEB)	(PEB1) Overall, GMF technology is useful to society (PEB2) Transgenic technology can increase crop yields and feed more people (PEB3) GMF creates a higher quality of life; it is a great technological advancement (PEB4) GMFs will eventually be accepted by the majority of people	[54, 56]
Perceived risks (PER)	(PER1) Overall, GMF can be dangerous to people (PER2) Eating GMF will lead to infertility (PER3) Eating GMF will change our genes or those of future generations (PER4) The production of GMF will destroy the diversity of animals and plants	[54–57]
Social trust (SOT)	(SOT1) Regulatory agencies (SOT2) Agricultural corporation (SOT3) Public research institution in the GMF domain	[18, 59]

normed χ^2 measure (i.e., the ratio of the χ^2 divided by its degrees of freedom), the comparative fit index (CFI), the nonnormed fit index (NNFI), and the root mean square error of approximation (RMSEA), were used to evaluate the model fit. When the CFI and NNFI values are greater than 0.90 and the RMSEA value is less than or equal to 0.08, it is considered adequate for model fit [61]. The normed χ^2 is used to identify two types of inappropriate models. First, values that are less than 1.0 indicate an "overfitted" model [62], and, second, values of more than 2.0 or a more liberal limit of 5.0 indicate that the model does not fit the observed data and has to be improved [63]. CFA was used to evaluate the standard factor load, internal consistency, convergent validity, and discriminant validity. The evaluation indices are as follows. The completely standardized item-factor loadings (≥0.60) and internal consistency of the constructs were measured using the composite reliability ($CR \geq 0.70$) [64]. Convergent validity was evaluated with the average variance extracted ($AVE \geq 0.50$) [64], whereas a discriminant validity was established when the AVE for each construct exceeds the squared correlations between that and another construct [65].

A multigroup CFA (MGCFA) was conducted to test measurement invariance [53]. Based on the principles of the measurement invariance test discussed in Section 2, the MGCFA was conducted to estimate and calculate the series of fit indices of each model (M0 to M3 in Table 1), and the fit indices of each model were compared with those of the reference model. Comparative analysis of the three indicators, $\Delta\chi^2$, ΔCFI, and RMSEA, was conducted to determine whether invariance exists. According to the suggestion made in the study of Cheung and Rensfold (2002), invariance is established when $\Delta\chi^2$ is not significant ($p > 0.05$) or $\Delta CFI < 0.01$ [44]. In addition, according to the suggestion of

Hu and Bentler (1999), measurement invariance can be assumed when the point estimates of RMSEA are very close and the confidence intervals of RMSEA have large overlaps [66]. Since $\Delta\chi^2$ and χ^2 are equally influenced by sample size and distribution pattern, Cheung and Rensfold (2002) suggested that when $\Delta\chi^2$ and ΔCFI tests are not consistent, the ΔCFI test results should be used as the basis to judge whether there is measurement invariance [44].

5. Results

5.1. Respondent Profiles. Table 4 lists the descriptive statistics of the data. The sample comprises 1091 individuals, with a mean age (standard deviation) of 32.93 (14.31) years. The self-reported knowledge of these 1091 respondents about gene technology ranges from 1 to 8. The mean of the knowledge score is 5.74, and the standard deviation is 1.61. The level of knowledge of 241 (22.1%) respondents is less than 5; they are categorized as the "low knowledge level group" (LK). The level of knowledge of 429 (39.3%) respondents is higher than 6, and they are categorized as the "high knowledge level group" (HK). The distribution of gender is roughly balanced, with 608 (55.7%) of the respondents being female.

The sample does not originate from strict random sampling, so the representativeness of the sample was evaluated. A χ^2 test was conducted to ensure that the sample in this study is representative of the entire population. Table 4 presents the characteristics of the sample and the results of the χ^2 test, which indicate that the sample roughly represents the Chinese population ($p > 0.05$).

5.2. Full Sample Analysis. Before conducting the invariance analysis, we examined the model fit of the data and parameter estimates for the entire sample ($n = 1091$).

The hypothesized measurement model had a chi-square of 340.189 with 84 degrees of freedom. The subjective fit indices indicate an adequate model-data fit of 0.052, 0.953, and 0.962 for RMSEA, NNFI, and CFI, respectively. These results indicate that the model is appropriate, a proper solution was obtained, and the solution fit the entire sample adequately.

As shown in Table 5, the results of the CFA show that the standardized factor loadings range from 0.663 to 0.877 and are significant ($p < 0.01$), which is more than the cut-off point of 0.60. All CR values range from 0.863 to 0.885, indicating acceptable levels of reliability of the constructs, since they are greater than the recommended 0.70 threshold. Moreover, all AVE values, which range from 0.613 to 0.687, are equal to or greater than the 0.50 standard for convergent validity, indicating acceptable levels of convergent validity of the constructs.

Table 6 lists additional descriptive statistics (i.e., mean and standard deviations) and the correlation matrix; the correlations among the constructs and the square root of the AVE are on the diagonal. The four diagonal elements of the latent variables are larger than their corresponding correlation coefficients, indicating that the metrics have appropriate discriminant validity.

5.3. Subgroup Analysis. Since the model fit the data adequately in the overall sample, we analyzed the model-data fit for each group.

The goodness-of-fit statistics for the single-sample CFA models are shown in Table 7. In all cases, the hypothesized models approached or exceeded the more stringent cut-off value for a well-fitting model, suggesting that the hypothesized model adequately accounts for the covariance matrices of the data of four samples, male, female, LK, and HK.

The results of the CFA for each country (see Table 8) show that the standardized factor loadings exceed the recommended minimum threshold of 0.60, ranging from 0.696 to 0.875 for males, from 0.640 to 0.899 for females, from 0.715 to 0.861 for LK, and from 0.615 to 0.883 for HK and were significant ($p < 0.01$).

As shown in Table 8, the CR values exceed the recommended threshold of 0.70, ranging from 0.873 to 0.882 for male, from 0.854 to 0.887 for female, from 0.836 to 0.877 for LK, and from 0.853 to 0.899 for HK, indicating acceptable levels of reliability of the constructs. Moreover, all the AVE values are greater than the 0.50 standard for convergent validity, ranging from 0.639 to 0.696 for male, from 0.595 to 0.681 for female, from 0.604 to 0.640 LK, and from 0.595 to 0.700 HK, indicating acceptable levels of convergent validity of the constructs.

In addition, the discriminant validity of the measures is accepted, since the AVE of each construct is greater than the squared correlation of the construct and other constructs in the model. Table 9 lists additional descriptive statistics (i.e., mean and standard deviations) and the correlation matrix, with the correlations among constructs and the square root of the AVE on the diagonal. The four diagonal elements of the latent variables of each group are larger than their corresponding correlation coefficients, indicating that the metrics have appropriate discriminant validity.

Based on the above CFA analysis, it can be concluded that the data support the measurement model of each subsample. The measurement models were replicable in each sample.

5.4. Invariance Analyses. Since the measurement models were replicable in each sample, we conducted a series of multisample structural equation models to identify any noninvariance in the measurement parameters across the gender and knowledge variables, respectively. We followed the invariance test process presented in Sections 2 and 3.

5.4.1. Male versus Female. The initial step was to test a model across the male and female groups simultaneously without imposing any equality constraints. The purpose of this step is to establish a baseline model to subsequently test the increasingly restrictive nested models. As shown in Table 10, the baseline model (M0) produced a good fit with the data. The result suggests that configural invariance is present in the gender groups; that is, males and females used the same pattern in measuring the items.

We then estimated a nested model that constrains the factor loadings to be invariant across the two samples. The

Table 4: Descriptive statistics of the sample.

Characteristic	Classification	Number	Sample (%)	Population (%)*	χ^2 test (p value)
Gender	Male	483	44.3	51.2	0.982 (0.322)
	Female	608	55.7	48.8	
Age	15–29 years and below	523	47.9	42.9	0.902 (0.637)
	30–50 years	447	41.0	42.3	
	51 years and above	121	11.1	14.8	
Type of living area	Rural inhabitant	585	53.6	55.9	0.081 (0.776)
	Urban inhabitant	506	46.4	44.1	
Education background	Primary education	183	16.8	27.7	4.744 (0.192)
	Junior high school	427	39.1	40.6	
	High school (including technical secondary school)	254	23.3	17.5	
	College degree and above (including junior college)	227	20.8	14.2	
Monthly income (Chinese yuan)	<3000	843	77.3%	Not available	
	3001–5000	204	18.7%	Not available	
	>5001	44	4.0%	Not available	
Knowledge	1-4 (LK)	241	22.1%	Not available	
	5–6	421	38.6%		
	7-8 (HK)	429	39.3%		

Note. LK = low knowledge level group; HK = high knowledge level group. *Source: National Bureau of Statistics of the People's Republic of China, 2016, 2015 national 1% population sampling survey main data bulletin, http://www.stats.gov.cn/tjsj/zxfb/201604/t20160420_1346151.html.

Table 5: Results of the confirmatory factor analysis (full sample).

Construct	Item	Loading	Se	T-value	CR	AVE
ACC	ACC1	0.815 **	0.012	66.882	0.885	0.659
	ACC2	0.755 **	0.016	46.427		
	ACC3	0.832 **	0.012	67.328		
	ACC4	0.841 **	0.010	83.812		
PEB	PEB1	0.857 **	0.010	88.514	0.880	0.649
	PEB2	0.807 **	0.021	38.881		
	PEB3	0.877 **	0.010	83.613		
	PEB4	0.663 **	0.033	20.039		
PER	PER1	0.686 **	0.024	28.820	0.863	0.613
	PER2	0.839 **	0.012	71.863		
	PER3	0.793 **	0.018	43.133		
	PER4	0.807 **	0.015	52.859		
SOT	SOT1	0.756 **	0.025	30.623	0.868	0.687
	SOT2	0.852 **	0.018	48.501		
	SOT3	0.874 **	0.015	57.738		

Note. ** $p < 0.01$; ACC = public acceptance; PEB = perceived benefits; PER = perceived risks; SOT = social trust.

Table 6: Mean (M), standard deviation (SD), and correlation matrix (full sample).

Construct	M	SD	ACC	PEB	PER	SOT
ACC	3.682	1.481	0.812			
PEB	4.479	1.232	0.507	0.805		
PER	3.887	1.129	−0.65	−0.36	0.783	
SOT	4.367	1.213	0.252	0.276	−0.210	0.829

Note. ACC = public acceptance; PEB = perceived benefits; PER = perceived risks; SOT = social trust.

Table 7: Goodness-of-fit statistics (subgroup).

Sample	Model	Goodness-of-fit statistics χ^2	df	χ^2/df	CFI	NNFI	RMSEA
Male	CFA	212.540	84	2.530	0.955	0.944	0.057
Female	CFA	261.636	84	3.115	0.955	0.944	0.057
LK	CFA	184.508	84	2.197	0.922	0.902	0.071
HK	CFA	205.348	84	2.445	0.957	0.947	0.058

Note. LK = low knowledge level group; HK = high knowledge level group.

invariance of the factor loadings is considered the minimum acceptable criterion for measurement invariance [67]. The analysis shows that the model exhibits a good fit with the data (Table 10, M1). According to the results in Table 11 (M0 versus M1), the change in χ^2 ($\Delta\chi^2$) with Δdf is not significant, and the fit statistics of the two models are also quite comparable ($|\Delta \text{CFI}| < 0.01$, $|\Delta \text{NNFI}| < 0.05$), justifying the presence of metric invariance.

After the validation of the metric invariance, a scalar invariance test was conducted to ensure that the regression intercepts between each measurement item and its representative factor are noninvariant. The chi-square difference test between M1 and M2 ($\Delta\chi^2 = 19.112$, $\Delta df = 15$, $p > 0.05$) is not significant, justifying the scalar invariance in the gender.

Based on the scalar invariance, a strict invariance test was conducted to ensure that the error terms of the two subgroups are noninvariant. The chi-square difference test between M2 and M3 ($\Delta\chi^2 = 26.337$, $\Delta df = 15$, $p < 0.05$) is significant, indicating that the restricted model failed the test of strict invariance in the groups. However, the difference in the CFI between M2 and M3 is only 0.002 (see Table 11),

Table 8: Factor loadings, composite reliability, and average variance extracted (subgroup).

	Male			Female			LK			HK		
	L	CR	AVE	L	CR	AVE	L	CR	AVE	L	CR	AVE
ACC		0.882	0.653		0.887	0.663		0.859	0.604		0.893	0.678
ACC1	0.802			0.825			0.813			0.802		
ACC2	0.751			0.758			0.715			0.758		
ACC3	0.836			0.829			0.794			0.869		
ACC4	0.840			0.842			0.783			0.858		
PEB		0.879	0.646		0.880	0.651		0.857	0.604		0.899	0.690
PEB1	0.872			0.848			0.835			0.866		
PEB2	0.793			0.817			0.793			0.819		
PEB3	0.844			0.899			0.861			0.880		
PEB4	0.696			0.640			0.591			0.751		
PER		0.876	0.639		0.854	0.595		0.877	0.640		0.853	0.595
PER1	0.709			0.672			0.819			0.615		
PER2	0.850			0.831			0.835			0.842		
PER3	0.827			0.765			0.761			0.816		
PER4	0.805			0.809			0.785			0.791		
SOT		0.873	0.696		0.864	0.681		0.836	0.630		0.875	0.700
SOT1	0.762			0.752			0.793			0.769		
SOT2	0.862			0.846			0.775			0.854		
SOT3	0.875		0.872		0.813		0.883					

Note. L = factor loadings; CR = composite reliability; AVE = average variance extracted; ACC = public acceptance; PEB = perceived benefits; PER = perceived risks; SOT = social trust.

Table 9: Mean, standard deviation, and correlation matrix (subgroup).

Subgroups/ constructs	M	SD	ACC	PEB	PER	SOT
Male						
ACC	3.636	1.511	**0.808**			
PEB	4.453	1.238	0.480	**0.804**		
PER	3.902	1.167	−0.624	−0.310	**0.799**	
SOT	4.418	1.295	0.163	0.238	−0.190	**0.834**
Female						
ACC	3.713	1.461	**0.814**			
PEB	4.498	1.236	0.529	**0.807**		
PER	3.886	1.103	−0.670	−0.402	**0.772**	
SOT	4.237	1.296	0.318	0.305	−0.225	**0.825**
LK						
ACC	3.073	1.369	**0.777**			
PEB	3.924	1.313	0.363	**0.777**		
PER	4.288	1.235	−0.661	−0.272	**0.800**	
SOT	4.015	1.387	0.216	0.321	−0.145	**0.794**
HK						
ACC	4.032	1.462	**0.823**			
PEB	4.802	1.117	0.578	**0.831**		
PER	3.667	1.068	−0.633	−0.417	**0.771**	
SOT	4.505	1.236	0.291	0.249	−0.323	**0.837**

Note. M = mean; SD = standard deviation; LK = low knowledge level group, HK = high knowledge level group; ACC = public acceptance; PEB = perceived benefits; PER = perceived risks; SOT = social trust.

indicating invariance. The point estimates of the RMSEA and RMSEA confidence intervals are almost the same in M2 (RMSEA = 0.038; 90% CI = 0.034–0.042) and M3 (RMSEA = 0.037; 90% CI = 0.034–0.041) (see Table 10), indicating invariance. Therefore, due to the small differences in the above goodness-of-fit indices, strict invariance between the unconstrained and constrained models is assumed.

5.4.2. LK versus HK. The initial step is to test a model across the LK and HK groups simultaneously without imposing any equality constraints. As shown in Table 12, the baseline model (M0) produced a good fit with the data. The result suggests that configural invariance exists in both knowledge level groups. LK and HK respondents used the same pattern in measuring the items.

The chi-square difference between M0 and M1 is significant ($\Delta\chi^2 = 42.704$, $\Delta df = 11$, $p < 0.01$) (see Table 13), whereas the difference in the CFI between M0 and M1 is only 0.008 (see Table 13), indicating invariance. The point estimates of the RMSEA and RMSEA confidence intervals are almost the same in M0 (RMSEA = 0.045; 90% CI = 0.039–0.050) and M1 (RMSEA = 0.046; 90% CI = 0.041–0.052). Therefore, since the differences in the goodness-of-fit indices are small, it can be assumed that metric invariance exists.

The next step (model 2) is to assess the scalar invariance. The chi-square difference between M1 and M2 is significant ($\Delta\chi^2 = 139.700$, $\Delta df = 15$, $p < 0.01$), whereas the difference in the CFI between M1 and M2 is 0.03, which is greater than 0.01. These results reveal a substantial decrease in the fit indices relative to M1, meaning that there is no invariance between the two groups in the regression intercepts between each measurement item and its representative factor.

According to the general invariance analysis procedure, since there is no invariance in M2, it is not necessary to conduct the next test of strict invariance; that is, it is not necessary to conduct the M3 estimation.

Table 10: Goodness-of-fit statistics for multisample structural equation models (male versus female).

Model	Invariance test	Goodness-of-fit statistics						
		χ^2	df	χ^2/df	CFI	NNFI	RMSEA	90% CI*
M0	Configural invariance (baseline)	474.176	168	2.823	0.955	0.944	0.040	0.036–0.045
M1	Metric invariance	490.755	179	2.742	0.954	0.947	0.039	0.035–0.044
M2	Scalar invariance	509.866	194	2.628	0.954	0.950	0.038	0.034–0.042
M3	Strict invariance	536.203	209	2.566	0.952	0.952	0.037	0.034–0.041

Note. *90% CI of the RMSEA.

Table 11: Model comparisons for multisample structural equation models (male versus female).

Comparison	$\Delta\chi^2$	Δdf	p-value	ΔCFI	ΔNNFI
M0 versus M1	16.578	11	0.121	−0.001	0.003
M1 versus M2	19.112	15	0.209	−0.000	0.003
M2 versus M3	26.337	15	0.035 *	−0.002	0.002

Note. * $p < 0.05$.

Table 12: Goodness-of-fit statistics for multisample structural equation models (LK versus HK).

Model	Invariance test	Goodness-of-fit statistics						
		χ^2	df	χ^2/df	CFI	NNFI	RMSEA	90% CI*
M0	Configural invariance (baseline)	389.856	168	2.321	0.946	0.933	0.045	0.039–0.050
M1	Metric invariance	432.560	179	2.417	0.938	0.928	0.046	0.041–0.052
M2	Scalar invariance	572.260	194	2.950	0.908	0.901	0.054	0.049–0.059
M3	Strict invariance	732.030	209	3.503	0.873	0.872	0.061	0.056–0.066

Note. *90% CI of the RMSEA.

Table 13: Model comparisons for multisample structural equation models (LK versus HK).

Comparison	$\Delta\chi^2$	Δdf	ΔCFI
M0 versus M1	42.704 **	11	−0.008
M1 versus M2	139.700 **	15	−0.030
M2 versus M3	159.770 **	15	−0.035

Note. * $p < 0.05$; ** $p < 0.01$.

Overall, the causal model only shows metric invariance but not scalar and strict invariance between the HK and LK groups.

6. Discussion

The quality of the measurement used in research determines the credibility of its conclusions. Measurement invariance is a logical prerequisite in evaluating substantive hypotheses about differences in a group, whether the comparison is as simple as a between-group mean differences test or as complex as testing whether some theoretical structural model is invariant across groups. Although the importance of measurement invariance is self-evident, only a few studies have focused on it in the field of public acceptance of GMF.

In this study, we use data from China to analyze the invariance of the causal model, which is widely used in the field. Based on a series of invariance analyses, we conclude that the model is configural invariance, metric invariance, scalar invariance, and strict invariance across gender. However, regarding knowledge level, it only has configural and metric invariances. This finding suggests that, generally, the male and female groups and the LK and HK groups conceptualize the causal model constructs (SOT, PEB, PER, and ACC) in the same way. This is consistent with the conclusion of Siegrist.

In the model, scalar invariance is not present between the HK and LK groups, which shows that the two groups have different starting points in the test score. Because the intercept does not affect the relative comparison results of the test score, this noninvariance has little effect on the evaluation of substantive hypotheses about the differences in the groups.

In addition, regarding strict invariance between the HK and LK groups, we find that the model construct is noninvariant. Because the measurement error directly affects the reliability of the measurement, this noninvariance is probably due to the different understanding of the words and questions used in the scales between the two groups. There are some key implications of this finding of noninvariance for researchers. They need to revisit the questionable items and evaluate the wording, semantics, and structure of each question to ensure improvements. However, researchers must also be aware of the fact that developing a questionnaire free of misconceptions for all different sample subgroups is almost impossible. Therefore, researchers should consider and validate measurement invariance across a sample population when designing their survey instrument.

There are also some limitations to this study. First, the intertemporal invariance is an important feature of measurement tools. Owing to limited cross-sectional data, the intertemporal invariance is not discussed. Finally, in the invariance analysis, cross-cultural invariance is often an important topic of concern, but, due to limited data, this study did not explore it. Future research can be deepened in these three aspects to make the measurement tools more reliable.

Data Availability

Data are available upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Dynamic Evaluation of Urban Sustainability Based on ELECTRE: A Case Study from China

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Sustainable urban evaluation is an important management tool to grasp the status of urban development in real time and to make policy adjustments. In this study, the evaluation indicator system is constructed from the three dimensions of economy, society, and environment. The ELECTRE (elimination et choice translation reality) model based on information entropy weighting is employed to evaluate urban sustainability. The model applies three-dimensional data to explore the dynamics of sustainable urban development. The spatial measurement model is used to explore the spatial effects of cities. Finally, 17 cities in Henan Province from 2013 to 2017 are used as case studies for urban sustainable development evaluation. The results show that, in 2013–2017, the sustainability of cities such as Zhengzhou, Luoyang, and Sanmenxia was stable at a high level, while the sustainability levels of Kaifeng, Luohe, and Xinyang showed a fluctuating downward trend, and the sustainability levels of Puyang, Nanyang, and Xinxiang showed a fluctuating upward trend. Among the 17 cities, Zhengzhou has the highest sustainability level and its economic and social sustainability levels are significantly better than other cities. Zhoukou is the city with the lowest level of sustainability. In addition, from 2013 to 2016, the level of urban sustainability was not spatially correlated but gradually presented positive spatial correlation and the characteristics of clustering distribution in 2017. The cities such as Zhengzhou, Luoyang, and Jiaozuo are mainly represented by "high-high (H-H)" agglomeration. In contrast, Shangqiu, Zhoukou, and Zhumadian are mainly represented by "low-low (L-L)" agglomeration. This research provides suggestions and decision-making support for promoting urban sustainability.

1. Introduction

As a carrier of human habitation, cities are closely related to people's daily lives. It is estimated that, by 2050, 67% of the population in the world will live in cities [1]. Since the reform and opening up in the late 1970s, China has experienced rapid urbanization. Especially, in the past 30 years, China has significantly accelerated urbanization and achieved a massive rural population transferring to cities. The urbanization rate in China increased from 17.4% in 1978 to 59.58% in 2018 [2]. However, with the acceleration of urbanization, while promoting local economic prosperity and improving people's living standards, which also brings severe ecological and social problems [3]. For example, a series of problems have appeared, such as severe air pollution, water quality degradation, energy consumption, resource scarcity, significantly increased temperature difference between urban and suburban areas, and decreased local plant species [4]. Therefore, how to maximize the resource utilization rate of urban socioeconomic activities, minimize the negative impact on the environment in the process of urban development and solve the problem of sustainable and coordinated development between economy, society, and environment in the process of urbanization are the critical research topics in the world today.

In 2015, the United Nations launched the 2030 Agenda for Sustainable Development, which called on countries to take action towards the achievement of 17 sustainable development goals over the next 15 years. Among them, Goal 11 is "to build an inclusive, safe, resilient sustainable city and human settlements". As a significant concentration of population, the sustainable development of cities has become a top priority. In the processes of sustainable urban construction, the policy decision-makers need to resort to evaluation indicators and methods to assess the status of sustainable urban development and make a comparison against other cities. They can recognize the strengths and weaknesses from perspectives of society, economics, and environment after one period, which supports them in making the development planning and correct policy interventions to guarantee the goal of sustainable urban development [5]. Therefore, the evaluation of urban sustainability is an important aspect and plays a crucial role in sustainable urban development. Many scholars have conducted extensive research on urban sustainability evaluation [5–10]. However, most of these studies adopt a single comprehensive evaluation method for static evaluation, which cannot understand the dynamic status of sustainable urban development. Therefore, to compare the level of sustainable development of each city in different periods, it is necessary to carry out the dynamic evaluation.

Realistic urban evaluation of sustainability require the followings: (1) the integration of diverse information concerning economic, social, environmental, and other objectives; (2) the handling of conflicting aspects of these objectives as a function of the views and opinions of the individuals involved in the evaluation process. The evaluation of urban sustainability is, therefore, increasingly regarded as a typical decision-making problem that could be handled by multicriteria decision aid (MCDA) methods. ELECTRE (elimination et choice translation reality) is a multicriteria decision-making tool. The basic idea is to eliminate the inferior schemes by constructing a series of weak dominance relations to gradually reduce the scheme set until the decision-maker can select the most satisfactory scheme from them. ELECTRE is a solution to deal with the multicriteria decision making for finite schemes. Because of its easy understanding principle, concise and straightforward logic, and good interactivity, it has been widely used in many areas [11, 12]. Kaya and Kahraman [13] combined the AHP (analytic hierarchy process) and ELECTRE methods for environmental impact assessment. Hatami-Marbini et al. [14] evaluated the safety and health of hazardous waste recycling facilities using the fuzzy group ELECTRE method. Comanita et al. [15] employed the ELECTRE method to assess the economic and environmental performance of bioplastics. In the ELECTRE method set, ELECTRE II focuses on the problem of ranking solutions with explicit decision-making data. Gao and Chen [16] proposed a simplified ELECTRE II ranking model. This model not only avoided the significant differences caused by the subjectivity of the threshold in the traditional ELECTRE method but also facilitated the ranking results based on the obtaining net superiority index value. Therefore, it avoided the complicated process of ranking solutions based on the strength/weakness relationship diagram and subjectively setting multiple thresholds. Besides, the traditional ELECTRE method is suitable for the static evaluation of two-dimensional data and cannot compare the overall level of multiple systems at different periods. This study builds an urban sustainability evaluation index system, whose data are expressed by three-dimensional data. A dynamic evaluation method based on ELECTRE is proposed to evaluate the urban sustainability of 17 prefecture-level cities in Henan Province from 2013 to 2017. The method can get the evaluation result of each period for objects and the overall evaluation value and the ranking results in a certain period for objects.

Henan is a typical landlocked province in China, with a large population and few resources, and rapid urbanization in recent years, highlighting the urban sustainability. Its pattern of development and the problems it encounters in the process of development is very representative of China. Therefore, it is typical to study the urban sustainability in Henan Province. The research methods and findings are typical of the nation.

The remainder of the paper is organized as follows: Section 2 provides a literature review of urban sustainability and evaluation methods. Section 3 constructs the urban sustainability evaluation indicator system from three dimensions: economy, society, and environment. Section 4 introduces the material and methods. Section 5 describes the result and discussion of this paper. Section 6 presents the research conclusion, limitations, and future research of this paper.

2. Literature Review

2.1. Urban Sustainability. Since the early 1990s, the concepts of sustainability and sustainable development have been applied to urban planning and design [17], leading to the emergence of urban sustainability and sustainable urban development. United Nations Centre for Human Settlements defines a sustainable city as that has achieved sustainable development in social, economic, and physical aspects and that possesses the natural resources on which sustainable development depends. Camagni [18] defined sustainable urban development as a process of synergistic integration and co-evolution between the various subsystems (economic, social, natural, and environmental) that make up a city. It is necessary to ensure that the local population's long-term health does not decline, does not damage the surrounding area's development potential, and reduces the harmful effects of development on the biosphere. Hamilton et al. [19] believed that urban sustainability refers to "the process of developing a built environment that meets people's needs while avoiding unacceptable social or environmental impacts". Zhao [20] argued that a sustainable city can maintain and improve urban ecosystem services and provide sustainable welfare to its inhabitants. Bibri and

Krogstie [21] believed that urban sustainable development strategies long-term goals, including environmental protection and integration, economic development and regeneration, and urban social equity and justice. In other words, sustainable urban development should improve the quality of life, reduce resource demand, and environmental impacts by providing healthy, livable, and prosperous human settlements to avoid burdening future generations with potential environmental degradation or ecological deficiencies. Wu et al. [22] defined urban sustainability as an adaptive process that promoted and maintained a virtual cycle between ecosystem services and human well-being by coordinating ecological, economic, and social actions to respond to changes inside and outside the city. Dias et al. [23] argued that urban sustainability was the coordinated development of three critical systems of environment, economy, and society, which provided goals, foundations, and conditions for sustainable urban development. Yang et al. [3] believed that sustainable urban development meant dividing urban systems from ecological inputs, social and economic benefits. It also included adjusting the dynamic balance between ecological investment and urban social, economic and environmental benefits, seeking maximize social, economic and environmental benefits, and pursuing the sustainable development of the city in time and space. In general, urban sustainability aims to improve long-term human well-being by balancing three aspects of sustainability: minimizing resource consumption and environmental damage, maximizing resource efficiency, and ensuring fairness and democracy [24].

2.2. Evaluation of Urban Sustainability. Sustainable development has gradually become a concept that governments, organizations, and industries are eager to adhere to. Evaluating sustainability quantitatively is an essential part of sustainability science research [22]. Agenda 21, adopted at the first Earth Summit in Rio DE Janeiro, Brazil, in 1992, called for the assessment methodologies of sustainable development. In the following years, many studies on sustainable development assessment have emerged [25–28].

Urban sustainability evaluation can help city managers to clearly understand the current level of sustainable urban development to make reasonable development plans [29]. Simultaneously, the evaluation of urban sustainability is a complex process with a strict system, an extended period, and a broad spatial scale. Therefore, scholars have developed many models and methods for assessing urban sustainability. Dijk and Zhang [30] adopted the Urban Sustainable Development Index to measure the sustainability of four medium-sized cities in China from three aspects: urban status, urban coordination, and urban potential. Ding et al. [31] proposed an inclusive framework for sustainable city assessment in developing countries, entitled "trinity of cities sustainability from spatial, logical and time dimensions". Zinatizadeh et al. [32] evaluated and predicted urban sustainability in different areas of Kermanshah city of Iran from three aspects of social welfare progress, economic growth, and environmental protection. Yi et al. [29] evaluated the sustainability of 17 cities in Shandong Province from three aspects of the economy, society, and environment using the deviation maximization method.

In addition, multicriterion decision-making analysis (MCDA) is considered an appropriate tool for sustainability assessment by considering different sustainability perspectives, including stakeholders, values, uncertainties, and intergenerational and internal considerations [33]. MCDA consists of a set of methods that allow for the explicit consideration of multiple criteria to support individuals or groups in the ranking, selecting, and/or comparing different alternatives (e.g., products, technologies, and strategies) [34]. The most commonly used MCDA methods include AHP (analytic hierarchy process), TOPSIS (technique for order preference by similarity to an ideal solution), ELECTRE (elimination et choice translation reality), and PROMETHEE (preference ranking organization method for enrichment evaluation) [35–38]. The MCDA methods are grouped based on three underlying theories: utility function, outranking relation, and decision rules [39, 40]. Among them, theory-based utility approaches (especially, multi-attribute utility theory and AHP) and outranking relation-based approaches (especially ELECTRE and PROMETHEE) are considered the most widely used MCDA tools in sustainability research [41]. In terms of urban sustainability, an increasing number of studies are beginning to evaluate the level of urban sustainability using the MCDA methodology. Ding et al. [7] used the TOPSIS-Entropy method to quantitatively evaluate the sustainable development level of 287 cities in China from three aspects of society, economy, and environment. Lu et al. [38] applied the TOPSIS method to measure and rank the sustainability of the selected 15 typical resource-based cities in northeast China. Liang et al. [8] developed a principal component analysis (PCA) and Grey TOPSIS methodology to measure urban sustainability for 13 cities in Jiangsu province from five aspects: environmental capacity, government supports, cultural entertainment, social security, and economic development. Tang et al. [5]proposed a modified TOPSIS model based on grey relational analysis to assess the sustainability of cities in three dimensions: economic, social, and ecological.

From the above literature, it can be seen that the urban sustainability evaluation method based on the indicator system has been extensively studied. At the same time, since urban sustainability evaluation is a multicriteria decision problem, the MCDA approach has been widely used. However, there is a lack of dynamic assessment and spatial agglomeration analysis to test the effects of sustainable policy implementation in cities.

3. Urban Sustainability Evaluation Indicator System

It is difficult to evaluate the sustainable development level of a city because we cannot fully grasp its development situation. However, we can have a detailed understanding of the macro situation through some micro and operable fragments of information in the system. The index system construction decomposes a complex and abstract problem into several concrete operable subsystems [29]. Based on the literature review, this study constructs an urban sustainability evaluation index system covering three dimensions of economy, society, and environment. Specific indicators are shown in Table 1.

3.1. Economic Indicators. Economic indicators reflect the economic development of a city. Economic development is the core issue of sustainable development for a city, which is the fundamental guarantee for social development, environmental improvement, and people's material and cultural life quality. At the same time, economic sustainability is also a guarantee for the sustainable development of cities [29, 43]. Therefore, in this study, GDP per capita, per capita investment in fixed asset, actually per capita of foreign capital utilized, the proportion of GDP contributed by tertiary industry, total import and export volume, retail sales of consumer goods, and urbanization rate are selected as the indicators to measure the sustainable development of the urban economy.

3.2. Social Indicators. Social sustainability considers both the basic needs of the present and the development of future generations [29]. It is the ultimate goal of urban sustainable development [43]. Social sustainability aims to promote the continuous improvement of people's quality of life and social spiritual civilization and provide people with a safe and comfortable living environment, good education opportunities, and social security [46]. Therefore, the establishment of social sustainability indicators should be people-oriented [5]. In this study, per capita disposable income of urban residents, urban unemployment rate, natural population growth rate, beds of medical institutions for per 10,000 people, number of buses for per 10,000 persons, per capita green area, per capita water resource, the coverage rate of old-age insurance, the proportion of government budgetary expenditure in education, and the proportion of government budgetary expenditure in science and technology are selected as the indicators to measure the sustainable social development of urban.

3.3. Environmental Indicators. Environmental sustainability is the foundation for urban sustainable development [43]. The low environments not only constrain the healthy development of the economy but also harm human health. Environmentally sustainable cities show a strong awareness and action for environmental protection, urban greening construction, pollution control, and treatment [29]. Therefore, in this study, the comprehensive utilization rate of industrial solid waste, industrial soot and dust emissions, industrial wastewater emissions, green coverage rate of built-up areas, annual average concentration of PM2.5, centralized sewage treatment rate, and household waste treatment rate is selected as environmental sustainability evaluation indicators.

4. Materials and Methods

4.1. Evaluation Framework. The evaluation process represents the flow and combination of information between indicators and alternatives, as well as the integration of information between subject and objective. Its goal is to provide an evaluation value, selection, and ranking. In most cases, it is ranking from the best to the least optimal option [47]. The basic procedure to solve the evaluation problem includes clarifying the purpose of evaluation, identifying relevant indicators and alternatives, obtaining indicator weights, selecting or constructing aggregation models, and calculating and ranking evaluation values. Based on this procedure, the urban sustainability evaluation processes are shown in Figure 1.

4.2. Research Area and Data Source. In this section, 17 cities in Henan Province are taken as the specific research area based on the economic-social-environmental framework. Based on various indices data of each city, the current situation of sustainable urban development in Henan Province is studied, which can provide a reference for the sustainable construction of each city. The distribution of cities is shown in Figure 2.

The rapid urbanization process of Henan Province has not only resulted in a vast increase in the demand for natural resources but also generates environmental problems. Exploring the dynamic development process of urban sustainability is crucial to improve environmental quality during the urbanization process and resultant urban development of these fast-growing regions. For this reason, Henan Province is seen as an appropriate study area to uncover the dynamic process of urban sustainability.

The data of the indicators in this study were collected from the Henan Province Statistical Yearbook (2014–2018) and China City Statistical Yearbook (2014–2018). The indicator data of the 17 cities in Henan Province from 2013 to 2017 were derived.

4.3. The Indicator Weight Determining Method—Entropy Method. The entropy method was first developed in thermodynamics and was further introduced to measure information or uncertainty in information theory [48]. This particular approach was gradually used in social science for determining the weights in evaluating performance and sustainability [32, 48, 49]. The basic logic behind such an approach is that when the index data contains more effective information, the entropy value is smaller, and the weight would be more extensive. The specific steps of this method are as follows:

Step 1. Constructing decision-making matrix: this evaluation system has m cities and n indicators. Let $X = (x_{ij})m \times n$ be the decision-making matrix and x_{ij} ($i = 1, 2, 3, \ldots, m$, $j = 1, 2, 3, \ldots, n$) be the index value.

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}. \tag{1}$$

Table 1: Urban sustainability evaluation indicator system.

Dimension	Code	Indicator	Unit	Property	References
Economy	C1	GDP per capita	Yuan	Benefit	Yi et al. [29]; Tang et al. [5]; Zhang et al. [10]; Ding et al. [7]; Lu et al. [38]; Xu et al. [9]; Yi et al. [42];
	C2	Per capita investment in fixed asset	Yuan	Benefit	Yi et al. [29]; Yi et al. [42]; Lu et al. [38]; Li et al. [43];
	C3	Amount of foreign capital utilized actually per capita	Dollar	Benefit	Yi et al. [29]; Yi et al. [42]; Li et al. [43];
	C4	Proportion of GDP contributed by tertiary industry	%	Benefit	Yi et al. [29]; Zhang et al. [10]; Ding et al. [7];Liang et al. [8]; Lu et al. [38]; Xu et al. [9]; Yi et al. [42];
	C5	Total import and export volume	10000 Dollar	Benefit	Tang et al. [5]; Lu et al. [38];
	C6	Retail sales of consumer goods	10000 Yuan	Benefit	Tang et al. [5]; Zhang et al. [10]; Lu et al. [38];Xu et al. [9]; Yi et al. [42];
	C7	Urbanization rate	%	Benefit	Yi et al. [29];
Society	C8	Per capita disposable income of urban residents	Yuan	Benefit	Tang et al. [5]; Ding et al. [7]; Lu et al. [38]; Yi et al. [42];
	C9	Urban unemployment rate	%	Cost	Yi et al. [29]; Tang et al. [5]; Zhang et al. [10]; Ding et al. [7]; Lu et al. [38]; Xu et al. [9]; Yi et al. [42];
	C10	Natural population growth rate	‰	Benefit	Lu et al. [38]; Yi et al. [42];
	C11	Beds of medical institutions for per 10,000 people	Unit	Benefit	Yi et al. [29]; Liang et al. [8]; Xu et al. [9]; Yi et al. [42];Zhang et al. [10];
	C12	Number of buses for per 10,000 people	Vehicle	Benefit	Ding et al. [7]; Xu et al. [9];
	C13	Per capita green area	㎡	Benefit	Yi et al. [29]; Lu et al. [38]; Zhang et al. [10];
	C14	Per capita of water resource	m3	Benefit	Yi et al. [29]; Tang et al. [5]; Zhang et al. [10];
	C15	Coverage rate of old-age insurance	%	Benefit	Yi et al. [29]; Liang et al. [8];
	C16	Proportion of government budgetary expenditure in education	%	Benefit	Yi et al. [29]; Ding et al. [7]; Liang et al. [8]; Lu et al. [38]; Xu et al. [9];
	C17	Proportion of government budgetary expenditure in science and technology	%	Benefit	Yi et al. [29]; Ding et al. [7]; Lu et al. [38]; Xu et al. [9];
Environment	C18	Comprehensive utilization rate of industrial solid wastes	%	Benefit	Yi et al. [29]; Tang et al. [5]; Zhang et al. [10]; Ding et al. [7]; Liang et al. [8]; Yi et al. [42]
	C19	Industrial soot and dust emissions	Ton	Cost	Yi et al. [29]; Zhang et al. [10]; Lu et al. [38]; Yi et al. [42];
	C20	Industrial waste water emissions	10,000 Ton	Cost	Yi et al. [29]; Tang et al. [5]; Zhang et al. [10]; Lu et al. [38]; Yi et al. [42];
	C21	Green coverage rate of built-up areas	%	Benefit	Tang et al. [5]; Zhang et al. [10]; Ding et al. [7]; Liang et al. [8]; Lu et al. [38]; Xu et al. [9];
	C22	Annual average concentration of PM2.5	Ug/m³	Cost	Ding et al. [7];Han et al. [44];He et al. [45]; Xu et al. [9];
	C23	Centralized sewage treatment rate	%	Benefit	Ding et al. [7]; Liang et al. [8]; Xu et al. [9];
	C24	Household waste treatment rate	%	Benefit	Ding et al. [7]; Liang et al. [8];

Step 2. Standardizing the decision matrix: the decision matrix $X = (x_{ij})m \times n$ is standardized according to the 0-1transformation, as matrix $Y = (y_{ij})_{m\times n}$. The indicators are divided into benefit and cost types.

$$\text{benefit indices } y_{ij} = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}}, \tag{2}$$

$$\text{cost indices } y_{ij} = \frac{\max x_{ij} - x_{ij}}{\max x_{ij} - \min x_{ij}}. \tag{3}$$

Step 3. Calculate the entropy value e_j of each indicator:

$$e_j = -k \sum_{i=1}^{m} \left(p_{ij} \ln \, p_{ij} \right). \tag{4}$$

In equation (4), $k = 1/\ln m$ and $p_{ij} = (y_{ij}/\sum_{i=1}^{m} y_{ij})$, $(i = 1, 2, 3, \ldots, m, j = 1, 2, 3, \ldots, n)$. When $p_{ij} = 0$, $\lim_{p_{ij} \longrightarrow 0} p_{ij} \ln \, p_{ij} = 0$.

Calculate the coefficient of variation h_j of each index. For one index, the larger the coefficient of variation h is, the smaller the e_j is. The greater the impact of the index on urban sustainability is, and the larger the corresponding weight coefficient is [50]. The formula for calculating the coefficient of variation h_j is as follows:

$$h_j = 1 - e_j. \tag{5}$$

Determine the weight value w_j of each evaluation index.

$$w_j = \frac{h_j}{\sum_{j=1}^{n} h_j}, \tag{6}$$

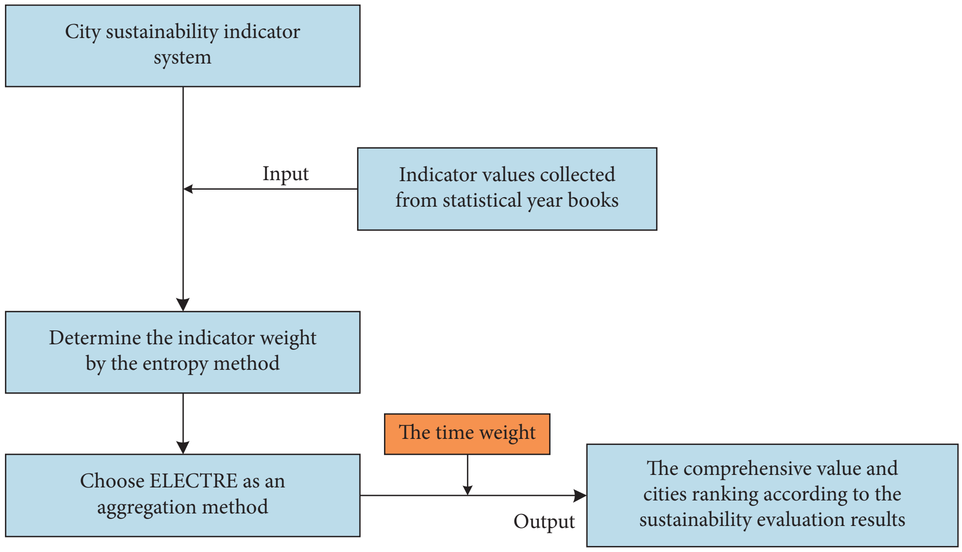

FIGURE 1: Urban sustainability evaluation processes.

FIGURE 2: Urban distribution map of Henan Province.

where $0 \leq w_j \leq 1$, $(j = 1, 2, 3, \ldots, n)$ and $\sum_{j=1}^{n} w_j = 1$.

4.4. Dynamic Evaluation of Urban Sustainability with ELECTRE Method. The evaluation of urban sustainability was carried out using the ELECTRE method, which employs the three-dimensional time-series data to present the dynamic process of the urban sustainability. The specific steps are as follows.

It is assumed that there are m alternatives, and each alternative is measured by n indicators. The evaluation value of the j th evaluation indicator of the i th alternative obtained in chronological order is $x_{ij}(t_k)$ $(i = 1, 2, \ldots, m;\ j = 1, 2, \ldots, n;\ k = 1, 2, \ldots, N)$.

(1) Constructing the original evaluation indicator value matrix $X(t_k)$.

$$X(t_k) = \left(x_{ij}(t_k)\right)_{m\times n} = \begin{pmatrix} x_{11}(t_k) & x_{12}(t_k) & \cdots & x_{1n}(t_k) \\ x_{21}(t_k) & x_{22}(t_k) & \cdots & x_{2n}(t_k) \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1}(t_k) & x_{m2}(t_k) & \cdots & x_{mn}(t_k) \end{pmatrix}. \tag{7}$$

(2) Normalizing value matrix. The original evaluation indicator value matrix is normalized to obtain a normalized decision matrix X'.

$$X'(t_k) = \left(x'_{ij}(t_k)\right)_{m\times n} = \begin{pmatrix} x'_{11}(t_k) & x'_{12}(t_k) & \cdots & x'_{1n}(t_k) \\ x'_{21}(t_k) & x'_{22}(t_k) & \cdots & x'_{2n}(t_k) \\ \vdots & \vdots & \ddots & \vdots \\ x'_{m1}(t_k) & x'_{m2}(t_k) & \cdots & x'_{mn}(t_k) \end{pmatrix},$$

$$\text{Benefit indices } x'_{ij}(t_k) = \frac{x_{ij}(t_k) - \min x_{ij}(t_k)}{\max x_{ij}(t_k) - \min x_{ij}(t_k)},$$

$$\text{Cost indices } x'_{ij}(t_k) = \frac{\max x_{ij}(t_k) - x_{ij}(t_k)}{\max x_{ij}(t_k) - \min x_{ij}(t_k)}. \tag{8}$$

(3) Calculating the weighted normalized decision matrix. A weighted normalized decision-making matrix is computed by multiplying the normalized decision-making matrix X' with the weights

$w_j(t_k)$ $(j = 1, 2, \ldots, n)$. The weighted normalized decision-making matrix $Y(t_k)$ is shown as follows:

$$
\begin{aligned}
Y(t_k) &= \left(y_{ij}(t_k)\right)_{m\times n} = x_{ij}'(t_k)\cdot w_j(t_k)\\
&= \begin{pmatrix} x_{11}'(t_k) & x_{12}'(t_k) & \cdots & x_{1n}'(t_k)\\ x_{21}'(t_k) & x_{22}'(t_k) & \cdots & x_{2n}'(t_k)\\ \vdots & \vdots & \ddots & \vdots\\ x_{m1}'(t_k) & x_{m2}'(t_k) & \cdots & x_{mn}'(t_k)\end{pmatrix}\begin{pmatrix} w_1(t_k) & 0 & \cdots & 0\\ 0 & w_2(t_k) & \cdots & 0\\ \vdots & \vdots & \ddots & \vdots\\ 0 & 0 & \cdots & w_n(t_k)\end{pmatrix}\\
&= \begin{pmatrix} x_{11}'(t_k)w_1(t_k) & x_{12}'(t_k)w_2(t_k) & \cdots & x_{1n}'(t_k)w_n(t_k)\\ x_{21}'(t_k)w_1(t_k) & x_{22}'(t_k)w_2(t_k) & \cdots & x_{2n}'(t_k)w_n(t_k)\\ \vdots & \vdots & \ddots & \vdots\\ x_{m1}'(t_k)w_1(t_k) & x_{m2}'(t_k)w_2(t_k) & \cdots & x_{mn}'(t_k)w_n(t_k)\end{pmatrix}\\
&= \begin{pmatrix} y_{11}(t_k) & y_{12}(t_k) & \cdots & y_{1n}(t_k)\\ y_{21}(t_k) & y_{22}(t_k) & \cdots & y_{2n}(t_k)\\ \vdots & \vdots & \ddots & \vdots\\ y_{m1}(t_k) & y_{m2}(t_k) & \cdots & y_{mn}(t_k)\end{pmatrix}.
\end{aligned}
\tag{9}
$$

(4) Determining the concordance matrix $C(t_k)$ and discordance matrix $D(t_k)$.

4.4.1. Determining the Concordance Set and the Discordance Set. Any two different rows are compared in the weighted normalized decision-making matrix Y. If the value of y in the i th row and j th column is higher than the value of y in l th row, the indicator represented by j th column would be classified into the concordance set; otherwise, it would be classified into the discordance set.

4.4.2. Calculating the Concordance Matrix. The concordance matrix $C(t_k)$ can be obtained by adding the weights of the indicators in each consistency set.

$$
\begin{aligned}
C(t_k) &= \left(c_{il}(t_k)\right)_{m\times m}, \quad (i = 1, 2, \ldots, m; l = 1, 2, \ldots, m; k = 1, 2, \ldots, N),\\
c_{il}(t_k) &= \frac{\sum_{j\in C_{il}'(t_k)} w_j + 0.5\sum_{j\in C_{il}''(t_k)} w_j}{\sum_{j=1}^{n} w_j}, \quad j = 1, 2, \ldots, n.
\end{aligned}
\tag{10}
$$

In equation (10), $c_{il}(t_k)$ $(i = 1, 2, \ldots, m; l = 1, 2, \ldots, m; k = 1, 2, \ldots, N)$ represents the relative advantage index of alternative i over alternative l at t_k moment. $C_{il}'(t_k) = \left\{j \mid y_{ij}(t_k) > y_{lj}(t_k)\right\}$ $(j = 1, 2, \ldots, n; k = 1, 2, \ldots, N)$ means that the value of y in the i th row and the j th column has a higher preference than the value of y in the l th row. $C_{il}''(t_k) = \left\{j \mid y_{ij}(t_k) = y_{lj}(t_k)\right\}$ $(j = 1, 2, \ldots, n; k = 1, 2, (t_k)$ $, N)$ represents that the preference of y in the i th row and the j th column is equal to the preference of y in the l row.

4.4.3. Determining the Discordance Matrix $D(t_k)$. The relative disadvantage index of the two alternatives is as follows:

$$
\begin{aligned}
D(t_k) &= \left(d_{il}(t_k)\right)_{m\times m}, \quad (i = 1, 2, \ldots, m; l = 1, 2, \ldots, m; k = 1, 2, \ldots, N),\\
d_{il}(t_k) &= \frac{\max_{j\in D_{il}'(t_k)}\left|y_{ij}(t_k) - y_{lj}(t_k)\right|}{\max_{l\in S}\left|y_{ij}(t_k) - y_{lj}(t_k)\right|}, \quad j = 1, 2, \ldots, n,\\
D_{il}'(t_k) &= \left\{j \mid y_{ij}(t_k) < y_{lj}(t_k)\right\},\\
S &= \{1, 2, \ldots, n\}.
\end{aligned}
\tag{11}
$$

In equation (11), $d_{il}(t_k)$ $(i = 1, 2, \ldots, m;\ l = 1, 2, \ldots, m;\ k = 1, 2, \ldots, N)$ represents the relative disadvantage index of alternative i over the alternative l at t_k moment. Comparing with $c_{il}(t_k)$ that which only contains the indicator weight information. $d_{il}(t_k)$ represents the difference between the weighted indicator values, which not only contains the weight information but also contains the information of the indicator value itself. Therefore, there is no complementarity between the relative advantage index and the relative disadvantage index. The greater the value of $d_{il}(t_k)$ is, the more likely i is to be inferior to l.

4.4.4. Revising the Discordance Matrix. According to the idea proposed by Sun [51], the discordance matrix $D'(t_k)$is revised and shown in the following equation:

$$\begin{aligned} D'(t_k) &= \left(d'_{il}(t_k)\right)_{m\times m} \\ d'_{il}(t_k) &= 1 - d_{il}(t_k). \end{aligned} \tag{12}$$

The larger $d'_{il}(t_k)$ means that the alternative i may be more inferior to alternative l at $t_k$moment.

4.4.5. Calculating the Revised Weighted Aggregation Matrix $E(t_k)$. The elements in the revised discordance matrix are the same as the elements in the concordance matrix. The higher the value is, the higher the degree of preference is. Therefore, the revised weighted aggregate matrix $E(t_k)$ can be obtained by multiplying the elements in the corresponding positions of the concordance matrix. The revised discordance matrix [16] is as follows:

$$\begin{aligned} E(t_k) &= \left(e_{il}(t_k)\right)_{m\times m}, \quad (i = 1, 2, \ldots, m;\ l = 1, 2, \ldots, m;\ k = 1, 2, \ldots, N), \\ e_{il}(t_k) &= c_{il}(t_k) \cdot d'_{il}(t_k). \end{aligned} \tag{13}$$

4.4.6. Calculating the Comprehensive Evaluation Value $u_i(t_k)$. This study applies the concept of net advantage value as follows [52]:

$$u_i(t_k) = \sum_{\substack{l=1 \\ l\neq i}}^{m} e_{il}(t_k) - \sum_{\substack{l=1 \\ l\neq i}}^{m} e_{li}(t_k), \quad i = 1, 2, \ldots, m. \tag{14}$$

The net advantage value u_i is the difference between the sum of the advantage indexes of alternative X_i to other schemes and the sum of the advantage indexes of other alternatives to X_i, which reflects the degree of the advantage of X_i in the alternative set. The larger the u_i is, the more advantageous alternatives the X_i will be.

4.4.7. Ranking the Alternatives. The alternatives are ranked according to the overall evaluation value of $u_i(t_k)$, with the greater the $u_i(t_k)$ meaning of the higher rank.

This study determines time weights using the method that the closer to the present, the more important the weight; conversely, the further from the present, the smaller is the weight. Within the time interval $[t_1, t_N]$, the time weight at t_k moment is w_k.

$$\begin{aligned} w_k &= \frac{k}{\sum_{k=1}^{N} k}, \\ \sum_{k=1}^{N} w_k &= 1, \quad w_k > 0. \end{aligned} \tag{15}$$

The comprehensive evaluation value of alternative i in the time interval $[t_1, t_N]$ is g_i.

$$g_i = \sum_{k=1}^{N} w_k u_i(t_k). \tag{16}$$

Finally, the alternatives are ranked according to g_i.

4.5. The Spatial Econometric Model. In this study, the spatial autocorrelation model is used to study the spatial dependence or spatial correlation between the sustainability level and the geographical location of cities. The spatial autocorrelation model can be divided into global spatial autocorrelation and local spatial autocorrelation. Global spatial autocorrelation adopts the global Moran index I to test whether there is an interaction between the sustainability levels of cities in a particular area.

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \overline{x})(x_j - \overline{x})}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\sum_{i=1}^{n}(x_i - \overline{x})^2}. \tag{17}$$

The value of the global Moran index I is between −1 and 1. $I > 0$ represents the positive spatial correlation; $I < 0$ represents the negative spatial correlation; $I = 0$ represents spatial randomness. n is the number of cities in Henan Province. x_i and x_j are the sustainability value of each city. $\overline{x}$ is the mean value; w_{ij} is the spatial weight matrix. If the two spatial units are adjacent to each other, the spatial weight value is 1; otherwise, it is 0.

Since the global Moran index can only test whether there is a spatial correlation between all cities in a region, and the specific spatial correlation between cities cannot be obtained [53]. Therefore, the local Moran spatial autocorrelation index I_i is calculated on the basis of the global Moran index.

$$I_i = \frac{n(x_i - \overline{x})\sum_{j=1}^{n} w_{ij}(x_j - \overline{x})}{\sum_{i=1}^{n}(x_i - \overline{x})^2}. \tag{18}$$

The local spatial autocorrelation is represented by the local Moran scatterplot to verify the existence of spatial clustering characteristics. The local Moran spatial autocorrelation index $I_i > 0$ indicates a high-high or low-low spatial clustering around the spatial unit; and the local Moran spatial autocorrelation index $I_i < 0$ indicates a high-low or low-high spatial clustering around the spatial unit.

5. Results

The sustainability of the 17 cities in Henan Province from 2013 to 2017 is evaluated using the mathematical model established in this study.

5.1. Calculating the Weight of Each Indicator. According to equations (1)–(3), the decision matrix A is established and normalized. Then, the entropy value e_j and weight w_j of each indicator are calculated by using equations (4)–(6). The specific calculation results of 2017 are shown in Table 2. Due to limited space, the data of other years are omitted.

Table 2: The weight of each indicator.

Indicator	e_j	w_j
C1	0.9284	0.0378
C2	0.8873	0.0595
C3	0.8139	0.0983
C4	0.9480	0.0275
C5	0.9127	0.0461
C6	0.8823	0.0621
C7	0.8851	0.0607
C8	0.9703	0.0157
C9	0.9096	0.0477
C10	0.9250	0.0396
C11	0.8787	0.0641
C12	0.8805	0.0631
C13	0.9478	0.0276
C14	0.9662	0.0179
C15	0.9220	0.0412
C16	0.8778	0.0645
C17	0.8328	0.0883
C18	0.9681	0.0168
C19	0.9681	0.0169
C20	0.9542	0.0242
C21	0.9440	0.0296
C22	0.9604	0.0209
C23	0.9711	0.0153
C24	0.9720	0.0148

5.2. Dynamic Evaluation of Urban Sustainability Based on ELECTRE. The dynamic evaluation value and ranking of sustainable urban development in Henan Province from 2013 to 2017 can be obtained by implementing the methods shown in Section 4, as shown in Table 3. According to equation (15), the time weight w can be calculated as follows:

$$w = (0.0667,\ 0.1333,\ 0.2000,\ 0.2667,\ 0.3333). \tag{19}$$

The comprehensive evaluation value is calculated by considering the time weight. Therefore, the ranking of the sustainability of 17 cities in Henan Province is shown in Figure 3.

Similarly, the results s can be obtained for 17 cities in Henan Province in the economic, social, and environmental dimensions of sustainable development, as shown in the Tables 4–6.

5.3. Ranking of Urban Sustainability. Figure 3 can directly reflect the level of sustainability of cities in Henan Province. Zhengzhou is the city with the highest score in Henan Province, that is, the city with the highest level of sustainability. Luoyang is ranked second place; Zhoukou has the lowest level of sustainability, followed by Shangqiu. Zhengzhou, the capital city of Henan Province, has invested much money in economic, social construction, and environmental protection in recent years to achieve great success. So its sustainability level is significantly higher than other cities in terms of actual development. Luoyang, as a sub–center city in Henan Province and a member of the Zheng–Luo–Xin National Independent Innovation Demonstration Zone, has developed rapidly in recent years to get a high level of sustainability. Zhoukou, Shangqiu, and Zhumadian are located in the regions with relatively concentrated cultivated land in Henan Province. Limited by the red line of agricultural land, it is challenging to develop the industry. The task of grain production restricts the economic development of the cities to some extent, which leads to the relatively backward economic level of these regions. Secondly, the permanent resident population of Zhoukou, Shangqiu, and Zhumadian is ranked in the third, fourth, and fifth place in the province, respectively. Due to the low economic level and large population, as well as the lack of corresponding science and education innovation resources and infrastructure, the level of urban sustainability of this region lags behind that of other cities in Henan Province.

Figure 4 shows the ranking of the sustainability levels of 17 cities in Henan Province in 2013–2017. It can be seen that Zhengzhou, Luoyang, and Sanmenxia were stable at higher levels during 2013–2017; Kaifeng, Luohe, and Xinyang show downward fluctuations; and Puyang, Nanyang, and Xinxiang show fluctuations upward. From 2013 to 2017, most of the cities are ranked relatively stable in terms of the sustainability level.

5.4. Spatial Autocorrelation Analysis

5.4.1. Global Spatial Autocorrelation. The purpose of spatial autocorrelation analysis is to explore whether the urban sustainability level is spatially correlated. If it appears that the closer the geographic location of the city, the more similar the level of urban sustainability is, which means that the urban sustainability level is positively correlated. If it appears that the closer the geographic location of the city, the more different the level of urban sustainability is, which means that the urban sustainability level is negatively correlated. If the urban sustainability level does not appear to be spatially correlated, it shows spatial stochasticity. The adjacency spatial weight matrix is employed to calculate the global Moran index using Data 13.0 software. The global

Table 3: The dynamic evaluation value and ranking of urban sustainable development in Henan Province from 2013 to 2017.

City	Abbreviation	Value					Ranking				
		2013	2014	2015	2016	2017	2013	2014	2015	2016	2017
Zhengzhou	ZZ	12.228	12.191	12.139	12.274	11.936	1	1	1	1	1
Kaifeng	KF	−1.840	0.701	4.013	−4.591	−5.265	11	9	3	15	16
Luoyang	LY	5.670	6.671	5.095	4.383	6.518	2	2	2	3	2
Pingdingshan	PDS	−1.844	−3.114	−2.350	−2.478	−2.470	12	14	11	11	12
Anyang	AY	−0.557	−1.800	−2.033	−3.375	−1.693	9	11	10	14	11
Hebi	HB	2.893	2.945	2.619	3.743	3.008	4	5	6	4	4
Xinxiang	XX	−1.357	−2.576	−3.144	−3.110	2.477	10	13	14	13	5
Jiaozuo	JZ	1.068	1.509	0.154	−0.477	1.557	7	7	8	8	6
Puyang	PY	−3.514	−4.005	−2.780	−0.521	−1.602	14	15	13	9	10
Xuchang	XC	0.093	0.837	−0.104	0.828	1.179	8	8	9	7	7
Luohe	LH	1.573	2.819	1.382	2.184	−1.046	6	6	7	6	9
Sanmenxia	SMX	5.091	5.938	3.985	4.759	6.148	3	3	4	2	3
Nanyang	NY	−2.524	−2.370	−2.355	−2.002	0.898	13	12	12	10	8
Shangqiu	SQ	−7.007	−7.127	−7.953	−6.670	−4.960	17	16	17	17	14
Xinyang	XY	1.664	3.787	2.681	3.316	−4.124	5	4	5	5	13
Zhoukou	ZK	−6.781	−7.277	−6.456	−5.487	−7.214	16	17	16	16	17
Zhumadian	ZMD	−4.856	−1.128	−4.893	−2.775	−5.059	15	10	15	12	15

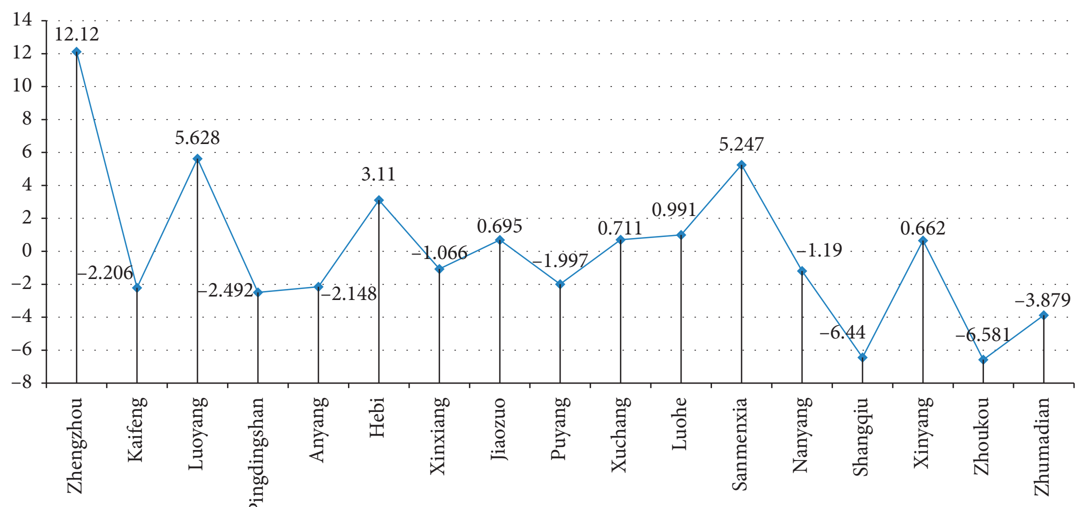

Figure 3: The comparison of the sustainability of cities in Henan Province.

Table 4: The sustainability evaluation value and ranking of each city in the economic dimension.

City	Value					Ranking					Consider the time weighting	
	2013	2014	2015	2016	2017	2013	2014	2015	2016	2017	Value	Ranking
Zhengzhou	16.000	16.000	16.000	16.000	15.959	1	1	1	1	1	15.986	1
Kaifeng	−1.722	−4.115	−2.655	−6.713	−3.365	12	12	12	14	13	−4.106	13
Luoyang	10.667	10.949	11.680	11.141	10.974	2	2	2	2	2	11.136	2
Pingdingshan	−1.305	−2.573	−2.613	−4.858	−2.866	11	11	11	12	11	−3.204	11
Anyang	0.567	1.173	1.136	−1.014	−3.286	8	9	9	10	12	−0.944	10
Hebi	1.619	1.928	2.246	1.494	2.039	6	6	6	7	6	1.892	6
Xinxiang	2.503	0.566	2.338	2.196	3.442	5	10	5	6	5	2.443	5
Jiaozuo	5.057	6.057	5.594	5.761	6.771	3	3	3	4	4	6.057	4
Puyang	−7.474	−5.833	−4.440	−2.913	−2.607	14	14	13	11	10	−3.810	12
Xuchang	0.094	2.994	1.439	2.473	1.255	10	5	8	5	7	1.771	7
Luohe	0.319	1.879	1.443	1.070	0.040	9	7	7	9	9	0.859	9
Sanmenxia	4.351	3.397	3.898	8.164	8.552	4	4	4	3	3	6.551	3
Nanyang	1.333	1.195	0.573	1.337	0.523	7	8	10	8	8	0.894	8
Shangqiu	−10.104	−9.632	−10.755	−10.827	−11.735	17	17	17	17	17	−10.908	17
Xinyang	−3.771	−5.783	−7.850	−5.760	−6.960	13	13	14	13	14	−6.449	14
Zhoukou	−8.326	−8.680	−8.482	−8.539	−7.668	15	15	15	15	15	−8.242	15
Zhumadian	−9.810	−9.523	−9.551	−9.011	−11.070	16	16	16	16	16	−9.927	16

Table 5: The sustainability evaluation value and ranking of each city in the social dimension.

City	Value					Ranking					Consider the time weighting	
	2013	2014	2015	2016	2017	2013	2014	2015	2016	2017	Value	Ranking
Zhengzhou	8.074	7.312	8.107	8.271	2.705	1	2	1	1	5	6.242	1
Kaifeng	−0.838	2.838	6.503	−0.852	−4.791	12	5	2	13	16	−0.201	11
Luoyang	3.042	3.820	3.678	1.049	5.433	4	3	5	5	1	3.539	3
Pingdingshan	0.783	−1.131	−0.286	−0.772	0.368	8	12	8	12	9	−0.239	12
Anyang	0.992	0.282	−1.338	0.838	1.332	6	11	12	6	7	0.504	7
Hebi	3.560	1.333	1.432	5.679	0.305	3	6	6	2	10	2.317	4
Xinxiang	−1.270	−2.590	−2.936	−0.273	4.619	13	14	14	9	4	0.450	8
Jiaozuo	0.537	0.711	−0.767	−0.387	0.876	9	7	9	10	8	0.166	10
Puyang	−3.349	−5.590	−2.745	0.385	−1.443	14	15	13	7	11	−1.896	14
Xuchang	−0.364	0.371	−0.909	−0.973	1.918	10	10	10	14	6	0.223	9
Luohe	0.871	0.561	0.666	0.371	−2.470	7	8	7	8	12	−0.458	13
Sanmenxia	7.168	8.236	5.521	2.190	4.761	2	1	3	4	3	4.851	2
Nanyang	−0.811	−1.249	−1.315	−2.166	5.000	11	13	11	15	2	0.605	6
Shangqiu	−7.298	−9.654	−9.157	−7.946	−4.523	16	17	17	16	15	−7.232	16
Xinyang	2.505	3.720	4.589	5.075	−2.739	5	4	4	3	13	2.021	5
Zhoukou	−8.832	−9.383	−7.247	−9.988	−7.741	17	16	16	17	17	−8.533	17
Zhumadian	−4.770	0.414	−3.798	−0.499	−3.610	15	9	15	11	14	−2.359	15

Table 6: The sustainability evaluation value and ranking of each city in the environmental dimension.

City	Value					Ranking					Consider the time weighting	
	2013	2014	2015	2016	2017	2013	2014	2015	2016	2017	Value	Ranking
Zhengzhou	−6.494	−5.929	−4.561	−1.585	−6.498	17	15	13	12	17	−4.724	15
Kaifeng	−5.587	−4.822	4.919	−2.492	−2.705	15	14	3	13	12	−1.598	11
Luoyang	−2.226	4.410	2.159	−3.411	1.011	9	6	7	15	7	0.299	10
Pingdingshan	−4.919	−3.656	−1.983	4.905	1.658	13	12	9	3	6	0.649	7
Anyang	−4.959	−3.571	−4.043	−3.391	−3.610	14	11	12	14	14	−3.723	14
Hebi	7.784	−0.217	7.778	−0.069	3.740	2	9	2	10	4	3.274	4
Xinxiang	−4.319	−3.979	−4.632	−7.228	−6.055	11	13	14	16	16	−5.690	16
Jiaozuo	−4.807	−5.987	−5.305	−9.704	−4.292	12	16	16	17	15	−6.198	17
Puyang	3.326	5.915	−2.015	−0.108	0.116	6	4	10	11	10	0.617	8
Xuchang	5.323	6.148	4.547	3.069	3.800	4	3	4	4	3	4.169	3
Luohe	12.037	6.484	8.818	5.618	3.605	1	2	1	2	5	6.131	2
Sanmenxia	−2.473	0.228	−5.507	1.083	−2.656	10	8	17	8	11	−1.832	12
Nanyang	−5.617	−8.620	−4.759	1.154	−2.854	16	17	15	7	13	−3.119	13
Shangqiu	−0.866	4.863	2.710	0.149	4.675	8	5	6	9	2	2.731	5
Xinyang	6.534	7.356	0.310	2.125	0.123	3	1	8	6	9	2.086	6
Zhoukou	2.261	−0.542	−2.749	3.064	0.462	7	10	11	5	8	0.500	9
Zhumadian	5.003	1.919	4.312	6.819	9.478	5	7	5	1	1	6.429	1

Moran index is shown in Table 7, and the Moran scatter plot is shown in Figure 5. As showing in Table 7, the Moran index of urban sustainability level from 2013 to 2016 is not significant. It means that there is no significant spatial correlation between cities from 2013 to 2016. It may be because these cities are in the stage of development transformation. These cities develop independently and are not closely related. The Moran index in 2017 is positive and passes the significance test ($Z > 1.65$, $p < 0.1$), indicating a positive correlation between the urban sustainability level in 2017.

5.4.2. Local Spatial Autocorrelation. The local spatial autocorrelation in 2017 is analyzed with the Moran scatter plot in Figure 5.

The numbers in the figure are labeled according to the order of cities in Table 3: 1 representing Zhengzhou, 2 representing Kaifeng, and 17 representing Zhumadian. The figure shows that most cities are clustered in the first quadrant (high–high, H–H) and the third quadrant (low–low, L–L), while a few cities are in the second quadrant (low–high, L–H) and the fourth quadrant (high–low, H–L). The result indicates that, in 2017, most cities in Henan Province are in the high–high and low–low clustering, and few are in the low–high and high–low clustering. That is, these cities with higher levels of sustainable development are clustered together, and cities with lower levels of sustainable development are clustered together. Among them, Zhengzhou, Luoyang, Jiaozuo, and Sanmenxia are in the high–high clustering. Shangqiu, Zhoukou, and Zhumadian

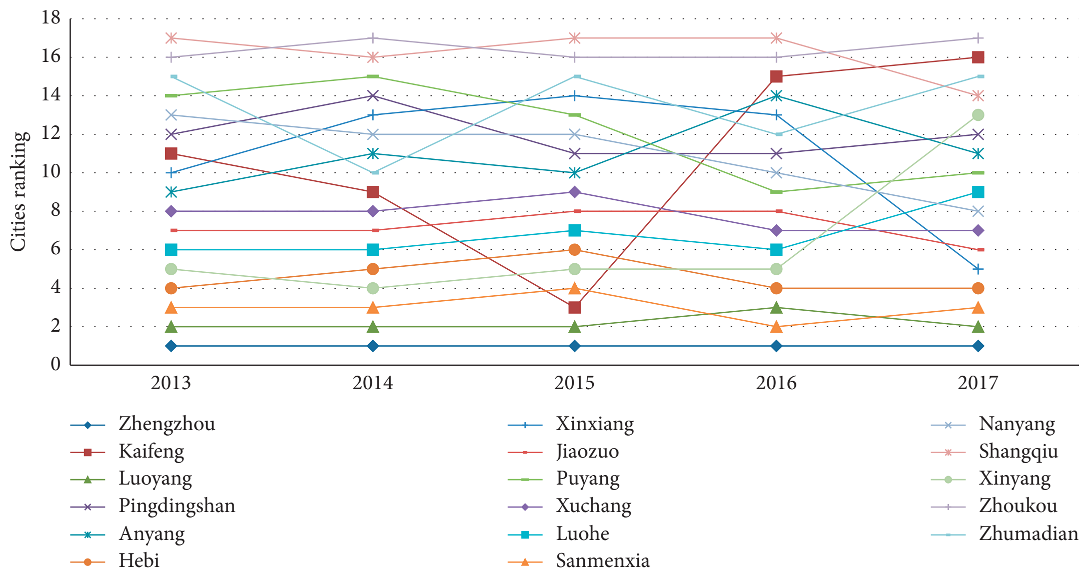

FIGURE 4: Ranking of urban sustainability in Henan Province from 2013 to 2017.

TABLE 7: Global Moran index of the urban sustainability level.

years	I	Z	p
2013	0.145	1.328	0.074
2014	0.116	1.164	0.122
2015	0.056	0.786	0.216
2016	0.047	0.735	0.231
2017	0.337	2.608	0.005

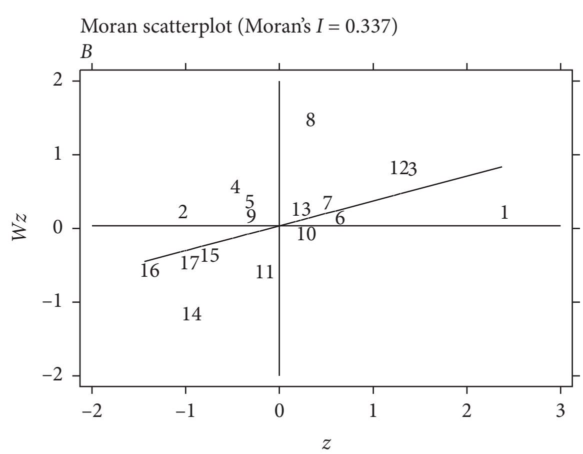

FIGURE 5: Moran scatter plot of urban sustainability level in 2017.

are in the low–low clustering. The results indicate that the high–high clustering cities are mainly concentrated around Zhengzhou and Luoyang, and the low–low clustering cities are mainly concentrated in the southeast of Henan.

6. Discussion

6.1. Economic Dimension. During the period 2013–2017, as showing in Figure 6, Zhengzhou has been ranked first in economic sustainability. As the capital city of Henan Province, Zhengzhou is a political, economic, cultural, and transportation center with the best resources in the province and plays a leading role in the development process. The economic sustainability of Luoyang, Sanmenxia, Jiaozuo, Xinxiang, Hebi, and Xuchang has also been maintained at a relatively high level. As cities bordering Zhengzhou, Luoyang, Jiaozuo, Xinxiang, and Xuchang have advantages in transportation, technology, and markets, thus making their economic development more dynamic. Especially in recent years, driven by the strategies of aerodrome economy, Zhengzhou-Europe Shuttle Train, and national central city development, the economy of Zhengzhou is significantly more potent than other regions. As a deputy central city in Henan Province and a member of The National Independent Innovation demonstration zone of Zhengzhou-Luoyang-Xinxiang, Luoyang has experienced rapid economic development in recent years. Xuchang is close to the aviation port area and has experienced remarkable economic growth in recent years. The excellent business environment has brought opportunities for the development of private enterprises in Xuchang. Jiaozuo, as a representative of the successful transformation of a resource–depleted city, is now focusing its economic development on commerce trade and tourism. The rapid development of sunrise industries has made per capita GDP and the proportion of tertiary industry in the national economy perform well. Cities in the eastern and southern regions, such as Shangqiu, Zhumadian, Zhoukou, and Xinyang have limited economic drive and relatively weak industrial manufacturing due to their predominantly agricultural farming areas.

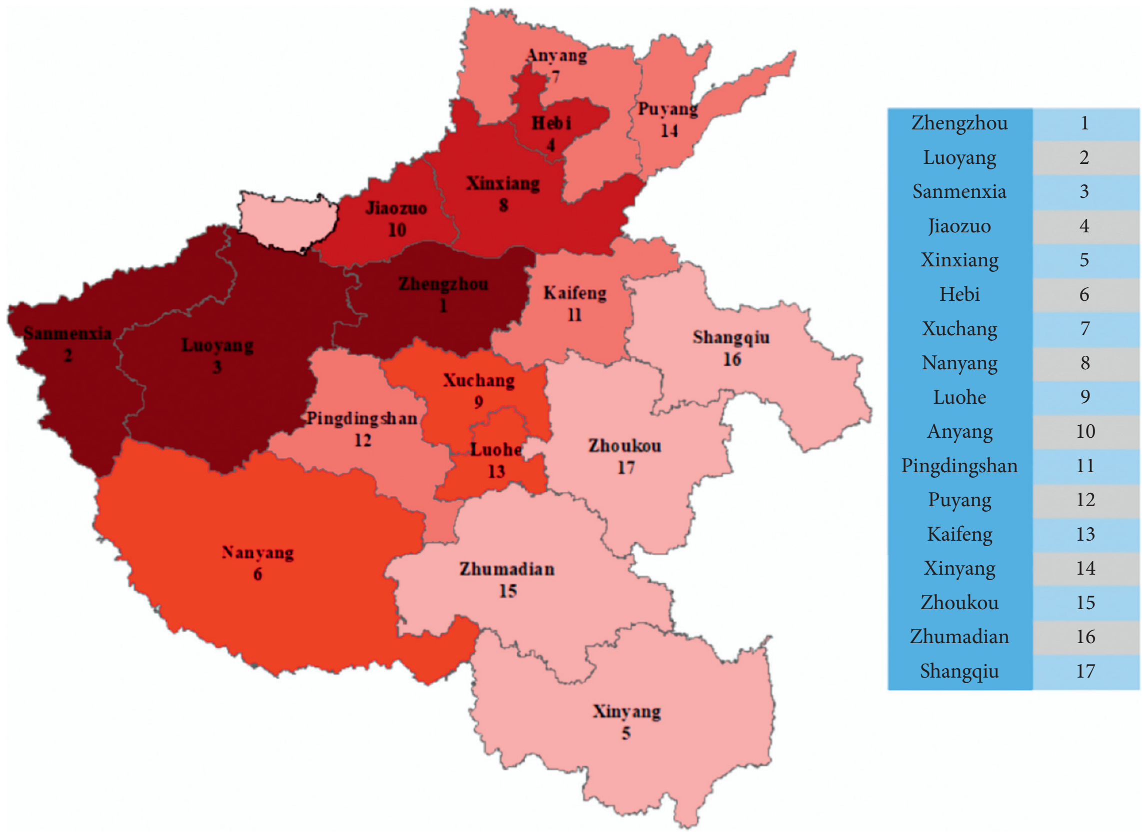

Figure 6: A comprehensive ranking of the sustainable development of cities in Henan Province in the economic dimension.

Simultaneously, due to the low concentration of high technology and limited market scope, the economic sustainability ranking is significantly lower. A comparative analysis of the indicators of the economic dimension shows that, in order to improve the sustainability of the city, it is necessary to improve the overall economic level [5]. For these cities, the government should focus on providing more policy and financial support, including strengthening investment attraction, creating a favorable market atmosphere and emphasizing the development of the tertiary sector and modern agriculturalization.

6.2. Social Dimension. In the social dimension, as showing in Figure 7, the highest level of sustainability is still Zhengzhou, the capital of Henan Province. At the same time, its social sustainability level has remained stable at a high level during 2013–2017. In addition, cities such as Sanmenxia, Luoyang, Hebi, Xinyang, and Anyang have relatively high levels of social sustainability. These cities have well-developed public infrastructures and relatively high investment of public resources. From specific indicators, it can be found that these cities have higher expenditures on education, science and technology and medical care, as well as higher pension insurance coverage rates and a more comprehensive social security system. In the southeastern region, social sustainability is at a low level due to a small economy and a large population, and insufficient investment in people's livelihoods. In particular, cities such as Zhoukou, Shangqiu, and Zhumadian have low per capita disposable income for urban residents and inadequate pension insurance coverage. Financial investment in science and technology, medical care, and other areas is also relatively low. At the same time, the urban registered unemployment rate is high. Therefore, the level of social sustainability is the worst. For these cities, the social security system needs to be further strengthened in the later development process to promote "people-oriented" sustainable development.

6.3. Environmental Dimension. From 2013 to 2017, as showing in Figure 8, the cities with high environmental sustainability levels in Henan Province include Zhumadian, Luohe, Xuchang, Hebi, and Shangqiu. Luohe, Xuchang, and Hebi have relatively good environmental quality due to their excellent environmental foundation and specific economic strength for environmental governance. For cities like Zhumadian and Shangqiu, due to their low industrialization level, the emission of industrial soot and dust and industrial wastewater is less. Cities with poor environmental quality include Jiaozuo, Xinxiang, Zhengzhou, Anyang. Jiaozuo has steel, coal, building materials, textile, and other traditional industries. Most of these industries are raw materials and high energy consumption. Therefore, Jiaozuo's industrial wastewater emissions and the annual average concentration of MP2.5 are relatively high. In addition, Jiaozuo's comprehensive utilization rate of industrial solid wastes, the ratio of wastewater centralized treated, and the green coverage

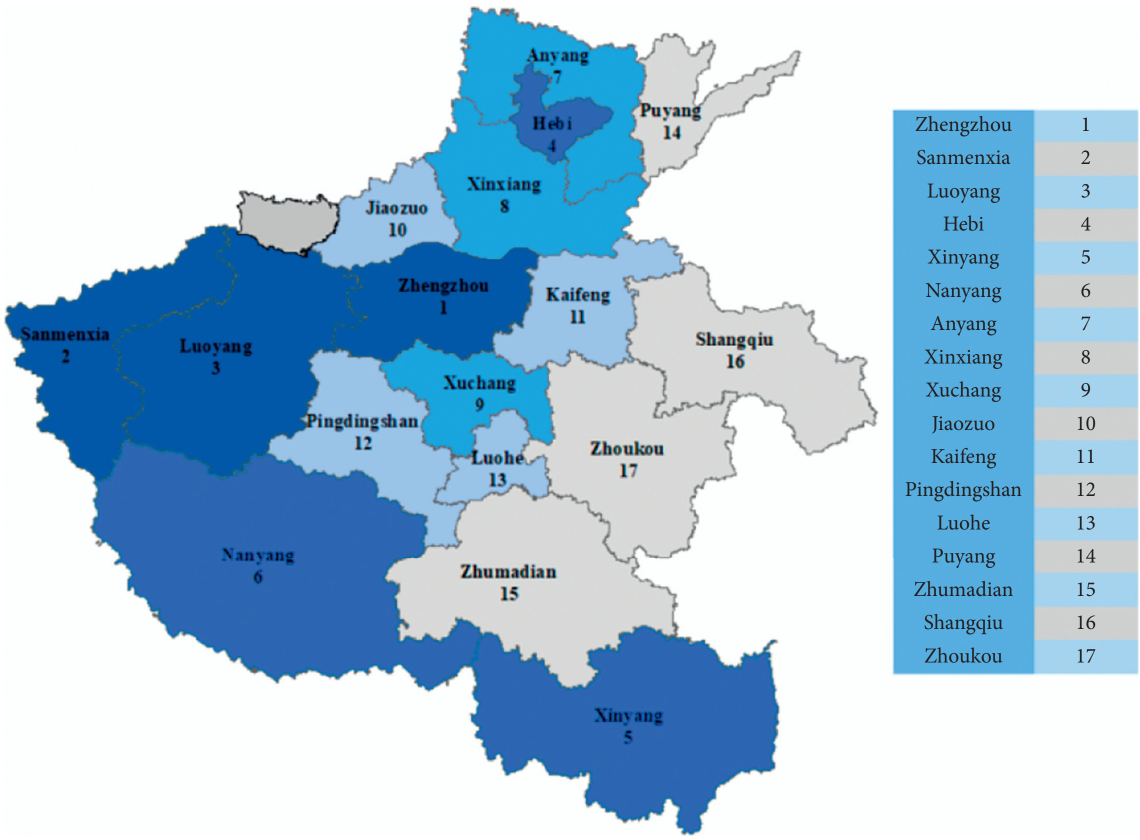

Figure 7: The comprehensive ranking of the sustainable development of cities in Henan Province in the social dimension.

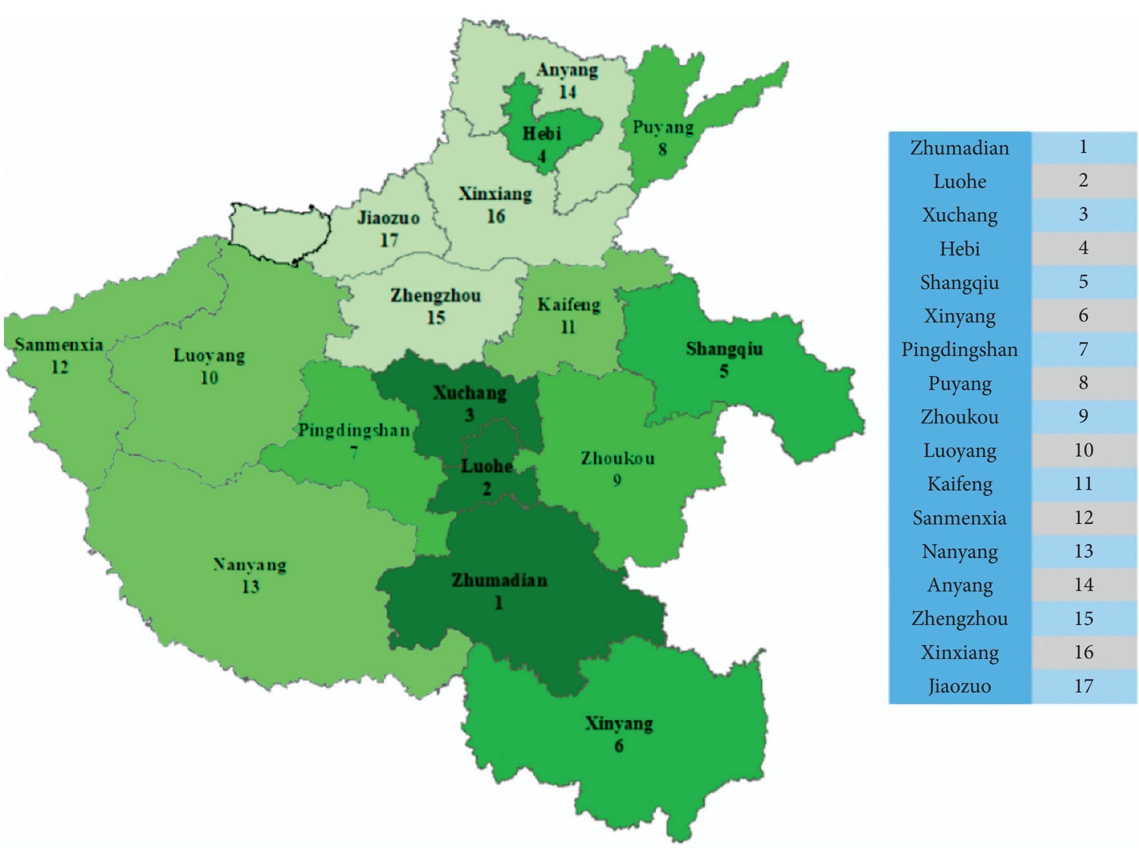

Figure 8: The comprehensive ranking of the sustainable development of cities in Henan Province in the environmental dimension.

rate of built–up areas are low. Therefore, it has always been at the bottom place of urban environmental sustainability in Henan Province from 2013 to 2017. Cities like Xinxiang and Anyang have many heavy industries, such as machinery manufacturing, building materials, and energy. Urban heavy industry has a significant negative impact on environmental sustainability. For example, in the past five years, the average industrial wastewater emissions in Xinxiang ranked first place among 17 cities in Henan. The annual average concentration of PM2.5 ranked third. Anyang has the highest average industrial soot and dust emissions in the past five years, and the annual average concentration of PM2.5 ranks second, after Zhengzhou. With the rapid economic development of Zhengzhou, people's living standards have been greatly improved. Zhengzhou is the city with the largest number of public vehicles per capita among the 17 cities. As a result, its annual average concentration of PM2.5 is the highest. In addition, the industrial wastewater emissions, industrial soot, and dust emissions of Zhengzhou are also relatively high. Therefore, Zhengzhou has been ranked at the last place of the environmental sustainability level during the period 2013–2017. Research has found that the low level of environmental sustainability in some cities has a great deal to do with their rapid economic development. Therefore, a balance should be struck between economic, social, and environmental sustainable development, avoiding the old path of "pollute first, cure later". In addition, in the process of urban development, the construction of ecological civilization should be integrated into all areas of society. The "greening" strategy should be used to promote the transformation and upgrading of industries and to realize green industrial production with high technology, high efficiency, low pollution, and low consumption.

6.4. Spatial Autocorrelation Analysis. The results of global spatial autocorrelation analysis show that the spatial correlation between cities in Henan Province from 2013 to 2016 is not significant. This is largely due to the fact that these cities are in a stage of development and transformation. Cities develop independently of each other without close ties. At the end of 2016, the National Development and Reform Commission issued the Development Plan for Central Plains City Clusters, Zhengzhou as the capital of Henan Province, becoming the center to lead the development of Central Plains City Clusters. Under the background of this policy, there is a positive correlation between the level of urban sustainability in Henan Province from 2017.

And the local spatial autocorrelation analysis shows that cities with higher levels of sustainable development in Henan Province clustered together in 2017, while cities with lower levels of sustainable development are clustered together. Among them, the high-high clustering cities are mainly concentrated around Zhengzhou and Luoyang, and the low-low clustering cities are mainly concentrated in the southeast of Henan Province. As the capital of Henan Province and the central city of the Central Plains Economic Zone, Zhengzhou ranks first in the Central Plains Economic Zone in terms of urban comprehensive strength, which has a strong attraction to the surrounding areas, prompting the concentration of population, resources and other factors in the surrounding cities to it, strengthening the connection between Zhengzhou and other cities. Zhenzhou has a strong external radiation capacity, driving the development of the surrounding cities. The eastern and southern regions of Henan Province are mainly agricultural, with limited economic capacity, relatively weak industrial manufacturing, and no obvious resource advantages or core industries. Therefore, the overall level of sustainability is relatively weak.

7. Conclusions

Urban sustainability evaluation plays a crucial role in sustainable urban development, and the evaluation results can provide support for stakeholders and decision-makers to formulate urban development plans and correct policy interventions. This study constructs an urban sustainability evaluation indicator system from the three dimensions of economy, society, and environment. The two-dimensional data with time-series data is extended to three-dimensional data. A dynamic evaluation model based on ELECTRE is employed to evaluate the sustainable development of 17 cities in Henan Province from 2013 to 2017. The research results show that, from 2013 to 2017, cities such as Zhengzhou, Luoyang, and Sanmenxia remained stable at a relatively high level, while the sustainability levels of cities such as Kaifeng, Luohe, and Xinyang showed a trend of downward fluctuations. The cities such as Puyang, Nanyang, and Xinxiang showed a trend of upward fluctuations. The results based on the spatial measurement model showed no spatial correlation in the sustainability level among cities in Henan Province from 2013 to 2016. However, the correlation between urban sustainability began to emerge in 2017. The cities showing high-high clustering are mainly concentrated around Zhengzhou and Luoyang, while those showing low-low clustering are mainly concentrated in the southeastern part of Henan. Specifically, Zhengzhou is the city with the highest level of sustainability among the 17 cities. Its economic and social sustainability levels are significantly higher than any other city. Zhoukou is the city with the lowest level of sustainability among the 17 cities. In the economic dimension, Zhengzhou has the highest sustainability level, and Shangqiu has the lowest level. In the social dimension, Zhengzhou ranks first, and Zhoukou ranks the lowest place. In the environmental dimension, Zhumadian has the highest sustainability level, and Jiaozuo has the lowest.

According to the evaluation results, this paper puts forward specific suggestions. Firstly, cities such as Shangqiu and Zhoukou are economically and socially underdeveloped. The government should provide them with more financial and policy support, including strengthening investment attraction, creating a favorable market environment, and emphasizing the development of the tertiary sector and modern agriculture. In addition, the social security system needs to be further strengthened to promote "people-oriented" sustainable development. Secondly, cities such as Zhengzhou, Xinxiang, and Jiaozuo have high economic sustainability levels but low levels of environmental sustainability. In the process of development, a balance should be struck between the economy, society, and the environment. The construction of ecological civilization should be integrated into all areas of society. The "greening" strategy should be used to promote the transformation and upgrading of industries, to achieve high-technology, high-efficiency, low-pollution, and low-consumption green industrial production and to promote the high-quality development of cities.

Based on the classic triple bottom line framework of sustainable development theory, this paper considers the characteristics of urban development and constructs an urban sustainability evaluation index system from economic, social, and environmental dimensions. And the ELECTRE method is used to dynamically evaluate urban sustainability based on three-dimensional data. The index system constructed and the research method adopted in this paper provide tools for measuring the sustainability status of a city (not only Henan but also other cities), which has certain theoretical and practical significance.

The research contributions of this study are manifested in three aspects. Firstly, the ELECTRE method is used to evaluate the urban sustainability level, and the time weights are considered to obtain the dynamic sustainability level of each city in annual, overall, as well as in the three dimensions of economy, society, and environment. Secondly, a spatial measurement model is used to identify the difference and clustering in the spatial distribution of urban sustainability levels. Finally, the research results provide a useful reference for city managers to clarify the current sustainability level of cities and to formulate reasonable development plans to promote sustainable development further.

At the same time, this study also has certain limitations. In the evaluation process, the method used to calculate the weighting system ignored the existence of interaction among indicators. Urban sustainability is a complex system affected by economic, social, and environmental dimensions, with the existence of interaction and conflict among factors. For example, many studies have concluded that there is an inverted "*U*" relationship between economic growth and environmental pollution in China. Therefore, in the future, we will continue to improve the calculation method of weights and pay more attention to the interaction among indicators.

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

Two-Stage Robust Counterpart Model for Humanitarian Logistics Management

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In the early stages of a major public emergency, decision-makers were troubled by the timely distribution of a large number of donations. In order to distribute caring materials reasonably and efficiently, considering the transportation cost and time delay cost, this paper takes the humanitarian logistics management as an example to study the scheduling problem. Based on the actual situation of insufficient supply during the humanitarian logistics management, this paper using optimization theory establishes a two-stage stochastic chance constrained (TS-SCC) model. In addition, due to the randomness of emergency occurrence and uncertainty of demand, the TS-SCC model is further transformed into the two-stage robust counterpart (TS-RC) model. At the same time, the validity of the model and the efficiency of the algorithm are verified by simulations. The result shows that the model and algorithm constructed are capable to obtain the distribution scheme of caring materials even in worst case. In the TS-BRC (with box set) model, the logistics service level increased from 89.83% to 93.21%, while in the TS-BPRC (with mixed box and polyhedron set) model, it increases from 90.32% to 94.96%. Besides, the model built in this paper can provide a more reasonable dispatching plan according to the actual situation of caring material supply.

1. Introduction

In recent decades, the global ecological environment has deteriorated dramatically. The frequent occurrence of major public emergencies not only poses a great threat to people's life and health but also hinders the national economic operation. In disaster area, not only casualties and economic losses will occur but also local transportation and communication will be paralyzed. Emergencies generally cover a wide range and have a great impact on current society and long-term development. Muhammad et al. found that dengue fever causes about 100 million infections per year [1]. Due to the randomness of emergencies, management departments cannot cope with excessive relief work in time in actual relief work, which leads to further aggravation of the severity of emergencies [2, 3]. It is necessary to study humanitarian logistics. Humanitarian logistics is an activity for emergency rescue in response to natural disasters, production accidents, and other emergencies [4]. When the emergencies occur, humanitarian logistics can quickly make judgments and deliver materials to disaster areas and personnel. In the process of crisis resolution, reasonable planning of humanitarian logistics plays an important role. Humanitarian logistics can effectively respond to emergencies and not only improve logistics efficiency but also accelerate the rescue speed, which helps to reduce the adverse impact of emergencies.

At present, many scholars focus their research on humanitarian logistics mainly on deterministic conditions, but do not discuss uncertainties. The research on humanitarian logistics can be divided into two aspects: location selection and distribution. In terms of logistics facility location, Amideo et al. discussed the challenges of optimizing models in the context of deterministic shelter location and evacuation routes [5]. Yi and Özdamar established the deterministic humanitarian logistics location model to minimize material relief and personnel treatment delays [6]. Widener et al. discussed material issues and established a layered location model for disaster relief materials [7]. Wohlgemuth et al. established a dynamic vehicle routing optimization model for deterministic demand with minimum time delay [8]. Chou et al. developed a dynamic optimal path model to study resource allocation and vehicle routing problems [9]. These studies provide a good reference for emergency management, but can be further incorporated into uncertain optimization studies. In terms of emergency material allocation, some scholars have studied its uncertainty and irregularity [10, 11]. Okumura studied the distribution and delivery of local, municipal and national warehouses for emergency material management [12]. The above study discussed the distribution, management, and system of emergency materials, but neglected the uncertainty of emergency demand and distribution of emergency resources. These research studies have explored the system model of humanitarian logistics location and material distribution, respectively, and provided effective suggestions for emergency management, but the disadvantage is that they neglect the uncertainty of the problem itself and data on the premise of defining conditions. Therefore, these studies have shortcomings in practical application and cannot cope with the situation of stochastic.

In traditional emergency dispatch management research, many scholars focus on single-stage uncertainty research, while few experts focus on two-stage stochastic programming. The two-stage stochastic optimization model is widely used in financial investment, supply chain management, emergency material dispatching, industrial engineering, and smart grid. Some scholars have studied the problem of random or uncertain real scenes [13, 14]. Yasari et al. established a two-stage stochastic chance constrained model for the two-stage optimization problem and solved it by heuristic algorithm [15]. Dillon et al. studied the optimization of blood supply chain network using a two-stage stochastic optimization model [16]. Christoph et al. studied two-stage optimization of supply chain network with delayed payment strategy under uncertain demand [17]. Chen et al. studied the problem of the size of a dedicated service station with opportunity constraints using two-stage distributed robust optimization models [18, 19]. All of the above are recent studies on the two-stage optimization model. Research involves how to model, how to solve the model, and even how to upgrade the algorithm. These phenomena show that the two-stage optimization model has been recognized by the majority of scholars and gradually widely used in practice. Solving a two-stage stochastic optimization model is usually complicated because it requires calculating the expected value of a multivariable. Scenario-based stochastic optimization is a common method to solve two-stage stochastic optimization problems. Maggioni et al. [20] and Venkitasubramony and Adil [21] considered using the discrete scenario optimization model to study supply chain optimization. However, the solution of the scenario-based stochastic optimization model depends heavily on the defined scenario and its probability of occurrence [22], and the solution of such a model is prone to fall into dimension disaster problem as the number of scenarios increase. Sainathuni et al. studied inventory transportation to determine the optimal distribution plan from the supplier to the customer to minimize total costs [23]. Rong et al. established a mixed integer linear programming model [24]. Rezaee et al. considered the design of a green supply chain network with stochastic demand and carbon price [25]. The above optimization models usually assume that the probability distribution is known beforehand, which is inconsistent with the actual situation. In addition, these models are not robust enough for small disturbances in input parameters, i.e., small changes in actual demand will affect the results.

In recent years, scholars have introduced robust optimization methods to various problems of supply chain management to improve the robustness of the model. In addition, optimization theories including robust optimization are found to involve in practical applications, such as the large-scale group decision-making [26] and multicriteria bilevel games [27]. Gülpınar et al. proposed a robust optimization model for equipment location under the worst-case scenario by assuming that the stochastic demand belongs to an uncertain set [28]. Zokaee et al. studied the optimization of a robust supply chain network by assuming that demand, inventory capacity, and some cost parameters belong to box sets [29]. The above robust optimization models consider that uncertain parameters belong to a certain set, and the decision-making problem with minimum total cost in the worst case is studied. In practice, the decision results of stochastic programming model are often too conservative since the probability of stochastic programming model does not usually occur. In order to reduce the chance stochastic problems, the theoretical methods of the robust optimization model have been extensively studied.

In the research of humanitarian logistics management, as far as we know, few scholars have studied it through the two-stage model. The innovation and contribution of this paper is to study how to construct the TS-RC model to discuss uncertainty. The first-stage decision is the selection of temporary warehouse locations and the quantity of basic inventory, and the second-stage decision is the transportation from the warehouse to the point of demand. First, in order to improve the satisfaction of logistics transportation service, a TS-SCC model with opportunity constraints is considered, in which the uncertain set is composed of the first and second moment of stochastic demand. Unlike the classical TS-SCC facility location problem, this model does not assume a preknown probability distribution of stochastic demand. Compared with the stochastic programming model, this model does not assume that uncertain demand belongs to a predetermined set. Secondly, by using the Karush–Kuhn–Tucher (KKT) condition, the TS-SCC model is equivalently transformed into a TS-RC model. In addition, according to the universality of the model, we construct three RC models with different undefined sets. In order to effectively solve the problem of robustness, its convergence is proved by writing an algorithm. Finally, in a numerical example, the emergency dispatching problem is studied. Using historical sales data, the first and second moments of stochastic demand are estimated by data-driven method. Seven different probability distributions are randomly generated for out-of-sample data. The test results show that the model in this paper has better stability than the nonrobust optimization model and the classical stochastic programming model.

The rest of this paper is set up as follows. Section 2 describes two stages of humanitarian logistics management. Section 3 transforms the TS-SCC model into TS-RC models.

Section 4 verifies the solution algorithm of the model by simulation. The performance of the models is analyzed and compared in detail in Section 5. Section 6 summarizes the conclusions of this study and future research directions.

2. Problem Description and Model Establishment

2.1. Problem Description. After disaster incidents, in addition to rescue work, how to protect people's livelihood is also a very important issue. In order to reduce the loss and ensure the safety of life, strict closure measures are generally adopted to minimize the contact behavior of the people. In order to protect people's livelihood, caring materials from all over the country have been flowing into the core area of the incident. How to effectively distribute these caring materials has become an urgent problem to be solved. On the premise of comprehensive analysis of the real scene, this paper constructs a TS-SCC model. The specific model framework is shown in Figure 1.

In an uncertain demand context, the first-stage decision is to choose a warehouse. In the second stage, the base stock of the selected warehouse and the distribution ratio of goods from the warehouse to the point of demand are determined. The goal of optimization problems is to minimize the total cost under the constraints of meeting the demand. Problems with adequate supply: to combat the outbreak, it does not need the material production manufacturer to return to work, expand their capacity, and strengthen the production force of materials loving for plague prevention. At the same time, large volumes of loving material will also need to be called in from other regions to combat the outbreak. Against this background, the rational distribution of charity donations plays an important role in the fight against outbreaks. The problem considered in this paper concerns a material scheduling problem from the distribution center to the site of demand. As far as possible, fairness in the distribution of the charity donations is guaranteed, minimizing the delay loss caused by the inadequate supply of materials and the costs incurred during storage and distribution.

2.2. Basic Assumptions and Symbols. In order to introduce the TS-SCC model and its application to the site selection path planning problem, the related parameters and signs of decision variables are summarized in Table 1.

Considering the practical problem that the material supply under the influence of the new corona pneumonia outbreak is not sufficient, the following assumptions are proposed:

(1) Because materials are uniformly distributed, the manufacturer of materials delivers the manufactured materials to the logistics consolidation center, which is then uniformly distributed by the consolidation center

(2) The paths from the consolidation center to the distribution center and from the distribution center to the fixed hospital are interconnected, and the shortest path is chosen

(3) Since the supplies are dispensed on day by day, the supplies are dispensed in one stage of the day (24 h)

(4) Both the distribution centers are capable of storing supplies that arrive the same day

(5) The individual site-directed hospitals had known requirements for a variety of supplies

2.3. Two-Stage Stochastic Chance Constrained Model. Based on the above basic assumptions, a TS-SCC model is constructed. The model aims to minimize the total cost on the basis of maximizing customer demand. The specific model is shown as follows. Based on a real-world scenario, the first stage of a TS-SCC model is designed to minimize the total cost. Random variables are defined in probability space $(\Xi, \mathscr{F}, P)$ and assume that the first and second moments are known precisely in advance, that is, $E_P[\varepsilon] = \mu_0, E_P[(\varepsilon - \mu_0)(\varepsilon - \mu_0)^T] = \Sigma_0 \succ 0$. Assume $\Xi = \mathbb{R}^{|\mathscr{I}|}$, and the closed convex set $\mathscr{P}$ contains all probability distribution functions with second-order moments as P, which are defined as: $\mathscr{P} := \{P\colon P\{\varepsilon \in \Xi\} = 1, E_P[\varepsilon] = \mu_0\}$ and $\mathscr{P} := \{P\colon E_P[(\varepsilon - \mu_0)(\varepsilon - \mu_0)^T] = \Sigma_0\}$.

$$\min\left\{\sum_{j\in\mathscr{J}} x_j c_f + \max E\left[C_2\left(\widetilde{D}_j\colon c\right)\right]\right\}, \tag{1}$$

$$\text{s.t. } x_j \in \{0,1\}, \quad \forall i \in \mathscr{I}. \tag{2}$$

The first of the objective functions (1) is fixed cost, which is the investment cost of infrastructure, including office equipment consumption cost and basic hydropower cost. Fixed cost is not related to vehicle routing. The second cost is affected by the uncertain parameters of the second stage. Constraint (2) represents a 0-1 variable and participates in the corresponding logistics operation only if and only if $x_j = 1$. In the second phase of the TS-SCC model, demand is maximized with uncertain parameters:

$$C_2\left(\widetilde{D}_j\colon c\right), \tag{3}$$

$$\text{s.t. } c_t^2 \sum_{i\in\mathscr{I}}\sum_{j\in\mathscr{J}} x_i\left(\frac{d_{ij}}{\overline{v}_i} - t_0^j\right) + \max\left\{c_v^2 \sum_{i\in\mathscr{I}}\sum_{j\in\mathscr{J}} \frac{y_{ij}\widetilde{D}_j d_{ij}}{h_j} + \sum_{i\in\mathscr{I}}\sum_{j\in\mathscr{J}} x_j c_h y_{ij}\widetilde{D}_j\right\} \le C_2\left(\widetilde{D}_j\colon c\right), \tag{4}$$

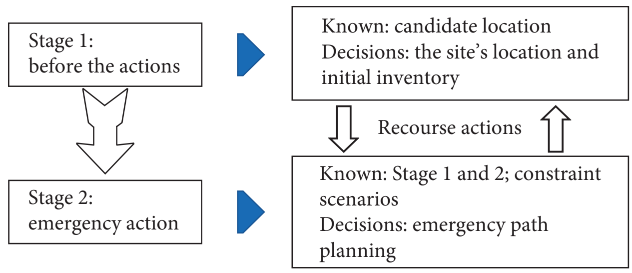

FIGURE 1: Schematic of the TS-SCC model.

TABLE 1: Description of relevant parameters.

Symbol	Description
D_j	Demand
c_f	Fixed operating cost
H_j^{Max}	Maximum inventory
h_j	Maximum load capacity
c_v	Fuel consumption cost per vehicle transit
E_c	Unit oil consumption of the vehicle
c_t	Unit delay penalty cost
d_{ij}	Origin and distance between initial requirement site
$\overline{v}_i$	Vehicle average speed
t_j	Baseline arrival time
T_j^{Max}	Maximum arrival time
x_i	$x_j \in \{0,1\}$, if $x_j = 0$, select site j; otherwise, unselected
y_{ij}	$y_{ij} \in [0,1]$, continuous variable, if $y_{ij} \neq 0$, path y_{ij} is selected
I	The set of i
J	The set of j

$$\sum_{j\in\mathcal{J}} y_{ij} \le 1, \quad \forall j \in \mathcal{J}, \tag{5}$$

$$y_{ij} \le x_j, \quad \forall i \in \mathcal{I}, \forall j \in \mathcal{J}, \tag{6}$$

$$\sum_{j\in\mathcal{J}} y_{ij}\widetilde{D}_j \le H_j^{\text{Max}}, \quad \forall i \in \mathcal{I}, \tag{7}$$

$$\lceil y_{ij} \rceil \left(\frac{d_{ij}}{\overline{v}_j} \right) \le T_{ij}^{\text{Max}}, \quad \forall j \in \mathcal{J}, \tag{8}$$

$$\begin{aligned} &P\left\{\varepsilon | \varepsilon \notin \Xi_j\right\} \le \alpha_j, \\ &\widetilde{D}_j = D_j^0 + \varepsilon D_j^0, \quad \forall j \in \mathcal{J}, \end{aligned} \tag{9}$$

$$0 \le y_{ij}, x_i \in \{0,1\}, \quad \forall i \in \mathcal{I}, \forall j \in \mathcal{J}. \tag{10}$$

The total cost when the objective function maximizes demand. Specific constraints: constraint (4) includes vehicle transportation costs, time costs, and handling costs; constraint (5) means that the total loading and unloading capacity cannot be higher than the total demand of the product, and there is no other outflow part; constraint (6) indicates that only the selected initial node will participate in the corresponding logistics operation; constraint (7) represents maximum capacity; constraint (8) represents maximum time constraints; constraint (9) represents random probability constraints, ε is a random influence factor, $\alpha_j \in (0,1)$ is a confidence level parameter, and $P\{\cdot\}$ represents the probability distribution function of random demand. Constraint (10) is a dependent variable. In solving problems (1)–(9), the following difficulties are encountered: on the one hand, in practical applications, the probability distribution of random parameters is unknown. Even if it is assumed to obey a known probability distribution and if ε is a continuous random variable, the objective function contains expectations and involves the calculation of multiple integrals, which is extremely difficult to calculate. On the other hand, in the second-stage optimization problem, there are multiple opportunity constraints because the probability distribution of random demand is unknown, the opportunity constraint is nonconvex, which is also very difficult to compute.

3. Establishment of TS-RC Model

Due to the diversity and irregularity of the real world, the TS-SCC model is not feasible. Specifically, the external market environment is full of uncertainties, and it is often difficult to obtain the law of key parameters development, especially the probability distribution of demand parameters [30]. The scope of application of an idealized random probability model is very limited. Therefore, we introduce the concept of robust optimization. Robust models provide an effective measure of uncertainty. Robust optimization studies are more applicable and stable than others. In this section, the above deterministic TS-SCC models transformed into a robust counterpart model by applying robust optimization theory. In robust models, the uncertain parameters change within an uncertain set, so that the probability distribution independent of the model can also be used to study inventory routing problems. Based on the random model, the initial node demand is defined as the random demand parameter $\widetilde{D}_j = D_j^0 + \widehat{D}_j$, where D_j^0 is the nominal demand, the fluctuation of demand is $\widehat{D}_j = \varepsilon D_j^0$, and the disturbance proportion is ε [31]. On this basis, three two-stage robust counterpart models are established.

3.1. TS-BRC Model. In the two-stage robust counterpart model for box sets (TS-BRC model), the uncertain demand is $\widetilde{D}j$ and the uncertain set is the box set [32]. Based on the robust optimization theory, the TS-SCC models are further transformed into a TS-BRC model. The domain of the uncertainty parameter is $\mathbb{U}_B = \left\{\{\varepsilon\}\colon \|\varepsilon\|_\infty \le \Psi_j\right\} = \{\varepsilon\}\colon |\varepsilon_j| \le \Psi_j\}$, where Ψj is the uncertainty level parameter (i.e., the security parameter) and Ψj indicates at most one parameter deviates from the nominal value.

Theorem 1. *Under the condition of uncertainty, when the uncertain parameter is not 0, the key constraints in the TS-BRC model* $\min_{+}\{\sum_{j\in\mathcal{J}} x_j c_f + \max E[C_2(\widetilde{D}_j\colon c)]\}$ *is equivalent to them in the TS-SCC model* $\left\{\inf Z_B\colon \sum_{j\in\mathcal{J}} x_j c_f + \sup_{\mathbb{U}_B} E[C_2(\widetilde{D}_j\colon c)] \le Z_B\right\}$. *When the uncertain parameter is 0, the TS-BRC model degenerates into a two-stage linear optimization model.*

The first stage of the TS-BRC model is (11)–(13), which aims to minimize the total cost under uncertain conditions:

$$\inf Z_B, \tag{11}$$

$$\text{s.t.} \sum_{j\in\mathcal{J}} x_j c_f + \sup_{\mathbb{U}_B} E\left[C_2\left(\widetilde{D}_j\colon c\right)\right] \le Z_B, \tag{12}$$

$$x_j \in \{0,1\}, \quad \forall i \in \mathcal{J}. \tag{13}$$

The second stage of the TS-BRC model is (14)–(21), which aims to minimize the initial distribution cost while maximizing the satisfaction of demand:

$$\inf C_2\left(\widetilde{D}_j\colon c\right), \tag{14}$$

$$\text{s.t.}\ C\left(D_j^0\right) + \sup_{\mathbb{U}_B}\left[\Psi_j\left(c_v^2 \sum_{i\in\mathcal{J}}\sum_{j\in\mathcal{J}} \frac{y_{ij}\widehat{D}_j d_{ij}}{h_j} + \sum_{i\in\mathcal{J}}\sum_{j\in\mathcal{J}} x_j c_h y_{ij}\widehat{D}_j\right)\right] \le C_2, \tag{15}$$

$$\sum_{i\in\mathcal{J}}\sum_{j\in\mathcal{J}} x_i c_t^2\left(\frac{d_{ij}}{\overline{v}_i} - t_0^j\right) + D_j^0\left(\sum_{i\in\mathcal{J}}\sum_{j\in\mathcal{J}} x_j c_h^2 y_{ij} + \sum_{i\in\mathcal{J}}\sum_{j\in\mathcal{J}} \frac{c_v^2 y_{ij} d_{ij}}{h_j}\right) \le C\left(D_j^0\right), \tag{16}$$

$$\sum_{i\in I} y_{ij} \le 1, \quad \forall j \in \mathcal{J}, \tag{17}$$

$$\sup\left(\sum_{j\in\mathcal{J}} y_{ij} D_j^0 + \Psi_j' \sum_{j\in\mathcal{J}} y_{ij}\hat{D}_j\right) \le H_j^{\text{Max}}, \quad \forall i \in \mathcal{J}, \tag{18}$$

$$\lceil y_{ij} \rceil \left(\frac{d_{ij}}{\overline{v}_j}\right) \le T_{ij}^{\text{Max}}, \quad \forall j \in \mathcal{J}, \tag{19}$$

$$\mathbb{P}\left\{\varepsilon | \varepsilon \notin \mathbb{U}_B\right\} \le \alpha_j, \quad \forall j \in \mathcal{J}, \tag{20}$$

$$0 \le y_{ij} \le x_i, \quad x_i \in \{0,1\}, \forall i \in \mathcal{J}, \forall j \in \mathcal{J}. \tag{21}$$

Proof. The constraints of the uncertain linear programming (LP) in question are "hard," and the decision-maker cannot tolerate violations of constraints when the data are in $\mathbb{U}$. General linear programming (LP) problem is $\{\max C^T X | AX \le B, L \le X \le U\}$. Under uncertain conditions, the uncertain LP problem can be expressed as $\{\min_{\mathbb{U}_B}\{C^T X + D\colon AX \le B\}\}$. Among them, the cost function is $C^T X + D$, the basic constraint is $AX \le B$, and the support set is $\mathbb{U}_B$. Consider the matrix A, assume that element $\widehat{a}_{ij}$ in A is uncertain, and then define that $\widetilde{a}_{ij} = a_{ij} + \widehat{a}_{ij}\xi_{ij}$, where $\widetilde{a}_{ij}$ is the really value, a_{ij} is nominal value, while $\widehat{a}_{ij}$ is fluctuation and ξ_{ij} is factor $(\xi \in \mathbb{U}_B)$. So, they can be replaced equivalently. Then, uncertain sets and their corresponding robust equivalences are as follows: $\sum_j a_{ij}x_j + \max_{\xi\in\mathbb{U}} \sum_j \widehat{a}_{ij}x_j\xi_{ij} \le B$. And, it is equivalent to $\sum_{\mathcal{J}} a_{ij}X + \Psi\sum_{\mathcal{J}}\widehat{a}_{ij}|X| \le B$. Set $\mathbb{P}_\infty = [\mathcal{J}_{L\times L}; \mathbb{O}_{1\times L}]$, $+_\infty = [\mathcal{O}_{L\times 1}; \Psi]$, $\mathbb{K}_\infty = \{[\theta_{L\times 1}; t]\colon \|\theta\|_\infty = t\}$, where L is the number of uncertain parameters. Therefore, the inner layer maximization in it can be rephrased as $\max_{\xi\in\mathbb{U}^B}\{\sum_j \widehat{a}_{ij}X\xi_{ij}\colon \mathbb{P}_\infty\xi + +_\infty \in \mathbb{K}_\infty\Psi\}$. Define the dual variable as w_i and λ_i, according to dual cone theory $\mathbb{K}^*_\infty = \{[\theta_{L\times 1}; t]\colon \|\theta\|_l \le t\}$. Then, we can get $\min_{w,\lambda}\{\Psi\lambda_i\colon w_{ij} = \widehat{a}_{ij}X, \forall j, \sum_{\mathcal{J}}|w_{ij}| \le \lambda_i\}$, and $\min_{w,\lambda}\{\Psi\sum_{\mathcal{J}}|w_{ij}|\colon w_{ij} \le \widehat{a}_{ij}X, \forall_j\}$ is equivalent. Thus, it can be reformed as in the second stage $\Psi\sum_{\mathcal{J}}\widehat{a}_{ij}X$, and $\inf Z_B\colon \sum_{j\in\mathcal{J}} x_j c_f + \sup_{\mathbb{U}_B} E[C_2(\widetilde{D}_j\colon c)] \le Z_B$. So, Theorem 1 was proved. □

3.2. TS-ERC Model. In the TS-RC model for ellipsoid sets (TS-ERC model), when the uncertain parameter is defined by l_2 norm and made it float in the range of ellipsoid set,

$$\mathbb{U}_E = \left\{\varsigma \in \mathbb{R}^{|I|}\colon \|\varepsilon\|_2 \le \Omega_j = \varepsilon\sqrt{\sum_J \left|\varepsilon_j\right|^2}, \quad \varepsilon \in \mathbb{R}^{|I|\times|I|}, \Omega_j \in \mathbb{R}\right\}. \tag{22}$$

In this model, $\mathbb{R}$ is a closed convex set. Ω_j is an adjustable safety parameter and the ball diameter of the uncertain set [33]. The matrix $\varepsilon = \Sigma^{1/2}$ can be obtained and Σ is the covariance matrix。

Theorem 2. *Under the condition of uncertainty, when the uncertain parameter is not 0, the key constraints in the TS-ERC model* $\min_+\{\sum_{j\in\mathcal{J}} x_j c_f + \max E[C_2(\widetilde{D}_j\colon c)]\}$ *is equivalent to them in the TS-SCC model* $\{\inf Z_E\colon \sum_{j\in\mathcal{J}} x_j c_f + \sup_{\mathbb{U}_B} E[C_2(\widetilde{D}_j\colon c)] \le Z_E\}$. *When the uncertain parameter is 0, the TS-ERC model degenerates into a two-stage linear optimization model.*

The first stage of the TS-ERC model is (23)–(25), which aim to minimize the total cost under uncertain conditions:

$$\inf Z_E, \tag{23}$$

$$\text{s.t.} \sum_{j\in\mathcal{J}} x_j c_f + \sup_{\mathbb{U}_E} E\left[C_2\left(\widetilde{D}_j\colon c_m^2\right)\right] \le Z_E, \tag{24}$$

$$x_j \in \{0,1\}, \quad \forall j \in \mathcal{J}. \tag{25}$$

The second stage of the TS-ERC model is (26)–(35), which aims to minimize the initial distribution cost based on maximizing satisfaction.

$$\inf C_2\left(\widetilde{D}_j\colon c\right), \tag{26}$$

$$\text{s.t. } C_2\left(D_j^0\right) + \Omega_j\Upsilon_j + \sup_{\mathbb{U}_E} E\left[C_3\left(\widetilde{D}_k\colon c_n^3\right)\right] \le C_2, \tag{27}$$

$$\sum_{i\in I}\sum_{j\in J} x_j c_t^2\left(\frac{d_{ij}}{\overline{v}_i} - t_0^j\right) + \sup_{\mathbb{U}_E}\left(\sum_{i\in\mathcal{J}}\sum_{j\in\mathcal{J}} x_j c_h^2 y_{ij} D_j^0 + \sum_{i\in I}\sum_{j\in J}\frac{c_v^2 y_{ij} D_j^0 d_{ij}}{h_j}\right) \le C\left(D_j^0\right), \tag{28}$$

$$\Upsilon_j \ge \sqrt{\sum_{j\in J}\widehat{D}_j^2 r_i'^2}, \quad \forall i \in \mathcal{J}, \forall j \in \mathcal{J}, \tag{29}$$

$$r_i' \ge \sum_{i\in I}\sum_{j\in J}\left(x_j c_h^2 y_{ij} + \frac{c_v^2 y_{ij} d_{ij}}{h_j}\right), \quad \forall i \in \mathcal{J}, \forall j \in \mathcal{J}, \tag{30}$$

$$\sum_{j\in J} y_{ij} D_j^0 + \Omega_j\Upsilon_j \le H_j^{\text{Max}}, \quad \forall i \in \mathcal{J}, \tag{31}$$

$$\sum_{i\in I} y_{ij} \le 1, \quad \forall j \in \mathcal{J}, \tag{32}$$

$$\lceil y_{ij} \rceil \left(\frac{d_{ij}}{\overline{v}_j} \right) \leq T_{ij}^{\text{Max}}, \quad \forall j \in \mathcal{J}, \tag{33}$$

$$\mathbb{P}\{\varepsilon | \varepsilon \notin \mathbb{U}_E\} \leq \alpha_j, \quad \forall j \in \mathcal{J}, \tag{34}$$

$$0 \leq y_{ij} \leq x_j, \qquad x_j \in \{0,1\}, \forall i \in \mathcal{I}, \forall j \in \mathcal{J}. \tag{35}$$

Proof. The ellipsoid uncertainty set is $U^E = \{a_i \in R^n\colon a_i = \overline{a}_i + \Delta\xi, \ \xi \leq \Omega\}$, where $\Delta = \sum^{1/2}$. The constraints $\max a_i^T X \leq B$ of it can be translated as $\max\{a_i^T X\colon (a_i - \overline{a}_i)^T \Sigma^{-1} (a_i - \overline{a}_i) \in \Omega^2\}$. As for Σ is positive, so it is a convex problem. Therefore, LP can be solved by Karush–Kuhn–Tucher condition. $\min \mathcal{F}(a_i^*) = -a_i^{*T} X$ and s.t. $g(a_i^*) = (a_i^* - \overline{a}_i)^T \Sigma^{-1} (a_i^* - \overline{a}_i) - \Omega^2 \leq 0$. Thus, in our decision-making environment, meaningful solutions to an uncertain problem are exactly its robust feasible solutions. It remains to decide how to interpret the value of the objective (which can also be uncertain) at such a solution. As applied to the objective, the "worst-case-oriented" philosophy makes it natural to quantify the quality of a robust feasible solution x by the guaranteed value of the original objective, that is, by its largest value $\sup \mathbb{U}_E E[C_2(\widetilde{D}_j\colon c)]$. Thus, the best possible robust feasible solution is the one which solves the optimization problem $\min_+ \{\sum_{j\in\mathcal{J}} x_j c_f + \max E[C_2(\widetilde{D}_j\colon c)]\}$ in the TS-SCC model or which is the same to $\{\inf Z_E\colon \sum_{j\in\mathcal{J}} x_j c_f + \sup_{\mathbb{U}_E} E[C_2(\widetilde{D}_j\colon c)] \leq Z_E\}$ in the TS-ERC model. The latter problem is called the robust counterpart of the original uncertain problem. Above all, Theorem 2 can be proved. □

3.3. TS-BPRC Model. In the TS-RC model for mixed set of box and polyhedron (TS-BPRC model), the set of uncertain requirements is mixed of a box and a polyhedron set, where the box set is defined by the l_∞ norm and the polyhedron set by the l_1. Based on robust optimization theory, the TS-SCC model is further transformed into a TS-BPRC model with the domain of uncertainty parameters defined as

$$\begin{aligned}
\mathbb{U}_{\text{BP}} &= \{\mathbb{U}_\infty \cap \mathbb{U}_1\} = \{\mathbb{U}_{Bj} \cap \mathbb{U}_{Pj}\} \\
&= \{\{\varepsilon\}\colon \|\varepsilon\|_\infty \leq \Psi_j, \|\varepsilon\|_1 \leq \Gamma_j\} \\
&= \left\{\{\varepsilon\}\colon \left|\varepsilon_j\right| \leq \Psi_j, \{\varepsilon\} \cdot \sum \left|\varepsilon_j\right| \leq \Gamma_j\right\}.
\end{aligned} \tag{36}$$

Here, Ψ_j and Γ_j are uncertain parameters. To simplify the tedious expression, $\Lambda_j = \min\{\Psi_j, \Gamma_j\}$, where Λ_j is set as security parameters in the mixed intersection robust counterpart model.

Theorem 3. *Under the condition of uncertainty, when the uncertain parameter is not 0, the key constraints in the TS-BRC model* $\min_+ \{\sum_{j\in\mathcal{J}} x_j c_f + \max E[C_2(\widetilde{D}_j\colon c)]\}$ *is equivalent to them in the TS-SCC model* $\{\inf Z_{BP}\colon \sum_{j\in\mathcal{J}} x_j c_f + \sup_{\mathbb{U}_{BP}} E[C_2(\widetilde{D}_j\colon c)] \leq Z_{BP}\}$. *When the uncertain parameter is 0, the TS-BPRC model degenerates into a two-stage linear optimization model.*

The first stage of the TS-BPRC model is (37)–(39), which aims to minimize the total cost under uncertain conditions:

$$\inf Z_{\text{BP}}, \tag{37}$$

$$\text{s.t.} \sum_{j\in\mathcal{J}} x_j c_f + \sup_{\mathbb{U}_{\text{BP}}} E\left[C_2\left(\widetilde{D}_j\colon c\right)\right] \leq Z_{\text{BP}}, \tag{38}$$

$$x_j \in \{0,1\}, \quad \forall j \in \mathcal{J}. \tag{39}$$

The second stage of the TS-BPRC model is (40)–(47), which aims to minimize the distribution cost while maximizing the satisfaction of demands:

$$\inf C_2\left(\widetilde{D}_j\colon c\right), \tag{40}$$

$$\text{s.t. } C\left(D_j^0\right) + \sup_{\mathbb{U}_{\text{BP}}} \Lambda_j \left(c_v^2 \sum_{i\in\mathcal{I}} \sum_{j\in\mathcal{J}} \frac{y_{ij} \hat{D}_j d_{ij}}{h_j} + \sum_{i\in\mathcal{I}} \sum_{j\in\mathcal{J}} x_j c_h y_{ij} \hat{D}_j \right) \leq C_2, \tag{41}$$

$$\sum_{i\in\mathcal{I}} \sum_{j\in\mathcal{J}} x_j c_h^2 y_{ij} D_j^0 + c_v^2 \sum_{i\in\mathcal{I}} \sum_{j\in\mathcal{J}} \frac{y_{ij} D_j^0 d_{ij}}{h_j} + c_t^2 \sum_{i\in\mathcal{I}} \sum_{j\in\mathcal{J}} x_i \left(\frac{d_{ij}}{\overline{v}_i} - t_0^j \right) \leq C\left(D_j^0\right), \tag{42}$$

$$\sum_{i\in I} y_{ij} \leq 1, \quad \forall j \in \mathcal{J}, \tag{43}$$

$$\sum_{j\in\mathcal{J}} y_{ij} D_j^0 + \Lambda_j' \sum_{j\in\mathcal{J}} y_{ij} \widehat{D}_j \leq H_j^{\text{Max}}, \quad \forall i \in \mathcal{I}, \tag{44}$$

$$\lceil y_{ij} \rceil \left(\frac{d_{ij}}{\bar{v}_j} \right) \leq T_{ij}^{\text{Max}}, \quad \forall j \in \mathcal{J}, \tag{45}$$

$$\mathbb{P}\{\varepsilon | \varepsilon \notin (\mathbb{U}_B \cap \mathbb{U}_P)\} \leq \alpha_j, \quad \forall j \in \mathcal{J}, \tag{46}$$

$$0 \leq y_{ij} \leq x_j, \quad x_i \in \{0, 1\}, \forall i \in \mathcal{I}, \forall j \in \mathcal{J}. \tag{47}$$

Proof. General linear programming (LP) is $\{\max C^T X | AX \leq B, L \leq X \leq U\}$. And $\sum_j a_{ij} x_j + \Gamma_i p_i \leq B_i$, $p_i \geq \hat{a}_{ij} |x_j|$. Defining $\mathbb{P}_1 = [\mathcal{J}_{L\times L}; \mathbb{O}_{1\times L}], +_1 = [\mathcal{O}_{L\times 1}; \Gamma]$, $\mathbb{K}_1 = \{[\theta_{L\times 1}; t]: \|\theta\|_1 = t\}$, $\mathbb{P}_\infty = [\mathcal{J}_{L\times L}; \mathbb{O}_{1\times L}]$, $+_\infty = [\mathcal{O}_{L\times 1}; \Psi]$, $\mathbb{K}_\infty = \{[\theta_{L\times 1}; t]: \|\theta\|_\infty = t\}$, where L is the number of uncertain parameters . In the TS-BPRC model, the set is defined as $\mathbb{U}_{\text{BP}} = \{\mathbb{U}_\infty \cap \mathbb{U}_1\}$. Therefore, the problem of inner layer maximization can be rephrased as $\max_{\xi \in U^P} \{\sum_{\mathcal{J}} \hat{a}_{ij} X \xi_{ij}: \mathbb{P}_{1,\infty} \xi + +_{1,\infty} \in \mathbb{K}_{1,\infty} \Gamma, \Psi\}$. Then, we can get the problem $\min_+ \{\max E[C_2(\tilde{D}_j: c)]\}$, and the problem $\{\inf Z_{\text{BP}}: \sup_{\mathbb{U}_{\text{BP}}} E[C_2(\tilde{D}_j: c)] \leq Z_{\text{BP}}\}$ is equivalent. Thus, it can be reformed as $\{\inf Z_{\text{BP}}: \sum_{j\in\mathcal{J}} x_j c_f + \sup_{\mathbb{U}_{\text{BP}}} E[C_2(\tilde{D}_j: c)] \leq Z_{\text{BP}}\}$ in the first stage and $\sup_{\mathbb{U}_{\text{BP}}} \Lambda_j(C^T X)$ in the second stage. In summary, Theorem 3 can be proved. □

4. Simulation

In the case of emergency management, how to allocate emergency relief materials reasonably and effectively is a very important and difficult problem. According to the actual situation, this section takes the material dispatching system of Aba Prefecture earthquake in Sichuan Province as the research object and carries out indepth analysis (Figure 2). The earthquake has brought a huge impact on the lives of local people, under the auspices of the government part of the emergency rescue work. Among them, how to protect people's livelihood has become the primary issue. Specifically, the affected areas received a variety of vegetables and other materials from all over the country. The distribution of these materials is very complicated. The reasons are as follows: on the one hand, the category of donated relief materials is single, which cannot be directly distributed to the affected people. It cannot directly distribute the demand to retail investors and needs professional personnel to sort, pack, and deliver. It is almost impossible to operate in the emergency state, and it cannot be completed. On the other hand, the donated materials must be distributed within the fresh-keeping period, and the remaining disposable distribution time is very short without long-distance transportation time. The most effective way to solve these problems is to establish a temporary transit center. In the temporary center sorting and distribution, the efficiency is relatively high.

In this paper, a TS-SCC model is established to solve the problem of material supply in emergency, considering the material classification and variable supply. In the actual rescue process, the Rescue Department is faced with the two-stage vehicle path planning problem. The first stage is the location problem of temporary storage station, and the goal is to determine the location node and calculate the total cost. According to the actual situation of the disaster area, after comprehensive analysis, the flat and wide sites in the disaster area are selected as candidate temporary sites, which are represented by S_1, S_2, S_3, S_4, and S_5. These temporary storage centers have dual functions: one is responsible for the screening and sorting of materials and the other is to provide material reserve services for subsequent scheduling. On the basis of comprehensive consideration of various location factors, the origin of rescue materials is determined as the transfer yard of the bus station. The second stage is path planning. The goal of the second stage is to minimize the initial distribution cost, including material handling cost, transportation cost, and time cost.

There are 5 temporary storage sites in total, which are the candidate temporary storage sites determined in the first stage. There are 8 demand sites, which are represented by $D_1, D_2, \ldots, D_8$. In the complex humanitarian logistics system, there are 1 material origin, 5 temporary storage stations, 8 demand points, and any alternative path corresponds to different transportation costs. In the process of simulation, in addition to the comprehensive calculation cost of real-time oil price and actual distance, traffic congestion and time constraints are also involved.

4.1. Related Basic Parameter Data. Basic data information [34] includes fixed operating costs, demand, and average vehicle speed of storage stations (Table 2). The actual distance between nodes directly obtained through Google Map is shown in Table 3.

4.2. Results of TS-SCC Model and RC Model. In this section, we use MATLAB as the programming platform and Gurobi as the solvers to solve the above models, respectively. The results of the TS-SCC model are shown in Table 4. The results of the model are affected by the probability distribution. In this section, the common probability distribution is selected for simulation experiments. With increasing the mean value of parameters $(0.05 \longrightarrow 0.15)$, the total cost of the model shows an upward trend. Under different distribution functions, the total cost of emergency management is also very different. This means that, in the TS-SCC model, changing the parameters will directly affect the total cost. However, in the actual emergency environment, the development of events is uncertainty, and it is difficult to obtain sufficient historical data to calculate the specific distribution function or even to accurately estimate the

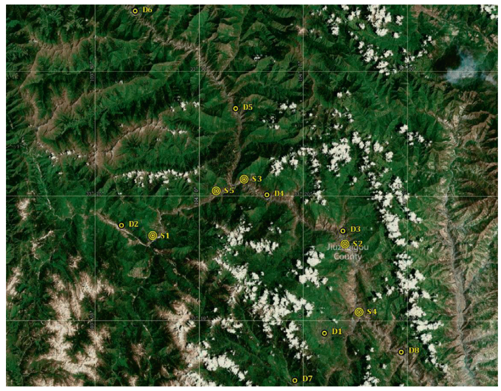

Figure 2: Location of emergency management.

Table 2: Basic information of temporary inventory site.

Storage sites	S_1	S_2	S_3	S_4	S_5
Distance	41.5	7.1	23.6	9.3	28
Maximum Inventory	1750	1600	1400	1350	1400
Average speed	45	40	40	45	35
Fixed cost	7500	6500	5500	4500	4200
Oil consumption	14.4	14.4	14.4	14.4	14.4
Load capacity	4–6	4–6	4–6	4–6	4–6
Demand sites	$M1$	$M2$	$M3$	$M4$	$M5$
Nominal demand	700	900	500	400	300
Demand sites	M_6	M_7	M_8	—	—
Nominal demand	600	800	750	—	—

Table 3: Distance between sites.

	M_1	M_2	M_3	M_4	M_5	M_6	M_7	M_8
S_1	39.7	6.3	38.2	23.6	30.3	56.4	71.7	60.8
S_2	1.1	47.2	3.1	16.4	33.6	60.5	33.9	22.4
S_3	21.5	27.7	19.6	4.7	13.8	41.8	53.2	42.3
S_4	12.1	58.2	14.7	27.2	45.9	72.7	21.8	10.7
S_5	26.1	22.6	24.7	9.3	15.4	43.2	58.1	46.4

Table 4: Results of TS-SCC model.

Distribution	Mean	Cost	Time	Mean	Cost	Time	Mean	Cost	Time
Normal	0.05	$8.8933E+04$	851.2	0.1	$8.8912E+04$	816.5	0.15	$8.8931E+04$	961.9
Poisson	0.05	$8.8929E+04$	813.1	0.1	$8.8928E+04$	909.4	0.15	$8.8929E+04$	893.4
Uniformity	0.05	$8.8939E+04$	903.1	0.1	$8.8938E+04$	896.9	0.15	$8.8936E+04$	865.3
Bernoulli	0.05	$8.8901E\ +0\ 4$	906.5	0.1	$8.8924E+04$	796.6	0.15	$8.8930E+04$	996.1
Index	0.05	$8.8926E+04$	897.6	0.1	$8.8929E+04$	897.4	0.15	$8.8926E+04$	988.4
Gamma	0.05	$8.8912E+04$	602.1	0.1	$8.8918E+04$	906.7	0.15	$8.8936E+04$	978.6
Weber	0.05	$8.8937E+04$	912.4	0.1	$8.8929E+04$	903.4	0.15	$8.8933E+04$	985.3

mean value and variance. So, the TS-SCC model in emergency management has a very low feasibility.

Through MATLAB programming, the following results are obtained. It can be seen from Table 5 that, with the increase of safety parameters, the three total costs show a gradual upward trend. When the $SP = 0$ (mean value is 0), the TS-RC is equivalent to the TS-SCC model. In the two-stage box set TC model, when the security parameters increase from 1 to 8, the total cost increases from $3.71E+04$ to $3.78e+04$, with an increase of 1.887%. In the TS-ERC model, when the security parameters increase from 1 to 8, the total cost increases with an increase of 2.695%. In the TS-RC model for mixed set of box and polyhedron, when the security parameters increase from 1 to 8, the total cost increases with an increase of 1.617%. The TS-BPRC model is more robust.

Table 5: Results of TS-RC model.

SP	ε	TS-BRC model		TS-ERC model		TS-BPRC model	
		Cost	Time	Cost	Time	Cost	Time
0	0.05	$8.8933E+04$	419.2	$8.8933E+04$	419.2	$8.8933E+04$	419.2
1	0.05	$8.8933E+04$	420.0	$8.8933E+04$	433.4	$8.8933E+04$	469.7
2	0.05	$8.8934E+04$	413.8	$8.8934E+04$	431.8	$8.8934E+04$	459.1
3	0.05	$8.8935E+04$	409.2	$8.8935E+04$	426.9	$8.8937E+04$	453.0
4	0.05	$8.8937E+04$	418.1	$8.8937E+04$	436.5	$8.8939E+04$	455.5
5	0.05	$8.8939E+04$	419.6	$8.8939E+04$	440.3	$8.8940E+04$	455.5
6	0.05	$8.8939E+04$	424.6	$8.8941E+04$	422.4	$8.8941E+04$	470.3
7	0.05	$8.8941E+04$	426.2	$8.8944E+04$	438.7	$8.8943E+04$	471.9
8	0.05	$8.8943E+04$	416.6	$8.8946E+04$	445.2	$8.8944E+04$	475.0
1	0.10	$8.8933E+04$	432.5	$8.8933E+04$	448.8	$8.8933E+04$	489.0
2	0.10	$8.8934E+04$	420.5	$8.8934E+04$	467.4	$8.8935E+04$	464.8
3	0.10	$8.8935E+04$	423.6	$8.8936E+04$	446.8	$8.8938E+04$	475.1
4	0.10	$8.8937E+04$	422.1	$8.8939E+04$	453.3	$8.8939E+04$	474.9
5	0.10	$8.8944E+04$	423.4	$8.8942E+04$	467.2	$8.8940E+04$	475.5
6	0.10	$8.8945E+04$	426.6	$8.8945E+04$	446.8	$8.8942E+04$	490.0
7	0.10	$8.8946E+04$	428.9	$8.8946E+04$	456.4	$8.8942E+04$	473.1
8	0.10	$8.8948E+04$	430.0	$8.8947E+04$	466.7	$8.8943E+04$	474.5

4.3. Path Planning for TS-SCC and TS-RC Model. According to the operation results of the TS-SCC model, the path planning scheme can be obtained. Materials donated are gathered from all over the country and transported to stations by transport vehicles. Due to the implementation of traffic control, the routes of rescue materials transportation vehicles are distributed in a radial pattern, and they rush to the rescue site at the fastest speed. At the same time, in addition to redistribution of materials, station also serves as a temporary warehouse to store materials. Under the TS-SCC model, S_2, S_3, S_4, and S_5 was selected as the initial sites location to undertake the main relief material supply service, but $S1$ temporary storage node was not activated. The second stage is distribution service, which is represented by dotted lines. Distribution routes go through almost all feasible routes while meeting the needs of all designated hospitals. Careful analysis reveals the following conclusions.

As shown in Figure 3, under the TS-SCC model, the cost of distribution routing accounts for a large proportion of the total cost. Although this planning method can ensure stable supply of materials and meet rescue needs, it still faces some problems in the specific service path planning. For example, the cost increases associated with long-distance transportation; circuitous transportation resulting from cross-distribution routes, which increases costs; unreasonable use of major temporary storage sites, which increases the cost of retransshipment; and once uncertainties arise in the actual rescue process, such as increased demand fluctuations, the stability and sustainability of the TS-SCC model cannot be guaranteed. Certification, which makes the logistics service of relief materials, faces some challenges and difficulties. Therefore, in the process of rescue, it is necessary to plan rationally and explore more optimized improvement strategies, i.e., to optimize the distribution route.

As a whole, three TS-RC models are quite different from TS-SCC models. In the TS-RC model, $S2$ is selected. As can be seen from Figures 4–6, selection of S_2 will greatly shorten the transportation distance of logistics, thus improving the

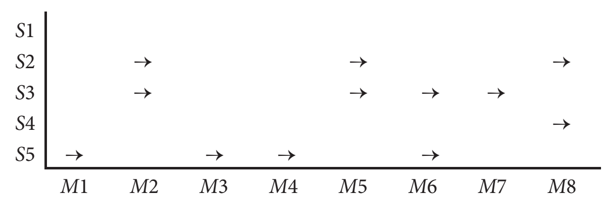

Figure 3: Distribution route of the TS-SCC model.

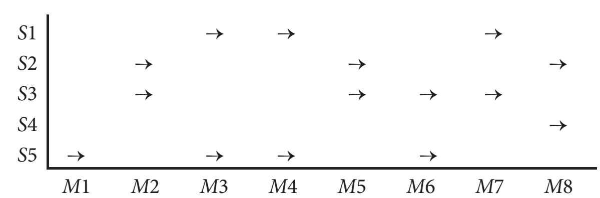

Figure 4: Distribution route of the TS-BRC model.

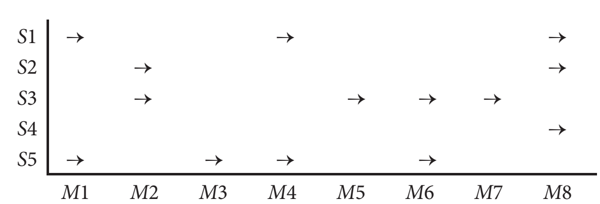

Figure 5: Distribution route of the TS-ERC model.

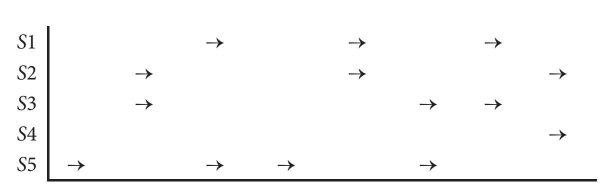

Figure 6: Distribution route of the TS-BPRC model.

operation efficiency. In detail, the TS-BPRC model is compared with the other three models. In the initial route planning of the first stage, the transit proportion is relatively balanced among the major transfer centers, and the transit capacity and load pressure of each temporary storage station are relatively balanced. As can be clearly seen in Figure 6, the nodes have been deeper into the hinterland of the disaster area and closer to the demand points, which also make the path planning more reasonable. In the second-stage planning, compared with the other two robust corresponding models, the proportion of long-distance line transportation is further reduced and the proportion of short-distance transportation is increased, especially after fully utilizing this node deep inside the hinterland. Comparatively speaking, the service proportion in each path tends to be short-haul route, which bears less cost and therefore increases the proportion of material supply. As a result, onboard mileage is more efficient, and delivery routes are more accurate and fast, showing better optimization performance.

5. Model Sensitivity Analysis

This section compares and analyses the performance of each model, including operational efficiency, uncertainty, and degree of demand fluctuation.

5.1. Model Run-Time Performance Comparison. This section analyses the operating efficiency of the four models. To facilitate comparison and run in the same computer environment, the security parameters are set as unique variables, and the running time of the models is observed.

Figure 7 shows the operational efficiency of three TS-RC models and TS-SCC model. It can be seen that the TS-SCC model has the highest operational efficiency, and the overall running time is much lower than the TS-RC model (green line). The effect of volatility on time is significant. On the whole, there is a clear boundary, and the running time of the model with low volatility is short. The main reason is that the demand parameters can converge quickly. In the comparison of RC models, it is found that when the volatility is high, the time performance of the TS-BRC model and the TS-ERC model fluctuates violently, while TS-BPRC model is relatively robust. Therefore, when solving practical problems, we can build an appropriate model according to the size of real data.

5.2. Comparative Analysis of Temporary Node Storage Ratio. Figure 8 shows the utilization ratio of each temporary logistics storage site. In the TS-SCC model, S_1 and S_4 accounts for a large proportion, and S_1 is not used (the proportion of S_1 is 0). In the TS-RC models, due to the difference of uncertain parameters, the proportion of transshipment is also variable. In terms of details, the transport ratio of S_1 showed an increasing trend. In particular, in the TS-BPRC model, the proportion of S_1 is more than 20%. The enabling of site S_1 is the biggest difference between the TS-RC model and the TS-SCC model. As site S_1 is deeply rooted in the hinterland of the target area, it will play a very important role in adjusting the transportation plan.

From Figure 9, it can be concluded that the temporary stations S_1 and S_3 has a downward trend among all stations compared with the TS-SCC model and the TS-RC model. The decrease in the proportion of transshipment in transit stations indicates that the importance of the stations is reduced, which in turn reduces the influence in the distribution path of the second stage. Among other sites, S_4 has the lowest fluctuation range and remains basically unchanged. It is worth noting that the proportion of S_2 and S_5 transshipment shows an upward trend, and the change of inventory proportion directly affects the fluctuation of cost and logistics service level. S_2 and S_5 will play a greater role in the TS-RC model.

5.3. The Impact of Demand Fluctuation on Total Cost. In this section, we compare and analyze the impact of demand volatility on the total cost in the four models and explore the impact of the fluctuation of random parameters on the total cost under the condition of fixed security parameters ($\Psi_j = \Omega_j = 3$ or $\Psi_j \cap \Gamma_j = 3$). The calculation results are shown in Figure 10. The total cost of the TS-SCC model is higher than that of the two-stage robust corresponding model. In the robust counterpart model, the increasing trend is quite different. The TS-BRC model and the TS-ERC model have greater randomness, and the TS-BPRC model has strong ability to resist uncertainty. Careful observation shows that the growth rate is slightly different. The cost of the TS-SCC model increases sharply, while that of the TS-BPRC model increases slowly.

5.4. Impact of Security Parameters on Service Level. In this section, the performance of the model is analyzed through the level of service (SL). Due to the high demand for timeliness of material scheduling in humanitarian logistics management, this section compares the service level of models through time difference and analyzes the advantages and disadvantages of different models. The calculation formula of service level is as follows:

$$\mathrm{SL} = \left[1 - \frac{\sum_J \left(y_{ij} \widetilde{D}_j d_{ij} / \bar{v}_{ij} \right) - t_j \sum_J \widetilde{D}_j}{t_j \sum_J \widetilde{D}_j}\right] \times 100\%, \tag{48}$$

where I and J are the number of arcs in the model. The simulation results under different parameters are shown in Figure 11.

Figure 11 illustrates the effect of SP on the SL of the model under the condition of fixed stochastic demand volatility ($\varepsilon = 0.15$). Fortunately, it can be seen that the service level tends to increase with the increase of security level. Safety parameters have good performance. This partly compensates for the cost of robustness (increased total cost) due to uncertainty and also mitigates the loss of reduced service levels due to demand volatility. Careful comparison shows that, in TS-BRC model, when SP increases from 1 to 8, logistics service level increases from 89.83% to 93.21% in the

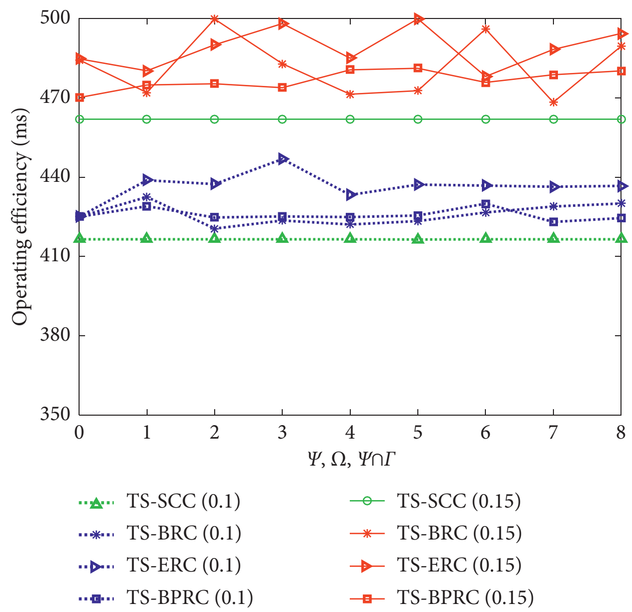

Figure 7: Model operation efficiency comparison.

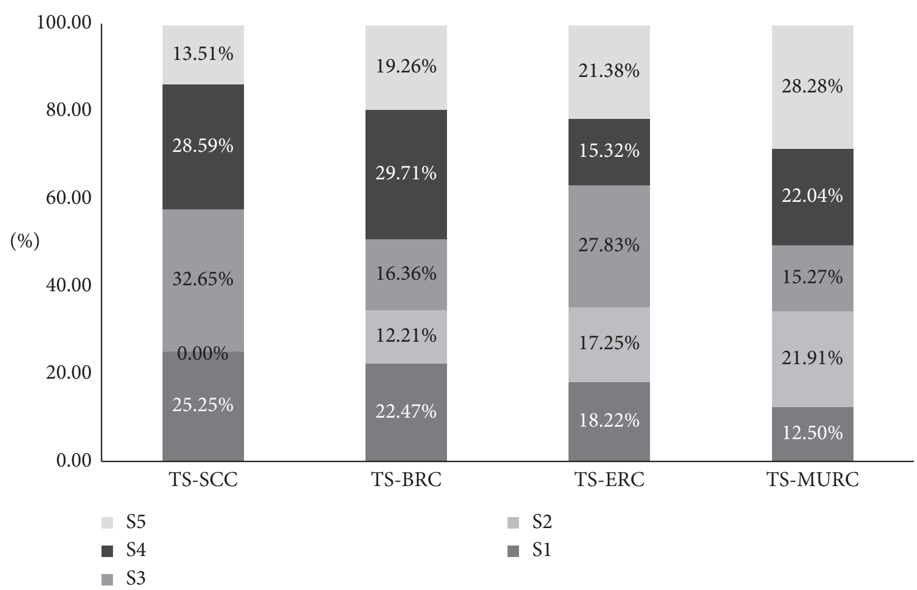

Figure 8: Inventory proportion of the temporary storage site.

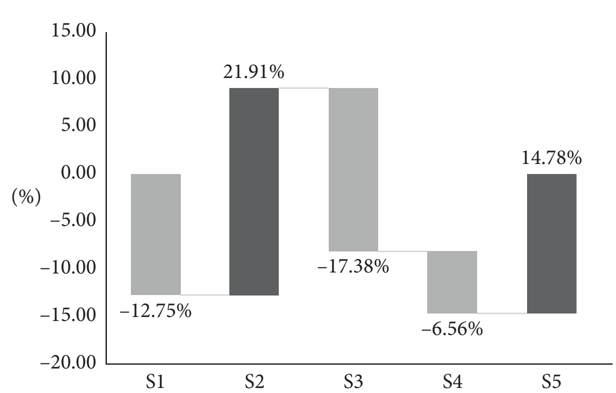

Figure 9: Inventory change range of the temporary storage site.

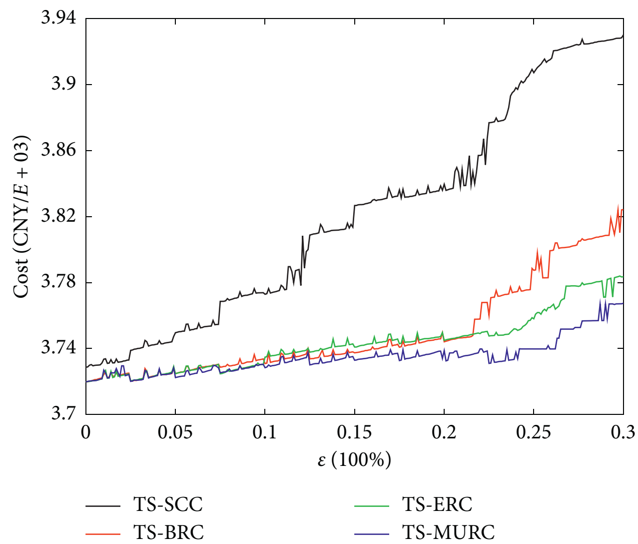

Figure 10: The influence of demand fluctuation on total cost.

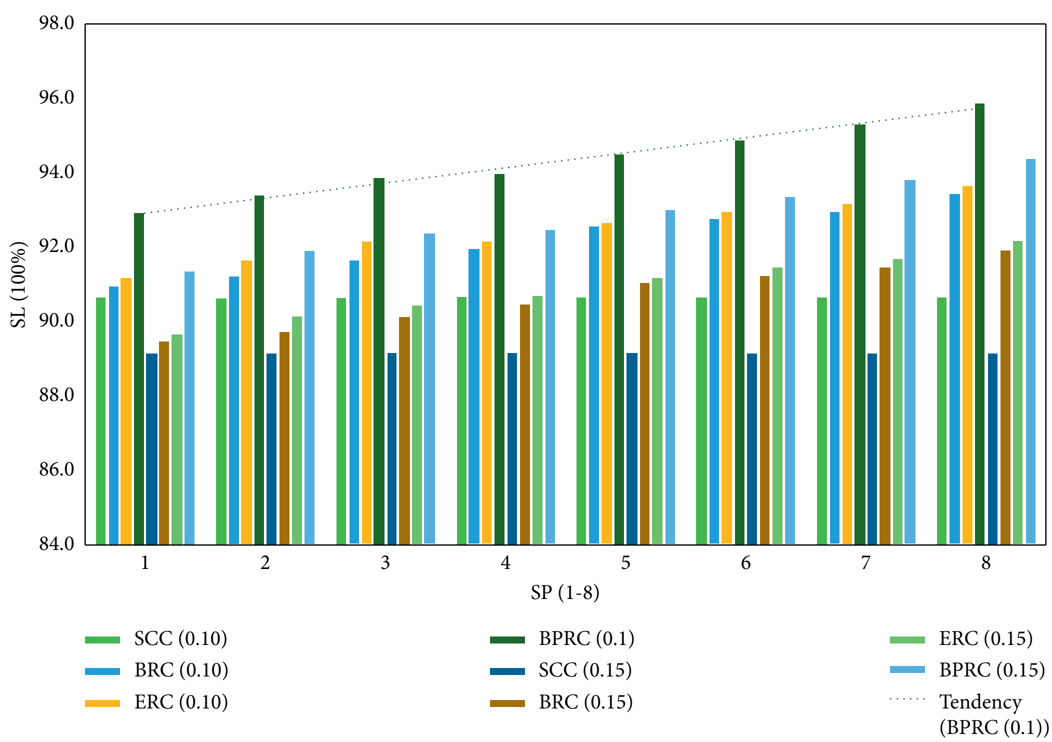

Figure 11: Service level affected by SP.

path planning stage. The TS-BPRC model has strong robustness. When SP is increased from 1 to 8, the logistics service level increased from 90.32% to 94.96% in the path planning stage. In the process of emergency management, rapid responsiveness must be paid attention to by managers. Considering uncertainties, although robust corresponding models in each two stages can give a more robust route planning scheme, the performance and application scope of each scheme is also different. Therefore, emergency rescue decision-makers must review the situation and work out the most reasonable path according to local conditions. This scheme can minimize the loss caused by delay and ensure the fairness of caring material distribution, but the logistics cost of this scheme is the highest among all schemes. Generally, in the process of public health emergencies, caring materials are relatively scarce, especially in the early period of public health emergencies, so it is necessary to control logistics costs properly. Decision-makers need to weigh the various

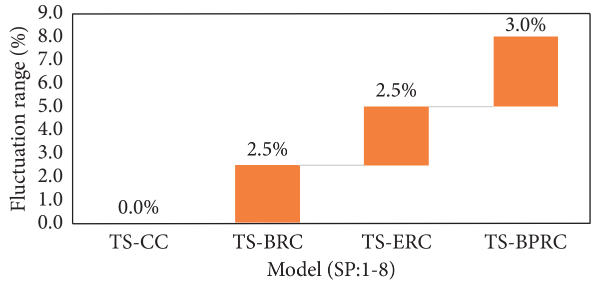

Figure 12: Service level fluctuation in different models.

objectives against the actual situation and trends of the epidemic and choose the ideal alternative for decision-making. Ideally, the limited resources of love should be fully utilized while minimizing all costs to achieve cost savings.

Figure 12 shows the change value of the growth rate of logistics service level. Based on TS-SCC model, the service level change trend of other models is compared. When the level of security parameters increases from 1 to 8, the service level of TS-BRC model and TS-ERC model increases by 2.5% relative to each other, while the increase of TS-BPRC model is 3.0%. The rise in service level demonstrates the advantages of robust optimization, and robust route planning can still be developed under uncertain conditions. This has a clear guiding significance for the emergency management department to formulate the rescue plan.

6. Conclusion

Due to the emergency, there is a serious shortage of living materials. In order to ensure the supply of materials in the incident area, we conducted a study on the issue of humanitarian logistics management. The research focuses on the material allocation problem with huge impact, which aims to carry out reasonable location and path planning for materials according to the actual situation, so as to minimize losses and save costs. In this paper, firstly, a two-stage stochastic chance constrained model is established and solved by using a solver. Due to the influence of uncertain demand, this paper further transforms the two-stage stochastic chance constrained model into a two-stage robust counterpart model. The validity and practicability of the model and the algorithm are validated by specific cases.

The following conclusions are drawn. When the volatility is high, the time performance of the two-stage box set robust counterpart model and the two-stage ellipsoid set robust counterpart model fluctuates violently, while the mixed set robust counterpart model is relatively robust. Furthermore, the two-stage mixed set robust counterpart model has strong ability to resist uncertainty. In the two-stage box set robust counterpart model, the logistics service level increases from 89.83% to 93.21% in the path planning stage when the safety parameters increase. The two-stage mixed set robust counterpart model does have the strong robustness. When gradually promoting, the level of logistics service increases from 90.32% to 94.96% in the path planning stage.

The innovation and contribution of this paper are mainly reflected in the following: how to construct a two-stage robust counterpart model to discuss uncertain optimization problems. To start with, in order to improve the satisfaction of logistics transportation service, a two-stage stochastic chance constrained model with opportunity constraints is considered, in which the uncertain set is composed of the first and second moment of stochastic demand. Unlike the classical two-stage stochastic problem, this model does not assume a preknown probability distribution of stochastic demand. Compared with the stochastic model, this model is unwillingly to suppose that uncertain demand belongs to a predetermined set. Moreover, the two-stage stochastic chance constrained model is equivalently transformed into a two-stage robust counterpart model. In addition, according to the universality of the model, we construct three robust counterpart models with different undefined sets. In the process of study, this paper considers that the storage node is fixed, while the actual location of the node may be mobile, which depends on the source and quantity of the caring material, as well as the type and quality difference of the material. This will also be the starting point or research direction of future research.

Data Availability

No data were used to support this study.

Conflicts of Interest

The author declares no conflicts of interest.

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Research Article

Sustainable and Optimal "Uniqueness" Contract in Public-Private Partnership Projects of Transportation Infrastructure

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To control the "uniqueness" risk in Public-Private Partnership (PPP) projects of transportation infrastructure, we design a simplified "uniqueness" contract model by incorporating the impact of the initial investment which is based on the Bertrand model. The nonlinear programming method is adopted to derive the optimal "uniqueness" contracts for incumbent private capital, the public, and the social welfare, respectively. The simulation results show that the achievement of the optimal "uniqueness" contract is essentially the result of a compromise between the private capital, the public, and social welfare. The extent to which such a contract reduces the probability of "uniqueness" risk mainly depends on the equilibrium relation between the interests of private capital and the public. The initial investment is not related to the government default when the contract does not take into account the interests of the private capital. Furthermore, the "uniqueness" contracts between private capital and the government are mainly for anticompetitive purpose in the PPP market of transportation infrastructure. Unless the contract terms focus on the improvement of social welfare, entering a "uniqueness" contract will cause social welfare losses.

1. Introduction

Due to the long investment period and large capital expenditures associated with public-private partnership (PPP) projects in transportation infrastructure, participants face complex risky conditions that may hinder the delivery of sustainable projects [1]. The "uniqueness" risk is a special critical risk in PPP projects of transportation infrastructure that adopts a user-paid model. It occurs when there is a new similar project or the government and other investors rebuild the project [2]. The risk of "uniqueness" stems from the conflict of interest between the government and private capital. Although both government and private capital can use the user-paid model to operate transportation infrastructure, the government aims to maximize the total social welfare, while private partners strive to maximize their profits [3]. These two goals are contradictory and cannot be achieved at the same time. For example, a profitable toll road does not necessarily increase the total social welfare; however, a project that maximizes social welfare may suffer losses [4]. Therefore, to increase the output of transportation services, the government is motivated to build new transportation infrastructure near the existing transportation infrastructure operated by other private partners to improve social welfare. But, the impact on the existing PPP projects is usually severe. It will not only reduce the demand for existing transportation infrastructure projects but also cause the project to fail and or become a waste of resources. The results will also discourage other private capitals to participate in PPP projects. "Uniqueness" risk events usually lead to a series of subsequent risks, such as demand risk, income risk, and credit risk [5]. Since the emergence of the PPP model in the twentieth century, there have been many failures in the PPP construction projects of transportation infrastructure due to the outbreak of "uniqueness" risks (the Quanzhou Citong Bridge BOT project was the first transportation infrastructure project in China to adopt the PPP model, and it was terminated early due to a "uniqueness" risk [6]).

If there is no restriction on the behavior of build new transportation infrastructure by the government, the "uniqueness" risk is wholly borne by the private capital. The government can decide to build a new infrastructure to increase social welfare at any time. However, the private capital will lose the whole market by the competition from the newly built transportation infrastructure. Since the private capital can predict the risks, many projects may fail bids due to the excessive "uniqueness" risk borne by the private capital. To attract the appropriate private capitals to participate the PPP projects, the government has the motivation to share the "uniqueness" risk with the private capital. To reduce the probability of "uniqueness" risk and reduce the loss caused by the risk to an acceptable level, the private capital participating in the PPP project demands restricting the government from building new competitive transportation infrastructure during the concession period in the form of a contract.

In many countries, governments are often restricted in constructing "unnecessary competitive projects" by law to encourage private capitals to participate in the PPP projects. For example, the pertinent "PPP Project Contract Guide" issued by the Ministry of Finance in China states that "In a project that adopts the user-paid model, the project company needs to charge the project users to generate income from the investment. Thus, it must ensure that there are enough users to use the project facilities and pay the fees" [7]. In view of this, the government is usually obliged to prevent unnecessary competition projects, the so-called "uniqueness" clause in PPP contracts. When the "uniqueness" contract is signed, part of the "uniqueness" risk is transferred to the government. If the government defaults and builds a new competitive transportation infrastructure, a compensation for the liquidation should be paid to the private capital providers by the government. At this time, the probability of "uniqueness" risk can be computed as the probability of default by the government.

Essentially, an exclusive contract *per se*, the "uniqueness" contract sets up barriers to entry to prevent new competitors from entering the existing market. There are a number of studies on exclusive transactions. Most of them focused on the challenge that unless the project is sufficiently efficient, the current seller will not be able to pay the buyer enough to accept the exclusive contract [8–12]. The consequences of exclusive contracts are usually very complicated. Whether an exclusive contract is relevant, anticompetitive, or enhancing efficiency and social welfare depends on the characteristics of the market. In the PPP relationship, both parties have the motivation to sign a "uniqueness" contract. The private capital is concerned about the extent to which the "uniqueness" contract it signs with the government can lock the two parties in a "uniqueness" relationship. The government expects to increase the output of transportation services and improve social welfare by signing a "uniqueness" contract, in addition to enhancing the government's reputation and attracting more private capitals to participate in PPP projects in the region.

To control the "uniqueness" risk in the PPP of transportation infrastructure, we adopt the nonlinear programming method to construct four models and simulate the optimal "uniqueness" contract. The nonlinear programming method has two advantages. One is to help identify whether the optimal contract solution exists and the number of solutions. The other is that we can find out an optima numerical solution by the nonlinear programming method which can provide direct support for the decision-making of both the government and the private capital. Although a clear optimal numerical solution of a "uniqueness" contract may be difficult to achieve in the current institutional environment, it sets goals for the government and private capital. The government is encouraged to improve the institutional environment to reach a contract close to the optimal solution with the private capital and enable it to be effectively implemented.

In this paper, we first find that the effect of "uniqueness" risk depends on the contract objective. The optimal contract of incumbent private capital and the optimal contract of the public can significantly reduce the probability of government default, while the optimal contract of social welfare is weakly related to government default. Among them, the optimal contract of incumbent private capital reduces the risk probability and increases the private capital return the most significant, followed by the optimal contract of the public. The optimal contract after weighting can take into account the objectives of incumbent private capital, the public, and social welfare and can achieve the "uniqueness" risk control objective.

Furthermore, we show that the barrier effect of initial investment depends on whether the contract takes into account the interests of the incumbent private capital. Under the optimal "uniqueness" contract of incumbent private capital, with the increase of the initial investment cost, the "uniqueness" risk probability shows a unilateral downward trend, showing a barrier effect. Under the optimal "uniqueness" contract of the public, the "uniqueness" risk probability does not change with the initial investment cost. Under the optimal "uniqueness" contract of social welfare, as the initial investment cost increases, the "uniqueness" risk probability presents a temporary increase in the initial stage. This shows that when the "uniqueness" contract clause fully considers the benefits of the incumbent private capital, the "uniqueness" risk has a negative co-relationship with the initial investment. To be specific, as the initial investment cost increases, the "uniqueness" risk probability appears downtrend. The more the "uniqueness" contract conforms to the interests of private capital, the stronger the correlation.

Our results indicate that an optimal "uniqueness" contract in practice is a compromise result of multiple objectives. Although social welfare is an important aspect that needs to be taken into account in the PPP projects, maximizing social welfare will harm the construction and operation of the projects. Project risk will be increased. The interests of the public and incumbent private capital are directly related to the project; they are more concerned about the signing of a “uniqueness” contract. They have more motivation to lobby the government. Therefore, the optimal “uniqueness” contract should simultaneously encourage the incumbent private capital to do a good job in the construction and operation of the project, protect the interests of the public, and improve the total social welfare by striving to make the cake bigger. The “uniqueness” contract programming model after weighting can take into account the objectives of all three stakeholders while improving the welfare of all parties, while effectively controlling the “uniqueness” risks, and enhance project sustainability.

Our work not only makes contributions to the academic literature but also to the policy debate on preventing competitive projects. Policymakers have concerns that the law preventing competitive projects may induce private capitals to set up anticompetitive practices as a protection against potential competitors in the PPP market. We find that the incumbent private capital signs the “uniqueness” contract with the government at the cost of lowering tolls. In the short term, this will increase the benefit of the public and improve the social welfare. But, in the long run, the “uniqueness” contract will prevent more efficient private capitals from entering the PPP market of transportation infrastructure. This will deter the improvement of social welfare. This is very valuable for the government to formulate policies on PPP projects of transportation infrastructure.

2. Literature Review

The “uniqueness” contract is essentially an exclusive contract. Aghion and Bolton [8] established the analysis framework of “one seller and one buyer” and found that current sellers facing the threat of entering the market are willing to sign an exclusive contract with the buyer, even if the contract does not completely prevent low-cost sellers from entering. In addition, when the seller has the information advantage of the possibility of entry, the duration of the exclusive contract can be used as a signal of the true possibility of entry. Rasmusen et al. [9] extended the model of Aghion and Bolton and found that when a monopolist needs multiple buyers to pay its fixed costs, the incumbent monopolist only needs to lock in some customers to effectively prevent potential competitors from entering the market. Bernheim and Whinston [10] found that exclusive transactions may not matter, anticompetitive, or improve efficiency depending on the setting. Bedre-Defolie and Biglaiser [11] studied the market of noncritical buyers and found that whether new entrants are more efficient or consumers’ default amounts are high or low, signing a “uniqueness” contract can effectively prevent potential competitors from entering. This study shows that prohibiting exclusive transactions will improve social welfare, unless incumbents and entrants have similar inefficiency. Kitamura et al. [12] incorporated Nash bargaining into the “one buyer and seller” model and proved that the low efficient existing suppliers can prevent effective suppliers from entering the society through exclusive contracts. Zhu and Berry [13] analyzed the wireless service market under the background of greater unlicensed access to spectrum and found that incumbents will always offer an exclusive contract to customers. The expected social welfare may increase or decrease depending on the demand and technology. Ulsaker [14] studied the downstream market where differentiated buyers compete with each other and proofed that the seller can prevent the entry of potential competitors, even when the entry would increase the industry profit.

To verify the theoretical expectations of exclusive dealings, some papers have conducted research using empirical data. Sass [15] analyzed the company-level data of nearly 400 beer distributors in the United States and investigated the impact of economies of scale and restricted promotional activities on exclusive dealings, as well as the impact of exclusive dealings on cost, pricing, and output. The results support the view that exclusive dealings can minimize conflicts between manufacturers and distributors and improve social welfare. Asker [16] assessed the impact of exclusive distribution arrangements on competition in the Chicago beer market in 1994, and found no anticompetitive effects. Ater [17] found exclusive contracts would reduce sales and did not comply with the efficiency principle based on the evidence of the exclusive dealings between burger restaurants and large shopping malls in Israeli market. As a result, shopping malls should use exclusive contracts for anticompetitive purposes. Nurski and Verboven [18] studied whether exclusive contracts between manufacturers and retailers constitute barriers to entry. Through modeling and empirical analysis using data from the European auto market, they found that there is no unilateral motive for maintaining monopoly transactions but collective motives for the entire industry. The widespread use of exclusive contracts in the entire automotive industry will not have anticompetitive effects. However, consumers will benefit from a ban of exclusive dealings, mainly because of increased space availability not because of fierce price competition.

In addition, there is some experimental literature studying exclusive contracts. Consistent with the expectations of theoretical research, these studies found that the consequences of signing exclusive contracts depend on the characteristics of the market environment, including communication, price discrimination [19], sequentiality and confidentiality [20], and the number of buyers [21].

Since the government can only increase the output of transportation services and social welfare by adding new transportation infrastructure in a state of high demand, the “uniqueness” risk event can only occur when the demand for transportation services is high. The high demand refers to the state in which consumers are willing to pay higher than the upper limit set by the government [22]. Due to the high demand, the monopoly nature of the transportation service market will change, and the market will become competitive and the excess return rate will attract potential competitors to enter the market [23]. This provides the government with an incentive to mobilize new entrants to build and operate a competitive transportation infrastructure.

In the private goods market, monopolists can maximize their profits by determining monopoly prices based on marginal revenue and marginal costs. Transportation services are quasi-public products, and the output of public services under monopoly pricing is suboptimal for social welfare. Therefore, to increase the output of transportation services and improve social welfare, the government will place restrictions on transportation pricing or private capital's return on capital, so that private capital only can obtain an "acceptable" project profit. This "acceptable" profit should be lower than the monopoly profit. This is the trigger for the "uniqueness" risk. If the rate of return obtained by the private capital by providing public services is too high, it will reduce the social welfare generated by the project and cause government dissatisfaction and public opposition. The direct consequence of government dissatisfaction and public opposition is the occurrence of "uniqueness" risk events. Anecdotal evidence from the previous project supports this inference: when the Hangzhou Bay Bridge project in China has been under construction for less than two years and the Shaoxing Hangzhou Bay Bridge in Shangyu which is only about 50 kilometers apart has been stepping up preparations. One of the reasons may be due to the local government dissatisfaction with the high rate of return on the Hangzhou Bay Bridge. In the case of Xinyuan Minjiang No. 4 Bridge in China, although the local government and private capital agreed on a return rate of 18% in the contract, the government later believed that the agreed return rate was too high. As a result, the local government built the third phase of the Second Ring Road. A large number of vehicles bypassed the toll station of Xinyuan Minjiang No. 4 Bridge. Private capital's income shrank sharply. At last, the government failed to fulfill its promise to compensate for insufficient private capital income. The project was hopeless to recover the investment cost [24]. In addition, the Shenzhen Wutong channel in China has also attracted dissatisfaction from the government and public opposition because of the high rate of return of private capital [25].

In PPP projects, there are three important stakeholders: private capital, government, and the public. Private capital is the provider of transportation services with the goal to maximize profits. The government is the purchaser of PPP services. During the tender period, the government negotiates with private capital on behalf of the public.

The government has established a principal-agent relationship with the public [26]. As an agent, the government should first satisfy the public interest. The government pursues public interest as its first goal, which maximizes consumer surplus [27]. In addition, as the government is the administrator of the society, the government needs to consider the impact of PPP projects on society. Social welfare should be one of the goals that the government should consider at the same time. The public is the principal in the PPP service procurement relationship, the end-user of transportation services, and one of the most important stakeholders of the project. The public's interest claims are achieved through the government. When the public's interest is harmed, the public will press the government to take actions to protect its rights through litigation, lobbying, and other means.

The "uniqueness" contract signed by the government and the incumbent private capital is based on the agreement of toll pricing and liquidated damage. The simplified expression of the "uniqueness" contract is $\{P, P_0\}$. P is the toll pricing agreed by both parties and P_0 is the liquidated damage parameter. Liquidated damage is the compensation that the government needs to pay to the incumbent private capital for the construction of a competitive transportation infrastructure for violating the "uniqueness" contract. Let it be V. The liquidated damage V is a function of P and P_0. Suppose that V is equal to the benefit to consumers that the toll pricing is reduced from P to new equilibrium price P_e due to the additional transportation service supply by competitive transportation infrastructure:

$$V = P_0 * \frac{(D(P) + D(P_e))}{2}. \tag{1}$$

3. Model

3.1. Model Assumptions

3.1.1. Pricing Constraints and Government Default Probability. Assume that private capital invests in the construction of transportation infrastructure in accordance with the PPP contract and the investment cost is compensated by charging users tolls. The maximum traffic volume in the concession period is 100 units, and the upper limit of the price that the public wishes to pay is 1. Let Q be the demand and P be the toll pricing, then the inverse demand function is

$$P = 1 - \frac{Q}{100}. \tag{2}$$

Let the incumbent private capital's service cost per standard traffic volume be C, the depreciation cost per standard traffic volume be α, and the operating expense per standard traffic volume be β, then $C = \alpha + \beta$. Suppose that the workload method is acceptable by GAAP (generally accepted accounting principles), and it is used to depreciate the transportation infrastructure assets. The unit depreciation amount α is a fixed value under the accounting method, and the unit operating expense β is generally considered to be stable. So, the unit cost C is also a fixed value.

Assume that the unit cost of private capital is $C = (1/2)$. Private capital faces the entry risk of potential competitors, and the unit cost C_e of potential competitors is unknown. Assume that the unit cost C_e of potential competitors follows the average distribution among {0, 1}. If a potential competitor decides to enter the market and construct and operate a new competitive transportation infrastructure, it will provide the public with transportation services of the same quality as the incumbent private capital. Since the incumbent infrastructure and the new competitive infrastructure are usually very close in space, coupled with the provision of transportation services of the same quality, it can be considered that the transportation services provided by the two are homogeneous. This makes the competition between incumbent private capital and the new entrant comply with the Bertrand model. In the Bertrand model, oligarchs producing homogeneous products will compete with price as the decision variable. Since the products of the two oligarchs are completely replaceable, the oligarch pricing the product lower will win the entire market. The one pricing higher will not get any profit at all. This is highly consistent with the transportation market investigated in this paper (in fact, when there are two highly competitive transportation infrastructures, the one with the lower toll price tends to occupy most of the traffic flow, for example, there are four bridges across the Yangtze River in Nanjing, China; only the Nanjing Yangtze River Bridge is free of charge; this has caused most drivers to choose the free but congested Nanjing Yangtze River Bridge; for other bridges, few vehicles are passing due to tolls). According to the Bertrand model, the incumbent private capital will compete with potential competitors in price at this time. The Bertrand equilibrium price P_e can be defined as

$$P_e = \max\left\{\frac{1}{2}, C_e\right\}, \tag{3}$$

If $C_e = (1/2)$, the entrant is unprofitable. Therefore, for potential competitors, only when their unit cost $C_e \leq (1/2)$, they will really decide to enter the market. Therefore, the probability that potential competitors agree to the government's offer and decide to enter the market and build a competitive transportation infrastructure is 50%. Let it be Φ:

$$\Phi = \Pr\left(C_e \leq \frac{1}{2}\right) = \frac{1}{2}. \tag{4}$$

If potential competitors do not enter the market, then the incumbent private capital will operate the existing PPP projects at a monopoly pricing. As shown in Figure 1, according to MR = MC, the equilibrium point C can be obtained, where the monopoly price is (3/4) and the equilibrium traffic volume is 25. The triangle ABC becomes the benefit obtained by consumers. The consumer surplus is (25/8) by calculating the area of this triangle. According to the principal-agent relationship, the government as the purchaser of PPP services is the direct agent of the public. Therefore, the direct benefit obtained by the government from the PPP projects should be measured by the consumer surplus obtained by the public through consuming transportation services, that is, the area of triangle ABC which is (25/8).

If a potential competitor enters the market, according to the Bertrand model, the market equilibrium price will be reduced to the unit cost of the incumbent private capital which is $P_e = C = (1/2)$. And, the entrant will get the traffic flow of the entire market. Substituting the equilibrium price (1/2) into the demand function, the equilibrium point is E. At this time, the marginal revenue is 0 and the equilibrium traffic flow increases from 25 to 50 units. The entrant will realize a profit $\pi = 50 * ((1/2) - C_e)$, and the incumbent

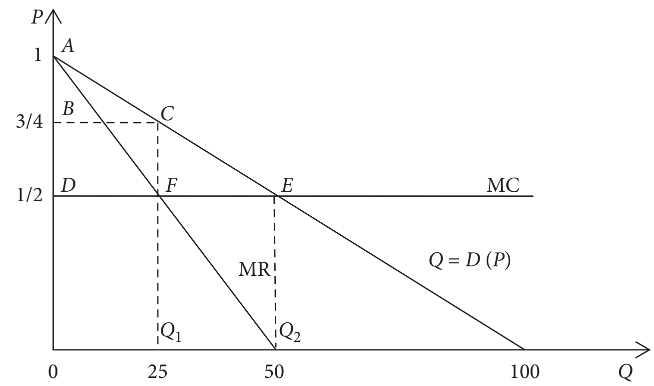

Figure 1: Pricing equilibrium.

private capital is unprofitable. The direct benefit obtained by the government can be obtained by calculating the area of the triangle ADE, which is (25/2).

Therefore, if the government does not sign a "uniqueness" contract with the incumbent private capital, the government's expected value of the direct benefit can be expressed in terms of expected consumer surplus:

$$S_{ge} = 1 - \Phi * \frac{25}{8} + \Phi * \frac{25}{2} = \frac{125}{16}. \tag{5}$$

We note that the government is motivated to invite new partners to construct a competitive transportation infrastructure project to obtain more social welfare. By having new competitors, the government's direct benefit (i.e., consumer surplus) has increased from (25/8) to (25/2). The profit of the incumbent private capital has dropped from (25/4) directly to 0. As shown in Figure 1, the total social welfare will be increased from ADFC to ADE. This is not a Pareto improvement process. The interests of incumbent private capital have been sacrificed. Advocates of PPP believe that the advantage of PPP is that it can achieve a win-win between the government and private capital, which obviously does not occur in this case. Incumbent private capital will withdraw from the PPP relationship as the project is not profitable. The government introducing new partners will also have a negative impact on other private capital to participate in PPP projects in the region in the future. Therefore, to control the "uniqueness" risk, incumbent private capital has the motivation to sign a "uniqueness" contract with the government to prevent potential competitors from entering the market in the future.

Assume that the government is risk-neutral, the calculation of the government's expected return S_{ge} indicates the bottom line of the government. Only by ensuring that the government can obtain at least $S_{ge} = (125/6)$ can it sign a "uniqueness" contract with the incumbent private capital, which stipulates the cost constraints of the "uniqueness" clause.

If the government does not default, the benefit (i.e., consumer surplus) becomes

$$S = 50 * (1 - P)^2. \tag{6}$$

If the government defaults, the entrant should at least provide the benefit of S to the public. Assume that the government only considers benefits, it will sign a "uniqueness" contract with the incumbent private capital when the benefits are higher than the expected benefit from the unsigned contract:

$$S \geq S_{ge}. \tag{7}$$

Substituting the formulas S and S_{ge} into the above equation, the constraint of price P can be obtained:

$$P \leq 1 - \frac{1}{4} * \sqrt{\frac{5}{2}} \approx 0.6047. \tag{8}$$

The government will be attracted to sign the contract only the market equilibrium price after the entry of potential competitors P_e meets the condition $P_e \leq P - P_0$. According to the Bertrand model, P_e can be directly derived as follows:

$$P_e = P - P_0. \tag{9}$$

Note that when the toll price reaches the equilibrium price P_e, it must also ensure that the profit of the entrant is non-negative:

$$P_e - C_e \geq 0. \tag{10}$$

The probability of potential competitors entering the market after signing the "uniqueness" contract is available (i.e., the government's probability of default). Let it be $\varnothing^*$, and the formula is expressed as follows:

$$\varnothing^* = \max\{0, P - P_0\}. \tag{11}$$

3.1.2. The Impact of the Initial Investment. Among the transportation infrastructure projects that adopt the PPP mode, some projects do not require an initial investment or require a less initial investment, such as ROT (Renovate-Operate-Transfer) projects, MC (Management Contract) projects, and other PPP projects that do not require construction or do not require large-scale transformation such as part of TOT (Transfer-Operate-Transfer) projects. During the concession period, no matter when private capital withdraws, there will be no fixed cost loss. However, for new construction projects or projects that require large-scale reconstruction and expansion expenditure using DBFO (Design-Build-Finance-Operate) mode, BOT (Build-Operate-Transfer) mode, etc., the private capital must assume the obligation to invest in the construction of the project infrastructure. Therefore, the project will incur huge initial investment costs, and the private capital will bear its risks. This initial investment cost can be gradually compensated by toll revenue during the concession period. Given the annual toll revenue, the higher the initial investment, the longer the compensation period.

If the government decides to build a new competitive transportation infrastructure before the initial investment cost of the incumbent project is fully compensated, the private capital will completely lose the market according to the Bertrand model. The remaining uncompensated part of the initial investment will be directly recognized as a loss. When the incumbent private capital and the government negotiate the terms of the "uniqueness" contract, the contingent losses caused by the uncompensated initial investment cost due to the government's default must be considered.

Therefore, it is necessary to measure the impact of uncompensated initial investment on profit. Assume that all initial investments cost of the project meets the infrastructure asset recognition and measurement principles specified by GAAP. As the project begins to operate, the fixed value of transportation infrastructure assets will gradually be transferred to the cost of transportation services in the form of depreciation. Correspondingly, with the consumption of infrastructure assets, physical performance will inevitably gradually decrease. In the transportation infrastructure PPP project, to ensure the quality of transportation services and fulfill the promise of infrastructure quality at the end of the concession period, private capital should maintain and repair infrastructure assets on a regular basis. With the gradual consumption of the initial asset value, the maintenance and repair expenses to keep the assets' physical status will gradually increase. We assume that all the maintenance and repair expenses provided by the incumbent private capital are to restore the infrastructure asset to its original physical status. Assume all maintenance and repair expenses are capitalized into the book value of infrastructure assets and the net book value of transportation infrastructure assets is always in a relatively stable status during the long concession period. Since the initial investment cost will be gradually transferred to the unit cost C in the form of depreciation expenses, the proportion of depreciation of initial investment in the unit cost C decreases as the accumulated traffic volume increases.

Regardless of operating expenses, suppose that the unit cost C consists of two parts: the depreciation of the initial investment cost (d) and the amortization of the maintenance and overhaul expenses (a). Both are a function of the actual traffic volume Q. The unit cost C can be expressed as the following formula:

$$C = d + a. \tag{12}$$

Let $d = f(Q)$. Assume that the unit cost C of the first standard traffic only contains the depreciation of the initial investment cost, that is, $f(0) = C$. When the accumulated traffic volume reaches Q^*, the value of the initial investment will be all depreciated, that is, $f(Q^*) = 0$. As the maintenance and overhaul expenses will increase with the use of transportation infrastructure, the proportion of the depreciation of the initial investment cost will reduce. Therefore, suppose the first derivative of the depreciation function is less than 0, that is, $\dot{f} < 0$. Correspondingly, when the accumulated traffic flow $Q \leq Q^*$, the amortization function of maintenance and overhaul expenses can be expressed as

$$a = C - f(Q). \tag{13}$$

When the accumulated traffic volume $Q > Q^*$, the initial investment cost has been completely depreciated. The unit cost C only includes maintenance and overhaul expenses.

Figure 2 depicts the unit cost C changing with the initial investment cost and maintenance and repair expenses when the actual traffic volume accumulates. Let the initial investment cost of the project be I or the area of COQ^* which can be obtained by integrating $f(Q)$ in $[0, Q^*]$:

$$I = \int_0^{Q^*} f(q)\mathrm{d}q. \tag{14}$$

Let the predicted traffic volume be Q_0. When the actual accumulated traffic volume $Q \leq Q^*$, the profit (or loss) π of the incumbent private capital is

$$\pi = \int_0^{Q} [P(Q_0) - C]\mathrm{d}q - \int_Q^{Q^*} f(q)\mathrm{d}q. \tag{15}$$

When the actual traffic volume $Q > Q^*$, the initial investment of the incumbent private capital has been fully depreciated. So, the asset-related expenditure only includes maintenance and overhaul expenses. These expenses are highly variable in nature, so the profit (or loss) π can be directly expressed as

$$\pi = \int_0^{Q} [P(Q_0) - C]\mathrm{d}Q. \tag{16}$$

If the actual traffic volume has not been accumulated to fully compensate the initial investment in transportation infrastructure, the incumbent private capital will lose the undepreciated part of the initial investment because of the potential competitor entering the existing market. If the actual traffic volume can fully compensate for the initial investment in transportation infrastructure, the incumbent private capital can withdraw without any loss regardless of whether a potential competitor entering the market.

Therefore, when the accumulated traffic volume is Q and the government chooses to entrust the construction of a new competitive transportation project (i.e., potential competitors choose to enter the market), the profit function of the incumbent private capital is segmented. Taking into account that it takes time to construct a new transportation infrastructure, there will be a certain buffer period before the new infrastructure is put into operation, during which the incumbent private capital can still receive toll income. Let the accumulated traffic flow occurring during the buffer period be Q' and the predicted traffic volume regardless of potential entry be Q_0, where Q_0 should meet the restriction condition $Q + Q' \leq Q_0$. Then, the profit function of the incumbent private capital can be expressed as

$$\pi = \begin{cases} \int_0^{Q+Q'} [P(Q_0) - C]\mathrm{d}q - \int_{Q+Q'}^{Q^*} f(q)\mathrm{d}q, & Q + Q' \leq Q^*, \\ \int_0^{Q+Q'} [P(Q_0) - C]\mathrm{d}q, & Q + Q' > Q^*. \end{cases} \tag{17}$$

3.1.3. The Expected Time of Government Default. For a "uniqueness" contract signed by the government and incumbent private capital, if the cost information is known by both incumbent private capital and potential competitors, the incumbent private capital will not sign the validity period

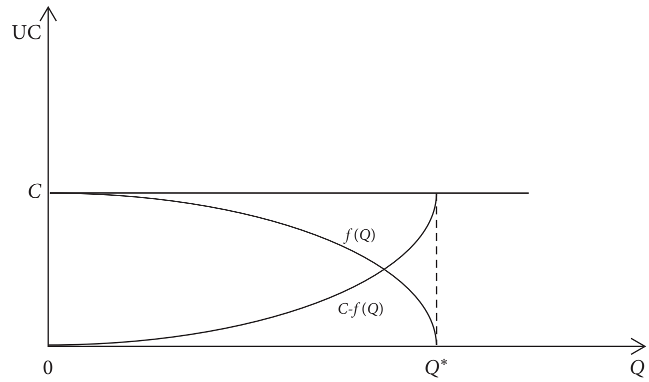

FIGURE 2: Distribution of unit cost (UC) composition.

of the "uniqueness" contract with the government. The "uniqueness" contract should be valid throughout the project period. The probability of potential competitors entering the market is the same at any time as private capital.

Assuming that the traffic volume is evenly distributed on the time axis and the probability of potential competitors entering the market during each period is known to be $\varnothing^*$, it can be derived that the probability of the potential competitor entering the market at time t obeys the exponential distribution with the parameter Q^* during the concession period, denoted as $T \sim E(\varnothing^*)$. The probability density function is written as

$$f(t) = \begin{cases} \varnothing^* e^{-\varnothing^* t}, & t > 0, \\ 0, & t \leq 0. \end{cases} \tag{18}$$

From the probability expectation formula, the expected time t at which the government will incorporate a potential competitor is $(1/\varnothing^*)$:

$$E(T) = \frac{1}{\varnothing^*}. \tag{19}$$

3.2. Model Specifications. Assuming that the concession period of the PPP project is N, the predicted traffic volume of each period is $(D(P)/N)$ and the traffic volume that has passed at the time $(1/\varnothing^*)$ is $(D(P)/N\varnothing^*)$. Assuming that the construction period of a new transportation infrastructure is n, the new project is completed and operated by the entrant at the time $((1/\varnothing^*) + n)$. The cumulated traffic volume will be $((1/\varnothing^*) + n) * (D(P)/N)$. Let $((1/\varnothing^*) + n) * (D(P)/N)$ be Q. Let the expected return of the incumbent private capital be Z. It can be expressed in the form of the following segmented function:

$$Z = \begin{cases} (P - C) * Q + V * \left(1 - \frac{Q}{D(P)}\right) - \int_Q^{Q^*} f(q)\mathrm{d}q, & Q \leq Q^*, \\ (P - C) * Q + V * \left(1 - \frac{Q}{D(P)}\right), & Q > Q^*. \end{cases} \tag{20}$$

Let the government's direct benefit be S, that is,

$$S = \frac{(1-P)*Q}{2} * + \frac{D(P_e)*(1-P_e)}{2} * \left(1 - \frac{Q}{D(p)}\right). \tag{21}$$

Let the total social welfare generated by the project is M. It can be expressed as

$$M = \begin{cases} \dfrac{(P-2C+1)*Q}{2} + \dfrac{\{P_e - 2C_e + 1\} * D(P_e) * (1-(Q/D(p)))}{2} - V * \left(1 - \dfrac{Q}{D(P)}\right) - \displaystyle\int_Q^{Q^*} f(q)\mathrm{d}q, & Q \le Q^*, \\ \dfrac{(P-2C+1)*Q}{2} + \dfrac{\{P_e - 2C_e + 1\} * D(P_e) * (1-(Q/D(p)))}{2} - V * \left(1 - \dfrac{Q}{D(P)}\right), & Q > Q^*. \end{cases} \tag{22}$$

In the social welfare objective function M, C_e is the conditional probability expectation of the unit cost of the new competitor, taking $C_e = 0.25$. To get the optimal "uniqueness" contract, three nonlinear programming models are specified for incumbent private capital, government, and social welfare.

3.2.1. Optimal "Uniqueness" Contract Model for Maximizing the Profit of Incumbent Private Capital. To ensure the intuitiveness and comprehensibility of the solutions, some additional settings for the parameters need to be specified. First, let N be the same as the upper limit of the project operation period prescribed by law. For example, the Regulation on the Administration of Toll Highway issued by China's Ministry of Transport in 2018 stipulates that "The operating period of toll highway projects is determined in accordance with the principle of recovering investment and reasonable returns, and generally shall not exceed 30 years" [28]. We make N to be 30, i.e., $N = 30$. Second, let the construction period of the project n be 3 for generality. Therefore, the expected time of the government default should be less than the 27th year. Once the contract is successfully fulfilled to the 27th year, the incumbent private capital will lock in all revenue. Therefore, the constraints $0 \le P_0 \le P - (1/27)$ can be set. Finally, let the depreciation function f of project assets be a linear function, and its expression is

$$f(q) = C - \frac{C}{Q^*} * q = \frac{1}{2}\left(1 - \frac{q}{Q^*}\right). \tag{23}$$

Substituting the above formula into the integral function of the undepreciated initial investment cost of incumbent private capital, we get:

$$\int_Q^{Q^*} f(q)\mathrm{d}q = \int_Q^{Q^*} \frac{1}{2}\left(1 - \frac{q}{Q^*}\right)\mathrm{d}q = \frac{1}{4} * \left(Q^* - 2Q + \frac{Q^2}{Q^*}\right). \tag{24}$$

Based on the above, a nonlinear programming model for the optimal "uniqueness" contract of incumbent private capital can be specified:

$$\max Z = \begin{cases} (P-C)*Q + V * \left(1 - \dfrac{Q}{D(P)}\right) - \displaystyle\int_Q^{Q^*} f(q)\mathrm{d}q, & Q \le Q^*, \\ (P-C)*Q + V * \left(1 - \dfrac{Q}{D(P)}\right), & Q > Q^*. \end{cases} \tag{25}$$

$$\begin{aligned} \text{S.T. } 0.5 \le P \le 1 - \frac{1}{4} * \sqrt{\frac{5}{2}}, \\ 0 \le P_0 \le P - \frac{1}{27}, \\ \varnothing^* = \max\{0, P - P_0\}, \\ \int_Q^{Q^*} f(q)dq = \frac{1}{4} * \left(Q^* - 2Q + \frac{Q^2}{Q^*}\right), \\ Q = \left(\frac{1}{\varnothing^*} + n\right) * \frac{D(P)}{N}, \\ N = 30, \\ n = 3, \\ P_e = P - P_0, \\ D(P) = 100 * (1-P), \\ V = P_0 * \frac{(D(P) + D(P_e))}{2}, \\ C = 0.5. \end{aligned} \tag{26}$$

3.2.2. Optimal "Uniqueness" Contract Model for Maximizing the Consumer Surplus. Consumer surplus represents the government's direct benefit, and the constraints of the function remain unchanged. To get the optimal "uniqueness" contract of maximizing consumer surplus, the nonlinear programming model can be specified as

$$\max S = \frac{(1-P) * Q}{2} * + \frac{D(P_e) * (1-P_e)}{2} * \left(1 - \frac{Q}{D(p)}\right). \tag{27}$$

3.2.3. Optimal "Uniqueness" Contract Model for Maximizing the Total Social Welfare. To get the optimal "uniqueness" contract of maximizing total social welfare, the nonlinear programming model can be specified as

$$\max M = \begin{cases} \dfrac{(P-2C+1) * Q}{2} + \dfrac{\{P_e - 2C_e + 1\} * D(P_e) * (1-(Q/D(p)))}{2} - V * \left(1 - \dfrac{Q}{D(P)}\right) - \displaystyle\int_Q^{Q^*} f(q)\mathrm{d}q, & Q \le Q^*, \\ \dfrac{(P-2C+1) * Q}{2} + \dfrac{\{P_e - 2C_e + 1\} * D(P_e) * (1-(Q/D(p)))}{2} - V * \left(1 - \dfrac{Q}{D(P)}\right), & Q > Q^*. \end{cases} \tag{28}$$

To make the programming function meaningful, we need to ensure that the incumbent private capital can at least obtain the expected benefit of not signing the "uniqueness" contract, which is Z_b. Because there is the initial investment cost of the project in this model, the guaranteed return of incumbent private capital should be the expected profit with the no contract minus the undepreciated initial investment. Z_b should be a function of Q^*. Therefore, when solving $\max M$ for each Q^* value, the restriction condition $Z \ge Z_b$ should be added after the conditions.

4. Model Simulation

4.1. Optimal Contract Simulation of Incumbent Private Capital. From the integral formula of depreciation, we note that Q^* has a positive correlation with the initial investment cost I. The larger the Q^*, the greater the initial investment cost I. Table 1 lists the simulation results of the optimal contract of the incumbent private capital under the different values of the parameter Q^*.

The explanation of the parameters in the tables is shown below:

P: optimal price given Q^*

P_0: optimal liquidated damage parameter given Q^*

Q^*: the accumulated traffic flow where it just happens that the initial investment cost is fully depreciated

Q: the accumulated traffic flow before the new entry

$E(T)$: the time when the government decides to default

$\varnothing^*$: the probability of the government default

$\max Z$: the expected benefit of the incumbent private capital in the optimal contract of incumbent private capital

$\max S$: the expected consumer surplus in the optimal contract of the public

$\max M$: the expected social welfare in the optimal contract of social welfare

Z_b: the least obtained benefit by the incumbent private capital with not signing the "uniqueness" contract

Z: the expected benefit of the incumbent private capital in the optimal contract not pursuing for maximum profit

S: the expected consumer surplus in the optimal contract not pursuing for maximum consumer surplus

M: the expected social welfare in the optimal contract not pursuing for maximum social welfare

Table 1 shows that the optimal solution for toll price is on the upper limit 0.6047. When $Q^* \le 14$, the initial investment cost I has no effect on the optimal solution of the "uniqueness" contract. The optimal solution is $\{0.6047, 0.4791\}$. When $Q^* \ge 15$, with the increase of the initial investment cost I (I increases with the increase of Q^*), the profit of the incumbent private capital shows a marginal diminishing trend, and the liquidated damages parameter P_0 and the expected default time $E(T)$ show a marginal increase trend, although the change is small. The actual liquidated damage parameter P_0 is in the interval (0.4791, 0.5121). The expected time $E(T)$ of government default remains unchanged when $Q^* \le 14$. When $Q^* \ge 15$, $E(T)$ increases monotonically with Q^* but not sensitive. In general, the optimal "uniqueness" contract solution and expected default time are not sensitive to the initial investment cost. However, the project profit is sensitive to the initial investment cost. As the initial investment cost increases, the maximum expected profit of the incumbent private capital is rapidly diminishing.

When $Q^* = 113$, the profit of incumbent private capital has reached the lower limit. If the initial investment cost increases further, the incumbent private capital will enter the loss range, and the user-pay model will not be feasible. This means that, given the traffic demand, the higher the initial investment cost, the lower the expected return of the incumbent private capital. Therefore, due to demand restrictions, not all transportation infrastructure projects can compensate its costs only by charging tolls. If the project exceeds a certain size, the government needs to subsidize the project to ensure private capital can get enough revenue to compensate for the costs.

Table 1: Optimal solutions for the "uniqueness" contract of incumbent private capital.

P	P_0	Q	Q^*	$\max Z$	$E(T)$	$\varnothing^*$	Z_b
0.6047	0.4791	14.4411	0	20.8148	7.9600	0.1256	1.0417
0.6047	0.4791	14.4411	5	20.8148	7.9600	0.1256	1.0069
0.6047	0.4791	14.4411	10	20.8148	7.9600	0.1256	0.1910
0.6047	0.4791	14.4411	14	20.8148	7.9600	0.1256	−0.6850
0.6047	0.4802	14.5334	15	20.8105	8.0300	0.1245	−0.9144
0.6047	0.4877	15.2140	20	20.4808	8.5466	0.1170	−2.0920
0.6047	0.4927	15.7161	25	19.8282	8.9276	0.1120	−3.2986
0.6047	0.4963	16.1038	30	18.9999	9.2220	0.1084	−4.5197
0.6047	0.4990	16.4143	35	18.0645	9.4576	0.1057	−5.7490
0.6047	0.5011	16.6694	40	17.0588	9.6511	0.1036	−6.9835
0.6047	0.5028	16.8830	45	16.0042	9.8133	0.1019	−8.2215
0.6047	0.5042	17.0650	50	14.9143	9.9514	0.1005	−9.4618
0.6047	0.5112	18.0397	100	3.1826	10.6912	0.0935	−21.9184
0.6047	0.5121	18.17	113	0.0269	10.7923	0.0927	−25.1634

From Table 1, we observe that the probability of "uniqueness" risk is significantly reduced by signing the "uniqueness" contract. If the "uniqueness" contract is not signed, the probability of "uniqueness" risk is 50%, and the expected time of starting to build a competitive transportation infrastructure is the end of the year 2. The construction will be completed at the end of year 5. If the "uniqueness" contract is signed, the probability of the government default is reduced to between 9.27% and 12.56%. The expected time of the government default is between the end of year 8 and the fourth quarter of the year 11. And, the time when the competitors actually enter the market is approximately between the end of year 11 and the fourth quarter of year 14. Table 1 also shows that the profit of incumbent private capital after signing the "uniqueness" contract is significantly higher than the benefits of not signing the contract.

The simulation solution indicates that the incumbent private capital transfers part of the benefits in exchange for the signing of the "uniqueness" contract. The price of the contract is lower than the monopoly price $P = 0.75$. The lower price will cause the incumbent private capital to lose part of the profit and increase the output of transportation services, and the public will benefit from it. In addition, Table 1 reports the change in the social welfare of the project under the optimal "uniqueness" contract of private capital. M is the social welfare under the "uniqueness" contract, and M_0 is the social welfare without signing the contract. Due to the negative impact of payment of liquidated damages which is $V * (1 - (Q/D(P)))$, M is significantly smaller than M_0, which means signing the "uniqueness" contract has a negative effect on social welfare.

4.2. Optimal Contract Simulation for the Public. Table 2 lists the simulation results of the optimal solution of the "uniqueness" contract with the maximum consumer surplus. The optimal toll price of the maximizing consumer surplus is $P = 0.5$, which is the same as the unit cost of incumbent private capital. The optimal contract solution for the public is {0.5, 0.3753}, and the consumer surplus is the largest. This contract is not relevant with the initial investment, and the maximum value of consumer surplus is $\max S = 28.8282$. The probability of government default under this contract is about 12.47%. The expected time of government default $E(T)$ is the beginning of year 9, and potential competitors enter the market is about the beginning of the year 12. Under this contract, the incumbent private capital can only compensate for its cost from toll revenue. The liquidated damage is the only source of profit with greater uncertainty, which can only be counted as contingent profit.

Table 2 shows that as a function of the initial investment cost, the expected return of incumbent private capital exhibits the same trend of change as the expected return under the optimal contract of incumbent private capital. When $Q^* \leq 18$, the expected return of incumbent private capital $Z = 16.3282$, which remains unchanged. When $Q^* \geq 19$, the expected return of incumbent private capital presents a marginal diminishing trend as the initial investment cost increases. $Q^* = 98$ is the upper limit of the initial investment cost. If it exceeds the threshold, the project will incur losses. The incumbent private capital will find it difficult to maintain the project operation, and the risk of project failure will greatly increase.

Under the optimal "uniqueness" contract of the public, the government can obtain the maximum direct benefit by maximizing consumer surplus. Under this contract, the incumbent private capital compensates its unit cost by operating transportation infrastructure. But, whether there is net profit depends on the probability of government default and the differences between the liquidated damages and the undepreciated part of the initial investment cost, which are highly uncertain. In addition, consistent with the "uniqueness" contract of incumbent private capital, the "uniqueness" contract of the public that seeks to maximize consumer surplus also has a negative impact on social welfare, as shown in Table 2.

4.3. Optimal Contract Simulation of Social Welfare. As shown in Table 3, with the goal to maximize social welfare, the "uniqueness" contract tends to limit the toll price to the incumbent private capital's unit cost, which is $P = 0.5$. But,

Table 2: Optimal solutions for the "uniqueness" contract of the public.

P	P_0	Q	Q^*	Z	$E(T)$	$\varnothing^*$	$\max S$
0.5	0.3753	18.3706	0	16.3282	8.0224	0.1247	28.8282
0.5	0.3753	18.3706	5	16.3282	8.0224	0.1247	28.8282
0.5	0.3753	18.3706	10	16.3282	8.0224	0.1247	28.8282
0.5	0.3753	18.3706	18	16.3282	8.0224	0.1247	28.8282
0.5	0.3753	18.3706	19	16.3230	8.0224	0.1247	28.8282
0.5	0.3753	18.3706	20	16.2950	8.0224	0.1247	28.8282
0.5	0.3753	18.3706	25	15.8887	8.0224	0.1247	28.8282
0.5	0.3753	18.3706	30	15.2012	8.0224	0.1247	28.8282
0.5	0.3753	18.3706	35	14.3529	8.0224	0.1247	28.8282
0.5	0.3753	18.3706	40	13.4043	8.0224	0.1247	28.8282
0.5	0.3753	18.3706	45	12.3886	8.0224	0.1247	28.8282
0.5	0.3753	18.3706	50	11.3261	8.0224	0.1247	28.8282
0.5	0.3753	18.3706	98	0.1526	8.0224	0.1247	28.8282

the liquidated damage is extremely low. The maximum value of the parameter P_0 is only about 0.0245. As the initial investment cost increases, P_0 decreases monotonically. It shows that this contract fails to effectively reduce the probability of government default, which is about 47.55% to 50%. The expected time $E(T)$ of government default is between the end of year 2 to the beginning of year 3. The window period is very narrow. When $Q^* = 12$, P_0 drops to the value of 0, which means that, while the price is restricted, the government does not bear any penalty for breach of contract. Such a contract will not be accepted by the private capital. The return of incumbent private capital Z, which gradually decreases with the increase of the initial investment cost, reaches the minimum positive value at $Q^* = 10$. Then, the project will cease to attract private capital with initial investment further increasing. This means that if the ultimate objective is to maximize social welfare, the user-pay model has its own limitations. A low expected rate of return is difficult to attract high-quality private capital to participate in the PPP project. Unless the project demand is high, the user-pay model is not feasible for large-scale transportation infrastructure projects.

In addition, under the optimal contract of social welfare, consumer surplus is suboptimal, with a value between 12.5 and 13.54, which is significantly lower than the consumer surplus under the optimal contracts of the public and the incumbent private capital. As for the optimal solution value of the social welfares of the project, as Q^* increases, it increases at the beginning and then decreases. When $Q^* = 107$, social welfare reaches the lowest positive value. If the initial investment increases further, no positive social welfare will be produced.

The results in Table 3 show that, with the goal to maximize social welfare, signing a "uniqueness" contract can increase social welfare in the interval $Q^* \geq 5$. However, the contract is only feasible for transportation infrastructure PPP projects that do not require an initial investment or low initial investment and cannot effectively motivate incumbent private capital. The expected consumer surplus is also squeezed out by potential competitors. Therefore, both the incumbent private capital and the public have incentives to lobby the government to increase their own benefits.

5. Discussion

The simulation results show that the goal to maximize incumbent private capital profit, consumer surplus, and total social welfare at the same time is not attainable. Although the PPP contract is entered between the government and the incumbent private capital, it involves the interests of all stakeholders. The government not only needs to consider the interests of the public directly but also needs to take into account the social welfares generated by the project. Therefore, the final PPP "uniqueness" contract must be the result of a trade-off between the goals of stakeholders.

Based on the participation and influence of each stakeholder in contract negotiations, the importance of the individual party's goal can be ranked. First, the public is the direct beneficiary. The public's interests should be guaranteed so that the public can obtain benefit from the use of transportation infrastructure. Second, to ensure the feasibility of the PPP project, the government should attract qualified private capital to participate in the project, encourage private capital to improve the quality of transportation services, and guarantee that the PPP contract can be effectively fulfilled during the whole concession period. So, it is necessary for the government to provide the opportunity that the private capital can make profit. Finally, it is essential to take into account other potential stakeholders of the project by making sure that the project can enhance total social welfare.

According to the importance of these goals, we establish a multiobjective programming model to get the optimal "uniqueness" contract by weighting function S of the public, function Z of the incumbent private capital, and function M of the total social welfare. Assuming that S, Z, and M are assigned a weight of 1.5, 1.5, and 1, respectively, a new programming function T is established (we weigh S, Z, and M here to discuss the change of the optimal contract solution under multiobjectives; 1.5, 1.5, and 1 are just a special case of them; objectives of profit, consumer surplus, and social welfare for different projects are different):

$$\max T = 1.5S + 1.5Z + M. \quad (29)$$

Table 3: Optimal solutions for the "uniqueness" contract of social welfare.

P	P_0	Q	Q^*	Z	Z_b	$E(T)$	$\varnothing^*$	S	max M
0.5	0.0245	8.5051	0	1.0417	1.0417	2.1031	0.4755	13.5417	22.3155
0.5	0.0245	8.5051	4	1.0417	1.0417	2.1031	0.4755	13.5417	22.3155
0.5	0.0237	8.4992	5	1.0069	1.0069	2.0995	0.4763	13.5069	22.3368
0.5	0.0138	8.4281	8	0.5825	0.5825	2.0569	0.4862	13.0825	22.5898
0.5	0.0096	8.3985	9	0.3927	0.3927	2.0391	0.4904	12.9028	22.6832
0.5	0.0061	8.3748	10	0.1910	0.1910	2.0249	0.4939	12.7570	22.7094
0.5	0.0033	8.3557	11	−0.0196	−0.0196	2.0134	0.4967	12.6393	22.6818
0.5	0	8.3333	20	−1.7014	−2.0920	2	0.5	12.5	21.2153
0.5	0	8.3333	25	−2.7778	−3.2986	2	0.5	12.5	20.1389
0.5	0	8.3333	30	−3.9120	−4.5197	2	0.5	12.5	19.0046
0.5	0	8.3333	35	−5.0794	−5.7490	2	0.5	12.5	17.8373
0.5	0	8.3333	40	−6.2674	−6.9835	2	0.5	12.5	16.6493
0.5	0	8.3333	45	−7.4691	−8.2215	2	0.5	12.5	15.4475
0.5	0	8.3333	50	−8.6806	−9.4618	2	0.5	12.5	14.2361
0.5	0	8.3333	100	−21.0069	−21.9184	2	0.5	12.5	1.9097
0.5	0	8.3333	107	−22.7456	−23.6656	2	0.5	12.5	0.1711

Table 4 lists the simulation results of the "uniqueness" contract programming function under different initial investment costs. Among them, each of the optimal solutions is the result of the compromise of all parties involved in the project. The optimal solutions take into account of the interests of the social welfares, the public, and the incumbent private capital.

Table 4 shows that, when the projects have different scales, the impact of the initial investment cost on the optimal solution of the "uniqueness" contract will gradually change. When the initial investment cost is small ($Q^* \leq 13$), the initial investment cost has no significant impact on the optimal solution of the "uniqueness" contract of the project. In this model, the price P can be set on the upper limit which is $P = 0.6047$ when $Q^* \leq 14$. When the project scale increases and the initial investment cost further increases ($Q^* \geq 15$), the price P will gradually decrease to the unit cost, which is $P = 0.5$. The liquidated damages parameter P_0 changes with Q^* which first remains unchanged, then increases, and finally gradually decreases. The gap between the pricing P and the liquidated damage parameter P_0 has gradually reduced. So, the government default probability Q^* gradually decreases with the increase of the initial investment cost. The expected default time $E(T)$ is at the end of year 7. As the initial investment cost increases, it is expected that the default time point can be delayed up to the beginning of the third quarter of the year 10.

As the initial investment cost increases ($Q^* \geq 14$), the incumbent private capital return Z under the optimal "uniqueness" contract shows a monotonous downward trend, while the social welfare M shows a downward trend after it first increases. When $Q^* = 53$, the social welfare M reduces to the lowest positive value. Therefore, when the traffic demand remains unchanged, $Q^* = 53$ is the critical point for the implementation of the traffic PPP project of the user-pay model. We note that the optimal contract after linear weighting can support the development of large-scale transportation infrastructure projects.

6. Conclusions

We model whether the incumbent private capital and the government have an optimal "uniqueness" contract in the PPP market by considering the impact of initial investment cost. We construct four models and simulate the optimal "uniqueness" contract. The extent to which such a contract reduces the probability of "uniqueness" risk depends on the equilibrium relation between the interests of private capital and the public. We find that the effect of "uniqueness" risk depends on the contract setting. The optimal contract of incumbent private capital and the optimal contract of the public can significantly reduce the probability of government default, while the optimal contract of social welfare is weakly related to government default. Among them, the optimal contract of incumbent private capital reduces the risk probability and increases the private capital return the most significantly, followed by the optimal contract of the public. The optimal contract after weighting can take into account the objectives of incumbent private capital, the public, and social welfare and can achieve the "uniqueness" risk control objective.

Furthermore, we show that the barrier effect of initial investment depends on whether the contract takes into account the interests of the incumbent private capital. Under the optimal "uniqueness" contract of incumbent private capital, with the increase of the initial investment cost, the "uniqueness" risk probability shows a unilateral downward trend, showing a barrier effect. Under the optimal "uniqueness" contract of the public, the probability of "uniqueness" risk does not change with the initial investment cost. Under the optimal "uniqueness" contract of social welfare, as the initial investment cost increases, the probability of "uniqueness" risk increase to the maximum 0.5 and then remains unchanged. These show that, when the clause of "uniqueness" contract fully considers the benefits of the incumbent private capital, the "uniqueness" risk has a negative co-relationship with the initial investment. The

Table 4: Optimal solutions for the "uniqueness" contract after weighting.

P	P_0	Q	Q^*	Z	Z_b	$E(T)$	$\varnothing^*$	S	M	$\max T$
0.6047	0.4605	13.0892	0	20.6378	1.0417	6.9340	0.1442	27.0797	3.1281	74.70436
0.6047	0.4605	13.0892	5	20.6378	1.0069	6.9340	0.1442	27.0797	3.1281	74.7044
0.6047	0.4605	13.0892	10	20.6378	0.1910	6.9340	0.1442	27.0797	3.1281	74.7044
0.6047	0.4605	13.0892	13	20.6378	−0.4589	6.9340	0.1442	27.0797	3.1281	74.7044
0.6047	0.4628	13.2341	14	20.6653	−0.6850	7.0440	0.1420	27.1024	3.0216	74.6732
0.5552	0.4231	15.6678	20	18.6172	−2.0920	7.5680	0.1321	27.8776	3.8961	73.6383
0.5188	0.3930	17.5703	25	16.6891	−3.2986	7.9530	0.1257	28.4916	4.4601	72.2312
0.5005	0.3781	18.6014	28	15.5613	−4.0300	8.1720	0.1224	28.8157	4.6657	71.2312
0.5	0.3787	18.7445	29	15.4144	−4.2747	8.2467	0.1213	28.8211	4.5215	70.8748
0.5	0.3798	18.8655	30	15.2827	−4.5197	8.3193	0.1202	28.8158	4.3560	70.5038
0.5	0.3844	19.4139	35	14.5400	−5.7490	8.6484	0.1156	28.7752	3.4955	68.4684
0.5	0.3880	19.8854	40	13.6911	−6.9835	8.9313	0.1120	28.7198	2.5885	66.2049
0.5	0.3910	20.2972	45	12.7672	−8.2215	9.1783	0.1090	28.6573	1.644	63.7804
0.5	0.3936	20.6609	50	11.7880	−9.4618	9.3965	0.1064	28.5920	0.6678	61.2378
0.5	0.3949	20.8589	53	11.1797	−10.2069	9.5154	0.1051	28.5526	0.0692	59.6677

more the "uniqueness" contract conforms to the interests of private capital, the stronger the correlation.

The simulation results show that the achievement of the optimal "uniqueness" contract is essentially the result of a compromise between the private capital, the public, and social welfare. Although the social welfare is an important issue that needs to be taken into account in PPP projects, maximizing the social welfare will do harm to the construction and operation of the projects. The project risk will be increased. The interests of the public and incumbent private capital are directly related to the project; they are more concerned about the signing of "uniqueness" contract. They have more motivations to lobby the government. Therefore, the optimal "uniqueness" contract should simultaneously encourage the incumbent private capital to do a good job in the construction and operation of the project, protect the interests of the public, and improve the total social welfare by striving to make the cake bigger. The optimal solution after weighting proves that signing the "uniqueness" contract can effectively control the "uniqueness" risk and increase transportation service output of incumbent infrastructure but not enhancing total social welfare. Our findings provide a guide for the two parties of the contract to make their own optimal decisions.

Finally, we show that entering a "uniqueness" contract is not good for social welfare. Consistent with Ater [17] and Nurski and Verboven [18], the incumbent private capital and the government sign the "uniqueness" contract mainly for anticompetitive purposes. Unless the clause considers the improvement of social welfare, the signed "uniqueness" contract is associated with social welfare losses. The government has an incentive to sign a "uniqueness" contract to attract more private capital to participate in the construction of the region. The extent to which this effect can offset the loss of social welfare is not discussed in this article, and it is an important question for further research. In the future, current research can also be extended to consider issues like sustainability [29] and corporate social responsibility [30].

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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