Complexity

Complex System Models and Their Application in Industrial Cluster and Innovation Systems

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Editorial

Complex System Models and Their Application in Industrial Cluster and Innovation Systems

Su Yi,[1] **Yang Zaoli**,[2] **Xie Xuemei**,[3] **and Garg Harish**[4]

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Industrial clusters and innovation systems are complex systems composed of heterogeneous subjects. They present complex characteristics such as self-organization, nonlinearity, emergence, and adaptability [1–3]. This makes it impossible for traditional reductionist ideas to study and explore them in depth. The traditional linear approach cannot explain the dynamic interaction behavior of multiple subjects in complex systems. In the research of industrial clusters and innovation systems, the linear idea of reductionism becomes more and more powerless as the research dimension increases and the research difficulty gradually increases. With the effective application of complex systems theory in the field of natural science research, more and more scholars also consider it as an effective tool in the field of innovation management research [4–6].

With the development of system theory, new theories such as quantum theory, synergy theory, dissipative structure theory, and catastrophe theory have opened new doors for us to study socially complex systems. They can address complex features that cannot be explained by reductionism, especially the dynamic interaction behavior of subjects in industrial clusters and innovation systems. Quantum theory can explain the breakthrough innovation of knowledge in innovation systems, the leap of technology trajectory. Based on the nonlinear model in the field of physics and chemistry, it can study how some self-organized systems break through the threshold and evolve from disorder to order. Mutation theory can explain the reasons for the sudden nature change of innovation systems [7–10]. Therefore, the application of complex system models to solve problems in innovation management research is conducive to in-depth research in social sciences and promotes the development of innovation management.

The traditional reductionism is no longer applicable to the study of socially complex systems. It is imperative to propose new theories and new methods. Based on the theory of complex systems, the research model of social complex systems can effectively describe the complex characteristics of industrial clusters and innovation systems through intelligent technology, mathematical models, physical models, and chemical models. It is helpful to explain the complex environment in the innovation management research field and reveal its essence and law. Therefore, the application of complex system models to solve the problems in innovation management research is conducive to the in-depth study of social science and promotes the development of innovation management.

1. Model Extension and Algorithm Optimization

Y. Wei et al. optimized the traditional PageRank algorithm by incorporating a text similarity approach (TSA) into their study and validated the algorithm using Chinese environmental health standards. F. Zhang et al. optimized an industrial product service system. They incorporated affinity propagation (AP), quality function development (QFD), and axiomatic design (AD) to solve many difficulties such as uncertain customer requirements, subjective experience design, and long debugging time. J. Liu et al. examined university ranking from the perspective of complex systems and proposed an innovative university ranking method. L. Zhang and W. Chen used complex network theory as the basis to construct a multilayer knowledge sharing network environment and proposed a knowledge sharing model in the complex network environment. H. Jiang et al. expanded their research, reconstructed the echo model, and extended the theory of complex adaptive systems.

2. Industry Cluster Innovation and Regional Innovation

Y. Zhao et al. explored how R&D alliance networks relate to knowledge attributes and organizational innovation capabilities based on a multilevel network approach. They studied 86 groups in a network of R&D alliances in five high-tech industries in China and found that centrality in R&D alliance networks plays a limited role in the relationship between knowledge attributes and organizational innovation capacity. B. Zhang et al. explored the upgrading process of China's automobile industry and provided a scientific basis for industrial policy adjustment and industrial structure optimization. F. Zhou and B. Zhang detected and visualized the Beijing-Tianjin-Hebei city cluster innovation community based on a patent cooperation network and concluded that Beijing-Tianjin-Hebei collaborative innovation should strengthen the cooperation between Tianjin and Hebei. Y. Su constructs a tripartite evolutionary game model with government, parent company, and subsidiary to study reverse knowledge transfer in cross-border M&A of Chinese high-tech industries.

3. Multicriteria Decision Making

A new CNPI team member selection model was constructed by J. Su et al. using fuzzy sets and social network analysis. They verified its validity with real cases. Y. Zhang et al. proposed an evolutionary game model from the perspective of behavioral deviance. It can provide help for corporate strategy selection.

4. Corporate Innovation and Growth

X. Yu et al. found that digital companies exhibit discontinuous growth as they move from existing core businesses to new ones. This growth pattern often ends in failure. This is mainly because companies devote most of their resources to maintaining the value network of their existing core business, which eventually leads to a "lock-in" effect. They use fractal theory to eliminate the threats posed by this phenomenon and provide effective countermeasures and suggestions for business growth.

5. Innovation Ecosystem

Y. Chen et al. discuss how to build a good innovation ecosystem, using the example of a representative Chinese artificial intelligence company, KDDI. W. Yang et al. analyzed the digital transformation of the innovation ecosystem in the era of digital economy.

The above studies make effective use of complex system models. These studies can provide a more scientific, accurate, and comprehensive response to the internal interaction behaviors of social complex systems and provide contributions to the study of social complex systems.

Conflicts of Interest

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

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We would like to thank all the authors who have made valuable contributions to this special issue, who have been of great help in the application of complex systems models in the social sciences. We would also like to thank all the reviewers for their efforts in providing valuable suggestions. We hope that this special issue will provide valuable scholarly perspectives and facts for complex science and social science and provide a good foundation for further scholarly research in this direction.

Yi Su
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Garg Harish

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Research Article

Interorganizational Knowledge Networks, R&D Alliance Networks, and Innovation Capability: A Multilevel Network Perspective

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R&D alliances and knowledge networks are vital to the innovation process. Based on the multilevel network approach, our study comprehensively investigates several knowledge attributes of interorganizational knowledge networks and explores how R&D alliance networks are relevant for the relationship between knowledge attributes and organizational innovation capability. Samples in our research include 86 cliques from 2010 to 2015 in five Chinese high-tech industries' R&D alliance networks. Results from the negative binomial regression model show that different knowledge attributes show a distinct effect on organizational innovation capability, including linear relationship, inverted U-shaped curve relationship, and inverted S-shaped curve relationship. Besides, our results identify that the central position within R&D alliance networks plays a limited role in the relationship between knowledge attributes and organizational innovation capability. Our findings could be used to help organizations sort out their knowledge attributes of knowledge bases, come to understand the impact of the interaction between the interorganizational knowledge network and R&D alliance network on the organizational innovation capability, and then make a targeted strategy to carry out innovation activities.

1. Introduction

The emergence of the knowledge economy and information technology has increased the value of research and development (R&D) alliances in a wide range of industries. In recent years, R&D alliances have also developed rapidly in China. Previous researchers have conclusively shown that R&D alliance networks have potentially distributed a vast range of innovative benefits to organizations [1–3]. Organizations can mostly access diverse external knowledge from their alliance partners, which is particularly essential to improving their innovation capability [4]. However, when organizations aim to strengthen their innovation capability, some challenges are faced by innovation managers. How to get more innovative benefits from the R&D alliance network to improve organizational innovation capability? What kind of knowledge combination strategy should be adopted in R&D alliance networks to improve organizational innovation capability? Therefore, many scholars have extended from studying the R&D alliance network to its interorganizational knowledge networks. Our research sets out to investigate the innovation capability implications of interorganizational knowledge networks under the context of R&D alliance networks.

As a vital component of networks, the clique is a group of mutually and directly linked actors in networks [5, 6]. It is a microlevel network within networks possessing several unique structural characteristics. For example, the clique is a locally cohesive group, comprising groups of players linked but sparsely tied to others, which can span clique and connect actors located in distinct and otherwise disconnected cliques [7]. In addition, Phelps [8] asserted that the clique has an attribute of network closure (wherein an organization's cooperators are also cooperators), and some researchers suggest that the network closure can increase knowledge transfer and improve innovativeness [9, 10]. Besides, a considerable amount of literature has been published on cliques [6, 11–13]. These studies have reported that clique has emerged as a knowledge-sharing platform for alliance partners, and it, with a diverse knowledge base and fast direct connections, increases the probability of value creation. Thus, our study undertakes in-depth research on the vital component (cliques) of R&D alliance networks and their interorganizational knowledge network.

In terms of interorganizational knowledge networks, Powell et al. [2] claimed that, as an industry's technology is widely distributed and rapidly developing, the locus of innovation would be found in interorganizational knowledge networks rather than within organizations. Currently, scholars have shown an increased interest in interorganizational knowledge networks and suggest that it is crucial for innovation outcomes [14–16]. However, researchers have tended to study the knowledge networks among inventors and neglected to explore the significance of the interorganizational knowledge networks that consist of all knowledge elements from alliance partners. Although one or two structural characteristics of interorganizational knowledge networks have been shown to affect organizational innovation capability [14], some additional knowledge attributes of interorganizational knowledge networks still need study further.

In addition, one major issue in recent research concerns the existence of an interaction effect between social networks (e.g., inventor networks and membership networks) and their intraorganizational knowledge networks [17–19]. Brennecke and Rank [17] found that knowledge networks' structural attributes can affect personal communication among inventors, thus influencing knowledge transfer and even the probability of knowledge recombination. This communication means that there is an interaction effect between inventor networks and their knowledge networks in the innovation process. Moreover, some researchers have shown that social networks among inventors and their interorganizational knowledge networks are decoupled [14, 20]. Overall, several studies have examined the interaction effects between social networks and interorganizational knowledge networks or intraorganizational knowledge networks. However, few researchers investigated the intereffect between alliance networks and their interorganizational knowledge networks. Therefore, in this study, we fill this gap and explore how R&D alliance networks among organizations are relevant for the relationship between interorganizational knowledge networks and organizational innovation capability.

Our research provides new insights into the study of interorganizational knowledge networks. First, most prior studies paid more attention to the field of intraorganizational knowledge networks, while only a few studies investigated interorganizational knowledge networks [14–16]. Guan and Liu [14] examined several structural characteristics of interorganizational knowledge networks that may affect innovation outcomes. To extend this research, our study applied a multilevel network method [17–19] to examine additional knowledge attributes of interorganizational knowledge networks. Second, since few studies have examined the relationship between alliance networks and knowledge networks in the interorganizational research field, our study explores the interaction effect between R&D alliance networks and their interorganizational knowledge networks further. Specifically, the R&D alliance networks' structural attribute is chosen to test how it influences the relationship between interorganizational knowledge networks and organizational innovation capability.

The purpose of our study is to address these gaps based on the multilevel network approach. Our research emphasizes the central position within alliance networks to provide a new dimension to study the relationships between interorganizational knowledge networks and organizational innovation capability. Within the developed research framework, our study addresses the two following research questions:

> *Question 1.* How do knowledge attributes of interorganizational knowledge networks (knowledge combinatorial potential, knowledge uniqueness, knowledge diversity, and knowledge proximity) bring about organizational innovation capability?
>
> *Question 2.* How does the structural attribute of R&D alliance networks (e.g., degree centrality) moderate the relationship between knowledge attributes of interorganizational knowledge networks and organizational innovation capability?

2. Theoretical Framework

2.1. Research and Development Alliance Networks. Previous studies mostly defined R&D alliances as innovation-based relationships established by several actors who collaborate to develop a new product or technology [21, 22]. Following previous researchers [8, 23], our study has used similar alliance network construction criteria to develop the R&D alliance network. An R&D alliance network consists of organizations and their R&D cooperation relationships. For example, CHANGAN, GEELY, Alibaba, and AutoNavi established an R&D cooperation relationship since they aim to co-research a new navigation system generation; Similarly, Alibaba cooperates with SAIC Motor to jointly develop Internet cars; Baidu and GEELY cooperate to research AI smart cars and explore intelligent travel. As the nodes in R&D alliance networks, organizations linked by R&D partnerships can control knowledge diffusion and subsequent innovative outcomes [14]. Additionally, the ties among these organizations can serve as a means to attain knowledge and information through alliance partners. Current studies have shown that R&D alliance networks are regarded as one of the most useful tools for acquiring external knowledge [24], thereby providing a channel for knowledge transfer and recombination [25].

Moreover, organizations located in different positions within alliance networks might influence innovation outcomes [8, 26, 27]. Centrality is a significant indicator to present organizations' location in networks, which refers to the number of links incident upon an organization in alliance networks [28]. In our research, three types of centrality (degree centrality, betweenness centrality, and closeness centrality) will be explored. We choose degree centrality as the moderating variable to test the relationships between interorganizational knowledge networks and organizational innovation capability for the following reasons. First, the structural characteristics of degree centrality, or the number of alliance partners' link to a focal organization, show the distance from the center position of networks. Second, as Freeman [28] suggested, degree centrality is an ideal centrality indicator for seizing an actor's access to knowledge in networks. Third, degree centrality is more likely to associate with the relationship between interorganizational knowledge networks and organizational innovation capability. Organizations with a higher level of degree centrality in their alliance networks, linked to many other alliance partners (e.g., Figure 1(a) shows that GEELY connects two cliques, indicating it has a higher degree centrality than other alliance partners), imply richer external cooperation relations and higher capability to control knowledge resources in interorganizational knowledge networks than organizations with a lower level of degree centrality [29]. Besides, organizations with a higher degree centrality in R&D alliance networks are more likely to acquire more information from their interorganizational knowledge networks than those located on edge [30, 31], and they will gain experience and master the necessary skills to enrich their knowledge bases and enhance their innovation capabilities. Therefore, an interaction effect between interorganizational knowledge networks and R&D alliance networks can be predicted, that is, the different levels of degree centrality might moderate the impact of interorganizational knowledge networks on the organizational innovation capability.

2.2. Interorganizational Knowledge Networks. Knowledge elements are the essential components of knowledge networks. It can be defined as a category that includes a series of facts, concepts, methods, insights, or procedures related to a subject [20, 32]. In our research, technological knowledge elements are the key components in knowledge networks. Following previous research [8, 17, 20, 33], our study uses the four-digital International Patent Classification (IPC) code of patents as knowledge elements to develop the interorganizational knowledge network. The four-digital IPC code combines a section, class, and subclass, which can adequately capture the characteristics of patents [14].

Knowledge network is derived from an agglomeration of links among knowledge elements [34–36]. In our research, the interorganizational knowledge network consists of all knowledge elements of alliance partners and the relationships between knowledge elements. Consistent with previous research [34–36], the ties that link knowledge elements in interorganizational knowledge networks are represented by knowledge combinations in history and co-application of knowledge elements in patents, and if two organizations have one common knowledge element, the two groups of knowledge elements linked to this knowledge element would establish indirect connections. Figure 1 presents an example of an interorganizational knowledge network. As shown in Figure 1(a), there is a cohesive subgroup containing two cliques. One clique consists of CHANGAN, GEELY, Alibaba, and AutoNavi, aiming to co-research a new navigation system generation. Another clique consists of GEELY, VOLVO, and Geely Zhaoyuan, aiming to establish an R&D center for automobile parts. CHANGAN, GEELY, and VOLVO are automobile companies, and they have very similar knowledge bases. Figure 1(b) presents their interorganizational knowledge network showing the connections of knowledge elements among these organizations. It can be seen that these knowledge elements are automatically divided into several groups. Some knowledge elements are located at the edge, while some are located at the center of the interorganizational knowledge network.

2.3. Two-Mode Networks. The two-mode network is frequently used to show the relations between individuals and their parties or events with which these individuals are affiliated [37]. Thus, the two-mode network is also named affiliation networks [38]. Following Wasserman and Faust [38], we extend the conception of affiliation from a broad perspective to contain knowledge elements in organizations and alliances. Figure 1(c) shows their two-mode network, which links the R&D alliance networks to their interorganizational knowledge network. It can be seen that these five organizations (red nodes) connect to their knowledge elements (white nodes) in the two-mode network (Geely Zhaoyuan do not have knowledge elements). Moreover, after weighting the two-mode network, as shown in Figure 1(d), it can be seen that GEELY has 116 common knowledge elements with CHANGAN and 32 same knowledge elements with VOLVO. It also has many other fields of knowledge elements that the other five organizations do not possess, which indicates that GEELY's knowledge elements occupy a higher centrality in the interorganizational knowledge network. AutoNavi is a web mapping, navigation, and location-based services provider that masters a unique technology in the research program. Conversely, these knowledge elements of Alibaba and Geely Zhaoyuan are in a lower centrality position within their interorganizational knowledge network. Thus, these two companies might not benefit more from their alliance partners. Therefore, the location of knowledge elements in interorganizational knowledge networks might influence the organizational innovation capability [14].

2.4. Multilevel Networks. There is no clear and unified definition of the multilevel network. Previous scholars divided it into the multiplex network, timing network, network of network, interdependent network, and other different types according to the characteristics of the topological structure. In our study, we adopted the concept of the interdependent network. Buldyrev et al. [39] proposed that due to technological progress, modern systems are

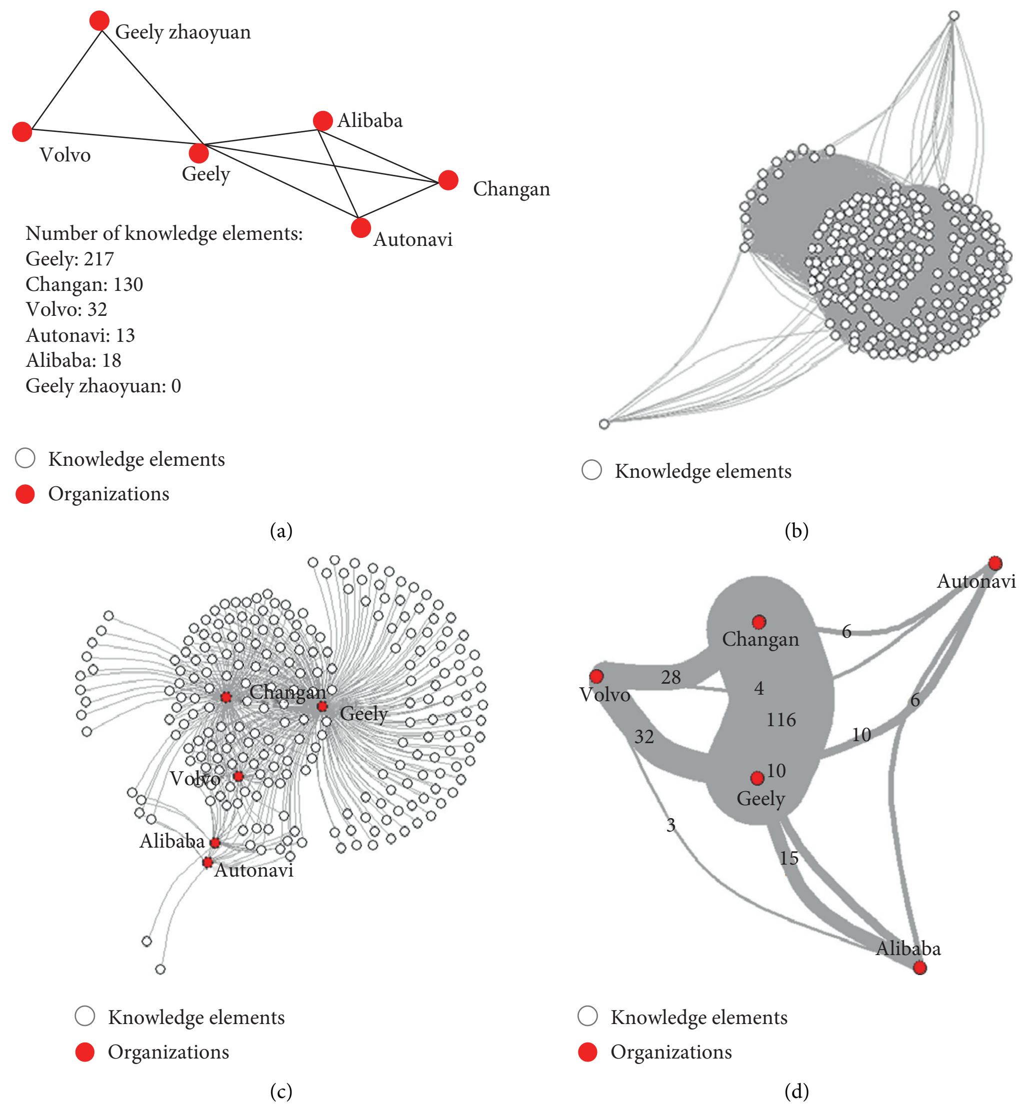

Figure 1: A case of interorganizational knowledge networks: (a) subgroup; (b) interorganizational knowledge network; (c) two-mode network; (d) weighted two-mode network, the weight is the number of same knowledge elements between two organizations.

becoming more and more coupled together. While in the past many networks would provide their functionality independently, modern systems depend on one another to provide proper functionality. For example, in our research, R&D alliance networks and their interorganizational knowledge networks are all one-mode networks and there exists a dependence relation between them. Knowledge elements in interorganizational knowledge networks are dependent or belong to organizations in R&D alliance networks. Organizations located in distinct network positions may affect the effectiveness of their knowledge combination in interorganizational knowledge networks, and the organizations' knowledge elements located in different positions of interorganizational knowledge networks may affect the organization's choice of its future alliance partners.

Previous researchers [17, 39–41] proposed that the interdependent multilevel network is composed of two or n single networks. The nodes in a single network are homogeneous, while the nodes between every single network are of different types. Besides, a multilevel level network has nodes of several different types, and each type represents a different level. A one-mode network can be defined within each level, and a bipartite (two-mode) network can be defined between nodes from two adjacent levels. Therefore, following previous research methods of multilevel network construction [17, 39–41], in our study, we developed a new multilevel network (see Figure 2), which includes three levels. That is, the nodes (organizations) at the below level, which is labeled as an R&D alliance network, the nodes (knowledge elements) at the top level, which is labeled as an interorganizational knowledge network, and the middle-level bipartite network as a two-mode network, which links each organization within R&D alliance networks to single knowledge elements, reflecting organization embeddedness in the interorganizational knowledge network. From Figure 2, we can see that some alliance partners share common

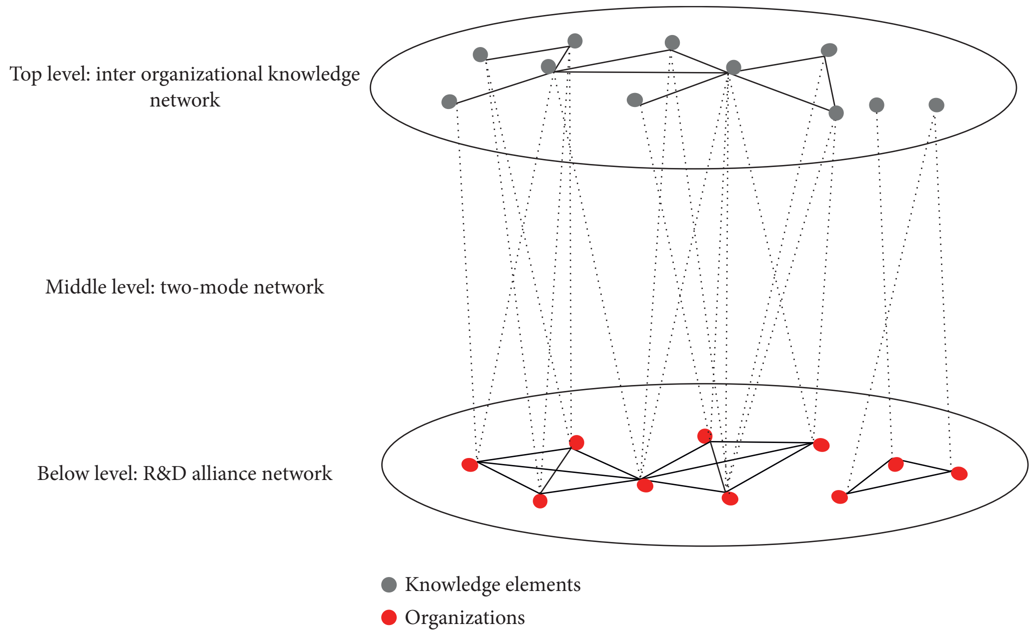

Figure 2: Overview of the theoretical framework of the multilevel network.

knowledge elements, and compared to others, some organizations possess a diversified knowledge base. Furthermore, some knowledge elements within their interorganizational knowledge network link many organizations, and some knowledge elements only connect to one or two organizations. Therefore, some knowledge attributes can be captured by the position of knowledge elements in interorganizational knowledge networks or the connection between knowledge elements and organizations. Consistent with Wang et al. [20] and Brennecke and Rank [17], our study classifies knowledge attributes into four categories: knowledge combinatorial potential, knowledge uniqueness, knowledge diversity, and knowledge proximity.

2.5. Hypotheses' Development

2.5.1. Knowledge Combinatorial Potential and Degree Centrality. Knowledge combinatorial potential draws on the connections between various knowledge elements, which were dependent on the knowledge combinatorial record in the past [42], and it is typically measured by the degree centrality of knowledge elements in knowledge networks [14, 17, 20].

A knowledge element with a higher degree centrality tends to present a high combinatorial potential in knowledge networks. The main reason is that knowledge elements with a higher degree centrality could increase the probability of knowledge combination, which would benefit organizations carrying out innovation activities and stimulate new ideas generation [14, 20]. For example, as in the case we discussed above, knowledge elements of automobile companies (e.g., GEELY and CHANGAN) have a higher degree centrality in their interorganizational knowledge network. Therefore, the knowledge combinatorial potential of these two companies might be higher than other alliance partners. Besides, organizations with a high combinatorial potential knowledge stock can integrate or connect more knowledge elements from different technology fields. For instance, high-tech firms tend to cooperate with traditional industries and upgrade their products (e.g., autonomous vehicles and smart home). Similarly, knowledge elements with higher combinatorial potential might be related to the subject matter [20], which might attract organizations with this local knowledge element to search for combinatorial spaces.

In summary, it can be predicted that knowledge combinatorial potential has a positive influence on organizational innovation capability, especially in an organization with a high knowledge combinatorial potential. Therefore, we suggest the following:

Hypothesis 1. Knowledge combinatorial potential positively influences organizational innovation capability.

Moreover, organizations with a central position (a higher degree centrality) within R&D alliance networks might affect the relationship between knowledge combinatorial potential and organizational innovation capability. Degree centrality is one of the critical indicators to present the central position of an actor in alliance networks, which is regarded as the number of cooperators that an actor is directly linked in alliance networks [22]. Degree centrality reflects a real-world situation in which organizations with a high degree centrality can control more resources and information in R&D alliance networks, enhance their commercial standing, and influence how their capabilities are perceived [43]. Nerkar and Paruchuri argued that degree centrality creates an attractiveness for prospective alliance partners to select new knowledge elements [44], and it is regarded as a source of innovativeness because an organization with a central position has more opportunities to access external information that is difficult to obtain in the market [43]. Besides, an organization located in a central position in alliance networks would have more chances to discover unexplored combinations, making it easy to appeal to other organizations that cooperate with influential organizations [45] and have timely access to promising projects, resulting in several subsequent R&D collaborations [2].

Therefore, our study posits that the different levels of degree centrality change the effect that the knowledge combinatorial potential has on the organizational innovation capability. Organizations with a low level of degree centrality are generally located at the edge of alliance networks and connected to fewer alliance partners. In this case, even though organizations have a high knowledge combinatorial potential, it is challenging to generate new combinations because they cannot access rich knowledge resources. However, if an organization has a high level of degree centrality in its alliance networks, it will support it to access external knowledge resources. Thus, even though the organization has less knowledge combinatorial potential, it still could benefit more from the frequent communication and diverse external knowledge resources.

With this logic, we further predict that degree centrality in R&D alliance networks can positively affect the relationship between knowledge combinatorial potential and organizational innovation capability. That is, when an organization has a low knowledge combinatorial potential, the frequent communication and intensity of knowledge transferring created by the high degree centrality in its alliance networks can steer its alliance partners to share their knowledge and technologies and, thus, more effectively facilitate the organization to acquire and combine the external knowledge shared by its alliance partners [46]. As the knowledge combinatorial potential increases, it can further benefit from the rich external resources brought about by the high degree centrality of R&D alliance networks.

In summary, degree centrality depending on intense connections facilitates a central organization to access diverse knowledge elements [47]. The benefits brought by degree centrality can positively moderate the effect of knowledge combinatorial potential on organizational innovation capability. Therefore, based on previous research, our study tends to examine this hypothesis:

Hypothesis 2. Degree centrality plays a positive moderating role in the relationship between knowledge combinatorial potential and organizational innovation capability.

2.5.2. Knowledge Uniqueness and Degree Centrality. Knowledge uniqueness can be defined as organizations being knowledgeable in a field that other partners are unfamiliar with [17]. Organizations are linked to several knowledge elements in their interorganizational knowledge networks that few other partners are linked to, which may affect knowledge combination. Scholars have long debated the impact of knowledge uniqueness on innovation outcomes.

Previous researchers have claimed that access to unique knowledge resources can be valuable for the organization [47]. Organizations with a certain number of unique knowledge elements might have advanced technology in some fields, attracting other organizations' attention and cooperation. This unique knowledge is better for carrying out a competitive strategy of differentiation as unique information and technology are sources of competitive parity [48]. Besides, organizations posses rare knowledge elements that are uncommonly distributed in a market. Thus, their unique knowledge is quaint to any competitors and is also a valuable property for organizational innovation.

However, some researchers have recently shown that organizations possessing an abundance of unique knowledge bases might reduce external exploration and thus less actively search for new information from their alliance partners [49]. Uniqueness is considered the degree of the knowledge's content specificity, which is not easy to transfer to other organizations or even difficult for other organizations to duplicate. That could be why it is not easy to be innovative based on unique knowledge [50]. Besides, with unique knowledge elements in their knowledge bases increasing, the knowledge protection mechanism might switch on and reduce external exploration, affecting knowledge sharing and transfer among alliance partners and eventually influencing organizational innovation capability in the long run.

As mentioned above, our study posits an inverted U-shaped relationship between knowledge uniqueness and organizational innovation capability. When the number of an organization's unique knowledge is lower, the organizational innovation capability may suffer from lacking core competitiveness in the market. As its knowledge uniqueness increases, the enhanced unique knowledge elements will enable an organization to benefit from its differentiated knowledge resources and appeal to more R&D ventures, thus improving its innovation capability. However, such enhanced unique knowledge elements will also commensurately hinder the knowledge transfer between organizations and their alliance partners because as the unique knowledge is possessed too much, the communication barriers and cost may exceed the knowledge-sharing benefits. Therefore, we propose this hypothesis:

Hypothesis 3. Knowledge uniqueness has an inverted U-shaped effect on organizational innovation capability.

Moreover, organizations with a central position in R&D alliance networks might influence the relationship between knowledge uniqueness and organizational innovation capability. Regarding the high degree centrality, organizations located in a central position in their R&D alliance network have many direct connections, enabling organizations to carry out more innovative activities and R&D programs with their alliance partners. That means organizations with a high degree centrality could access and control more diverse information from their alliance partners or deciding on new investment in R&D projects [47], which might facilitate them to carry out external innovation exploration and search for new knowledge combinations.

Our study posits that the different levels of degree centrality change the effect that the knowledge uniqueness has on the organizational innovation capability. That is, organizations with a high level of degree centrality might make up for the shortcomings of excessive unique knowledge elements that weaken innovation outcomes because the high degree centrality supports rich external cooperation relations and knowledge resources [29]. High degree centrality has implications for high levels of knowledge sharing in knowledge networks [51]. In other words, as an organization's degree centrality in its R&D alliance network is high, the enhanced mutual communications among alliance partners can promote the organization to share, combine, and transfer its unique knowledge effectively. Besides, intensifying mutuality enables alliance partners to share unique knowledge and generate innovations that cannot be achieved separately in R&D alliances [46]. As a result, the high degree centrality can effectively advance R&D cooperation and knowledge transferring among alliance partners and make up for the shortcomings of excessive unique knowledge elements that bring high cost of new knowledge combinations.

On this logic, we further assume that degree centrality can moderate the inverted U-shaped effect of the knowledge uniqueness on the organizational innovation capability. That is, when the knowledge uniqueness is weak, the frequent communication and intensity of knowledge sharing created by the high degree centrality enables the alliance participants to share their knowledge and information, thereby facilitating local organizations to timely access the external resources provided by their alliance partners [52]. As the knowledge uniqueness increases, it can further benefit from the high degree centrality of organizations with cohesive connections, which compensate for the organizations with an overabundance of unique knowledge that is difficult for transferring and combining new knowledge elements in interorganizational knowledge networks.

In summary, as the degree centrality of organizations gets higher, the benefits from the degree centrality tend to be enhanced, making the curve of inverted U-shaped effect of knowledge uniqueness on the organizational innovation capability weaker. Overall, our study poses this hypothesis:

Hypothesis 4. Degree centrality plays a moderating role in the relationship between knowledge uniqueness and organizational innovation capability.

2.5.3. Knowledge Diversity and Degree Centrality. Knowledge diversity can be defined as an abundance degree of knowledge elements, which is similar to technology diversity [8, 53]. In our research, knowledge diversity tends to be used to refer to the extent of an organization's knowledge diversity within its interorganizational knowledge network. Scholars have long debated the significance of knowledge diversity.

Many studies [54–56] have shown that knowledge diversity increases the probability of knowledge combinations and enhances organizations' capability for problem solving. By maintaining an extensive knowledge combination, organizations can explore and exploit new opportunities derived from diversified knowledge stock [57, 58]. Furthermore, knowledge diversity can act as a catalyst for innovation and knowledge transfer [59]. In particular, for high-tech industries, continuously acquiring diversified knowledge in technology fields is essential for survival [60].

However, some researchers have suggested that overdiversified knowledge might affect organizational absorptive capability. As knowledge diversity increases, the technological distance among alliance partners becomes more extensive, which might weaken their ability to recognize and absorb new knowledge and expand the cost of innovation activities [35, 61]. This enormous R&D funding investment might disrupt the regular operation of organizations. Notably, some small-scale organizations do not have strong cognitive capabilities and rich experiences to comprehend overdiversified knowledge [36]. Besides, seeking to grasp and integrate highly diverse knowledge elements can cause information overburden [8, 62].

Therefore, our research posits an inverted U-shaped relationship between knowledge diversity and organizational innovation capability. When the number of an organization's diverse knowledge is lower, the organizational innovation capability may suffer from lacking novel knowledge elements to combinate. As its diverse knowledge increases, the enhanced new knowledge elements will enable organizations to benefit from new combinations and products, thus improving their innovation capability. However, such enhanced diverse knowledge bases will also increase high R&D costs. When the diverse knowledge is possessed too much, the cost may exceed the knowledge combination benefits, and the marginal revenue would be reduced generally by the overnumber of diverse knowledge elements. Thus, we propose this hypothesis:

Hypothesis 5. Knowledge diversity has an inverted U-shaped effect on organizational innovation capability.

Moreover, organizations with a central position within R&D alliance networks might affect the relationship between knowledge diversity and organizational innovation capability. Organizations with a leading position are considered reference objects for other alliance partners, influencing the likelihood of new knowledge combinations and potential causes of operating losses [63]. The bright side is that organizations from the central location in networks could establish a higher standing, reduce their risk perception in resource expansion, and inspire other alliance partners to proactively engage in R&D ventures. Besides, the central organization's visible reputation can be collectively evaluated. Such an organization can make better partner choices and set up more stable cooperative partnerships than the organizations at the edge of R&D alliance networks [64].

Our study posits that the different levels of degree centrality change the effect that the knowledge diversity has on the innovation capability. That is, the high level of degree centrality might make up for the shortcomings of excessive diverse knowledge elements that weaken innovation outcomes because a high degree centrality can support more stable long-term cooperation relationships and frequent information exchanging [64]. According to resource dependency theory [65], the aim for the establishment of alliances between organizations is that they depend on mutually unique resources. Organizations at the center of networks occupy richer resources than other organizations at the edge of networks [29]. Participants establish direct cooperative relationships with central organizations, which means they have a strong dependence on the central organizations' resources and implies a more stable and intensive cooperative relationship with the central organization than those at the edge of networks. In R&D alliance networks, as an organization's degree centrality gets higher, the increased mutual and frequent communications among alliance partners brought by stable and intensive cooperative relationships can mostly facilitate the organization to combine its diverse knowledge with other alliance partners effectively. Although some small-scale organizations do not have strong cognitive capabilities to integrate overdiversified knowledge [37], a central position within networks can strengthen their recognizing and absorbing capability and promote knowledge transferring effectively. Notably, central organizations typically are the industry leaders, who have strong cognitive capabilities and extensive experiences to bear a high combination cost that is brought by excessive diverse knowledge elements.

With this logic, we further predict that degree centrality can moderate the inverted U-shaped effect of knowledge diversity on organizational innovation capability. That is, when the knowledge diversity is weak, the frequent communication and intensity of knowledge flow created by the high degree centrality enable the participants to share their knowledge in networks. As knowledge diversity increases, it can further benefit from stable cooperation relationships created by the high degree centrality, which would reduce the high cost of those organizations processing overabundant of knowledge elements to combine and integrate new knowledge elements with other organizations.

In summary, as the degree centrality of organizations gets stronger, the benefits from the degree centrality tend to be increased, making the curve of inverted U-shaped effect of knowledge diversity on the organizational innovation capability weaker. Overall, our study poses this hypothesis:

Hypothesis 6. Degree centrality plays a moderating role in the relationship between knowledge diversity and organizational innovation capability.

2.5.4. Knowledge Proximity and Degree Centrality. Knowledge proximity can be defined as the extent of cognitive proximity among cooperators [66]. In our study, knowledge proximity is measured by the degree to which two organizations are connected to same knowledge elements in their interorganizational knowledge network [17]. The effect of knowledge proximity on innovation capability is a much-debated topic in previous research.

Based on the absorptive capacity theory, connecting proximity knowledge elements could stimulate the communication between alliance partners because they have similar technology cognition [67, 68]. Thus, the cooperation costs are lower, and knowledge sharing and transferring are more efficient [17]. Besides, previous research studies have demonstrated that organizations can make it easier to absorb new technologies from their alliance partners through knowledge sharing when they have proximity knowledge bases, which can be a precondition for generating innovativeness [69, 70]. Based on the resource-based view theory, the mutual incentive to collaborate is decided by the resource complementarity [71]. Organizations search for technology partners who are faced with a trade-off of resource complementarity; thus, a common knowledge base increases the possibility and willingness to cooperate. Moreover, a high level of knowledge proximity helps alliance partners reduce communication costs, consequently weakening risks of confusion and misunderstanding [72]. Thus, knowledge proximity promotes knowledge sharing and increases the possibilities of recombining mutual knowledge elements into innovations.

However, knowledge proximity is not always beneficial for innovation. With the knowledge proximity among organizations increasing, the influence on new combinations may reduce or even turn negative. Crescenzi et al. argued that extreme proximity might lead to a lock-in effect, and redundant common knowledge in alliance knowledge bases might restrain innovation [66]. When the knowledge elements among alliance partners are homogenesis, organizations may face searching barriers and limiting potential recombination scope. Recombination requires seeking new interdependencies among different knowledge elements [73]. The homogenesis knowledge bases may restrict cooperative organizations' conceptual capabilities and raise the challenges of generating new combinations. Besides, new recombination frequently comes from different technological areas. As knowledge proximity surpasses a specific value, the effectiveness of utilizing cooperation for innovative combination will vanish, owing to the declined diverse knowledge elements. Therefore, in the recombination practice, organizations should have certain homogenesis knowledge bases to fully absorb the knowledge shared by collaboration partners, but unique and diverse knowledge is significant to support novel recombination.

Therefore, our research posits an inverted U-shaped relationship between knowledge proximity and organizational innovation capability. That is, when the number of an organization's proximity knowledge with other alliance partners is lower, the organizational innovation capability may suffer from lacking common knowledge bases, thus increasing the difficulty of integration. As its proximity increases, the enhanced common knowledge bases among alliance partners will reduce the cost of new knowledge combinations and improve innovation capability. However, such enhanced proximity knowledge bases will also decline the innovation activities of alliances. When the proximity knowledge is possessed too much, the benefits from knowledge combination and sharing will reduce. Thus, we propose this hypothesis:

Hypothesis 7. Knowledge proximity has an inverted U-shaped effect on organizational innovation capability.

Moreover, organizations with a central position within R&D alliance networks might affect the relationship between knowledge proximity and organizational innovation capability. Gilsing et al. [74] showed that degree centrality plays a critical role in searching for novel combinations. Organizations with a higher degree centrality can better familiarize what is going on in their alliance networks, which might increase the possibilities of combining innovative knowledge elements [75]. Besides, as a resource controller in R&D alliance networks, the higher status and power to control knowledge resources would increase the bargaining power [76] and bring diverse knowledge elements for organizations with overproximity knowledge bases with their alliance partners.

Therefore, our study posits that the different levels of degree centrality change the effect that the knowledge proximity has on the innovation capability. That is, the high level of degree centrality of organizations might make up for the shortcomings of overproximity knowledge elements that weaken innovation outcomes because high degree centrality could support rich and diverse knowledge resources for organizations with excessive proximity knowledge bases and promotes new knowledge combinations [74]. Degree centrality is recognized as a source of innovativeness because organizations with a central position have more opportunities to access external diverse information and resources [43]. Besides, an organization with a high degree centrality tends to have more chances to combine new knowledge elements and attract more influential organizations for R&D projects [45] that would bring more diverse and specialized knowledge elements for central organizations to develop new combinations and enhance innovation capability.

On this logic, we further predict that degree centrality can moderate the inverted U-shaped effect of the knowledge proximity on the organizational innovation capability. That is, when the amount of proximity knowledge is too low between an organization with its alliance partners, it may lack a common knowledge base to develop new combinations [69, 70]. However, if the organization has a central position in alliance networks, the frequent communications created by the high degree centrality would promote new combination generation even though it has a lower level of knowledge proximity with its alliance partners. Furthermore, eventhough an organization has high proximity knowledge elements with its alliance partners, it still could generate new combinations because rich resources and information brought by the high degree centrality might weaken the lock-in effect. In this case, organizational innovation capability could benefit from diverse knowledge resources brought by the high degree centrality of R&D alliance networks.

In summary, as the degree centrality gets stronger, the benefits from the degree centrality tend to be increased, making the curve of inverted U-shaped effect of knowledge proximity on the organizational innovation capability weaker. Overall, our study poses this hypothesis:

Hypothesis 8. Degree centrality plays a moderating role in the relationship between knowledge proximity and organizational innovation capability.

Therefore, based on these hypotheses mentioned above, the proposed research model of our study is shown in Figure 3.

3. Research Design

3.1. Data Collecting. Our research setting is in Chinese high-tech industries, including organizations in the semiconductor devices, aircraft, motor vehicles, communication equipment, and pharmaceutical industries. We chose these high-tech industries for the following reasons. First, these industries experience considerable changes in technology and competition, which results in increasing R&D alliances' activities. Second, these high-tech industries regularly patent their inventions [8], making it easy to quantify organizational innovation capability.

In this empirical study, we consider many types of cooperators, such as competitors, suppliers, customers, universities, research institutes, and collaborators from different industries. Furthermore, the alliance samples are limited to the large-scale organizations in these high-tech industries since complete and accurate alliance data are easier to access for industry leaders [8, 77]. As the regional release of Chinese alliances news is limited, some are only published in Chinese magazines. Thus, we collected alliance samples by going through many annual reports, Baidu News, corporate websites, and Industry Association Official websites using reptile software. Around 500 annual reports and over 1000 electronic articles and news reports were checked. After data cleaning, sorting, and deleting other types of alliances such as cooperation on marketing and production, the basic research dataset of our paper includes 442 R&D alliance samples from 2010 to 2015.

Furthermore, alliances generally last for more than one year, but the end date of alliances is rarely released. Therefore, following previous research approaches [8, 10, 23], our study assumes that the alliance relationship lasts for three years and uses a 3-year time window to observe R&D alliance networks. Therefore, R&D alliances in our samples were divided into four time windows (e.g., 2010–2012, 2011–2013, 2012–2014, and 2013–2015). According to previous studies [6, 11], in our research, the cliques were extracted from R&D alliance networks by the UCINET 12.0 software (Network—>Subgroups—>Cliques). Finally, though other dyad ties are eliminated, the final dataset for our study includes 86 R&D cliques during the period from 2010 to 2015. Figure 4 presents R&D alliance networks in these four time windows. It can be seen that the structural components are cliques and that some cohesive subgroups are connecting several cliques.

Following previous researchers [78, 79], the knowledge elements (four-digital IPC codes of patents) were collected from the INCOPAT patent database (https://www.incopat.com/) that includes information related to technology classes based on the International Patent Classification (IPC) system. The INCOPAT patent database is a Chinese authoritative data source with a global patent database and provides first-rate patent data and a platform for organizations (e.g., companies, universities, and research

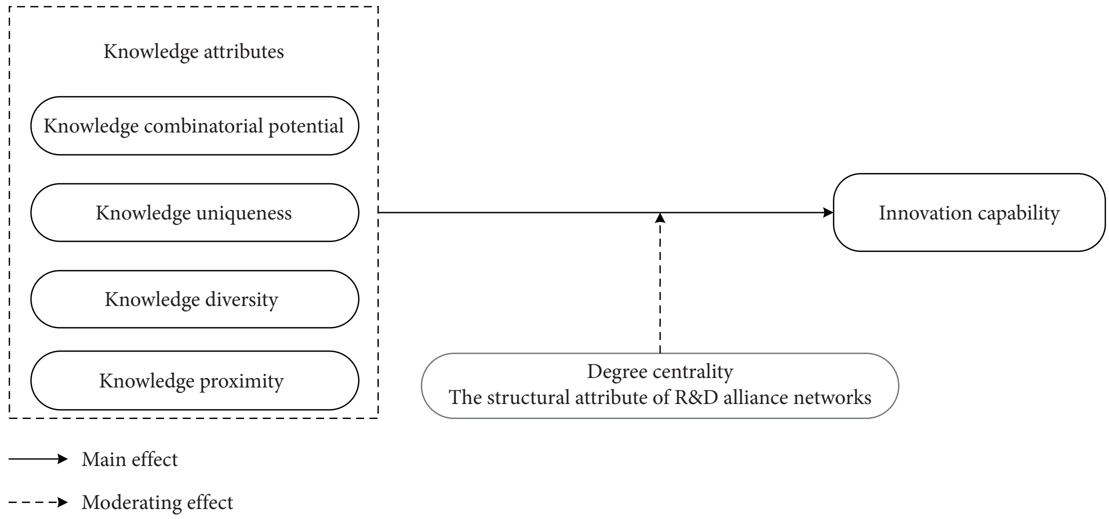

Figure 3: Proposed research model.

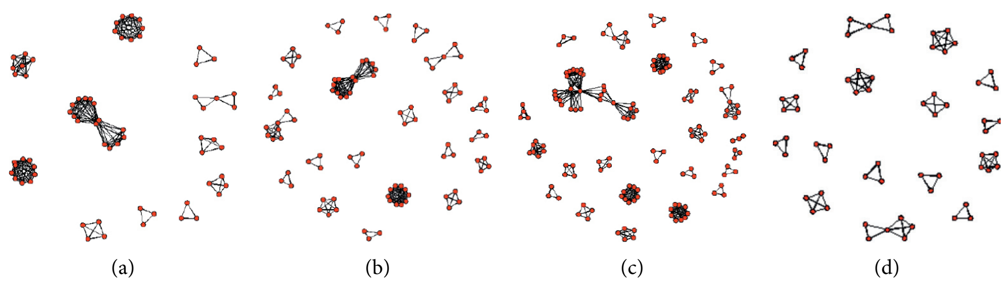

Figure 4: R&D alliance networks in five Chinese high-tech industries from 2010 to 2015 (four time windows from left to right). (a) 2010–2012, (b) 2011–2013, (c) 2012–2014, and (d) 2013–2015.

institutions). Drawing on a patent database from one country can ensure conformity, accuracy, and comparability across organizations [79].

3.2. Variables

3.2.1. Dependent Variable. Several definitions of innovation capability have been proposed. For Andrea [80], innovation capability refers to organizations' ability to exploit novel products, new processes, and accomplish significant technical and management achievement. Lawson and Samson [81] defined innovation capability as the ability to transfer knowledge into new products for the benefit of organizations. Vicente et al. [82] defined innovation capability as organizations' ability to exploit new products by combining innovative behaviors, strategic capabilities, and internal technical processes. While various definitions of innovation capability have been suggested, our paper will use the definition suggested by Lawson and Samson [81], who saw it as an organization's ability to transfer knowledge and ideas into the new product. For the measurement of innovation capability, the number of patents owned by an organization is a reliable indicator to measure innovation capability in these high-tech industries [8], which can be attributed to the patent that is the explicit knowledge of organizations and the output measure of the innovation capability [83]. In our study, since it frequently takes 2-3 years from patent application to patent authorization, our research adopts the number of granted patents in the third year of participating in alliances to measure the organizational innovation capability. We collected data on granted patents from the INCOPAT patent database.

3.2.2. Independent Variables from Interorganizational Knowledge Networks. As shown in our new multilevel network framework (see Figure 2), organizations within R&D alliance networks are linked to knowledge elements within the interorganizational knowledge network based on their affiliate relationships. Our study uses the connection between organizations and their knowledge elements to acquire information about knowledge attributes.

Following previous researchers [17, 20], the knowledge combinatorial potential is measured by the degree centrality of knowledge elements in interorganizational knowledge networks. As shown in Figure 5(a), the more knowledge elements a knowledge element connects, the higher this knowledge element's combinatorial potential. In our research, this variable represents the average degree centrality of an organization's knowledge elements. It can be calculated by two steps: first, computing the degree centrality of

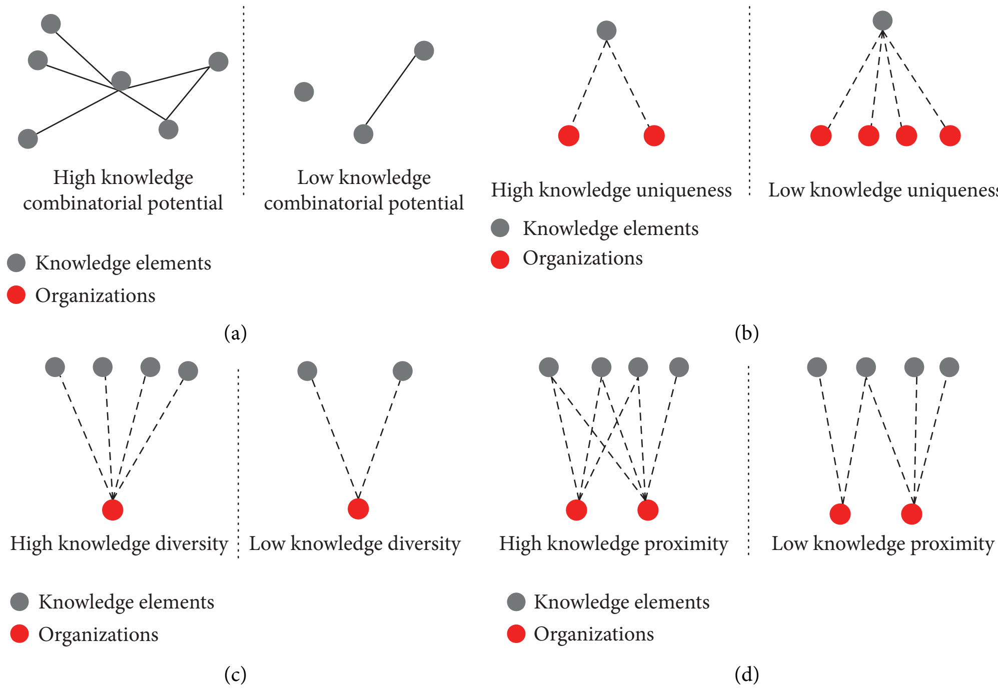

FIGURE 5: Graph explanation of these four knowledge attributes based on our multilevel network framework of Figure 2: (a) high and low knowledge combinatorial potential; (b) high and low knowledge uniqueness; (c) high and low knowledge diversity; (d) high and low knowledge proximity.

knowledge elements in their interorganizational knowledge networks at each time window, and second, finding out all knowledge elements belonging to each organization and calculating the average value. The formula of knowledge combinatorial potential is

$$CP_i = \text{avg} \sum_k \frac{x_k}{|N| - 1}, \quad (1)$$

where CP_i is the average degree centrality of organization i's knowledge elements, N is the number of knowledge elements in the interorganizational knowledge network x, and x_k is the number of knowledge elements that knowledge elements k connects directly in its interorganizational knowledge networks x.

Knowledge uniqueness can be measured by the number of organizations linked to one knowledge element in two-mode networks. Following the previous research method [17], this count is inverted in our model. As shown in Figure 5(b), the fewer the organizations that possess a knowledge element, the more unique it is. This variable represents the average connected number of an organization's knowledge elements, which can be calculated by this formula:

$$U_i = \text{avg} \sum_k (-1) a_k, \quad (2)$$

where U_i is the knowledge uniqueness of organization i and a_k is the number of organizations linked to knowledge elements k in the two-mode network a.

Knowledge diversity refers to the number of knowledge elements an organization owns [17, 20], which can be calculated as the number of four-digital IPC codes in granted patents of an organization. As shown in Figure 5(c), the more knowledge elements an organization possesses, the more diverse is its knowledge base. It can be calculated by the following formula:

$$\text{KD}_i = \sum_k a_k, \quad (3)$$

where KD_i is the knowledge diversity of organization i and a_k is the number of knowledge elements that organization i linked in the two-mode network a.

Knowledge proximity can be regarded as the degree to which two organizations are connected to the same knowledge elements in interorganizational knowledge networks [17]. As shown in Figure 5(d), the more knowledge elements that two organizations are similar in their interorganizational knowledge networks, the more the proximity between their knowledge bases. An organization's knowledge proximity is obtained by the percentage of common knowledge elements with its alliance partners and all knowledge elements in its interorganizational knowledge network. This variable represents the average proximity of an organization's knowledge bases with its alliance partners in their interorganizational knowledge network. It can be calculated by this formula:

$$P_i = \text{avg} \sum_j \frac{e_{ij}}{k}, \quad (4)$$

where P_i refers to the knowledge proximity of organization i with its partners, e_{ij} represents the number of co-possessed knowledge elements between organization i and its alliance partner j, and k is the sum of knowledge elements in the interorganizational knowledge network.

3.2.3. A Moderating Variable from Research and Development Alliance Networks. Degree centrality (DC) is one of the vital structural indicators used to describe the network position [22]. The high degree centrality reflects the central position of an organization in alliance networks. In our research, degree centrality is calculated by the UCINET 12.0 software [84, 85]. The formula of degree centrality is

$$DC_{\deg}(v) = \frac{d_v}{|N| - 1}, \tag{5}$$

where $DC_{\deg}(v)$ is the organization v's degree centrality, N is the number of alliance players in organization v's ego network, and d_v is the number of alliance partners that organization v connects directly in its R&D alliance network.

3.2.4. Control Variables. Our study added several control variables regarding the attributes of R&D alliance networks, knowledge, and organizations in our research model, and most of them have shown an effect on innovation capability in previous research.

Control variables at the R&D alliance network level: some structural attributes of R&D alliance networks have been shown to influence the dependent variable. Therefore, to specify the effects on the organizational innovation capability, we controlled two structural attributes of R&D alliance networks, which were calculated by the UCINET 12.0 software. Closeness centrality is defined as the extent to which an actor is far from other actors. Whoever has higher closeness centrality can efficiently communicate with others in networks [84, 86], thus yielding a greater probability of innovation output [87]. Closeness centrality is calculated as the sum of the paths from one alliance participant to all other participants in networks. The smaller the sum of paths, the shorter the path from one participant to all other participants in networks and the closer the participant is to all other participants. The sum of the shortest paths between one participant and other participants, after normalization, is a value between (0, 1). The larger the value, the higher the closeness of the participant to the center position in networks. Besides, when the numerator in the formula tends to infinity ∞, the value of closeness centrality tends to 0. Therefore, when an organization is very far away from all other organizations in R&D alliance networks, it is not at the center position, and its closeness centrality tends to 0. The formula of closeness centrality is

$$C(x) = \frac{1}{\sum_y d(y, x)}, \tag{6}$$

where $C(x)$ is the organization x's closeness centrality and $\sum_y d(y, x)$ is the sum of the distances from organization x to all other partners in its R&D alliance network. Betweenness centrality measures how frequently an organization lies along the shortest path between two other alliance partners [84]. If the value of an organization's betweenness centrality is 0, it means that it is located at the edge of R&D alliance networks and cannot control any alliance partners; if the value is equal to 1, it means the organization can completely control other alliance partners and possess enormous control power. Besides, the greater the betweenness centrality is for a participant, the greater the opportunities it gets to promote knowledge flow and the greater is its innovation capability [88, 89]. The formula of betweenness centrality is

$$bc_k = \sum_{i,j} \frac{g_{ikj}}{g_{ij}}, \tag{7}$$

where bc_k is the organization k's betweenness centrality, g_{ij} is the number of paths from organization i to organization j in R&D alliance networks, and g_{ikj} is the number of those paths that pass through organization k in R&D alliance networks.

Control variables at the knowledge level: presample patent number refers to knowledge accumulation before organizations engaged in alliances [90, 91], and organizational knowledge assets are key organizational factors responsible for innovation [92]. Following Guan et al. [91], the presample patent number is measured as the number of granted patents owned by organizations in the five years before joining its alliances. Cite patent refers to the number of patents that an organization cites from other organizations. This variable reflects the knowledge flow between organizations, which has been demonstrated to influence innovation capability [93]. These patent data were collected from the INCOPAT patent database.

Control variables at the organization level: we collected a set of organizational attributes from annual reports and corporation websites that might influence innovation outcomes. Organization age is regarded as the organizations' history from the establishment to the year of joining alliances. As organizations age, they tend to focus on their existing knowledge bases rather than search for new and unfamiliar knowledge [8], which might influence innovation outcomes. Organizations from different industries might have different innovation capabilities. Based on the International Standard Industrial Classification of All Economic Activities (ISIC), the industry is coded as a five-level variable (1 = semiconductor device manufacture (ISIC 3562), 2 = aircraft manufacture (ISIC 374), 3 = motor vehicles manufacture (ISIC 36), 4 = communication equipment manufacture (ISIC 392), and 5 = pharmaceutical manufacture (ISIC 27)). Region refers to the geographical location of organizations. In China, organizations located in different areas may have a distinct innovation capability relating to the influence of national policy and geographical environment. Since most of the organizations in our samples are from China, according to the Chinese Geographical Division, it can be regarded as an eight-level variable (1 = Northeast region, 2 = East China region, 3 = North China region, 4 = Central China region, 5 = South China region, 6 = Southwest region, 7 = Northwest region, and 8 = organizations from other countries).

3.3. Research Approach. As shown in Table 1, the dependent variable, innovation capability, is a count variable. Since the variance of innovation capability (4210.67) is higher than its

Table 1: Descriptive statistics and correlations analysis.

Variables		Mean	SD	Min.	Max.	1	2	3	4	5	6	7	8	9	10	11	12	13
1	Innovation capability	1400.32	4210.67	0.00	35582.00	1												
2	Presample patent number	229.18	989.13	0.00	11881.00	0.90	1											
3	Organization age	16.68	22.56	0.00	121.00	0.18	0.15	1										
4	Cite patent	2802.36	24357.58	0.00	346584.00	0.56	0.63	0.09	1									
5	Industry	3.39	1.43	1.00	5.00	0.11	0.10	0.08	0.06	1								
6	Region	3.73	2.06	1.00	8.00	0.07	0.15	0.19	0.15	0.15	1							
7	Closeness centrality	0.29	0.10	0.00	0.39	−0.02	−0.00	0.11	−0.01	−0.14	0.00	1						
8	Betweenness centrality	0.05	0.25	0.00	2.33	0.21	0.14	0.08	0.04	0.18	−0.07	0.03	1					
9	Degree centrality	0.07	0.05	0.00	0.35	0.19	0.13	0.0008	0.04	0.29	−0.14	−0.04	0.62	1				
10	Knowledge combinatorial potential	0.52	0.41	0.00	1.00	0.34	0.25	0.25	0.13	0.23	0.12	−0.05	0.14	0.16	1			
11	Knowledge uniqueness	0.23	0.32	0.00	1.00	0.42	0.33	0.23	0.22	−0.08	0.03	0.01	0.11	−0.11	0.51	1		
12	Knowledge diversity	35.19	69.36	0.00	402.00	0.71	0.50	0.27	0.23	0.09	−0.02	−0.04	0.39	0.32	0.50	0.55	1	
13	Knowledge proximity	0.04	0.06	0.00	0.35	0.35	0.19	0.14	0.02	0.10	0.12	−0.00	0.10	0.02	0.48	0.23	0.38	1

mean (1400.32), the negative binomial regression is adopted to analyze the unbalanced panel data [20]. Furthermore, the Hausman test [89] was employed to choose the fixed or random effects' model. Generally, the random effect model is accepted at the level of $p > 0.05$, and if $p < 0.05$, the fixed effect model is chosen. Moreover, correlation levels between variables (except dependent variables) are low, no more than 0.7, which excludes the possibility of multicollinearity.

4. Results

Tables 2 and 3 present the negative binomial regression results. Model 1 displays a basic model that tests all the control variables. Models 2–7 add independent variables related to knowledge attributes to the basic Model 1, separately. Models 8–11 add the moderating variable related to structural attributes of R&D alliance networks to the basic Model 1, respectively. Hypothesis 1 forecasts that the knowledge combinatorial potential facilitates organizational innovation capability. Model 2 in Table 2 shows a positive significant effect at the level of $p < 0.001$; thus, Hypothesis 1 is supported. The result indicates that organizations can benefit more from an increasing combinatorial potential of knowledge elements. However, Hypothesis 2 is not supported because there is no significant interaction effect between degree centrality and knowledge combinatorial potential (see Model 8 in Table 3).

Hypothesis 3 predicts that knowledge uniqueness has an inverted U-shaped effect on organizational innovation capability. Model 3 in Table 2 provides statistical support for the hypothesis. As shown in Model 3, knowledge uniqueness has a positive effect on innovation capability ($\beta = 8.203$ and $p < 0.001$), while knowledge uniqueness square has a significant negative effect on innovation capability ($\beta = -6.807$ and $p < 0.001$). Besides, our study tested the cubic of the variables further, and surprisingly, knowledge uniqueness cubic has a significant positive effect on innovation capability ($\beta = 8.252$ and $p < 0.05$) (see Model 4 in Table 2), which presents a nonlinear relationship. However, as shown in Figure 6, as the number of unique knowledge elements increases, it results in increasing of marginal returns in the early stage and slowly diminishing of marginal returns later. Therefore, Hypothesis 3 is partially supported. Hypothesis 4 forecasts that the degree centrality plays a moderating role in the relationship between knowledge uniqueness and organizational innovation capability. Model 9 in Table 3 shows a nonsignificant intereffect. Therefore, Hypothesis 4 is not supported.

Hypothesis 5 predicts that knowledge diversity has an inverted U-shaped relationship with organizational innovation capability. Model 5 in Table 2 provides statistical support for the hypothesis. That is, as shown in Model 5, knowledge diversity is positively related to its innovation capability ($\beta = 0.0349$ and $p < 0.001$), while the knowledge diversity square has a significant negative effect on innovation capability ($\beta = -0.0000638$ and $p < 0.001$). Besides, the results of the knowledge diversity cubic do not show in Table 2 because it is not significant. Therefore, with the diversified knowledge elements' overgrowth, the positive effect on innovation capability tends to reduce gradually (see Figure 7, the original curve). Hypothesis 6 forecasts that degree centrality plays a moderating role in the relationship between knowledge diversity and organizational innovation capability. Model 10 in Table 3 supports the hypothesis at a significant level of $p < 0.001$. Figure 7 presents an overview of the intereffect between knowledge diversity and degree centrality in three levels (high degree centrality, medium degree centrality, and low degree centrality), which shows that the inverted U-shaped effect of knowledge diversity on innovation capability is weaker for organizations with a high degree centrality in R&D alliance networks.

Hypothesis 7 forecasts that knowledge proximity has an inverted U-shaped effect on organizational innovation capability. As shown in Model 6, knowledge proximity is positively related to its innovation capability ($\beta = 26.75$ and $p < 0.001$), while knowledge proximity square presents a significant negative effect on innovation capability ($\beta = -73.83$ and $p < 0.001$). Besides, we tested the cubic of the variables further, and surprisingly, knowledge proximity cubic has a significant positive effect on innovation capability ($\beta = 488.5$ and $p < 0.001$) (see Model 7 in Table 2). It indicates that knowledge proximity shows an inverted S-shaped effect on innovation capability. Therefore, Hypothesis 7 is not supported. As shown in Figure 8, with the degree of knowledge proximity enhancing, it results in increasing of marginal returns in the early stage, sharply diminishing of marginal returns in the middle stage, and increasing of marginal returns in the later stage again. Hypothesis 8 predicts that degree centrality plays a moderating role in the relationship between knowledge proximity and organizational innovation capability. The result of Model 11 in Table 3 does not support this hypothesis.

5. Discussion and Conclusion

5.1. Discussion. Knowledge is a valued treasure and an essential resource for organizations. In our paper, the interorganizational knowledge bases are conceptualized as knowledge networks, and we investigated how knowledge attributes affect innovation capability. Besides, our research investigated one structural attribute of R&D alliance networks (degree centrality) and tested its interaction effects with the knowledge attributes of interorganizational knowledge networks in five Chinese high-tech industries based on the multilevel network approach.

The current study found that organizations with higher combinatorial potential in interorganizational knowledge networks can positively influence innovation outcomes. The result indicates that organizations with the high knowledge combinatorial potential have a higher opportunity to integrate and absorb diverse knowledge from their alliance partners. This finding is consistent with Brennecke and Rank [17], who found that inventors are dependent on the degree centrality of knowledge elements as the essential standard for inventive probabilities. In other words, high knowledge combinatorial potential plays a critical role in the innovation generation. However, this result differs from that of Wang et al. [20], who demonstrated that the average degree

Table 2: Negative binomial analysis of knowledge attributes and organizational innovation capability.

Variables	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Control variables							
Presample patent number	0.000436*** (11.32)	0.000386*** (12.20)	0.000336*** (5.79)	0.000333*** (5.85)	0.000118* (2.25)	0.000517*** (14.91)	0.000537*** (15.59)
Organization age	0.0126*** (5.37)	0.00378 (1.61)	0.00814** (2.79)	0.00819** (2.74)	0.00174 (0.89)	0.0107*** (4.88)	0.00982*** (4.53)
Cite patent	0.00000310 (1.95)	0.00000321* (2.28)	0.00000813*** (3.99)	0.00000793*** (3.95)	0.00000349 (1.69)	0.00000514*** (3.35)	0.00000557*** (3.62)
Industry	0.0303 (0.71)	−0.141** (−3.26)	0.248*** (4.36)	0.250*** (4.42)	0.101 (1.93)	−0.0418 (−1.03)	−0.0403 (−0.99)
Region	−0.00511 (−0.17)	−0.0183 (−0.63)	−0.0354 (−0.96)	−0.0416 (−1.13)	0.0667 (1.79)	−0.0853** (−2.92)	−0.0841** (−2.92)
Closeness centrality	−1.120 (−1.81)	−0.411 (−0.70)	1.253 (1.62)	1.123 (1.42)	−0.500 (−0.69)	−0.583 (−0.99)	−1.160* (−2.03)
Betweenness centrality	0.853*** (4.59)	0.841*** (5.97)	0.457 (1.92)	0.410 (1.73)	−0.0306 (−0.20)	0.834*** (4.92)	0.813*** (4.69)
Independent variables							
Knowledge combinatorial potential		2.746*** (15.25)					
Knowledge uniqueness			8.203*** (10.75)	11.81*** (7.15)			
Knowledge uniqueness^2			−6.807*** (−8.62)	−18.38*** (−3.81)			
Knowledge uniqueness^3				8.252* (2.42)			
Knowledge diversity					0.0349*** (18.13)		
Knowledge diversity^2					−0.0000638*** (−11.36)		
Knowledge proximity						26.75*** (10.35)	46.21*** (11.35)
Knowledge proximity^2						−73.83*** (−5.57)	−282.5*** (−7.17)
Knowledge proximity^3							488.5*** (5.72)
Constant	−1.725*** (−6.55)	−2.327*** (−9.14)	3.460*** (9.05)	3.495*** (9.05)	−2.249*** (−6.23)	−1.680*** (−6.70)	−1.636*** (−6.73)
Log likelihood	−2232.5325	−2096.8939	−1023.5422	−1020.5709	−997.10765	−2140.6111	−2123.298
Hausman test							
Wald chi2	6.65	14.41	14.84	16.49	0.00	−1.08	5.41
Prob > chi2	0.2553	0.0253	0.0382	0.0359	0.00	0.00	0.6100

Notes: observations = 381; z value in parentheses, * means $p < 0.05$, ** means $p < 0.01$, and *** means $p < 0.001$.

centrality of knowledge elements in knowledge networks has an inverted U-shaped relationship with exploratory innovation. A possible reason is that the dependent variable (the number of granted patents) in our research differs from exploratory innovation (the number of new knowledge elements explored by inventors). Concerning knowledge uniqueness, our study found that organizations with an excessive number of unique knowledge elements could hinder their innovation process. These results mirror previous studies that organizations possessing a large unique knowledge stock might decrease external exploitation and less actively search for new ideas from their alliance partners [33, 49].

Regarding knowledge diversity, results show that organizations cannot benefit more from overdiversified knowledge bases. These results are consistent with the findings of previous researchers that suggested that, as diversified knowledge elements increase, the technological distance becomes larger in knowledge networks, which may weaken organizational recognizing and absorbing capability [35, 61]. Moreover, previous researchers argue that knowledge networks and collaboration networks among inventors are decoupled [14, 20]. Our research found that they are slightly inter-act simultaneously after integrating studies of R&D alliance networks and their interorganizational knowledge networks. These results are similar to Brennecke and Rank [17], who found an interaction effect between knowledge networks and social networks among inventors. However, the distinct difference from previous research is that ours focuses on the interorganizational networks rather than the social networks in intra-organization. Our analysis of the interaction effects shows

Table 3: Negative binomial analysis of the interaction effect between knowledge attributes and degree centrality.

Variables	Model 8	Model 9	Model 10	Model 11
Control variables				
Presample patent number	0.000386*** (12.20)	0.000318*** (5.78)	0.000122** (2.62)	0.000527*** (14.72)
Organization age	0.00386*** (1.63)	0.00616* (2.10)	0.00257 (1.38)	0.0102*** (4.62)
Cite patent	0.00000319* (2.27)	0.00000853*** (4.68)	0.00000259 (1.34)	0.00000557*** (3.61)
Industry	−0.143* (−3.21)	0.144* (2.51)	0.112* (2.13)	−0.0642 (−1.49)
Region	−0.0176 (−0.59)	0.0155 (0.41)	0.0403 (1.05)	−0.0750* (−2.56)
Closeness centrality	−0.442 (−0.73)	−0.109 (−0.13)	−1.879* (−2.50)	−1.366* (−2.35)
Betweenness centrality	0.796*** (3.37)	0.254 (0.73)	0.452 (1.65)	0.514* (2.08)
Independent variables				
Knowledge combinatorial potential	2.703*** (8.99)			
Knowledge uniqueness		8.338** (2.84)		
Knowledge uniqueness^2		−10.07 (−1.22)		
Knowledge uniqueness^3		3.965 (0.70)		
Knowledge diversity			0.0510*** (15.30)	
Knowledge diversity^2			−0.000138*** (−10.10)	
Knowledge proximity				45.23*** (6.35)
Knowledge proximity^2				−267.5*** (−3.73)
Knowledge proximity^3				416.6** (2.57)
The moderating variable				
Degree centrality (DC)	−0.177 (−0.06)	6.101* (2.33)	0.574 (0.28)	2.240* (1.09)
Interaction effects				
Knowledge combinatorial potential × DC	0.592 (0.17)			
Knowledge uniqueness × DC		65.68* (1.99)		
Knowledge uniqueness^2 × DC		−127.9 (−1.45)		
Knowledge uniqueness^3 × DC		55.53 (0.93)		
Knowledge diversity ×DC			−0.109*** (−4.20)	
Knowledge diversity^2 × DC			0.000468*** (5.71)	
Knowledge proximity × DC				12.80 (0.13)
Knowledge proximity^2 × DC				−263.6 (−0.24)
Knowledge proximity^3 × DC				1536.1 (0.59)
Constant	−2.302*** (−7.20)	−3.312*** (−7.94)	−1.818*** (−5.27)	−1.681*** (−6.13)
Log likelihood	−2096.8635	−1005.4259	−982.69748	−2120.7159
Hausman test				
Wald chi2	15.43	152.34	28.24	18.41
Prob > chi2	0.0513	0.00	0.0004	0.00

Notes: observations = 381; z value in parentheses, * means $p < 0.05$, ** means $p < 0.01$, and *** means $p < 0.001$.

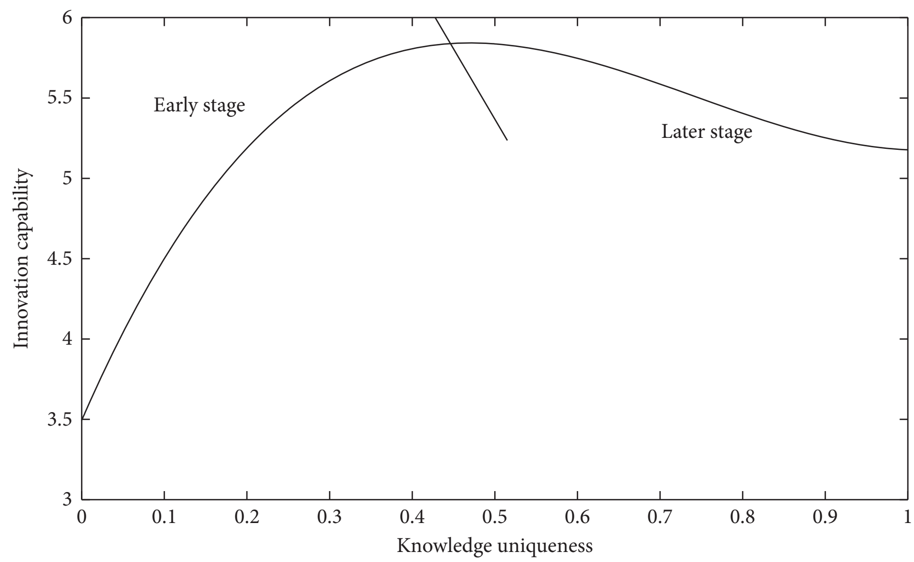

FIGURE 6: Effect of knowledge uniqueness and innovation capability.

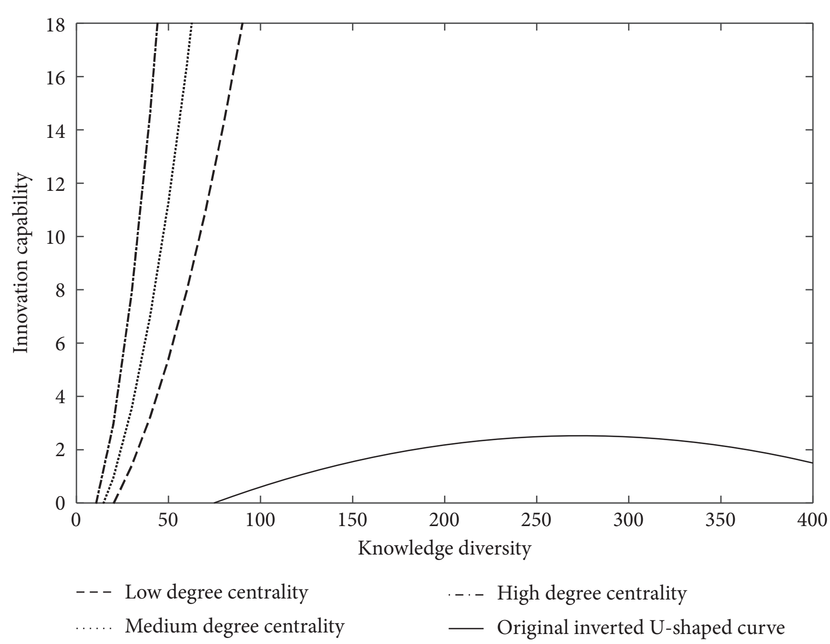

FIGURE 7: Effect of knowledge diversity and interaction effect between knowledge diversity and degree centrality.

that, among four knowledge attributes, organizations with diverse knowledge elements can receive more benefits from higher than from the lower degree centrality, which shows the advantages of high degree centrality in R&D alliance networks for organizations with overdiversified knowledge elements.

Furthermore, our research found that knowledge proximity has an inverted S-shaped effect on organizational innovation capability. Previous studies found that knowledge proximity facilitates knowledge sharing, exchange, and transfer among organizations [17]. However, in our study, we only find the increasing of marginal revenue in the early stage and later stage, which, to some extent, contradicts the technology lock-in effect [66, 94]. The possible reasons are as follows. First, when an organization has a low proximity knowledge base with its alliance partners in the early stage, technology complementary would increase the possibility of knowledge combination and enhance innovation capability. Second, at the middle stage, organizations could share part of diverse knowledge with their alliance partners, and the cost of integrating heterogeneous knowledge is still very high, so the marginal revenue turns to dimmish. Third, in the later stage, an organization has a high proximity knowledge base with its alliance partners and shares a common language. Although they only could share limited distinct knowledge, the cost of integrating heterogeneous knowledge is meager, which may increase the marginal revenue gradually.

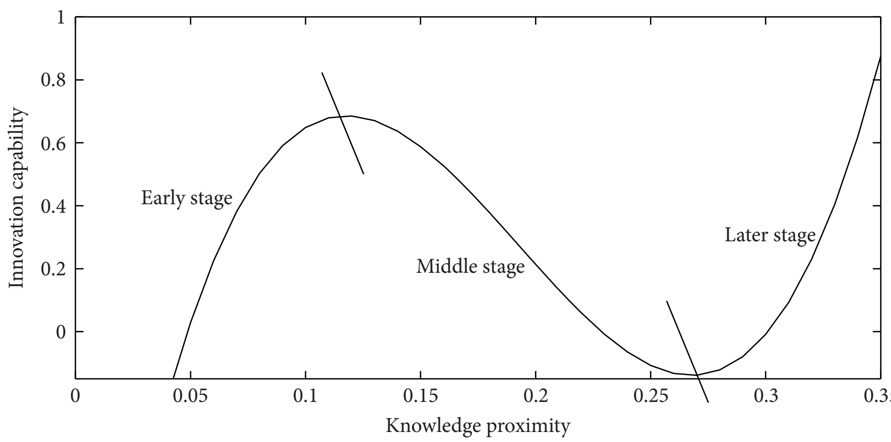

Figure 8: Effect of knowledge proximity and innovation capability.

6. Conclusion

The purpose of our research is to explore the impact of interorganizational knowledge networks' knowledge attributes on organizational innovation capability and to identify the impact of the interaction effect between R&D alliance networks and interorganizational knowledge networks on organizational innovation capability. The findings of our study answered the two research questions we proposed. First, different knowledge attributes show a distinct effect on organizational innovation capability, including linear relationship, inverted U-shaped curve relationship, and inverted S-shaped curve relationship. Empirical research results help us better understand how different knowledge attributes influence organizational innovation capability and stimulate interorganizational knowledge generation. Second, prior studies have noted the importance of the interaction effect between two distinct levels of networks in the interorganizational field [14]. We have examined this question further. Our findings show that the central position within R&D alliance networks finitely moderates the relationship between knowledge attributes of interorganizational knowledge networks and organizational innovation capability.

In the methodology, we introduced the multilevel network approach from the intraorganizational research field to address innovation management issues in the interorganizational field [17, 40, 41]. Only a few empirical studies use this method in the existing literature to analyze the R&D alliance network, especially for its interorganizational knowledge networks. Following the previous research method, we developed a new multilevel network framework to capture additional knowledge attributes. This approach will prove useful in expanding our understanding of how to integrate alliance networks and their interorganizational knowledge networks.

Our research has two unique contributions to the current study on interorganizational and network theory. First, we employ an interorganizational knowledge network perspective to describe the knowledge bases of alliances. Our study showcases the importance and viability of utilizing a multilevel network framework and advanced network analysis tools to explore the knowledge attributes of interorganizational knowledge networks. Second, above and beyond the traditional focus on alliance network structures, our research investigates the intereffect with the interorganizational knowledge network, which can enrich our understanding of interorganizational knowledge management from a new perspective.

Our findings have several implications for innovation managers. The main pertains to the knowledge management of R&D alliances. First, these results reported above suggest that knowledge combination potential is positively related to organizational innovation capability. Innovation managers should consider carrying out more innovative cooperation activities with their alliance partners. In this way, organizations could enrich their knowledge elements' combinatorial history and enhance the links between knowledge elements, which would lay a solid base for knowledge elements to occupy the central position in interorganizational knowledge networks. Second, another finding suggests that knowledge uniqueness cannot be possessed excessively by organizations because it presents an inverted U-shaped effect on innovation capability. For organizations with an excessive number of unique knowledge elements, they should consider exploring more cross-domain technology integration projects and improving the applicable fields of unique knowledge elements through increasing external exploration and actively searching for new information from their alliance partners. Third, for organizations with redundant knowledge elements, innovation managers can improve the ability to absorb and recognize new knowledge elements through training of R&D personnel and improving the R&D system or they can reduce the high cost of innovation activities in the form of R&D outsourcing, so as to increase the organizations' innovation benefits. Finally, innovation managers should be aware of controlling the degree of proximity knowledge with their alliance partners, avoiding getting stuck in the middle stage. This requires innovation managers to thoroughly measure the closeness of their own organizations' knowledge base to the target cooperators' knowledge bases and then to formulate targeted knowledge combination strategies to improve innovation income. For the second broad recommendation, innovation managers should be aware that the interaction of the R&D alliance network (interorganizational network based on R&D partnership) and the interorganizational knowledge networks (combination history of organizational or interorganizational knowledge elements) has an impact on the organizational innovation capability. R&D alliance networks and interorganizational knowledge networks are two different networks, but they inter-act with each other. Organizations located in distinct network positions could affect the effectiveness of their knowledge combination in interorganizational knowledge networks. According to our findings, organizations located in the central position within R&D alliance networks play a vital role in the relationship between knowledge diversity and organizational innovation capability. The positive influence of an organization with excessively diverse knowledge on innovation capabilities will not diminish when the organization is located in the center position of R&D alliance networks. Similarly, organizations' knowledge elements with distinct attributes or different locations in interorganizational knowledge networks could affect the organization's choice of its future alliance partners. Overall, our findings could be used to help organizations sort out their knowledge attributes of knowledge bases and come to understand the impact of the interaction between interorganizational knowledge network and R&D alliance network on the organizational innovation capability and then make a targeted alliance and knowledge management strategy to carry out innovation activities and enhance their innovation capability.

While our research has implications for theory and practice guidance, it is not without limitations. First, although we choose the alliance samples from five high-tech industries in China, our findings cannot be directly generalized to other countries. Nonetheless, the methodology of our study could be replicated in other settings. Second, our research only sets out the construction of interorganizational knowledge networks from explicit knowledge and ignores the essential tacit knowledge transfer between organizations. Our study uses the four-digital IPC code as the knowledge element because it is easy to display and quantify. However, these codes may not adequately present the process and mechanism of knowledge diffusion among organizations. Therefore, researchers are encouraged to expand our construction method of the interorganizational knowledge network in future research.

Data Availability

The (alliance sample) data used to support the findings of this study have not been made available because the data also forms part of an ongoing project. The (patent) data used to support the findings of this study were supplied by IncoPat patent database (https://www.incopat.com/) under license and so cannot be made freely available. Requests for access to these data should be made to Beijing INCOPAT CO., LTD., (service@incopat.com).

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

An Improved PageRank Algorithm Based on Text Similarity Approach for Critical Standards Identification in Complex Standard Citation Networks

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A standard system, which is a powerful tool in maintaining the normal operations and development of a specific industry, is intrinsically a complex network composed of numerous standards which coordinate and interact with each other. In a networked standard system, the identification of critical standards is of great significance when drafting and revising standards. However, a majority of the existing literature has focused on the citation relationships between standards while ignoring the intrinsic interdependent relationships between the contents of standards. To overcome this limitation, we utilize the text similarity approach (TSA) to quantify the relationship intensity between each pair of standards, in order to generate a directed weighted network. The critical contribution of this study is that the similarity computed by the TSA is incorporated into the traditional PageRank algorithm for the identification of critical standards. The improved algorithm comprehensively considers the quantity and importance of neighboring standards and the citation intensity, as quantified by TSA. The algorithm is finally validated using the Chinese environmental health standards through comparison with the traditional PageRank algorithm and different classic measurements.

1. Introduction

Standards refer to the normative documents formulated by consensus and issued by recognized institutions, in order to achieve the best operations within a certain scope. In the current knowledge economy era, the orderly operation of any industry is basically inseparable from standards, where the quality of standards reflects a country's economic and technological level to a large extent [1–4]. Standards often play a synergistic role in the form of a standard system, which refers to an organic whole composed of numerous standards that interact and coordinate with each other. The specific manifestation of interaction and coordination is the citation between standards, which maps the transmission of information and knowledge carried by standard documents. Therefore, a standard citation network is also a transmission network of information [5].

A networked standard system has the scale-free characteristic, in which a minority of standards play dominant roles in controlling the transmission of information and knowledge [6]. In standardization activities, it is very important to identify the critical standards, in order to assist decision-making in revising or drafting standards. Specifically, we should optimize the structure of existing standard systems in diversified application areas by creating effective and reasonable links between newly drafted standards and existing standards, with the aim of enhancing the systematicness, compatibility, and coordination. The newly created links, in the form of citations, should reflect the essential relationships between standards. In this situation, ignoring critical standards may lead to poor system structure or standard conflicts. In the process of revising standards, we also should pay attention to the most significant standards, in order to maximize their economic or social effects, due to limited resources (i.e., in terms of people, budgets, and time.)

However, it is difficult and/or time-consuming to identify the critical standards in massive standard documents when we consider only individual standards while ignoring their interactions. In addition to network methods, the criticality of standards can be assessed by many traditional methods, such as AHP, ANP, and TOPSIS [7–9]. However, these methods can hardly address the interactions between standards and are subjective in selecting measurements and determining weights. In recent years, the literature has begun to pay attention to identifying the critical standards in directed standard citation networks, which are useful in disclosing the evolution of standard networks [10, 11]. However, in the previous literature, the citations between standards have been represented by adjacent matrix without weights, which provide limited information. In reality, the citations between standards differ in intensity, which should be determined by assessing the intrinsic relationships between the contents of each pair of standards. To overcome this shortcoming, the text similarity approach (TSA) is introduced to quantify the relationship between each pair of standards and further form a directed weighted network. The similarity degree metric as computed by the TSA is used to improve the traditional PageRank algorithm for identification of critical standards.

The PageRank algorithm was originally used by Google to rank web-pages [12] embedded in search engines. As web page networks and citation networks have similar structures, many scholars have introduced this algorithm for the identification of important nodes [13–16]. However, the traditional PageRank algorithm also has some limitations. For example, in each iteration of this algorithm, every node distributes its PageRank (PR) value equally to its immediate downstream nodes, which makes it incapable of reflecting the fact that important nodes often have a stronger ability to build influence. Therefore, we argue that the PR value distribution is unbalanced; for example, a standard cites two other standards, then the standard with a more similar topic should be assigned a higher PR value than the other in each iteration. So, in order to overcome this limitation, we propose an improved PageRank algorithm based on TSA. In this new algorithm, PR values quantified by TSA are assigned as the weights in each iteration. The improved algorithm comprehensively considers the quantity and importance of neighboring standards and the citation intensity between each pair of standards, as quantified by the TSA. Our experimental results show that the improved PageRank algorithm behaves better than the traditional PageRank algorithm.

2. Literature Review

This study focuses on the identification of critical standards using an improved PageRank algorithm based on a network model. The network model was developed by integrating the information with respect to citations and similarity, as quantified by TSA. In the following, we review the two main streams of literature on citation network analysis and the application of TSA.

2.1. Citation Network Analysis. To date, citation network analysis has been widely used in different kinds of citation networks, such as journal citation networks, paper citation networks, and patent citation networks. However, its application in standard systems is still in its infancy. Based on citation networks, the collaborations between authors, institutions, and countries can be investigated by constructing collaboration networks. The theories and methods used in other citation networks are valuable for our investigation of standard citation networks, due to their similarities.

Garfield [17] originally proposed the evaluation of journal articles through citation criteria. The network analysis approach was introduced into the area of citation analysis by Small [18], in which co-citation was used to quantify the relationships between articles. In 1985, Doreian [19] proposed the concept of stratified journal network where the nodes are journals and the relations are citations aggregated over the articles in these journals. Calero-Medina et al. [20] constructed a paper citation network by collecting citation data between papers in specific fields from 1990 to 2005 and analyzed the development path of future research. With the pure number of citations becoming one of the most important factors of measuring the scientific impact and quality of authors, Fister et al. [21] established a three-layer network and proposed two scenarios with SPARQL queries to find citation cartels, which boldly revealed a common academic phenomenon. In 2014, Tobias et al. [22] analyzed the memes in scientific literature and defined the product of the frequency of occurrence and the propagation score along the citation graph as the meme score; this research provided new directions and inspiration for citation networks. In addition, many scholars have applied the PageRank algorithm to paper citation networks. Singh et al. [23] used the PageRank algorithm to rank papers based on a citation network. Qiao et al. [24] defined the value of each paper by using an improved weighted PageRank algorithm in combination with journal impact factors. Garcia et al. [25] transformed the rules of social impact of papers in a citation network into a mathematical equation, in order to predict the level of social impact of academic papers in the citation network, by using cooperative game theory.

Narin [26] was the first scholar to apply the citation network analysis method to the field of patents, opening up a new direction of patent literature measurement. Subsequently, Li et al. [27] analyzed the topological structure of a nanotechnology patent citation network through social network analysis (SNA). Cho and Shi [28] selected 42,650 patent documents issued by Taiwan from 1997 to 2008 and identified five core technologies and emerging technologies that affected Taiwan's economy by analyzing the associated patent citation network. Fujita et al. [29] established a directed weighted network with patent timeliness and text relevance between patents as mixed parameters, aiming to assess the limitations of undirected citation networks. Beltz et al. [30] adopted a sorting algorithm based on reinforcement learning to rank patents in the patent citation network, comparing it with the traditional PageRank algorithm. Their results showed that this algorithm behaves better than the traditional PageRank algorithm.

In addition, previous research on standards has mainly focused on standardization activities and the impact of standard implementation on social and economic benefits [31–34]. As introduced previously, many standards compiled together with complicated interactions form a complex standard network. The structure plays a fundamental role in achieving the objectives of standard systems. However, the previous research has remained incapable of addressing such structural problems. In recent years, some scholars have begun to pay attention to the topological characteristics of standard citation networks. For example, in 2018, Wei et al. [10] established a dynamic standard citation network model and analyzed the structural problems existing in the standard system of China's automobile industry. To identify important standards, Wei et al. [11] proposed an integrated multi-criteria decision-making method, which combined the entropy weight (EW) method and a TOPSIS method based on traditional node measurements, such as degree centrality and betweenness centrality. However, their existing research focused on simple 0-1 citation relationships, while ignoring the magnitude information of the relationships between pairs of standards, which can be reflected by their connections in terms of document contents.

2.2. Application of Text Similarity Approach. TSA, which is a type of text mining method [35–37], is employed to quantify the relationship between standards in this study. At present, the literature on TSA is extensive and many algorithms have been proposed, including the cosine similarity algorithm, Levenshtein distance algorithm, SimHash algorithm, and Euclid distance algorithm. These algorithms generally include four main steps: text segmentation, extracting text keywords, converting spatial vectors using the word frequency, and calculating the text similarity using the relevant algorithm.

The theories and methods of TSA have been widely used in various research fields. Originally, Salton et al. [38] proposed the VSM (vector space model) in the 1970s. The core idea of VSM is to simplify the processing of text content into vector operations in a vector space, as well as expressing semantic similarity using spatial similarity. This intuitive and understandable form is the most widely used method for text association analysis. Andy and Alice [39] designed an algorithm to extract the core content of the design model using the basic idea of text mining and the Bayesian belief network model, in order to promote the sharing of information among designers. In 2007, Tseng et al. [40] proposed a set of perfect text mining technologies to assist patent analysts in carrying out various types of data analysis, the specific algorithm used in the present paper was greatly inspired by this research. In addition, some scholars have attempted to introduce the TSA into the traditional PageRank algorithm, in order to develop a better algorithm for web page ranking [41, 42]. However, from the application perspective, to the best of our knowledge, the TSA or PageRank algorithm has seldom been used in analyzing standard documents.

In summary, the current research on standard citation networks is still at an early stage. The previous literature has failed to consider the intrinsic relationships with respect to content between standards, rather than just 0-1 citation scoring. Consequently, the existing network models are represented as adjacency matrices with only two elements: 0 and 1. This is highly insufficient for measuring the significance of standards. On the other hand, text mining has provided fruitful algorithms for quantifying the similarity between different kinds of documents, which motived us to use TSA for the identification of critical standards in standard networks.

3. Network Model Construction Based on TSA

In this paper, TSA is employed to quantify the relationship between each pair of standards and, further, to form a directed weighted network, which lays the foundation for designing an improved PageRank algorithm. The overall procedure for critical standard identification is shown in Figure 1. It is noteworthy to emphasize that the TSA is only applied to the pairs of standards with citation relationships, in order to improve the computational efficiency. This is particularly important in the situation where the number of standards is very large.

A directed unweighted standard citation network is firstly established. After obtaining the text similarities between pairs of standards with citation relationships, a directed weighted network based on text similarity is established. Finally, the improved PageRank algorithm is used for the identification of critical standards.

3.1. Quantifying the Citation Intensity with TSA. The key part of network construction lies in the calculation of similarity values between each pair of standards. In the following, the implementation of the text similarity algorithm is described. The source code for the TSA method is included in the supplementary material (available here).

This paper mainly combines the vector space model (VSM), the TF-IDF (term frequency-inverse document frequency) method, and the cosine similarity algorithm to calculate the text similarity value between each pair of standards with a citation relationship. The TF-IDF method is a common weighting technique used for information retrieval and data mining [43, 44]. After processing, the standard document is transformed into an n-dimensional vector composed of keyword frequencies. Further, the keyword frequencies are converted into keyword values by weighting with the TF-IDF method. Then, the text similarity values between standards are calculated using the cosine value algorithm.

The cosine value of two n-dimensional spatial vectors $\vec{x} = (x_1, x_2, \ldots, x_n)$ and $\vec{y} = (y_1, y_2, \ldots, y_n)$, $\cos\beta$, is calculated as

$$\cos\beta = \frac{\vec{x}\bullet\vec{y}}{|\vec{x}||\vec{y}|} = \frac{\sum_{i=1}^{n}(x_i \times y_i)}{\sqrt{\sum_{i=1}^{n} x_i^2} \times \sqrt{\sum_{i=1}^{n} y_i^2}}. \quad (1)$$

The specific process of the TSA is depicted as Figure 2.

Step 1 (content extraction from standard documents): content extraction lays the foundation for similarity

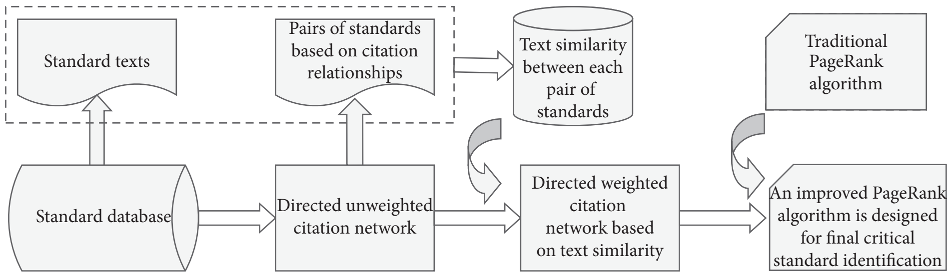


Figure 1: The overall procedure of critical standards identification.

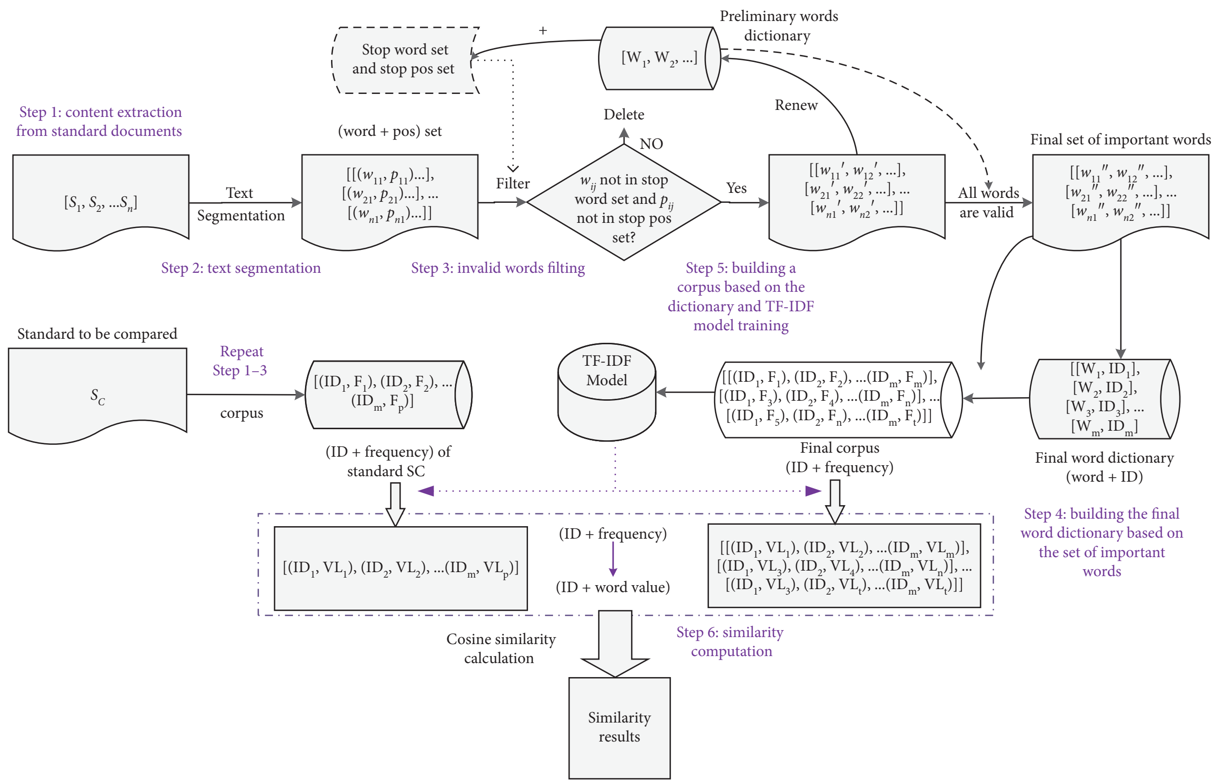


Figure 2: The specific process of text similarity analysis.

analysis. In this study, we do not extract all the sentences of an original standard document for similarity calculation, as the use of too many useless sentences greatly increases the computational time and may lead to large deviations in the similarity results. In this study, we manually reviewed all the standard documents and selected the most significant sentences that matched the theme of each standard. In particular, all the titles were included, whereas all the tables and figures were excluded from analysis.

The process includes six steps: content extraction, text segmentation, invalid words filting, building word dictionary, building corpus and TF-IDF model, and similarity computation.

Step 2 (text segmentation): text segmentation is an important step in the preprocessing of text mining. In this step, each original standard text is transferred into a set of "word + part of speech (pos)."

Step 3 (invalid words filtering): invalid words are automatically filtered out, in order to save storage space and increase computational efficiency during the text similarity calculation. In this step, we use a stop word set and a stop pos set to filter the invalid words. Invalid words mainly include auxiliary words and tone words. In this step, we have a list of invalid words and a list of corresponding pos (called stop word set and stop pos set). The words in the stop word set mainly include auxiliary words and tone words. As we cannot enumerate all the words, we think to be invalid at once, in order to increase the efficiency of filtration, we add an extra stop pos set including all the invalid, such as conjunctions and adverbs. Then, all the "word + pos" sets obtained in the previous step are double-conditionally filtered, where the words are retained only if the words and corresponding pos are neither in the stop word set nor the stop pos set. At the same time, the filtered results form a preliminary word dictionary. We check this dictionary carefully and add the missing words which we think are invalid into the list of invalid words, followed by filtering again. The above process is repeated until the word dictionary includes all the important words; this process also makes the final calculation results as scientific as possible.

Step 4 (building the final word dictionary based on the set of important words): the main work of this step is to assign a specific ID to all the important words for subsequent quantitative processing.

Step 5 (building a corpus based on the dictionary and TF-IDF model training): the corpus is a list of sparse vectors. After this step, each standard document is transferred into an important word list, stored in the form of "word ID + word frequency." Then, TF-IDF model training is in process. It can be understood that the TF-IDF model is used to measure a word's value, relative to an article, based on the word's word frequency. After obtaining the TF-IDF model, all the important word lists above are stored in the form of "word ID + word value."

Step 6 (similarity computation): the procedure from Step 1 to Step 3 is repeated for all the standards to be compared. Then, the standard contents are transferred into a list in the form of "word ID + word value" based on the corpus and TF-IDF model obtained in Step 5. Further, the text similarities between this standard and the other standards are calculated using formula (1), which gives the final standard's similarity matrix. After repeating all the steps for each standard, we finally obtain the final similarity result between each standard.

3.2. Network Model Construction. After calculating the text similarity of standards, we can quantify the citation intensity between each pair of standards. A weighted and directed standard citation network can be represented as a set composed of three subsets: $\mathcal{G} = \{\mathcal{N}_s, \mathcal{E}_c, \mathcal{T}_t\}$, where the node set $\mathcal{N}_s = \{s_1, s_2, \ldots, s_n\}$ includes n standards, $\mathcal{E}_c = \{\langle s_i, s_j\rangle > |s_i, s_j \in \mathcal{N}_s\}$ is the set of directed edges based on the citation relationship, and $\mathcal{T}_t = \{\xi_{ij} | \langle s_i, s_j\rangle \in \mathcal{E}_c\}$ is the set comprised of the text similarity of each pair of standards $\langle s_i, s_j\rangle$ corresponding to the edges in $\mathcal{E}_c$, as computed by the TSA algorithm described above. From the view of the model, the set $\mathcal{T}_t$ reflects the substantial difference between the model herein and the citation network model of standards in the existing literature, in which only the citation relationship has been considered [10, 11]. By incorporating the similarity relationship, the standard system becomes a directed and weighted network, which subsequently changes the network measurements. For ease of computation, the citation relationships between standards can be represented as a weighted adjacency matrix $\mathbf{A}^w = (a_{ij}^w)^{n\times n}$, $i, j \in \mathcal{N}_s$, in which $a_{ij}^w = \xi_{ij}$ if standard i cites standard j, and $a_{ij} = 0$ otherwise.

4. Critical Standards Identification with an Improved PageRank Algorithm

The standard network model provides an important foundation for the identification of critical standards. However, in this study, as the standard system is represented as a weighted network with similarities as weights, the network measurements are substantially different from those of traditional unweighted networks. In this study, we focus on the well-known PageRank algorithm, which has been used by Google for their search engine and has been widely applied in citation networks for node evaluation. We note that the traditional PageRank algorithm equally distributes the PR values to its downstream nodes, which can be improved by considering the importance difference of downstream nodes as characterized by the similarity metric. In this section, we start by analyzing the limitations of the traditional PageRank algorithm and then propose the improved PageRank algorithm for critical standard identification.

4.1. Traditional PageRank Algorithm. The PageRank algorithm was originally used by Google to evaluate the importance of web-pages. In a standard citation network, the higher PR value a standard has, the greater importance the standard has. Two basic assumptions are made when applying the PageRank algorithm to standard citation networks:

(1) *Quantity Assumption.* A standard cited by more other standards is more likely to be important.

(2) *Quality Assumption.* A standard cited by higher quality standards is more likely to be important.

The quantity assumption is usually reflected by other network measurements, such as degree centrality and entropy [45]. As the concept of quality is abstract, there are various quality or importance measurements for network nodes. In the PageRank algorithm, the quality or importance of a standard in a network is measured by its PR value. The PR value of a node can be transmitted to its neighboring nodes.

The process of the PageRank algorithm is described as follows. In the initial stage, each standard is evenly assigned a PR value $1/n$, where n represents the number of standards in the citation network. Then, a new round of PR value allocation follows, with each standard distributing its current PR value equally to the standards cited by this standard, based on its out-degree. Each cited standard obtains the corresponding PR value from the upstream citation standards. Then, each standard sums all the incoming PR values from the upstream citation standards, in order to update a new PR value. When each standard has an updated PR value, a round of PageRank calculations is completed. After some iterations, the PR value for each standard tends to a stable value, which is the final PR value of each standard. The specific formula of the algorithm is as follows:

$$\mathrm{pr}_t^i = (1-\gamma)\frac{1}{n} + \gamma \sum_{s_j \in \mathscr{M}(s_i)} \frac{\mathrm{pr}_t^j}{L(s_j)}, \quad (2)$$

where pr_t^i is the PR value of standard s_i, $\mathscr{M}(s_i)$ is the set of upstream standards that cite standard s_i, $L(s_j)$ is the number of standards that standard s_j cites, and γ represents the damping factor.

4.2. An Improved PageRank Algorithm. The traditional PageRank algorithm was originally designed to rank the importance of web-pages. However, there exist some differences between standard citation networks and the web page networks, in terms of network structure and topological properties. In the following, we introduce the limitations in the case where the algorithm is directly applied to the critical standards identification.

The major limitation is related to the distribution mechanism of the PR values. For a web page in a web page network, the quantity and quality of the web-pages linked to this web page determine the page's final PR value. The traditional PageRank algorithm is an unbiased allocation algorithm, namely, the PR value of a page is distributed equally, according to the number of pages linked to this page, in each iteration. However, in practice, the pages differ in information quality, and the quality of the pages linked to a page also highly differ. Hence, the final ranking results may be inconsistent with the real influence of web-pages, without considering the importance of linked pages and redesigning the distribution mechanism of PR values.

If a standard in a standard citation network distributes its PR value equally (i.e., only according to its out-degree), the final ranking results may also not be rational. This is because the information transmission between standards that are closely related to each other plays a critical role in forming the structure of the standard systems. In other words, we should take the citation quality between standards into account. To deal with this problem, we use the text similarity to reflect the citation quality and to distribute the PR values. When distributing the PR values in each iteration, the standards whose topics are close to that of standard s_j in $\mathscr{M}(s_i)$ obtain high PR values from standard s_j.

A minor limitation is related to the damping factor γ. The damping factor γ indicates the probability that an user will continue to browse a web page, and $1-\gamma$ indicates the probability that the user will reopen a new page to browse. In the traditional PageRank algorithm, the value of γ is set as 0.85 [46]. Chen et al. [47] found that the citation distance of the paper citation network is smaller than that in web page networks, where the average is 2. Therefore, when the PageRank algorithm is applied to a paper citation network, the damping factor has been suggested set as 0.5. As standard citation network and paper citation network have similar network structure and topological properties, we also set γ as 0.5.

4.3. An Improved PageRank Algorithm Based on Text Similarity Analysis. Based on the above description, we propose an improved PageRank algorithm based on TSA. The source code for the improved PageRank algorithm is included in the supplementary material. In this algorithm, the damping factor γ is set to 0.5, and every standard distributes its PR value using the weights measured by the TSA. The specific formula of the improved PageRank iteration algorithm is expressed as

$$\mathrm{pr}_m^i = (1-\gamma)\frac{1}{n} + \gamma \sum_{s_j \in \mathscr{M}(s_i)} \mathrm{pr}_m^j \times \frac{\xi_{ji}}{\sum_{s_k \in \mathscr{D}(s_j)} \xi_{jk}}, \quad (3)$$

where $\mathscr{D}(s_j)$ is the downstream standard set of standard s_j and ξ_{jk} is the text similarity value between standard s_j and standard s_k. Compared with the traditional PageRank algorithm, the substantial difference of our improved PageRank algorithm lies in the allocation mechanism of PR values, with consideration of the association degree between upstream and downstream standards, in terms of similarity.

5. Empirical Analysis

The area of environmental health focuses on all aspects of the natural and built environment affecting human health. Thus, improving environmental health is an important foundation for guaranteeing human safety and realizing sustainable development. The standards associated with environmental health have played effective roles in controlling the environmental factors and mitigating the related risks that affects public health through a series of standardization activities. Due to the interdependence of individual standards, an environmental health standard system is a typical complex network, which should be established with desired performance with respect to systematicness, compatibility, and coordination, which are intrinsically determined by the network structure. In the process of drafting and revising standards, we must pay attention to the critical standards, in order to optimize the system structure. Therefore, effective algorithms or measurements for the identification of critical standards are highly important.

In this section, we focus on demonstrating the effectiveness of the proposed improved PageRank algorithm, in contrast to the traditional one, with realistic data of environmental health standards. Since the existing measurements or algorithms differ from each other, it is difficult to compare them directly. Therefore, we propose two assumptions for indirect validation. Firstly, a strong algorithm should be closely related to classical measurements. Secondly, a strong algorithm should generally identify more common critical standards than classical measurements. These two assumptions are justified by the fact that different measurements or algorithms share a common objective of assessing node importance despite their distinctions. The validation process was carried out in two steps. In the fist step, we assessed the correlation differences between the two PageRank algorithms and classical measurements. In the second step, we compared the differences with respect to the capability of critical standards identification of these two algorithms. This was performed by analyzing the proportion of common critical standards identified simultaneously by the different classical measurements and each PageRank algorithm.

5.1. Data Collection and Network Visualization. We selected 103 standards on environmental health from the category of health-related standards from *National Health Commission of the People's Republic of China* (http://www.nhc.gov.cn/wjw/pgw/wsbz.shtml). The corresponding citation relationship was established by viewing the normative document of each standard and confirmed on the website of the *National Public Service Platform for Standards Information* (http://std.samr.gov.cn/gb) to ensure the accuracy of the data. After obtaining each standard's citation data, each standard was assigned with a unique ID from "S1" to "S103," and an initial adjacency matrix with 0-1 elements of the citation network, as established in the EXCEL 2019. The adjacency matrix of the standard citation network was then imported into Gephi, an open-source visualization software for network analysis, in order to visualize the network structure, in which each node represents a standard and each directed edge represents a citation relationship, as shown in Figure 3. The classical node measurements, including degree centrality, eigenvector centrality, eccentricity, and betweenness centrality, were also computed by Gephi. Then, the TSA was performed to update all the "1" elements in the adjacency matrix to form a weighted and directed network. After that, the improved PageRank algorithm was programmed in Python 3.7.3 to rank the importance of standards. The detailed information of standards mentioned in this paper is shown in Table 1. In the following, we represent the results of the classical measurements, in order to validate the effectiveness of our improved PageRank algorithm for critical standards identification.

Each node represents a standard; the directed edges represent the citation relationship. The size of nodes is displayed according to its in-degree, and the nodes holding the same out-degree share the same color.

5.2. Results of Classical Measurements

5.2.1. Selection of Classical Measurements. Extensive literature in the field of network analysis has been devoted to the concept of centrality, which aims at answering a fundamental question: which nodes occupy the core positions of a network? Some centrality measurements have been proposed to evaluate the importance of nodes [48–51]. We selected four widely investigated measurements, namely, degree centrality, eigenvector centrality, eccentricity, and betweenness centrality, to evaluate the importance of China's environmental health standards system and to validate the improved PageRank algorithm.

It should be noted that the weighted adjacency matrix constructed in this paper was only used in our improved PageRank algorithm. The citation relationship between standards here was represented as an unweighted adjacency matrix $A^u = (a^u_{ij})^{n\times n}$, $i, j \in \mathcal{N}_s$, in which $a^u_{ij} = 1$ if standard i cites standard j, and $a^u_{ij} = 0$ otherwise.

(1) Degree Centrality. In a directed standard citation network, degree centrality is divided into in-degree and out-degree. In general, a standard with high in-degree reflects the fact that many standards cite it, indicating its strong impact across the whole network [11]. In contrast, the relationship between out-degree and node importance is implicit. The in-degree of standard $i \in \mathcal{N}_s$, $\mathrm{dc}^i_{\mathrm{in}}$, is defined as $\mathrm{dc}^i_{\mathrm{in}} = \sum_{j\in\mathcal{N}_s} a^u_{ji}$, which reflects the number of standards that cite the concerned standard. Similarly, the out-degree of standard $i \in \mathcal{N}_s$, $\mathrm{dc}^i_{\mathrm{out}}$, is defined as $\mathrm{dc}^i_{\mathrm{out}} = \sum_{j\in\mathcal{N}_s} a^u_{ij}$, which reflects the citation count of standard i.

(2) Eigenvector Centrality. Degree centrality has the limitation of only considering the number of neighboring standards, while the eigenvector centrality, which is similar to the PageRank algorithm, overcomes this problem by considering the importance or quality of neighboring standards. The eigenvector centrality gives a relative score to each node in the network, as proportional to the sum of the eigenvector centrality of all the nodes connected to it [52]. In a standard citation network, the higher eigenvector centrality a standard has, the more important the standard is. The eigenvector centrality of standard $i \in \mathcal{N}_s$, ec^i, is represented as

$$\mathrm{ec}^i = \frac{1}{\lambda}\sum_{j\in\mathcal{N}_s} a^u_{ji}\mathrm{ec}^j, \quad (4)$$

where λ represents the eigenvalue of adjacency matrix $\mathbf{A}$.

(3) Eccentricity. Eccentricity is a different measurement, which defines the importance of a standard by describing its "influence transfer depth" in the network. Eccentricity refers to the maximal distance from a node to other nodes in a network [50]. In a standard citation network, a standard with high eccentricity has a persistent impact on other standards. The eccentricity of a standard $i \in \mathcal{N}_s$, et^i, is represented as

$$\mathrm{et}^i = \max\left(\mathrm{len}_{ji}\right)_{j\in\mathcal{R}_i}, \quad (5)$$

where $\mathcal{R}_i$ is the set of standards that standard i can transmit information to a certain path in the network and len_{ji} is the length of the shortest path between standard j and standard i.

(4) Betweenness Centrality. The betweenness centrality is a measure of centrality in a network based on the shortest paths, which refers to the ratio of the number of shortest paths passing through a node to the total number of all the shortest paths in the network [53]. Consequently, a standard with high betweenness centrality plays a hub-role in information transmission. The betweenness centrality of a standard $i \in \mathcal{N}_s$, bc^i, is represented as

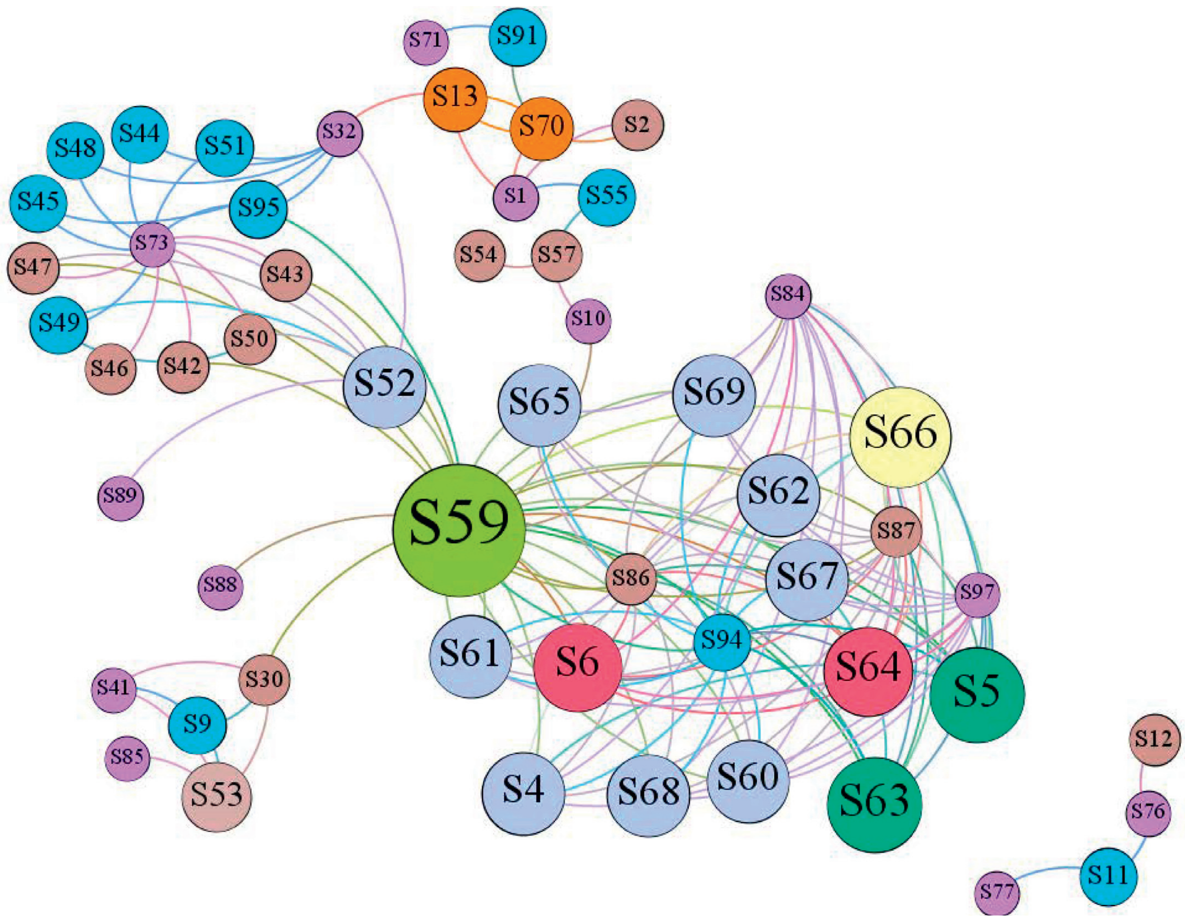


FIGURE 3: The China's environmental health standard citation network.

TABLE 1: The detailed information of the standards mentioned in this paper.

Id	Standards name
S59	Hygienic standards for drinking water
S66	Standard test method for drinking water: indicators of disinfection by-products
S5	Standard test method for drinking water: indicators of organic matter
S63	Standard test method for drinking water: sensory properties and physical indicators
S64	Standard test method for drinking water: indicators of inorganic nonmetal
S6	Standard test method for drinking water: indicators of metal
S4	Standard test method for drinking water: indicators of pesticide
S67	Standard test method for drinking water: indicators of disinfectant
S61	Standard test method for drinking water: collection and preservation of water samples
S60	General principles of hygienic standards for drinking water
S52	Hygienic standards for hotel
S30	Hygienic standards for planning of village and town
S95	Hygienic standards for restaurants
S94	Hygienic standards for secondary water supply facilities
S70	Indoor air quality standards
S47	Hygienic standards for gymnasiums
S91	Hygienic standards for inhalable particulate in indoor air
S53	Hygienic requirements for innocuous feces
S87	Safety evaluation standards for drinking water distribution equipment and protective materials
S97	Quality assurance specification for biological monitoring
S84	Standard for determining the chronic arsenic poisoning area of residents caused by environmental arsenic pollution
S86	Sanitary safety evaluation of chemical treatment agent for drinking water

$$\text{bc}^i = \sum_{m,n \in \mathcal{N}_s} \frac{\sigma(m,n|i)}{\sigma(m,n)}, \tag{6}$$

where $\sigma(m,n)$ is the number of all the shortest paths from standard m to standard n and $\sigma(m,n|i)$ is the number of those paths passing through standard i other than standard m or standard n. It is important to notice that standard i cannot be either the starting or ending node, that is, $i \cap (m,n) = \varnothing$.

It should be noted that this paper is not a denial of these classical measurements but, instead, inheriting and improving them. The improved PageRank algorithm not only comprehensively considers the quantity and quality of neighboring standards but also highlights the quality of the citation between the standards as quantified by TSA.

5.2.2. Results of Classical Measurements. In view of the large number of standards, we only represent the top ten standards in criticality identification in this paper, as shown in Table 2. As the in-degree can better reflect the importance of the standard than out-degree, we mainly analyzed in-degree centrality. As can be seen from Table 2, the top 10 standards are almost all standards relating to drinking water methods, indicating that the standards of drinking water occupy a very important position in the whole environmental health standards system. In addition, we found that, in the top 10 standards ranked by out-degree, only S59 and S66 are in the list of top 10 standards ranked by in-degree. It means that there exists a trade-off between in-degree and out-degree measurements.

The results of eigenvector centrality in Table 2 are normalized, which show that the top 10 standards, with respect to eigenvector centrality, are still the standards relating to drinking water; again verifying the importance of drinking water standards in China's environmental health standard system. In addition, S59 ranks first in both in-degree and out-degree, but drops to sixth in terms of eigenvector centrality. This phenomenon is due to the core idea of eigenvector centrality, which not only considers the number of neighboring standards, but also highlights the quality of them.

As can be seen from Table 2, the eccentricity of each standard in the network is not high, with a maximum of 3. As the eccentricity of a standard defines the importance of a node by describing the "transfer depth of influence" of a node in the network, in the citation network, the information transmission of a standard is interrupted by "three layers" at most. This, to some extent, indicates that the current environmental health standards do not have far-reaching impacts. In addition, it is noteworthy that most of the top 10 standards, in terms of eccentricity, are also about drinking water.

As we can see from Table 2, among the top 10 standards, the betweenness centrality values vary from each other. The two standards S59 and S52 are the most prominent, in terms of betweenness centrality, with values of 256.5 and 62.9, respectively. As can be seen from Figure 3, these two standards are indeed information hubs of the network. If these two nodes were removed, the entire network would be broken down into several isolated components, inevitably interrupting the information transmission between standards.

Table 2: Results of critical standards based on classical measurements.

Rank	Id	dc^i_{in}	Id	dc^i_{out}	Id	ec^i	Id	et^i	Id	bc^i
1	S59	14	S59	16	S66	1	S66	3	S59	256.5
2	S66	9	S94	14	S5	0.889	S6	3	S52	62.9
3	S5	8	S86	14	S63	0.888	S91	3	S30	17
4	S63	8	S87	14	S64	0.747	S63	3	S95	11.9
5	S64	7	S84	14	S6	0.673	S64	3	S66	9
6	S6	7	S97	13	S59	0.598	S5	3	S94	6
7	S4	6	S73	12	S61	0.452	S67	3	S70	5
8	S67	6	S32	7	S60	0.452	S61	3	S64	4
9	S61	6	S1	4	S4	0.452	S62	3	S61	4
10	S60	6	S66	3	S67	0.452	S60	3	S47	3.4

5.3. Results of Improved PageRank and Traditional PageRank

5.3.1. An Example. In this section, we compare the results of the two PageRank algorithms, in order to assess their differences with two exemplified standards. Table 3 shows that the PR values of the top five standards under the two PageRank algorithms are basically the same. However, the four standards S67, S87, S61, and S62 exhibit higher significance in the improved PageRank algorithm than the traditional PageRank algorithm. The four standards S5, S70, S52, and S53 are evaluated as more important by the traditional PageRank algorithm.

To explain the essential differences between the two PageRank algorithms, we selected two standards S5 and S67 due to their large ranking gaps in the two algorithms. Specifically, S5 ranks fourth in the traditional PageRank algorithm and 13$^{\text{th}}$ in the improved PageRank algorithm, while S67 ranks 20$^{\text{th}}$ in the traditional PageRank algorithm but rises to seventh in the improved PageRank algorithm. As a standard's PR value is derived from its upstream standards that cite it, we also analyze the upstream standards of the two standards. Table 4 shows that their upstream standards are almost the same; that is, S87, S97, S59, S84, and S86 all cite S5 and S67. Even if S5 has one more upstream standard S4 which ranks 16$^{\text{th}}$ and 28$^{\text{th}}$ in the improved PageRank and traditional PageRank algorithms, respectively, it does not have a significant impact on the PR values of S5 and S67. In addition, S5 has more upstream standards to distribute PR values than S67, but its final PR value is lower than S67, which is counterintuitive. Therefore, we can judge that the distribution mechanism of PR values of the two different PageRank algorithms leads to the substantial differences in the results presented in Table 3.

To analyze the interdependent relationships between standards, Figure 4 shows the word cloud diagrams of seven standards with the font size of keywords positively correlated to the keyword count in each standard. The cloud diagrams show that S59, S86, and S87 are closely related with each

Table 3: Results of critical standards based on two PageRank algorithms.

Rank	Id	pr_t^i	Id	pr_m^i
1	S59	0.100829319	S59	0.107478692
2	S66	0.069139751	S6	0.072567929
3	S6	0.048371879	S66	0.065847632
4	S5	0.044023854	S63	0.058175466
5	S63	0.044021582	S64	0.049741324
6	S70	0.04191036	S91	0.047526619
7	S64	0.036734466	S67	0.033505722
8	S52	0.033686738	S87	0.032926043
9	S91	0.032476497	S61	0.032181632
10	S53	0.030890666	S62	0.029800786

Table 4: Upstream standards of S5 and S67.

Id	Upstream standards
S5	S87, S97, S59, S84, S86, S4
S67	S87, S97, S59, S84, S86

other in terms of drinking water. The three standards S5, S59, and S67 simultaneously concern indicators. Their similarity values are further shown in Figure 5, which shows that the similarity between S67 and each upstream standard is generally higher than S5, implying that S67 receive more PR values from S87, S97, S59, S84, and S86 than S5. According to the improved PageRank algorithm, S67 has a stronger ability to acquire PR values than S5, due to having closer relationship with its upstream standards. Therefore, it is rational that S67 is identified as a more important standard than S5 by the improved PageRank algorithm. The above example demonstrates the superiority of our improved PageRank algorithm, with respect to the two exemplified standards.

Word cloud diagram presents the topics of a document. The standards S59, S86, and S87 are closely related with each other in terms of "drinking water," while the three standards S5, S59, and S67 simultaneously concern the "indicators."

The five upstream standards S59, S84, S86, S87, and S97 simultaneously cite S5 and S67; these five standards contribute to the final PR value of S5 and S67. The similarity between S67 and each upstream standard is generally higher than S5, which imply that S67 will receive more PR value from the five common standards than S5.

5.3.2. Performance Comparison of the Identification Capability of Critical Standards. The previous analysis demonstrates that the improved PageRank algorithm has a significant impact on the importance assessment of standards. In the following, we focus on exploring the relationships between the classical node measurements and the two PageRank algorithms by correlational analysis and by varying the parameter of the predetermined proportion of critical standards.

Each node in the graph represents a standard with data under the corresponding measurement. The left four figures show the correlation between the improved PageRank algorithm and classical measurements; the right ones show the correlation between the traditional PageRank algorithm and classical ones. γ represents the correlation coefficients between the corresponding measurements.

As shown in Figure 6, the left figure in each row represents the correlation between the improved PageRank algorithm and classical measurements, and the right figure in each row shows the correlation between the traditional PageRank algorithm and classical measurements.

By comparing the correlation coefficients of γ, we find that the correlations of the improved PageRank algorithm and the classical measurements are stronger than those of the traditional PageRank algorithm. This proves the assumption proposed previously that the improved PageRank algorithm is more comprehensive in the identification of critical standards. In addition, we can also see a phenomenon occurring with the improved PageRank algorithm, where the points with high PR values and high classical measurements data values are denser than the traditional PageRank algorithm. This means that the improved PageRank algorithm behaves better than the traditional algorithm in terms of differentiating capability.

In order to further demonstrate the efficacy of our improved PageRank algorithm, we analyze the proportion of common critical standards identified by the different classical measurements and each PageRank algorithm. We define a parameter pc_{hm} to represent the proportion of critical standards, which is calculated as

$$pc_{hm} = \frac{n_{cs}}{|\mathcal{N}_s|}, \quad (7)$$

where n_{cs} is the number of top critical standards selected and $|\mathcal{N}_s|$ is the total number of standards in the citation network $\mathcal{G}$.

Meanwhile, we define the proportion of common top critical standards identified by classical measurements, pc_{hc}, as

$$pc_{hc} = \frac{n_{cs}^{\chi}}{|\mathcal{N}_s|}, \quad (8)$$

where n_{cs}^{χ} is the number of common top critical standards identified by classical measurements and the PageRank algorithm.

The ideal function relationship between pc_{hm} and pc_{hc} is $y = x$, that is, the ranking results of standards between the improved PageRank algorithm and classical measurements are absolutely the same. As we can see from Figure 7, the relation curves between pc_{hm} and pc_{hc} with respect to the improved PageRank algorithm under different classical measurements is closer to $y = x$. In particular, in the interval of $(0.6, 1.0)$, the relation curve of the improved PageRank algorithm and the four classical measurements completely coincides with $y = x$, while that with the traditional PageRank algorithm deviates greatly.

A strong algorithm will generally identify more common critical standards as classical measurements. The standard ranking results obtained by the two PageRnk algorithms are fitted with the four classical measurements in the proportion

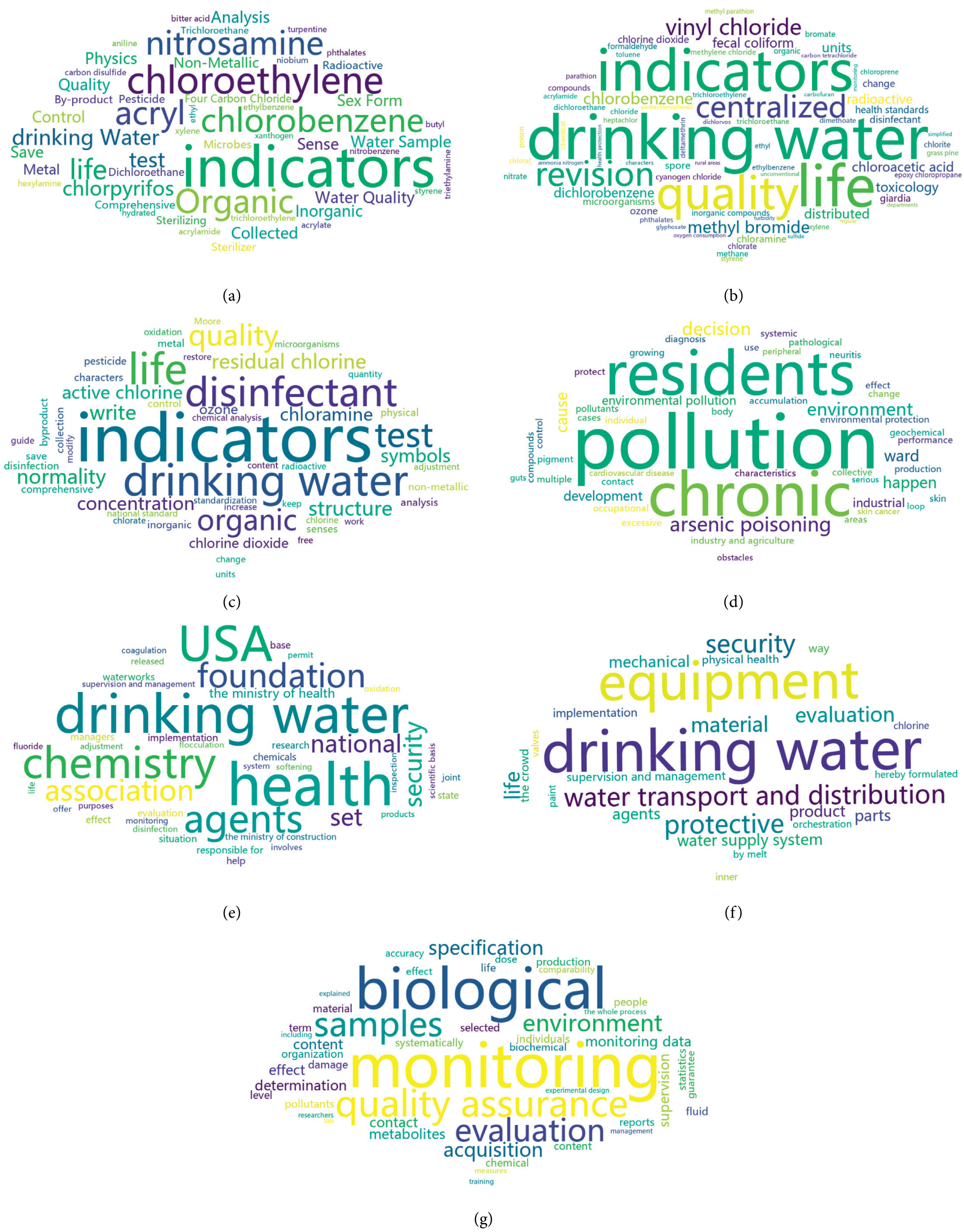


Figure 4: The word cloud diagram of seven standards. (a) S5. (b) S59. (c) S67. (d) S84. (e) S86. (f) S87. (g) S97.

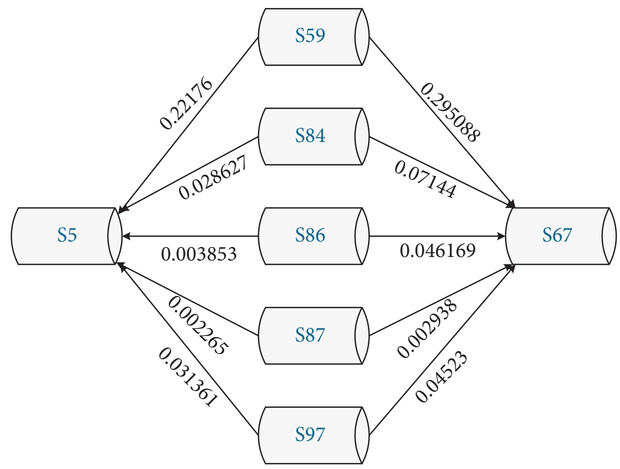
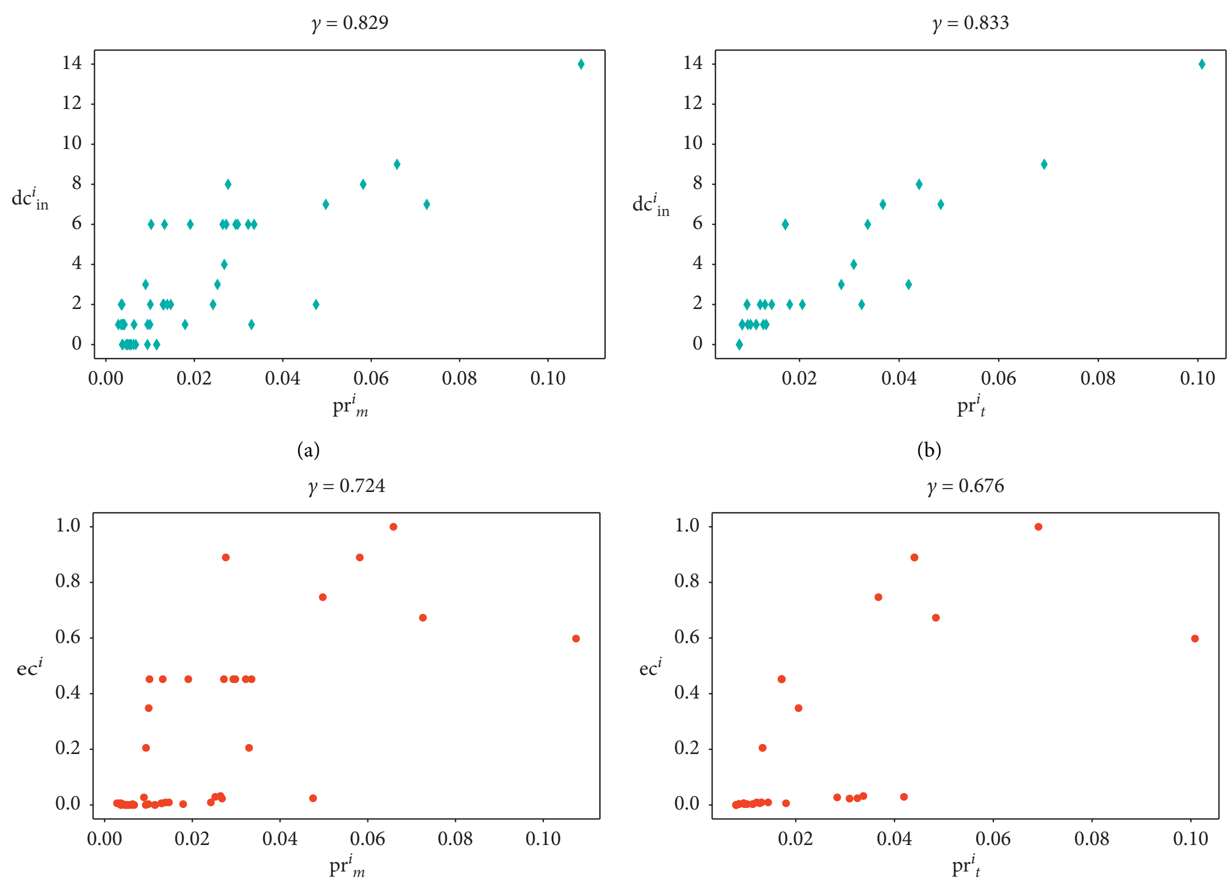


Figure 5: The text similarity of S5 and S67 with common upstream standards.



(a)

(b)

(c)

(d)

Figure 6: Continued.

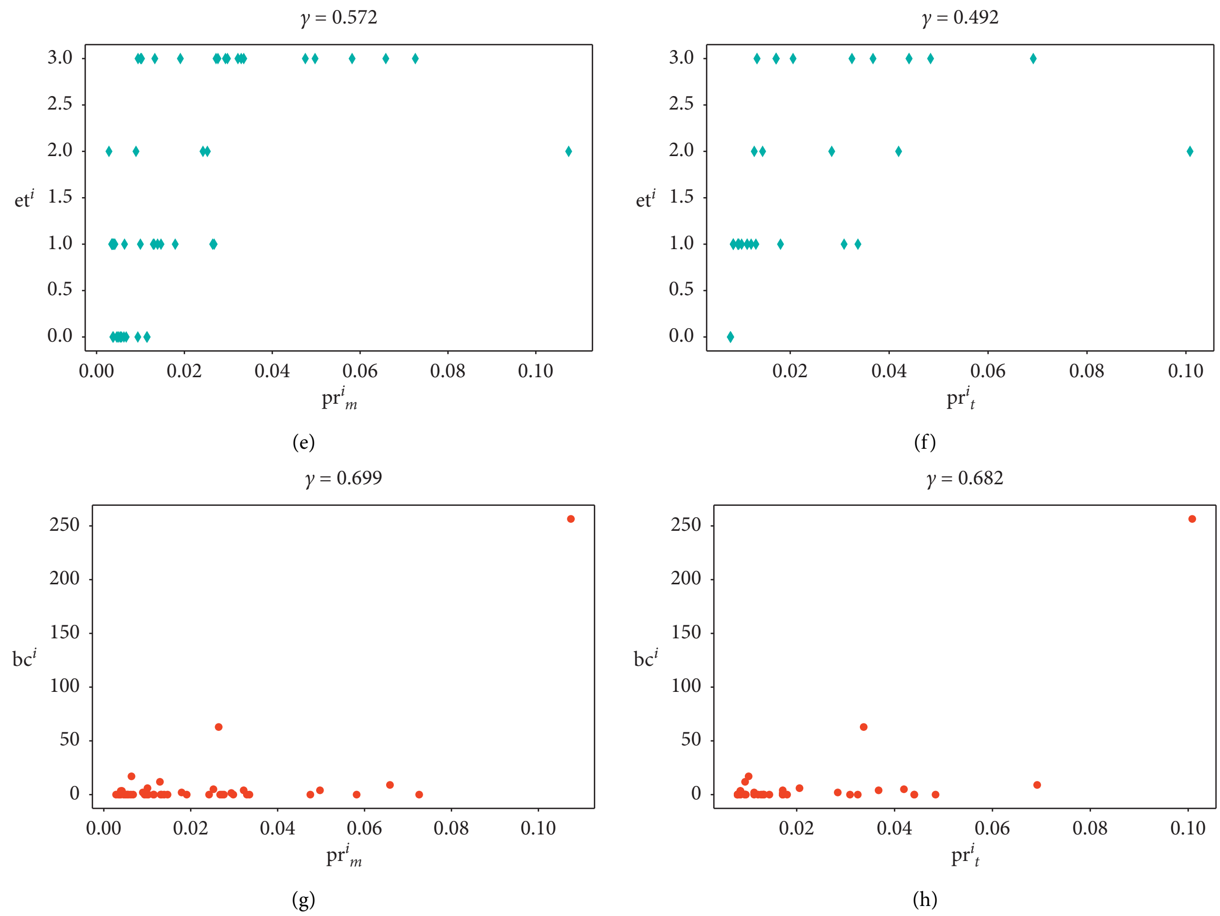


Figure 6: Correlation between two PageRank algorithms and classical measurements. Correlation between (a) pr_m^i prim and dc_{in}^i, (b) pr_t^i prim and dc_{in}^i, (c) pr_m^i prim and ec^i, (d) pr_t^i prim and ec^i, (e) pr_m^i prim and et^i, (f) pr_t^i prim and et^i, (g) pr_m^i prim and bc^i, and (h) pr_t^i prim and bc^i.

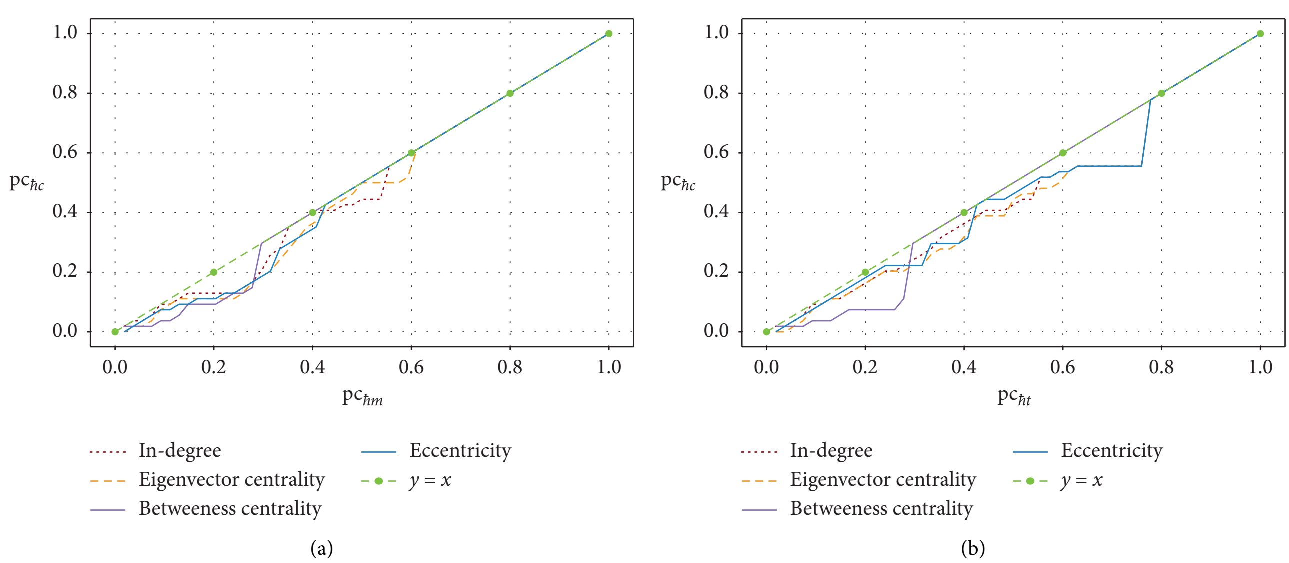


Figure 7: Proportion of common critical standards identified by different classical measurements and each PageRank algorithm. (a) Improved PageRank algorithm. (b) Traditional PageRank algorithm.

Table 5: Mean and variance of identification capability of critical standards of two Pagerank algorithms.

$(\mu_{ic}, \sigma_{ic}^2)$	In-degree centrality	Eigenvector centrality	Betweenness centrality	Eccentricity
Traditional PageRank algorithm	(2.519, 6.934)	(3.000, 7.170)	(1.426, 7.834)	(2.352, 7.440)
Improved PageRank algorithm	(1.259, 3.630)	(1.759, 4.715)	(1.130, 4.568)	(1.370, 4.162)

$(0.0, 0.2, 0.4, 0.6, 0.8, 1.0)$; dotted line $y = x$ represents the perfect fit. Compared with traditional PageRank algorithm, our improved PageRank algorithm does not show obvious advantage in proportion $(0.0, 0.6)$, while behaves much better in proportion $(0, 6, 1.0)$.

To quantify the distance between the relationship curve between pc_{hm} and pc_{hc} and $y = x$, we here define the two measurements of identification capability: the mean and variance of discrete deviations, μ_{ic} and σ_{ic}^2, which are represented as

$$\mu_{ic} = \frac{\sum_{n_{\text{cs}}=1}^{|N_s|} \left| n_{\text{cs}} - n_{\text{cs}}^{\chi} \right|}{|N_s|}, \quad (9)$$

$$\sigma_{ic}^2 = \frac{\sum_{n_{\text{cs}}=1}^{|N_s|} \left(\left| n_{\text{cs}} - n_{\text{cs}}^{\chi} \right| - n_{\text{cs}} \right)^2}{|N_s|}. \quad (10)$$

A PageRank algorithm with lower μ_{ic} is associated with stronger identification capability, regardless of the predefined proportion of critical standards pc_{hm}. Further, σ_{ic}^2 is associated with the stability or the variability of a measurement. The computational results of μ_{ic} and σ_{ic}^2 with respect with each class measurement are shown in Table 5. It can be seen that the improved PageRank algorithm is more capable of identifying the critical standards than the traditional PageRank algorithm.

6. Conclusion

This paper aimed to overcome the limitations of traditional PageRank in the context of standard citation networks, by incorporating the TSA. Specifically, an improved PageRank algorithm, which incorporates a different distribution mechanism for PR values, was proposed for the identification of critical standards. To demonstrate the effectiveness of the improved algorithm, we used standard data from the National Health Commission of the People's Republic of China. The verification process was carried out by analyzing the correlations between the two PageRank algorithms and classical measurements. We also defined two mean- and variance-based metrics, in order to evaluate the identification capability by computing the common proportion of critical standards identified by classical measurements and PageRank algorithms simultaneously. Our results show that the improved PageRank algorithm is superior to the traditional PageRank algorithm. Due to the substantial differences between weighted and unweighted networks, the network model is highly valuable in designing measurements for the importance evaluation of standard nodes.

It should be noted that there are some shortcomings in this paper, which deserve further exploration in our ongoing study. In addition to VSM, other TSA algorithms can also be applied to quantify the connectivity of standards; the relevant researches Onan et al. have done can provide great inspiration [35–37, 54]. Meanwhile, other network measurements can be proposed for the weighted standard citation network. A meaningful research direction would be to compare the differences of the results of critical standards between identification obtained by different network models. Finally, the improved PageRank algorithm is based on a small-scale standard citation network. The research idea proposed in this study can be employed to other large-scale standard citation networks in different application areas.

Data Availability

The data used to support 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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Supplementary Materials

The source code for the TSA method 180: the source code for the improved PageRank algorithm. (*Supplementary Materials*)

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Research Article

Research on Designing an Industrial Product-Service System with Uncertain Customer Demands

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The industrial product-service system (iPSS) is a kind of system engineering methodology, integration scheme, and business model to realize service value by adding intangible services in the whole life cycle. However, the design of the system involves many difficulties such as uncertain customer demands, strong subjectivity of the experience design, and long debugging times. Methods for solving upper problems are therefore essential. This paper presents a design model that integrates an improved affinity propagation (AP) clustering algorithm, quality function development (QFD), and axiomatic design (AD). The entire process of designing an iPSS can be split into three steps. First, uncertain customer demands is determined and standardized. Second, the functions of the product-service system are investigated. Finally, the structures of the system are determined. This paper examines the example of the control service of an iPSS for a water heater tank capping press. An improved AP clustering algorithm is used to determine standardized customer demands, the proposed QFD, and an AD integration model to initially establish a mapping between the customer demands domain and the function domain and clarify the design focus. Next, a QFD- and AD-integrated model is constructed to establish a mapping between the function domain and the structure domain and optimize the control scheme through the quality of its risk prediction. Finally the paper verifies that the upper process and methods can guide the design process effectively in production applications.

1. Introduction

The Made in China 2025 policy lists intelligent manufacturing as one of China's five key projects and presents a comprehensive plan to develop the intelligent manufacturing industry [1]. In 2006, the Weishang factory cooperated with Yuanfang Software Company to carry out the first furniture informatization renovation in China, and in 2016, it was awarded as the only smart manufacturing demonstration base in the home furnishing industry [2]. At the same time, Sinopec Jiujiang Branch integrated modern information technology and established a digital monitoring and optimization system, covering the entire process of "management, production, operation, and warehousing," becoming a sample of intelligent transformation of process-oriented manufacturing [3]. Zhejiang Toman Machinery Co., Ltd. introduced intelligent manufacturing technology in 2013 to improve product quality and production efficiency. Since 2014, Toman has used self-developed systems to provide SMEs (small and medium-sized enterprises) with customized solutions, such as TM-e (a production management system) and TM-SPC (a quality control system). Toman has transformed from an equipment manufacturer to a production system integrator [4]. With the continuous development of intelligent manufacturing in practice, a variety of different themes have emerged. These themes include the Internet of things [5], big data manufacturing [6], cloud manufacturing [7], and digital twin [8], which play a positive role in guiding the technological upgrading of the manufacturing industry. For example, Jiang et al. [9–11] developed a new MATLAB toolbox, the data-based key performance indicator-oriented fault detection toolbox

(DB-KIT), for evaluating the influence of the detected faults on systems behavior, reviewed the key scientific issues in the design and implementation of soft sensors in modern industry, and also proposed a research route centered on the construction of performance evaluation system and performance-oriented fault diagnosis methods. Su and Yu [12] constructed a spatial econometric model with geographical proximity as the spatial weight to study the effect of spatial agglomeration of new energy industries on regional pollution control performance. The development of the intelligent manufacturing industry has driven the rapid development of the industrial product-service system (iPSS) in China. Zhu et al. [13] comprehensively considered processing time, cost, and quality and proposed a machining capability model for quantifying and measuring machining capabilities of an mt-iPSS (industrial product-service system of a machine tool). Based on the tool-based industrial product-service system, Sun et al. [14] further studied the tool delivery method in the iPSS, established a cutting tool demand prediction model and a tool delivery model, and proposed a novel cutting tool service model. Ding et al. [15] discussed the multiobjective resource scheduling problem in the operation phase of iPSS, used an improved NSGA-II algorithm to solve the multiobjective problem including comprehensive customer satisfaction degree, resource utilization efficiency, and product-service cost, and verified the feasibility with a case of China Yufeng Electric Power Company. Leng et al. [16] proposed the concept of a cost-effective industrial product-service system for oil sands mining (om-iPSS). Haeberle et al. [17] proposed a method of systematically establishing service parameters to enhance the effectiveness of industrial service systems for establishing new services. However, there is no analysis and research on how the service parameters can be obtained from customer needs. Industrial electronic control systems constitute the control core of the iPSS of complete equipment. Usually, the control system's design is based on customer demands. The designer creates a control system's software and hardware design based on personal experience and professional knowledge. However, this design method is inadequate. First, customers are restricted by the professional's knowledge and resource conditions, customers' demands are often unclear and hard to determine, and the method involves too many ambiguities and uncertainties. Second, designers have different levels of experience and lack scientific theory to guide the design process. Therefore, when customer demands are uncertain, it is difficult for the designer to deliver a good product/service. It is, therefore, critical that the iPSS of complete equipment be provided with accurate information about customer demands to quickly design a satisfactory control system.

Quality function deployment (QFD) and axiomatic design (AD) are product design methods driven by customer demand that have been widely used in other product design fields. For example, Chang et al. [18] applied QFD theory to electric vehicles and provided an effective and scientific development tool for electric vehicle manufacturers. Wang et al. [19] used QFD theory to solve a multiobjective decision problem in a collaborative supply chain network. Han et al. [20] applied QFD theory to the field of augmented reality design, achieving collaborative customer innovation and improving customer satisfaction. Avikal et al. [21] constructed a new method based on the fuzzy Kano model and QFD theory for designing the exterior of a sport utility vehicle. The project QFD tool developed by Chao et al. [22] was used by an electronics company in Japan to engage in semiconductor projects and business model development to help deploy solution elements and resources. Vinodh et al. [23] considered environmental factors at various stages of QFD and proposed the QFDE method, which was applied to the Indian rotary switch manufacturing organization to achieve an environmentally conscious design in the early stages of product development. The SOFRAGRAF Company used QFD for the design of hand tools, staplers, nailing machines, etc. [24] In addition, QFD was used to design university textbooks and improve the quality of courses. Rainstar University in Scottsdale, Arizona, applied QFD to the redesign of higher education courses. [25] Liu et al. [26] established a conceptual design process model by applying the theory of inventive problem solving and AD to the innovative design of the manipulator. Tamayo et al. [27] combined AD and a design structure matrix to determine customer demands at the conceptual design stage of a manufacturing system. Goo et al. [28] introduced independence and failure modes in AD to improve the reliability of the product design process. Pétursson et al. [29] used AD to complete the research and development of shape-memory alloy spring static test equipment. Bae et al. [30] used independent axioms to define the relationship between hard points and suspension geometries and improve suspension system design and proposed a sequential kinematics design of suspension system based on the axiomatic design (AD). Lo and Helander [31] developed a method based on AD to identify couplings and make recommendations to eliminate couplings. This method was applied to the design of adjustable microscope workstations and the design of manual SLR (single-lens-reflex) cameras. Durmusoglu and Kulak [32] developed a method of designing efficient office operations using AD principles, which improves office operations and enhances business competitiveness by reducing customer delivery times. Ferrer et al. [33] proposed a two-stage method based on the AD method to define the structure of manufacturing knowledge and develop a knowledge-based DFM (Design for Manufacturing) application for connecting rod and internal combustion engine parts' design.

Given this background, QFD can clearly define the design focus of a product-service system, and the importance of customer demands can be transmitted by the house of quality (HoQ). However, QFD is based on an empirical design and lacks objective criteria; therefore, it is impossible to verify the rationality of the design process [34]. AD provides a set of scientific design methods and axioms that can verify this rationality, but there are no effective means to map between the customer demand domain and the function domain, and the design's emphasis cannot be clearly defined. This paper, therefore, introduces a new method integrated with AP, QFD, and AD to design a control system for the iPSS of complete equipment.

As shown in Figure 1, the design model starts with an analysis of customer demands. It then uses an improved AP clustering algorithm to complete the cluster analysis of the original customer demands information. Next, it establishes a system for the functional HoQ to complete the mapping between the demand domain and the function domain. Finally, following AD theory, the function domain is mapped to the structure domain. Moreover, based on this, risk prediction of the HoQ is established to optimize the system structure. The proposed QFD and an AD integration model initially establish a mapping between the customer demand domain and the function domain and clarify the design focus.

Moreover, in view of the vagueness, dispersion, and uncertainty of customer demands obtained from interviews and questionnaires, this paper proposes an AP clustering algorithm based on a weighted network. The algorithm uses an intuitionistic fuzzy decision matrix to quantify the correlation between demand nodes, uses a weighted network to determine the distribution density of demand nodes, and then determines the selection of initial deviation parameters P.

This paper will take the control service design of an iPSS for a water heater tank capping press as example. The improved AP clustering algorithm will be used to determine standardized customer demands. Then the QFD and an AD integration model will be used to initially establish a mapping between the customer demand domain and the function domain and clarify the design focus. Finally, a QFD- and AD-integrated model will be constructed to establish a mapping between the function domain and the structure domain and optimize the control scheme through the quality of its risk prediction.

2. Cluster Analysis of Customer Demands

QFD and AD are driven by customer demands; thus, the accuracy of these demands is very important. Fuzzy or uncertain customer demands will affect the rationality and accuracy of the subsequent design process. However, due to limitations in professional knowledge, resource conditions, and so on, customers' requirement descriptions have certain ambiguities and uncertainties. Therefore, to standardize customer demands, this paper proposes an AP clustering algorithm based on a weighted network for a cluster analysis of customer demands.

2.1. AP Clustering Algorithm Based on a Weighted Network. The basic idea of an AP clustering algorithm is to use all the data points as potential clustering centers and perform clustering on a similarity matrix of the data points [35]. The AP clustering algorithm has yielded good results in applications such as image processing, community detection, and fault diagnosis because of its strong clustering stability and lack of predefined information [36, 37]. Zhang proposed an improved K-means algorithm and an improved AP clustering algorithm to determine the modular configuration of service elements [38, 39]. However, research on the AP clustering algorithm in the processing of customer demand information is still lacking.

In the AP clustering algorithm, responsibility $r(i, k)$ and availability $a(i, k)$ represent two types of data object information [40]. As shown in Figure 2, $r(i, k)$ describes the suitability of data object k as the clustering center of data object i. It also represents the message from i to k. The term $A(i, k)$ describes the suitability of data object i as the clustering center of data object k. It also represents the message from k to i. At the end of the affinity propagation, the class representative point x_i is determined to be x_k, where k satisfies

$$\arg_k \min(a(i,k) + r(i,k)). \quad (1)$$

The iterative process of the AP algorithm involves alternating the updates of two information sources. As shown in the following equation, when the sum of the $r(i, k)$ and $a(i, k)$ values of all the data points for any x_i is calculated, the representative point of the class of x_i is x_k:

$$r(i,k) + a(i,k) = s(i,k) + a(i,k) - \max_{k' \neq k}\left[a(i,k') + s(i,k')\right]. \quad (2)$$

The AP algorithm refers to the message transmission of data points. Normally, a sample's representativeness can be determined by its reliability and validity. If the change value of $a(i, k)$ and $r(i, k)$ is the highest, then k_x is a representative sample of i_x. When the local $a(i, k)$ and $r(i, k)$ values no longer change, messaging will stop [41].

Additionally, the AP clustering algorithm introduces a damping factor λ and a deviation parameter P. The factor λ has a value range [0, 1] and is used to adjust the convergence rate of the algorithm and the stability of the iterative process. Generally, $\lambda = 0.5$ is selected. When the iterative process has large oscillations, the value of λ can be accordingly reduced or increased. The parameter P has a value range [0, 1], which is the criterion for a data point i becoming a cluster center. The larger the value, the greater the probability of the point becoming a cluster center, and vice versa. When P is less than or greater than a certain threshold, the number of clusters will change [42]. Therefore, the AP clustering algorithm has certain limitations in terms of the initial bias [43].

The steps of the AP clustering algorithm are as follows [44, 45].

Step 1: use the Euclidean distance between data points i and j to calculate the similarity $s(i, j)$:

$$s(i,j) = -x_i - x_j^2, \quad i \neq j. \quad (3)$$

Step 2: assign an initial preference to each data point in the sample, where the value range of P is [0, 1].

Step 3: calculate $r(i, k)$, such that

$$r(i,k) \leftarrow s(i,k) - \max_{j \neq k}[s(i,j) + a(i,j)]. \quad (4)$$

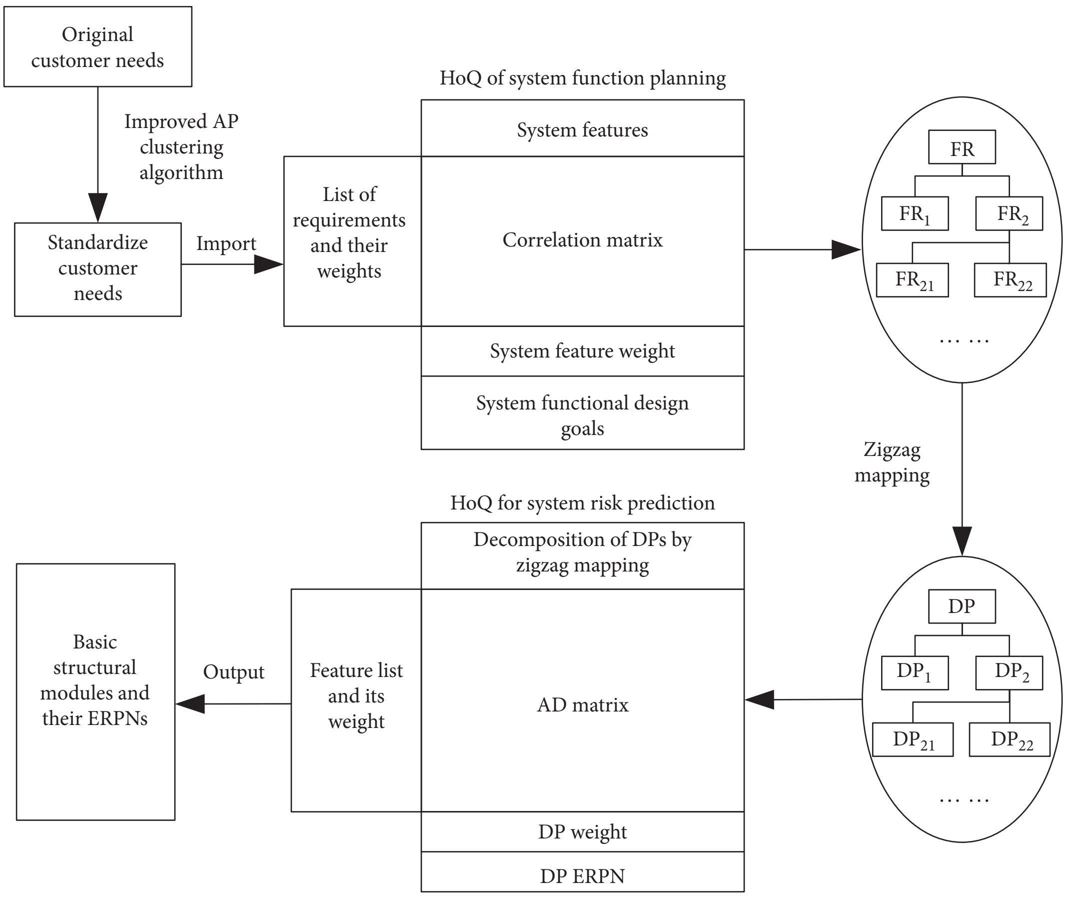


Figure 1: Design model integrating AP/QFD/AD, with functional requirements (FR), design parameters (DPs), and extended risk priority numbers (ERPNs).

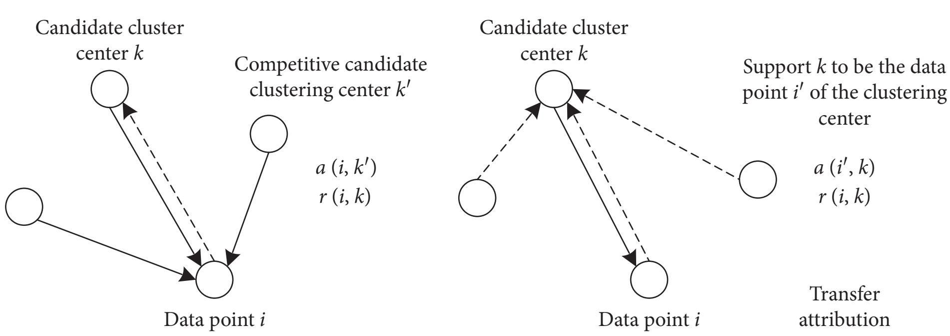


Figure 2: AP clustering algorithm message transmission.

Step 4: calculate $a\,(i,\,k)$, such that

$$a(i,k) \leftarrow \min\left\{0, r(k,k) + \sum_{j \neq i,k} \max[0, r(j,k)]\right\}, \tag{5}$$

$$a(k,k) \leftarrow \sum_{j \neq k} \max[0, r(j,k)]. \tag{6}$$

Step 5: update $r\,(i,k)$ and $a\,(i,k)$, respectively, according to

$$r_{i+1}(i,k) = \lambda \cdot r_i(i,k) + (1-\lambda) \cdot r_{i+1}^{ok_1}, \quad \lambda \in [0.5, 1], \tag{7}$$

$$a_{i+1}(i,k) = \lambda \cdot a_i(i,k) + (1-\lambda) \cdot a_{i+1}^{ok_1}(i,k), \quad \lambda \in [0.5, 1]. \tag{8}$$

Step 6: if the number of iterations exceeds the maximum value or the number of consecutive iterations of the cluster center no longer changes, the calculation is stopped; otherwise, go to Step 3 to continue the calculation.

According to the implementation steps of the AP clustering algorithm, two problems arise in the clustering of customer demands. The first is that the AP clustering algorithm uses the Euclidean distance to calculate the distance between two data points. The weight of each data point to the distance is the same by default, so the construction of the similarity matrix cannot truly reflect the correlation of the demands [46]. The second problem is that the initial P value is set manually, and the probability of each data point being a clustering center is the same, by default, which is obviously unreasonable.

Considering these two problems, this paper introduces a weighted network AP clustering algorithm for the cluster analysis of customer demands. This method uses intuitionistic fuzzy sets to transform the correlation of demands into quantized data to construct a weighted complex network and a weighted network model of customer demands to determine the initial P value.

Atanassov proposed the intuitionistic fuzzy set [47]. A weighted network can be used to describe complex correlations of nodes. It can clearly describe the interaction strengths of individuals, where the weights represent the connection tightness of the nodes in the network [44]. In a weighted network, $V = \{v_1, v_2, \ldots, v_n\}$ represents the set of nodes, (v_i, v_{ij}) represents the undirected edge between nodes v_{ii} and v_{ij}, and $E \in \{(v_{ii}, v_{ij}) : v_{ii}, v_{ij} \in V\}$ is the undirected edge set. The term w_{ij} represents the weight of the undirected edge (v_i, v_j), and $W = \{w_{ij} : (v_i, v_j) \in E\}$ is the weight set.

In a weighted network, the weights of the nodes reflect the interrelations and importance of each node in the network. The interaction strengths of the nodes are measured by the weights of the edges. In addition, the weights of the edges are related not only to directly connected nodes but also to neighboring nodes. Generally, the higher the number of neighboring nodes, the greater the strength of the interactions of the nodes [48]. Therefore, a weighted network used to analyze the distribution density of customer demand nodes should consider not just one factor, but all other relevant factors as well. In the customer demand-weighted network model, five basic indicators reflect the connection density around the demand nodes [49, 50], as shown in Table 1.

According to the basic principles of an AP clustering algorithm based on a weighted network, the nodes are the customer demand units, the edges represent the correlations of the demand units, and the weights of the edges represent the similarities of the demand units. An undirected weighted network model of customer demand can thus be established. Therefore, the subjective influence of an initial deviation parameter determined by local density can be avoided in the AP clustering algorithm. The entire process can be described as follows:

Step 1: construct an intuitionistic fuzzy decision matrix. Let CR_i and CR_j be any two customer demands. The decision maker evaluates the similarity u_{ij} and dissimilarity v_{ij} between CR_i and CR_j according to the intuitive fuzzy evaluation scale. The evaluation ranges of u_{ij} and v_{ij} are both [0, 1], and $0 \leq u_{ij} + v_{ij} \leq 1$. Then, the decision maker's intuitionistic fuzzy decision matrix Z for n demands is

$$Z = \left(d_{ij}\right)_{n\times n} = \left\{ \begin{array}{cccc} \left(u_{11}, v_{11}\right) & \left(u_{12}, v_{12}\right) & \ldots & \left(u_{1j}, v_{1j}\right) \\ \left(u_{21}, v_{21}\right) & \left(u_{22}, v_{22}\right) & \ldots & \left(u_{2j}, v_{2j}\right) \\ \vdots & \vdots & \ldots & \vdots \\ \left(u_{i1}, v_{i1}\right) & \left(u_{i2}, v_{i2}\right) & \ldots & \left(u_{nn}, v_{nn}\right) \end{array} \right\}, \tag{9}$$

where the intuitionistic fuzzy number $d_{ij} = \langle u_{ij}, v_{ij}\rangle$.

Step 2: solve the intuitionistic fuzzy similarity matrix. Let the intuitive fuzzy evaluation value between CR_i and CR_j be $d_{ij} = \langle u_{ij}, v_{ij}\rangle$. The similarity, dissimilarity, and hesitancy distances between CR_i and CR_j, respectively, are as follows.

Similarity distance:

$$d_1\left(a_i, a_k\right) = \sqrt[2]{\sum_{j=1}^{n}\left(u_{ij} - u_{kj}\right)^2}. \tag{10}$$

Dissimilarity distance:

$$d_2\left(a_i, a_k\right) = \sqrt[2]{\sum_{j=1}^{n}\left(v_{ij} - v_{kj}\right)^2}. \tag{11}$$

Hesitation distance:

$$d_3\left(a_i, a_k\right) = \sqrt[2]{\sum_{j=1}^{n}\left(\pi_{ij} - \pi_{kj}\right)^2}. \tag{12}$$

The intuitive fuzzy similarity of a_i and a_k is described by$\rho\ (a_i, a_k) = \langle\alpha_{ij}, \beta_{ij}\rangle = \langle 1 - d_1\ (a_i, a_k) - d_3\ (a_i, a_k), d_2\ (a_i, a_k)\rangle$:

$$D = \left(\rho_{ij}\right)_{n\times n} = \begin{bmatrix} \rho_{11} & \rho_{12} & \cdots & \rho_{1j} \\ \rho_{21} & \rho_{22} & \cdots & \rho_{2j} \\ \vdots & \vdots & \ldots & \vdots \\ \rho_{i1} & \rho_{i2} & \cdots & \rho_{nn} \end{bmatrix}. \tag{13}$$

Step 3: convert the intuitionistic fuzzy similarity matrix into a real matrix:

$$F = \left(f_{ij}\right)_{n\times n} = \alpha_{ij} + \eta\left(1 - \alpha_{ij} - \beta_{ij}\right), \tag{14}$$

where η is the satisfaction threshold, $\eta \in [0, 1]$, such that

Table 1: Weighted network indicators.

Indicators	Definition
Connectivity	Number of edges to which a node is directly connected in a weighted network
Weighted degree	Sum of the weights of all edges directly connected to nodes in a weighted network
Weighted aggregation	Degree of aggregation around a node in a weighted network
Agglomeration coefficient	Degree of connection between a node and its neighbors in a weighted network
Weighted network comprehensive eigenvalues	Local distribution density around a node in a weighted network

$$F = \left(f_{ij}\right)_{n\times n} = \begin{bmatrix} f_{11} & f_{12} & \cdots & f_{1j} \\ f_{21} & f_{22} & \cdots & f_{2j} \\ \vdots & \vdots & \cdots & \vdots \\ f_{i1} & f_{i2} & \cdots & f_{nn} \end{bmatrix}. \quad (15)$$

Step 4: use the demand units as the nodes, the correlations of the demand units as the edges in the weighted network, and the similarities of the demand units as the weights of the edges to establish an undirected weighted network model of customer demands.

Step 5: calculate the connectivity, weighted degree, weighted aggregation, clustering coefficient, and weighted network comprehensive eigenvalues of the nodes, respectively:

$$D_i = \left|\left\{\left(v_i, v_j\right): \left(v_i, v_j\right) \in E, v_i, v_j \in V\right\}\right|, \quad (16)$$

where D_i represents the connectivity of node i;

$$\mathrm{WD}_i = \sum_{\left(v_i,v_j\right)\in E} w_{ij}, \quad (17)$$

where WD_i represents the weighted degree of node i;

$$\mathrm{WK}_i = \sum_{\left(v_j,v_k\in R\right)} w_{jk}, \quad (18)$$

where WK_i represents the weighted aggregation degree of node i, with $R = \{(v_j, v_k) : (v_i, v_j) \in E, (v_i, v_k) \in E, (v_i, v_k) \in E, v_i, v_j, v_k \in V\}$;

$$\mathrm{WC}_i = \frac{2\mathrm{WK}_i}{\mathrm{WD}_i\left(\mathrm{WD}_i - 1\right)}, \quad (19)$$

where WC_i represents the aggregation coefficient of node i; and

$$\mathrm{WF}_i = \beta \mathrm{WC}_i + \frac{(1-\eta)\mathrm{WD}_i}{n}, \quad (20)$$

where WF_i represents the weighted network's comprehensive eigenvalue of node i, with β taking the value range of $[0, 1]$ and n as the total number of nodes in the weighted network. Finally, by normalizing the integrated eigenvalues of the weighted network of nodes, the initial P of each demand is determined.

Step 6: update the attraction and attribution values utilizing equations (4) to (8) until the stop condition is satisfied.

2.2. Cluster Analysis of Customer Demands for a Control Service System. To analyze customer demands, the example of a control service system for an iPSS for a water heater tank capping press is used. The capping press is for an enamel water tank liner of an air energy water heater, and it automatically presses the inner barrel and top cover in different diameters and lengths. The process flow diagram is depicted in Figure 3. The equipment uses a programmable logic controller (PLC) as the control core, an ABB robot as the top cover automatic feeding device, and a touch screen as the human-computer interaction interface.

The determination of customer demands can be divided into two stages. The first is the interview stage. When the water heater manufacturer purchases equipment, the designer obtains the customer's product and technical service demands by communicating with the customer group responsible for the purchase. After the interview, the questionnaire stage will be conducted. Use questionnaires to further obtain the use demands of maintenance personnel and operators.

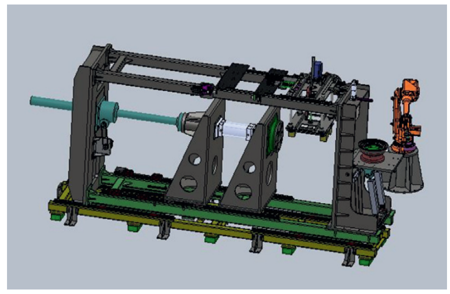
Finally, the customers' demands for a control service system are categories into 35 types, as shown in Table 2.

Furthermore, these customer demands can be clustered into subject categories. The design teams evaluate the similarity and dissimilarity of the demand units, and the evaluation results can be averaged, as shown in Table 3.

According to equations (10) to (14), the intuitionistic fuzzy similarity matrix D can be calculated as follows:

$$D = \begin{bmatrix} 1 & 0.243 & 0.102 & 0.097 & \ldots & 0.203 & 0.312 & 0.134 & 0.114 \\ 0.243 & 1 & 0.741 & 0.183 & \ldots & 0.302 & 0.241 & 0.177 & 0.715 \\ 0.102 & 0.741 & 1 & 0.162 & \ldots & 0.226 & 0.172 & 0.305 & 0.697 \\ 0.097 & 0.183 & 0.162 & 1 & \ldots & 0.152 & 0.181 & 0.629 & 0.407 \\ 0.203 & 0.302 & 0.226 & 0.152 & \ldots & 1 & 0.189 & 0.275 & 0.223 \\ 0.312 & 0.241 & 0.172 & 0.181 & \ldots & 0.189 & 1 & 0.096 & 0.164 \\ \vdots & \vdots & \vdots & \vdots & \ldots & \vdots & \vdots & \vdots & \vdots \\ 0.134 & 0.177 & 0.305 & 0.629 & \ldots & 0.275 & 0.096 & 1 & 0.304 \\ 0.114 & 0.715 & 0.697 & 0.407 & \ldots & 0.223 & 0.164 & 0.304 & 1 \end{bmatrix}. \quad (21)$$

In the weighted network, the demand units are represented by the nodes, the correlations of the demand units are represented by the edges, and the similarities of the demand units are represented by the weights of the edges. An undirected weighted network model of customer demand can be built by selecting the Force Atlas layout in the Gephi software, as shown in Figure 4.



(a) (b)

Figure 3: The capping press process.

Table 2: Customer demands for a control service system.

Number	Name	Number	Name
Cr_1	Information storage	Cr_{19}	Reset prompt
Cr_2	Parameter settings	Cr_{20}	Operation monitoring
Cr_3	Boot operation	Cr_{21}	Information query
Cr_4	Error alarm	Cr_{22}	Maintenance cost
Cr_5	Accident details	Cr_{23}	Graphical button size
Cr_6	Workpiece information	Cr_{24}	Picture color
Cr_7	Economical	Cr_{25}	Failure machine stop
Cr_8	Button layout	Cr_{26}	Line label
Cr_9	Selection error prompt	Cr_{27}	System upgrade
Cr_{10}	Part stability	Cr_{28}	Program structure
Cr_{11}	Part species	Cr_{29}	Program modification
Cr_{12}	Full features	Cr_{30}	Part replacement
Cr_{13}	Login authentication	Cr_{31}	Consistency check
Cr_{14}	Three levels of login authority	Cr_{32}	Clear interface marking
Cr_{15}	Operability	Cr_{33}	Equipment parameter query
Cr_{16}	Intensity	Cr_{34}	Operation feedback
Cr_{17}	Model switching	Cr_{35}	Error reset
Cr_{18}	Error self-diagnosis	—	—

Table 3: Customer demands: evaluation results.

	Cr_1	Cr_2	Cr_3	...	Cr_{33}	Cr_{34}	Cr_{35}
Cr_1	(1, 0)	(0.23, 0.72)	(0.12, 0.76)	...	(0.32, 058)	(0.16, 0.67)	(0.10, 0.82)
Cr_2	(0.23, 0.72)	(1, 0)	(0.71, 0.16)	...	(0.26, 0.60)	(0.18, 0.69)	(0.75, 0.12)
Cr_3	(0.12, 0.76)	(0.71, 0.16)	(1, 0)	...	(0.12, 0.69)	(0.34, 0.58)	(0.67, 0.18)
Cr_4	(0.08, 0.82)	(0.23, 0.59)	(0.12, 0.80)	...	(0.12, 0.72)	(0.69, 0.23)	(0.40, 0.48)
...	...	...	...	...	...	...	...
Cr_{32}	(0.18, 0.67)	(0.32, 0.59)	(0.24, 0.71)	...	(0.19, 0.68)	(0.28, 0.64)	(0.22, 0.58)
Cr_{33}	(0.32, 058)	(0.26, 0.60)	(0.12, 0.69)	...	(1, 0)	(0.09, 0.72)	(0.15, 0.69)
Cr_{34}	(0.16, 0.67)	(0.18, 0.69)	(0.34, 0.58)	...	(0.09, 0.72)	(1, 0)	(0.31, 0.64)
Cr_{35}	(0.10, 0.82)	(0.75, 0.12)	(0.67, 0.18)	...	(0.22, 0.58)	(0.31, 0.64)	(1, 0)

In the undirected weighted network model of customer demand, the parameter β is 0.5 according to equations (16) to (20). The calculation of the network attribute value of every node is shown in Table 4.

Since the range of the initial P value in the AP clustering algorithm is [0, 1], the initial P value of the customer requirements Cr_1, Cr_2, ..., Cr_{35} can be assumed to be $p_1, p_2, \ldots, p_{35}$. By adopting the normalization method to process the weighted network's comprehensive feature value of each node, the initial P value of every customer demand can be obtained, as shown in Table 5.

To facilitate calculation and programming, 35 random coordinate points are set to correspond to customer demands Cr_1, Cr_2, . . ., Cr_{35}. The values of the initial deviation parameters for every demand are shown in Table 5, where the maximum number of iterations is set to 500 and the

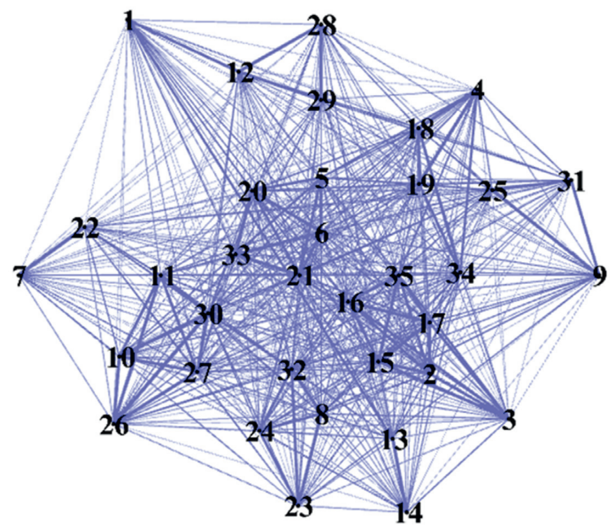


Figure 4: Undirected weighted network model of customer demands.

Table 4: Eigenvalues of the weighted network nodes.

Node	Degree	Weighted degree WD	Weighted aggregation	Aggregation coefficient WC	Weighted network's comprehensive eigenvalues
Cr_1	35	6.3	132.2	7.92	4.05
Cr_2	35	8.9	129.8	3.69	1.97
Cr_3	35	8.1	130.4	4.53	2.38
Cr_4	35	7.4	131.1	5.54	2.87
Cr_5	35	8.0	130.5	4.66	2.44
Cr_6	35	8.5	130.0	4.08	2.16
Cr_7	35	5.5	133.0	10.75	5.45
Cr_8	35	8.2	130.3	4.41	2.18
Cr_9	35	7.0	131.5	6.26	3.23
Cr_{10}	35	7.8	130.7	4.93	2.57
Cr_{11}	35	8.4	130.1	4.19	2.21
Cr_{12}	35	7.3	131.2	5.71	2.96
Cr_{13}	35	6.8	131.7	6.68	3.44
Cr_{14}	35	6.2	132.3	8.21	4.19
Cr_{15}	35	9.9	128.6	2.92	1.60
Cr_{16}	35	9.8	128.7	2.98	1.63
Cr_{17}	35	9.7	128.8	3.05	1.66
Cr_{18}	35	8.1	130.4	4.53	2.38
Cr_{19}	35	8.2	130.3	4.41	2.32
Cr_{20}	35	8.8	129.7	3.78	2.01
Cr_{21}	35	9.6	128.9	3.12	1.69
Cr_{22}	35	6.3	132.2	7.92	4.05
Cr_{23}	35	7.3	131.2	5.71	2.96
Cr_{24}	35	7.9	130.6	4.79	2.51
Cr_{25}	35	7.2	131.3	5.88	3.04
Cr_{26}	35	7.2	131.3	5.88	3.04
Cr_{27}	35	8.7	129.8	3.88	2.06
Cr_{28}	35	6.7	131.8	6.90	3.54
Cr_{29}	35	6.5	132.0	7.38	3.78
Cr_{30}	35	10.2	128.3	2.73	1.51
Cr_{31}	35	6.4	132.1	7.64	3.91
Cr_{32}	35	9.2	129.3	3.43	1.84
Cr_{33}	35	7.1	131.4	6.07	3.13
Cr_{34}	35	8.7	129.8	3.88	2.06
Cr_{35}	35	9.2	129.3	3.43	1.84

Table 5: Initial P value of every customer demand.

p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9	p_{10}	p_{11}	p_{12}
0.89	0.17	0.31	0.48	0.33	0.24	1	0.24	0.61	0.38	0.25	0.52
p_{13}	p_{14}	p_{15}	p_{16}	p_{17}	p_{18}	p_{19}	p_{20}	p_{21}	p_{22}	p_{23}	p_{24}
0.68	0.95	0.04	0.05	0.06	0.31	0.29	0.18	0.07	0.9	0.52	0.36
p_{25}	p_{26}	p_{27}	p_{28}	p_{29}	p_{30}	p_{31}	p_{32}	p_{33}	p_{34}	p_{35}	—
0.54	0.54	0.2	0.72	0.80	0	0.85	0.13	0.58	0.2	0.13	—

number of consecutive iterations of the cluster center without a change is set to 50. The value of λ is set to 0.5 in Matlab R2014b. Figure 5 shows the results.

In Figure 5, when $\lambda = 0.5$, after 40 iterations, the fitness value becomes stable at 22.20, indicating that the clustering center no longer changes and the value of λ is reasonable. There are nine clusters, where the dots represent demand items, demands in the same category are connected by straight lines, and different categories are displayed in various colors. According to the coordinate points corresponding to each demand, the customer demands displayed in Table 1 can be grouped into nine categories, {(Cr_1, Cr_{13}, Cr_{14}), (Cr_2, Cr_3, Cr_{15}, Cr_{16}, Cr_{17}, Cr_{35}), (Cr_4, Cr_{18}, Cr_{19}, Cr_{34}), (Cr_5, Cr_6, Cr_{20}, Cr_{21}, Cr_{33}), (Cr_7, Cr_{22}), (Cr_8, Cr_{23}, Cr_{24}, Cr_{32}), (Cr_9, Cr_{25}, Cr_{31}), (Cr_{27}, Cr_{10}, Cr_{11}, Cr_{26}, Cr_{30}), (Cr_{12}, Cr_{28}, Cr_{29})}. The customer demands for the control service system can then be divided into nine different subject categories, as shown in Table 6.

3. Function Domain Determination for a Control Service System

3.1. Overview of QFD. QFD, a typical customer-driven design method, was first proposed by Mizuno and Akao [51]. The basic display tool of QFD is the house of quality, an intuitive matrix framework for the conversion of customer demands [52]. As a customer-driven product development method, it is a simple and logical demand conversion tool. At present, the QFD configuration process can be broken down into four stages: the product planning quality house, the parts' development quality house, the process planning quality house, and the production planning quality house (see Figure 6). These four stages use various expansion tables to transform the important parts of the demands downward, step by step, to ensure that the product design process does not deviation from the customer's requirements.

In QFD, the correlation matrix is used to express the complex relation between every demand item and every technical feature of the product [53]. After determining the correlations between a customer's demands and the product's technical characteristics, the importance of the latter can be further determined. As shown in Table 7, a set of symbols is generally used to indicate the degree of correlation.

Furthermore, the product's technical features can be calculated by the equations

$$\begin{aligned} \mathrm{TIR}_j &= \sum_{i=1}^{n} \mathrm{CIR}_i \times R_{ij}, \ (i = 1, 2, \ldots, n; \ j = 1, 2, \ldots, m), \\ \mathrm{TIR}'_j &= \frac{\mathrm{TIR}_j}{\sum \mathrm{TIR}_j}, \ (j = 1, 2, \ldots, m), \end{aligned} \tag{22}$$

where n represents the number of customer demands, m represents the number of the product's technical features, CIR_i is the weight of the ith customer demand item, R_{ij} is the value of the correlation symbol between the ith customer demand item and the jth product technical feature item, TIR_j is the weight of the jth product technical feature item, and TIR'_j is the relative weight of the jth product technical feature item.

3.2. Function Planning for a Control Service System. After the customer demands have been standardized, a mapping analysis between the demand domain and the function domain is carried out. The system's functional characteristics are the customer's requirements, described in engineering and technical language. The control service system usually takes into consideration the process requirements, performance requirements, working environment, industry standards, and so on, as well as functional characteristics. For example, the equipment must be able to process multiple products. Therefore, the system should be compatible with multiple models. The customer demands include the real-time display of workpiece information. Therefore, system function monitoring is required. The customer demands also involve low labor intensity and the ability to convert quickly between different models of products. Therefore, the system must have the capability of automatically switching models. Table 8 shows the functional characteristics of the system, following the analysis.

In addition, some requirements in the customer demand domain have constraints on other functional features, although they might not individually correspond to specific functional features. For example, economic requirements hold throughout the entire design process because cost factors must be considered for every function. Therefore, a HoQ of system functions should be built to analyze the correlations between customer demands and system functional characteristics and clarify the system design's focus (see Figure 7).

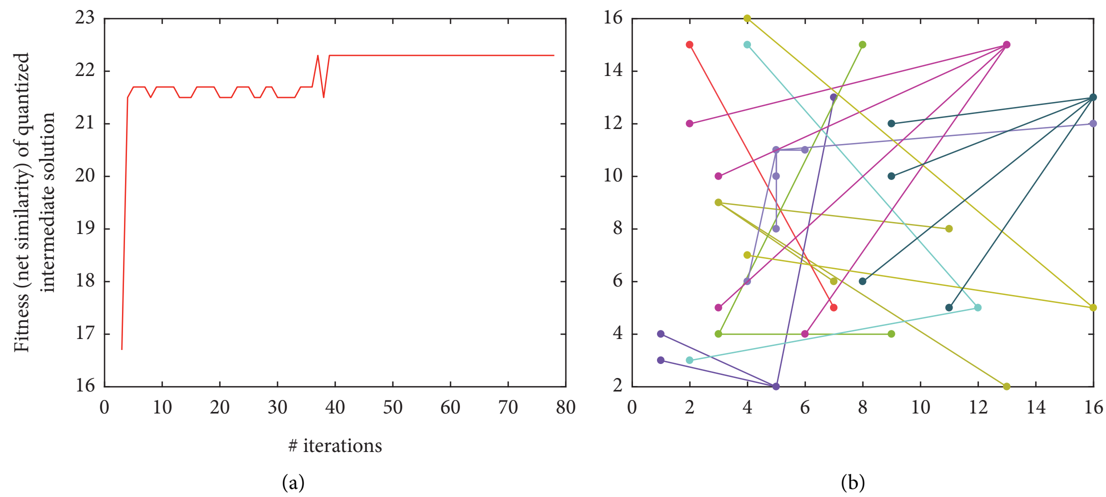


Figure 5: Clustering of customer demands.

Table 6: Architecture of customer demands.

Primary customer demands	Secondary customer demands	Tertiary customer demands
	Information security, CR_1	Cr_1, Cr_{13}, Cr_{14}
	Operability, CR_2	Cr_2, Cr_3, Cr_{15}, Cr_{16}, Cr_{17}, Cr_{35}
	Alarm prompt, CR_3	Cr_4, Cr_{18}, Cr_{19}, Cr_{34}
	Information query, CR_4	Cr_5, Cr_6, Cr_{20}, Cr_{21}, Cr_{33}
Customer demands for a control service system	User-friendly interface, CR_5	Cr_8, Cr_{23}, Cr_{24}, Cr_{32}
	System program, CR_6	Cr_{12}, Cr_{28}, Cr_{29}
	Error-proof design, CR_7	Cr_9, Cr_{25}, Cr_{31}
	Maintainability, CR_8	Cr_1, Cr_{10}, Cr_{11}, Cr_{26}, Cr_{30}
	Economy, CR_9	Cr_7, Cr_{22}

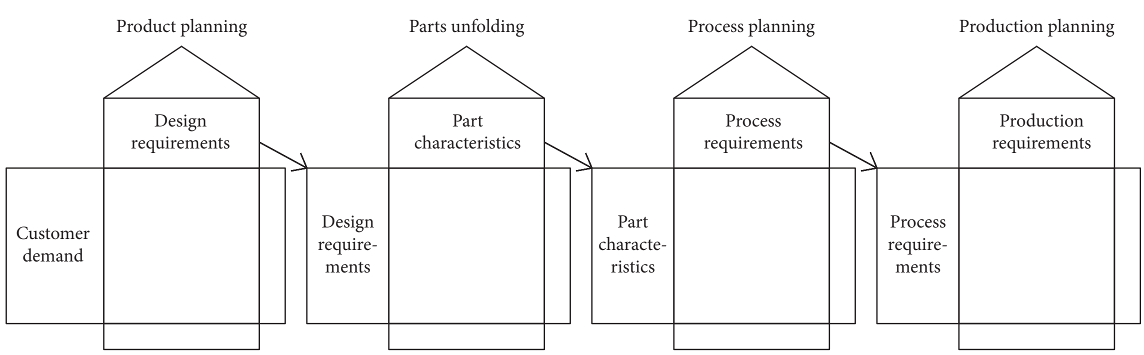


Figure 6: Four stages of QFD configuration.

Table 7: Evaluation and decision table for the correlations between the demand and technical characteristics.

Symbol	Value	Meaning
○	5	Strong correlation between the demand and technical characteristics
□	3	Medium correlation between the demand and technical characteristics
△	1	Weak correlation between the demand and technical characteristics
	0	No correlation with technical characteristics

Following the functional planning output of the HoQ, the designer can clarify major and minor points in the design process, focus on the main points, and avoid deviating from the customer's directions due to personal experience and cognitive limitations. The control service system requires nine functions: FR_1, compatibility with multiple models,

Table 8: Functional characteristics of the control service system.

Name	FR_1	FR_2	FR_3	FR_4	FR_5
Paraphrase	Compatible with multiple models	Automatic switching model	User login	Alarm function	Device driven
Name	FR_6	FR_7	FR_8	FR_9	—
Paraphrase	Automatic feeding	Multiple working modes	Monitoring function	Humanized design	—

		System features								
Demand	Weights	Compatible with multiple models	Automatic model switching	User login	Alarm function	Device driver	Automatic feeding	Multiple working modes	Monitoring function	Humanized design
Information security	0.0812	△		○					△	□
Operability	0.1882	□	○	□		□	□	○		□
Alarm prompt	0.1637	△			○	□				
Information query	0.0977					△	□		○	□
Pleasant interface	0.0636		□	△				○	□	○
System program	0.0783	○	○			□		□		
Error-proof design	0.0737	□	□		□		□			
Maintainability	0.1922	□			△	○				
Economy	0.0613	△			□	○				
Weights		4.0499	1.7444	1.0342	1.4157	2.6558	1.0788	1.4939	0.7605	1.4193
Relative weights		0.2587	0.1114	0.0661	0.0905	0.1696	0.0689	0.0954	0.0486	0.0907
Target expectations		Meet contract and functional requirements	Meet functional requirements	Meet contract and functional requirements	Meet contract and functional requirements	Meet contract and functional requirements	Meet contract and functional requirements	Meet contract and functional requirements	Meet functional requirements	Meet functional requirements

Figure 7: HoQ of the functional planning for the control service system.

FR_2, automatic model switching, FR_3, a user login, FR_4, an alarm function, FR_5, being device driven, FR_6, automatic feeding, FR_7, multiple working modes, FR_8, a monitoring function, and FR_9, humanized design. The relative importance levels of each functional characteristic are shown in Table 9.

4. Structure Domain Determination for the Control Service System

4.1. Overview of AD. The core of AD is the domain. According to Suh, the domain is the boundary of four design activities with different types and different modes in the product design phase [54]. The domains in axiomatic theory are the customer domain, the function domain, the structure domain, and the process domain. Between two adjacent design domains, the left domain represents the "what," that is, the purpose, and the right domain represents the "how," that is, the method that satisfies the left domain. The hierarchical structure and zigzag mapping are the core methods of the AD design process [55]. As depicted in Figure 8, the hierarchical structure describes the relation of various elements within the domain, and the zigzag mapping represents the mapping of the domains.

Figure 8(a) illustrates the hierarchical structure of collection self-decomposition in the domain. A group of subsystems can be composed of elements in the domain according to certain rules. Here, a top-down method is used to decompose the abstract total function into subfunctions, layer by layer, until the final design is produced. The correlations of the functional, structural, and process domains are described according to the zigzag mapping in Figure 8(b). The zigzag mapping is a top-down approach in the form of a Z, and it repeats the mapping of the same and different levels in every domain until the previous domain can no longer be decomposed.

To judge the reasonability of the design process, AD theory proposes a design axiom. While mapping the function domain to the structure domain, the designer can judge the appropriateness of the mapping according to the design axioms. The entire mapping can be described as

$$\{FR\}_{m\times 1} = A_{m\times n}\{DP\}_{n\times 1}, \quad (23)$$

where $\{FR\}_{m\times 1}$ represents the FRs, $\{DP\}_{n\times 1}$ represents the DPs, and $A_{m\times n}$ represents the design matrix, which can be expressed as

Table 9: Relative importance of system functional characteristics.

Features	FR_1	FR_2	FR_3	FR_4	FR_5	FR_6	FR_7	FR_8	FR_9
Relative weight	μ_1 0.2587	μ_2 0.1114	μ_3 0.0661	μ_4 0.0905	μ_5 0.0169	μ_6 0.0689	μ_7 0.0954	μ_8 0.0486	μ_9 0.0907

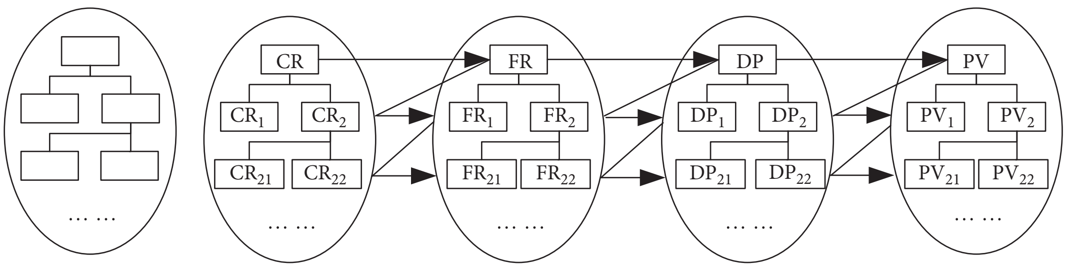


Figure 8: (a) Hierarchy and (b) zigzag mapping of AD.

$$A_{m\times n} = \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1n} \\ A_{21} & A_{22} & \cdots & A_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ A_{m1} & A_{m2} & \cdots & A_{mn} \end{bmatrix}, \quad (24)$$

where the matrix elements are determined by $A_{ij} = (\partial FR_i)/(\partial DP_j)$ $(i = 1, 2, \ldots, m;\ j = 1, 2, \ldots, n)$.

In an actual design, the numbers of FRs and DPs will not be the same. As shown in Table 10, given the relation between the numbers of FRs and the number of DPs, the design can be split into an ideal design, a redundant design, and a coupling design.

4.2. House of Quality for Risk Prediction. Once the basic structure of a control service system is described, high-risk modules in the structure domain can be predicted and analyzed to determine potential failure modes and analyze the possible consequences. These measures can be taken in advance. Because the importance of the elements in the domain cannot be evaluated in AD, this paper introduces a risk prediction HoQ model. This model transmits the decomposition and mapping results of the AD functional and structural domains to the HoQ, builds a risk prediction HoQ, and proposes the ERPN to measure every structural module and clarify the key points of the process.

The concept of ERPN is based on risk probability number. Taking into account the importance of the system functions, the system structure can be optimized to determine measures to reduce the chance of potential failure. The formula for the ERPN is

$$\text{ERPN} = \mu_j \cdot I_k \cdot S \cdot O \cdot D, \quad (25)$$

where μ_j is the relative weight of the jth system function characteristic in the HoQ, I_k is the weight of the kth subfunction characteristic in the risk prediction HoQ, and S is the severity (see Table 11).

Table 12 shows the scoring criteria for the frequency O.

Table 13 shows the scoring criteria for the degree of detection D.

4.3. Structure Domain Solution of the Control Service System. The system's functional characteristics are only a visual description of the control system and do not correspond directly to the basic composition of the system. Therefore, a practical system design is impossible. According to the principle of functional decomposition mapping in AD, the basic structure of the water heater liner top press control system can be determined through the zigzag mapping. Functions can then be transformed from the conceptual to the specific, and an overall system structure can be built. Finally, when all the basic components of the system are worked out, the structure can be optimized by establishing a HoQ for risk prediction.

In the example of the decomposition map of the automatic switching model function, FR_2, the corresponding basic structure module and risk prediction of the basic structure in question are proposed. The water heater tank capping press has an inner liner press and an inner liner top cover automatic feeding device. The automatic model switching function, FR_2, requires that the automatic feeding device of the top cover recognize different workpiece types and automatically feed different types of top covers. According to the equipment's execution sequence, FR_2 can be decomposed into two subfunctions, such as sending the workpiece model, FR_{21}, and receiving the workpiece model, FR_{22}. The corresponding mapping structures are the model identification module of the PLC system, DP_{21}, and the model identification module of the ABB robot control system, DP_{22}. The design equation of the mapping is thus

$$\begin{bmatrix} FR_{21} \\ FR_{22} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} DP_{21} \\ DP_{22} \end{bmatrix}. \quad (26)$$

The subfunctions of the sent workpiece model, FR_{21}, can be decomposed into the model selection carrier, FR_{211}, and the workpiece model selection item, FR_{212}, recognizes the selected workpiece model of the PLC system, FR_{213}, and transmits the

Table 10: Ideal, redundant, and coupling designs.

Design name	Condition	Design matrix
Ideal design	Number of FRs = number of DPs	Diagonal matrix
Redundant design	Number of FRs < number of DPs	Triangular matrix
Coupling design	Number of FRs > number of DPs	Nontriangular matrix and nondiagonal matrix

Table 11: Severity (S) scoring criteria.

Harm	Assessment criteria: severity of the impact on the system	Severity level
No warning hazard	No alarm is issued when the equipment is faulty and the control system is completely out of order	10
Warning hazard	Alarm when the equipment is faulty and the control system fails	9
Very serious	Has a serious impact on the control system and the system is difficult to repair	8
Serious	Has a serious impact on the control system, but the system can be partially repaired	7
Medium	Has a certain impact on the control system, but the system can be repaired	6
Low	Has a certain impact on the control system, but the system can be repaired completely	5
Very low	Has less impact on the control system and the system can be repaired more quickly	4
Slight	The impact on the control system is small, and the system can be repaired quickly	3
Very	The impact on the control system is very slight, and the system can be easily repaired	2
Nothing	No impact on the control system, and the system can work normally	1

Table 12: Frequency (O) scoring criteria.

Possibility of failure	Evaluation criteria: frequency of occurrence	Frequency
Very high	Greater than 1/2	10
	About 1/3	9
High	About 1/8	8
	About 1/20	7
Moderate	About 1/80	6
	About 1/400	5
	About 1/2000	4
Low	About 1/15,000	3
	About 1/150,000	2
Very low	Less than 1/150,000	1

Table 13: Scoring criteria for the degree of detection D.

Detectability level	Evaluation criteria: the possibility of detecting the cause of system failures in the prior art	Level
Infinitesimal	The prior art cannot detect the cause of the failure of the control system	10
Very tiny	Existing technology has difficulty detecting the cause of the failure of the control system	9
Tiny	Existing technology has more difficult detecting the cause of the failure of the control system	8
Very low	Need a control system designer to investigate the cause of the fault	7
Low	A technician can discover the cause of the failure	6
Medium	The control system has alarm tips, but does not display fault information	5
Higher	The control system has alarm tips and displays fault information	4
High	The cause of the fault can be determined by a simple test instrument	3
Very high	The cause of the failure can be visually identified	2
Almost certainly	The cause of the fault can be detected almost certainly	1

workpiece model information, FR_{214}. The working principle involves receiving the input signal of the workpiece model, generating a control signal after the program is run, and then issuing a control command. The corresponding mapping structures are the selection screen, DP_{211}, the workpiece selection list, DP_{212}, the PLC model judgment program, DP_{213}, and PLC workpiece model information output point, DP_{214}. The design equation of the mapping is

$$\begin{bmatrix} FR_{211} \\ FR_{212} \\ FR_{213} \\ FR_{214} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} DP_{211} \\ DP_{212} \\ DP_{213} \\ DP_{214} \end{bmatrix}. \quad (27)$$

The subfunctions of the received workpiece model, FR_{22}, can be decomposed into the ABB robot input workpiece

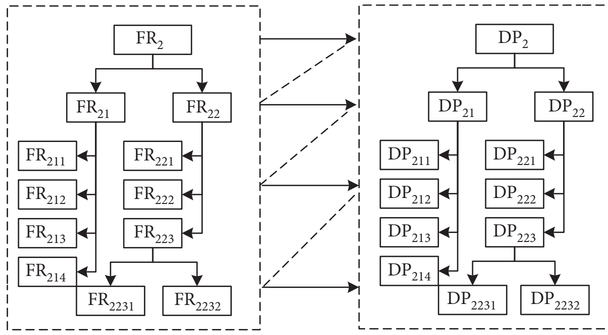


Figure 9: The zigzag mapping of FR_2.

		Importance	Layer 1	Layer 2		Layer 3						
			DP_2	DP_{21}	DP_{22}	DP_{211}	DP_{212}	DP_{213}	DP_{214}	DP_{221}	DP_{222}	DP_{223}
Layer 1	FR_2	μ_2										
Layer 2	FR_{21}	4		1	0							
	FR_{22}	4		1	1							
Layer 3	FR_{211}	3				1	0	0	0			
	FR_{212}	2				0	1	0	0			
	FR_{213}	3				0	0	1	0			
	FR_{214}	3				0	0	1	1			
	FR_{221}	2								1	0	0
	FR_{222}	3								1	1	0
	FR_{223}	4								0	0	1
Importance				8	4	2	3	6	3	5	3	4
ERPN				64.17	32.08	3.56	5.35	13.37	10.03	13.37	8.03	24.06

Figure 10: The risk prediction house of quality of DP_2.

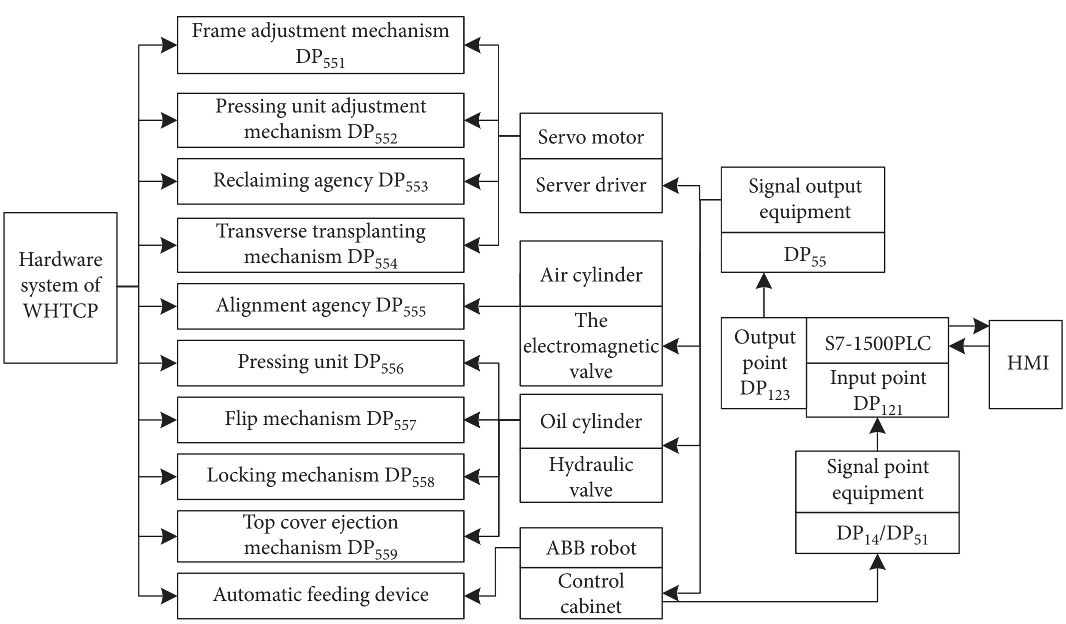


Figure 11: Hardware structure of the control service system.

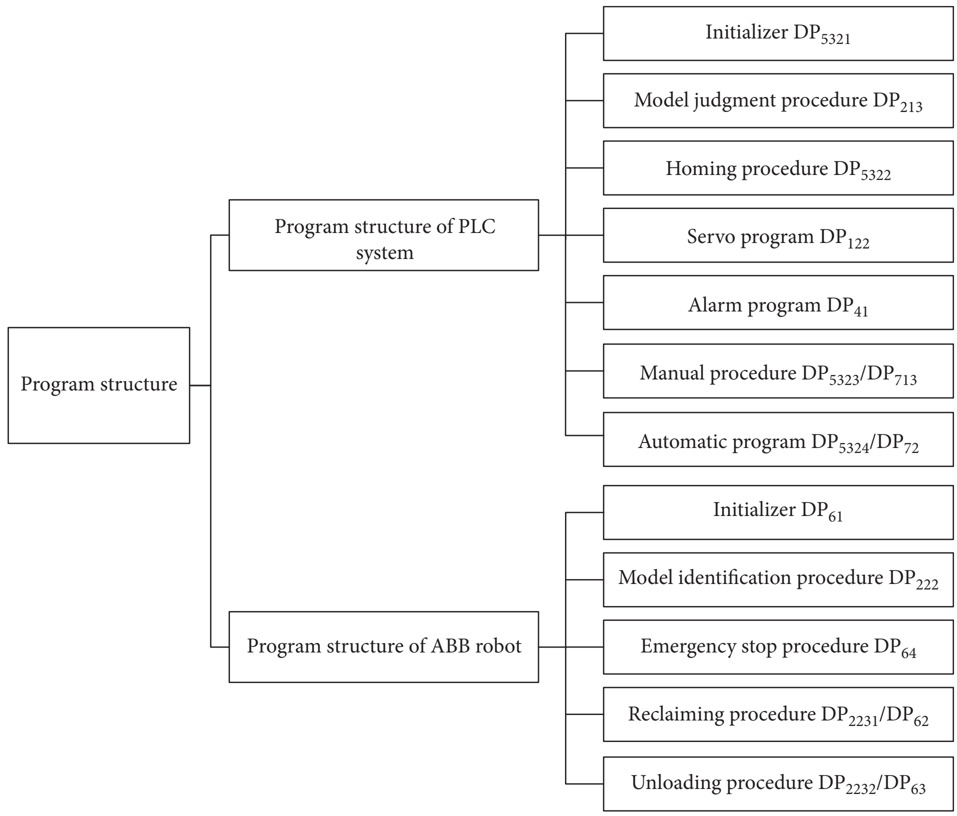


Figure 12: Control service system's program structure scheme.

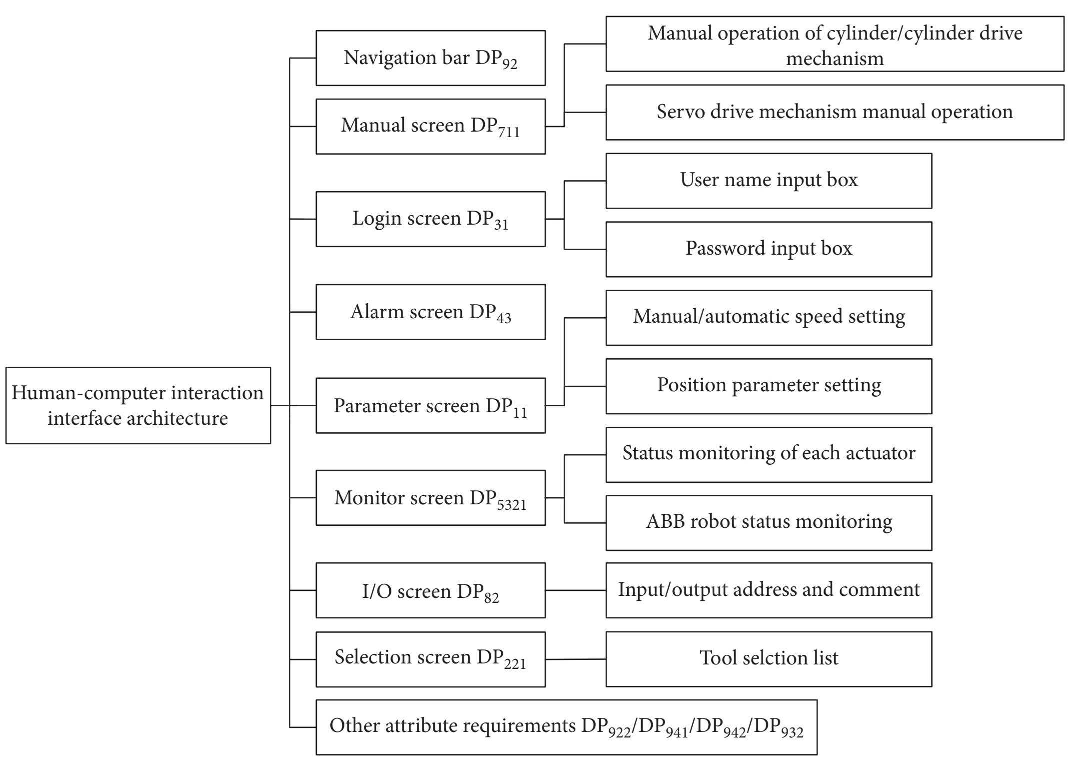


Figure 13: The human-machine interface of the control service system.

Table 14: Analysis of the potential failure risk of the control service system.

System	Module	Structure	Risk order	Fault description	Measures
Hardware	Solenoid valve	DP_{55}	97.69	Solenoid valve does not work when energized	Select an excellent solenoid valve, with timely detection and replacement
	Signal input device	DP_{14} DP_{51}	93.13 81.41	Unstable signal detection	Choose appropriate signal detection components and avoid vibration
	Servo motor	DP_{551} DP_{552} DP_{553} DP_{554} DP_{13}	67.84 67.84 67.84 67.84 66.23	Servo drive alarm	The installation and cable routing of the servo drive adhere to strict anti-interference measures; the servo drive is separately equipped with a 24 V DC power supply to ensure the stability of the current in the servo system
	Signal input element	DP_{52} DP_{121}	61.06 54.33	An abnormal or unstable input signal	Select a distributed PLC, paying attention to whether the power supply voltage of the I/O terminal is normal
	Signal output element	DP_{54} DP_{123}	56.98 37.25	An abnormal or unstable output signal	Select a ground wire of sufficient diameter and add an equipotential shielding plate
Program	Automatic program	DP_{5324}	32.56	Production cycle length	Become familiar with the process flow and plan the system action flow.
	Manual program	DP_{5323}	30.53	Misoperation or wrong action	Set delayed action and add error-proof design
	Alarm program	DP_{41}	26.87	Alarm is not timely	Create different alarm outputs for the different fault types
	Reclaiming program	DP_{62}	24.80	Poor movement	Refine the action; the span between each action command is easily insufficiently large, so set the appropriate speed and turning radius
	Unloading program	DP_{53}	24.80	Incorrect feeding position	Set a low speed when discharging, produce a linear motion, and prevent shaking
HMI	Action command	DP_{931}	13.06	Incorrect operation	Set button delay action and error proof the design
	Operation feedback	DP_{93}	9.79	Operation result unknown	Add operation process indicator and position indicator
	Navigation bar	DP_{92}	8.17	Cannot quickly switch between interfaces	Set a reasonable interface display area
	Element layout	DP_{942}	6.53	Cannot quickly find the operation button	Reasonably arrange the buttons and add notes

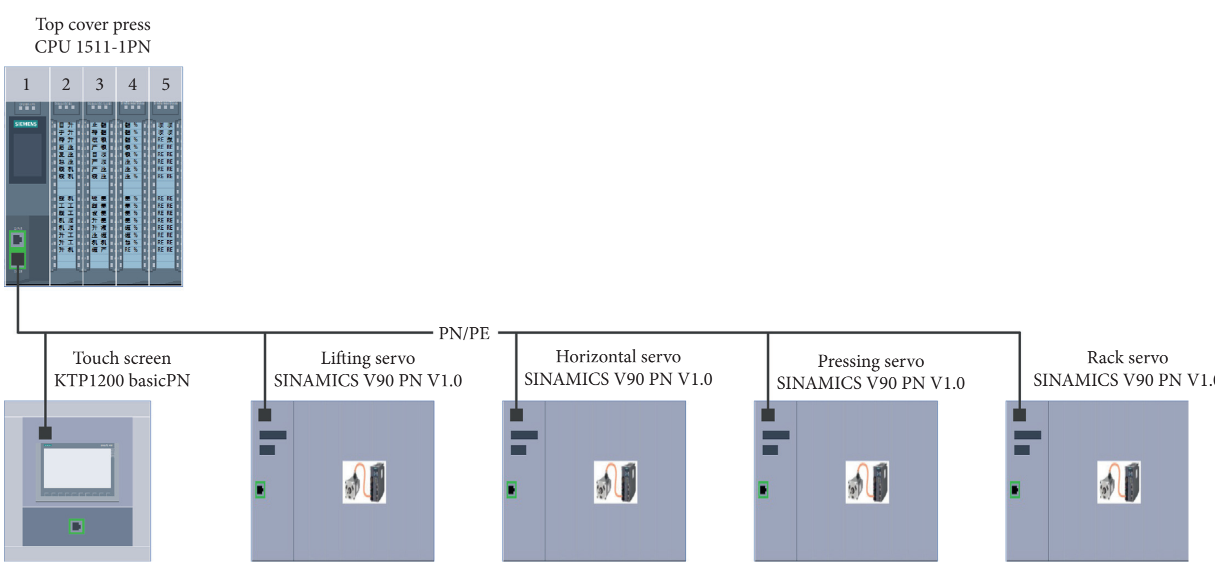


Figure 14: The equipment configuration network diagram of the control system of the water heater tank capping press.

information, FR_{221}, whereas the ABB robot can judge the workpiece model, FR_{222}, and executes the loading action, FR_{223}. The working principle of model, FR_{22}, is to receive input signals, generate control signals after the program is run, and then issue control commands. The function sequence relations are $FR_{221} > FR_{222} > FR_{223}$. The mapping

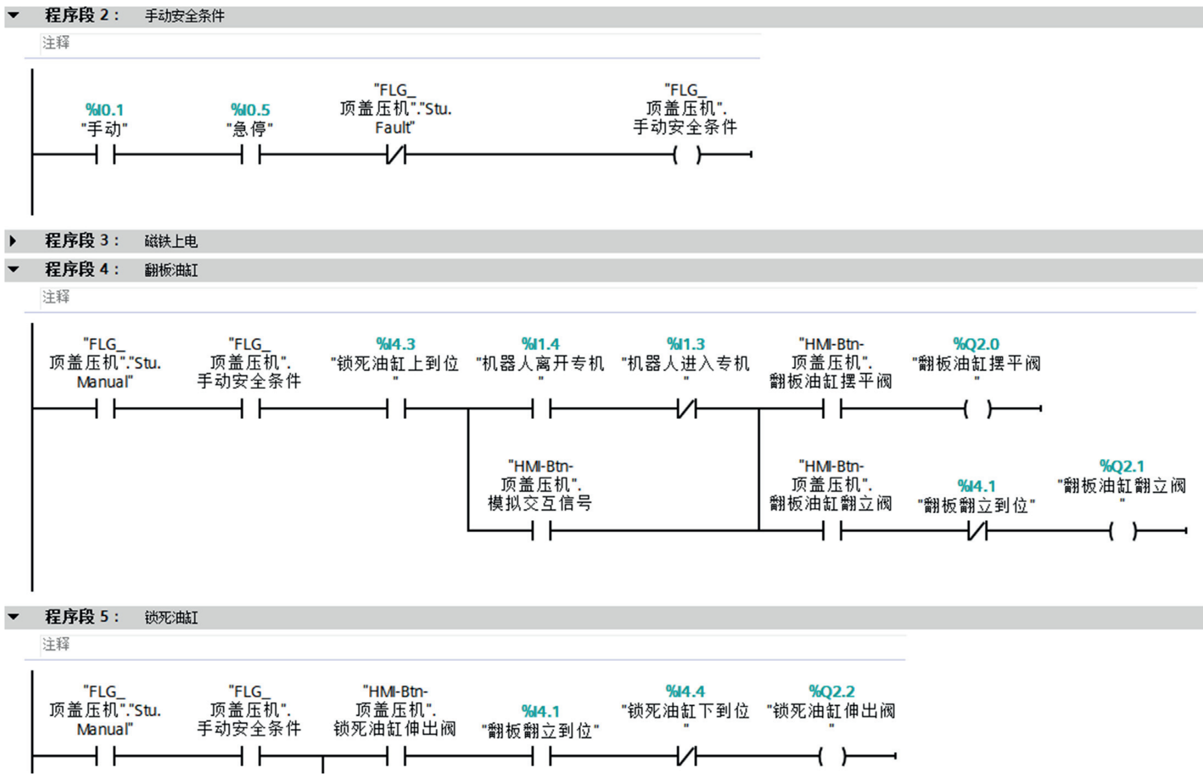


Figure 15: Part of the manual program of the water heater tank top press system.

structure is the ABB robot signal input point, DP_{221}, the ABB robot model program, DP_{222}, and feeding control program, DP_{223}. The design equation of the mapping is then

$$\begin{bmatrix} FR_{221} \\ FR_{222} \\ FR_{223} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} DP_{221} \\ DP_{222} \\ DP_{223} \end{bmatrix}. \quad (28)$$

The zigzag mapping of the functional structure of FR_2 is presented in Figure 9.

To reasonably evaluate the importance of each basic structure of DP_2 and clarify the design focus of the system, the risk prediction HoQ can be illustrated according to the decomposed mapping and the zigzag mapping matrix of FR_2. Furthermore, the ERPN of DP_2 can be obtained, as shown in Figure 10.

As shown in Figure 10, the modules of DP_{21}, DP_{223}, and DP_{22} have higher risk sequence numbers. Thus, the designers should focus on analyzing possible failures and incorporate preventive measures during the design process. Similarly, other system functions, such as FR_1 and FR_3 to FR_9 can be decomposed via mapping and solved to obtain all the basic structural modules.

5. Construction of the Control Service System

According to the solution for the functional structure of the control service system, the resulting basic structure can be split into a hardware system, a system program, and a human-computer interaction interface. According to the results of the risk prediction house of quality for each structural module, the structural modules are found to have a higher risk order in the hardware system, system program, or human-computer interaction interface, respectively. During the design stage, designers adopt targeted measures to resolve these potential risks and to reduce their impact on later system debugging. Figure 11 shows the hardware structural scheme of the control service system for the water tank liner top cover press system. Figure 12 shows the system's program structural scheme.

The basic structural schemes related to the human-computer interaction interface are screened to determine those related to the human-machine interaction interface. The basic structural schemes of the human-computer interaction interface should then be combined according to the designer's knowledge of industrial human-computer interaction interfaces. Figure 13 shows the structural design of the human-computer interaction interface of the control service system.

After the hardware system's structure scheme, the system's program structure scheme, and the control service system's human-computer interaction interface structure scheme are combined, the structural modules with higher risk order numbers in every scheme must be determined (see Table 14). An analysis of these modules can determine potential failure modes and the possible consequences, and, on that basis, provide corresponding preventive measures. Potential risks can thus be resolved during the design stage.

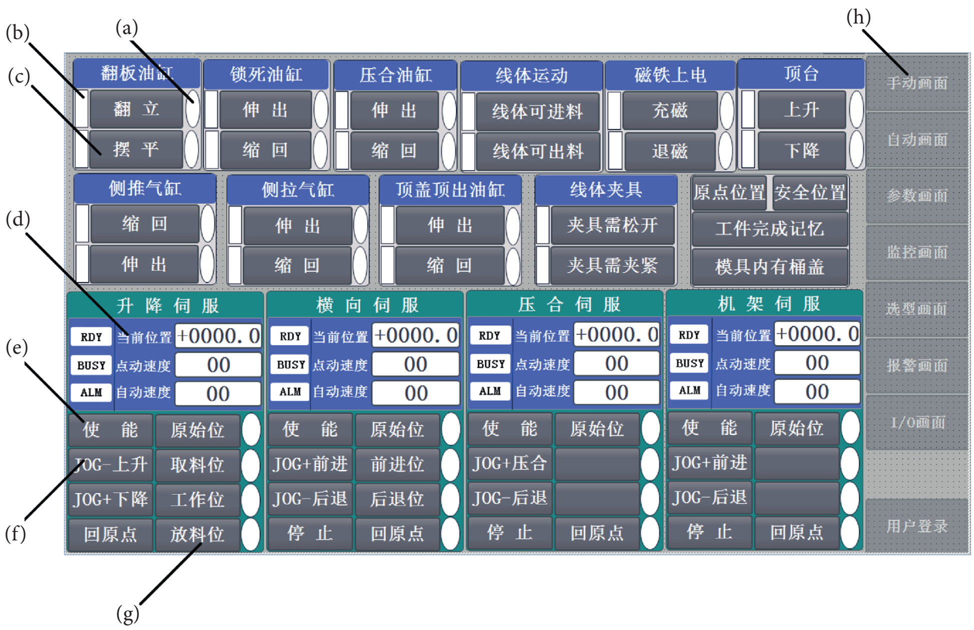
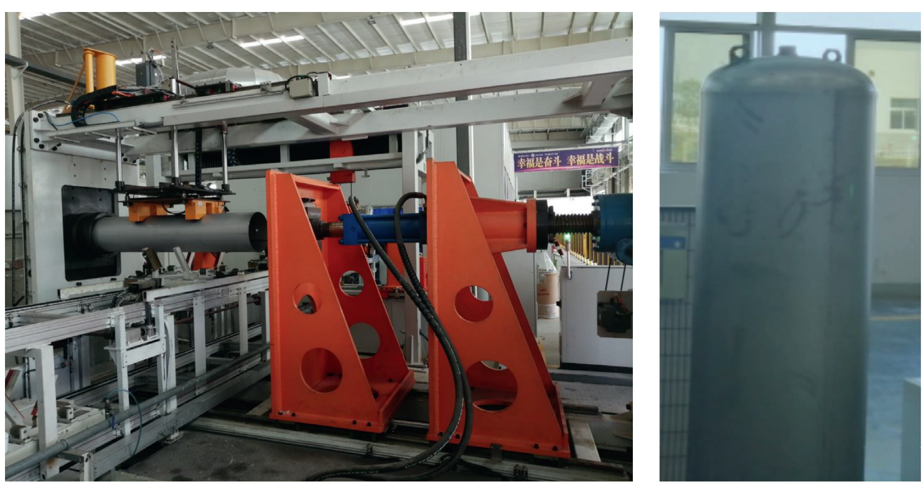


Figure 16: Manual operation interface of water heater tank top press system. (a) Operation feedback indication. (b) In-place instructions. (c) Operation button. (d) Servo motor monitoring. (e) Servo motor power up. (f) Servo motor inching control. (g) Step operation. (h) Navigation bar.



(a) (b)

Figure 17: The water heater tank capping press.

6. Conclusion

According to the structure scheme of the control system of the water heater tank capping press, the detailed design of each structural module is carried out. In TIAPortal, the CPU1511 of S7-1500, HMI panel, and 4 servo drives form a configuration network, and Profinet industrial Ethernet is used to communicate among each part, as shown in Figure 14.

Then, according to the program structure scheme, the PLC program of the control system of the water heater tank capping press is divided into automatic program module, initialization program module, manual program module, return to the origin program module, alarm program module, and servo motor program module. Part of the manual program module is shown in Figure 15. The touch screen interface design of the control system mainly includes parameter interface, monitoring screen, selection screen, alarm screen, automatic screen, manual screen, and I/O port screen. The manual screen is shown in Figure 16. The main body of the water heater tank capping press is shown in Figure 17.

After the design of the control system is completed, the water heater tank capping press is produced and operated in the actual working environment. The water heater tank capping press works stably and satisfies the production demands well. It is verified that the upper design method can effectively guide the design process of the control system.

The design method preferred in this paper is based on the analysis of customer demands to ensure the accurate input of the demand domain and to complete the mapping between the demand domain and the function domain and between the function domain and the structure domain. This approach makes up for the lack of a single design method, to a certain extent. It also has the advantages of accuracy, clarity, and being a complete system. It can guide the designers to make better design decisions and evaluations during the design process more quickly and improve the design efficiency and quality of the control project. This method improves the cluster analysis of customer demands and proposes a weighted network AP clustering algorithm to determine the characteristics of customers' demands, compensating for the lack of regularization of customers' requirements in traditional QFD and AD designs. On the contrary, the method takes full advantage of QFD and AD design methods, combining the empirical design and AD, not only benefiting from the designer's experience but also avoiding subjective influence. Finally, the effectiveness and feasibility of the proposed method are demonstrated by using the example of the design and production of the control service system for a water heater liner top cover press.

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

Winning and Losing Relationship: A New Method of University Ranking in the Case of Countries along the Belt and Road

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From the perspective of the complex system, university ranking is a complex system that involves multiagent actors, which evolve over time. Yet, current major university rankings fail to reflect the system dynamics of the university innovation system. In this paper, we apply the complex system model in the field of the university innovation system in the context of university ranking in the countries along the Belt and Road, which is a long-term overlooked field. We introduce a new method of university ranking based on the "winning and losing" relationship to measure the relative competitiveness between universities. This paper contributes to complex system research, the Belt and Road research, and the university ranking arena.

1. Introduction

University rankings (or college and university rankings) are rankings of institutions in higher education based on various combinations of various factors [1, 2]. As a common way to rank and evaluate universities, university rankings reflect the research quality, teaching quality, and a variety of other aspects of universities, thus could act as a reference for students' school choice or even as an evaluation index for a country's competitiveness in education and innovation [3]. For home students and international students, the role of university rankings is also different. The former mainly uses them to supplement existing information, while the latter uses rankings as an important decision-making basis [4]. In addition to the significant role in the national system of innovation, universities also play a major role in the regional innovation system or contribute to the whole society by formulating a university innovation ecosystem. Prior literature mainly focuses on the role of universities in the national or regional innovation system, such as a triple helix of the university-industry-government linkages [5–7], yet overlooking the system dynamics inside of the university innovation ecosystem [8, 9]. From a complex system perspective [10–12], each university is an agent actor in the university innovation ecosystem [13, 14]; thus, the evolution [15], the relative interdependence between each actor [16], and the interaction between actors should be the top topic of studies on the university innovation ecosystem and thus should be considered in university rankings. However, although there are several major global university rankings, none of them have taken the complex system models into account, thus failing to reflect the complex and dynamic nature of the university ecosystem. At present, due to the limitations of measurement indicators, mainstream university rankings do not play a significant role in promoting the quality of higher education [17]. In this paper, we introduce a new method of university ranking based on complex system models and apply the new method in a new field that current major university rankings have overlooked for decades.

In 2013, China adopted the Belt and Road Initiative (hereafter, BRI) as a global infrastructure development strategy, covering nearly 70 countries in Asia, Africa, Europe, the Middle East, and America. As an initiative aiming to "enhance regional connectivity and embrace a brighter future," the BRI has signed or developed 200 cooperation documents in 138 countries and 30 international organizations as of 2020. Building a regional university consortium or union is one of the major goals of the BRI [18]. With the closer cooperation between the BRI countries, the academic cooperation and knowledge flow between the BRI universities are also increasing. Thus, the mutual understanding between the BRI universities is in need to further enhance collaboration and communication. Yet, due to the long-term ignorance of the BRI countries, academia knows very little about the status and relative competitiveness of the BRI universities. In this paper, we apply our new method of university ranking in the BRI countries. This is the first time to rank universities in the BRI countries. This paper contributes to the BRI research by introducing a near-holistic system covering as much the BRI universities as possible, and by so doing offering a systematic view to examine and evaluate the relationship between the BRI universities.

The remainder of this paper is organized as follows. Section 2 reviews the current research on the university innovation system and cross-border academic talents' flow and then discusses the role of universities from countries across the Belt and Road and the deficiencies of current university ranking for neglecting these universities. Section 2 also reviews the literature on the university ranking from the perspective of a complex system and proposes the "winning and losing" relationship as a new method for university ranking. Then, model construction and methodology are reported in Section 3. Section 4 reports our data collection process. Next, the model results are studied in Section 5. Finally, Section 6 concludes the paper.

2. Literature Review and Theoretical Framework

2.1. The University Innovation System and Cross-Border Talents' Flow. With the in-depth development of globalization globally, the scale of education globalization has also expanded tremendously. The free flow of higher education and human resources has become a common phenomenon worldwide. The flow of talents tends to go to higher education institutions with higher education and higher quality. Under this circumstance, competitiveness has become one of the goals that the world's universities strive to pursue [19], making the world university ranking a significant demand for higher education institutions [20]. The university rankings provide references for students, researchers, policymakers, and other stakeholders to allocate educational resources, the choice of institutions, and other relevant issues.

More and more university rankings begin to appear in people's vision. The evaluation criteria and indicators they apply to are varied. However, various university rankings mainly use quantitative and qualitative indicators to evaluate three aspects of the development level of higher education institutions. Some use the student-student ratio, employer reputation, etc., to reflect the teaching level of colleges and universities [21] and use papers published and cited, academic standing, and the number of academic staff to reflect the achievements of academic research. Some rankings use the number of international students to demonstrate the degree of internationalization. More and more institutions evaluate and rank universities in recent years; the ranking content and methodology gradually become diversified. However, in the current world university rankings, some university rankings such as ARWU, NTU, and URAP, their ranking indicators, and methods show high similarity [22], so many people are trying to improve and synthesize the existing rankings using their own methodology, such as the introduction of entrepreneurial orientation [23], meta-ranking [24], and ranking aggregation [25]. In the process of specific ranking, the method of weighting and maximal normalization are extensively used to calculate the scores of each institution. However, there are still many problems in the current university rankings.

2.2. The Role of Universities from Countries across the Belt and Road in the World University Innovation System. Although the BRI countries are indispensable members of the world economy, most universities in the BRI countries are neglected in the current university rankings for decades. However, it is important to note that these universities also play an essential role in the global higher education and innovation system. Meanwhile, these universities play an indispensable role in their home countries.

There are four major global university rankings now: QS ranking, Leiden ranking, ARWU, and U-Multirank. The QS (Quacquarelli Symonds) World Ranking of Universities (hereafter, QS ranking) assesses university performance based on six indicators, including academic reputation, citations per faculty, student-to-faculty ratio, employer reputation, international faculty ratio, and international student ratio [19–21]. The QS ranking was first published in 2004 and was the result of the collaboration between the QS and the Times (the Higher Education edition, hereafter, THE). Yet, after the suspension of cooperation with the Times in 2009, QS and THE released their university rankings independently since 2010, but these two systems still use very similar indicators and calculation methods. The main shortcoming of the QS and THE ranking is they both neglect the importance of educational performance. Although they intend to measure the quality of teaching through a reputation survey, their results are easy to be influenced due to the lack of accuracy of the survey method. The two most important indicators in the QS and the ranking (academic reputation and employer reputation; these two indicators account for half of the weights) are based on global surveys [26, 27]. Yet, these surveys cannot reflect the exact quality of academic research and education due to the limited data, the subjective measurement, and the lack of transparency, which makes these two indicators highly problematic. Moreover, most of these ranking indicators are more beneficial to large-scale universities or those with large research funds [28]. Although many use quantitative methods such as PageRank to construct a citation network to measure reputation, however, such methods can only show the academic reputation of the institution rather than the overall reputation [29, 30].

The Academic Ranking of World Universities (hereafter, ARWU), formerly known as the Shanghai Jiao Tong index, is published annually by the Institute of Higher Education and Shanghai Jiao Tong University since 2003. Each year, ARWU ranks more than 1800 universities and publishes their top 1000. The indicators in ARWU ranking include number of alumni winning Nobel Prizes and Fields Medals, number of staff winning Nobel Prizes and Fields Medals, number of highly cited researchers in 21 broad subject categories, number of articles published in Nature and Science, number of articles indexed in Science Citation Index Expanded (hereafter, SCI-E) and Social Sciences Citation Index (hereafter, SSCI), and per capita academic performance of an institution. Because ARWU mainly focuses on academic performance, it inevitably fails to reflect the overall performance of the university [28]. Meanwhile, there are certain problems in the accuracy of academic publications and citation data [31]. Because of different biases towards the academic-level evaluation indicators, the ranking results of the academic level in the same school are quite different [32]. The measurement of academic achievements still requires more sophisticated quantification or calculation methods.

The Leiden Ranking was first published in 2009 [32], focusing on the academic performance of the university, and does not take the quality of teaching into consideration at all [31]. The Leiden ranking, therefore, could only reflect the level of scientific research and fails to picture the overall performance of universities. At the same time, the Web of Science (hereafter, WOS) publication and citation data are used in the Leiden Ranking, which are also inaccurate [33]. However, this method relies too much on the publication and citation of academic papers [34], and one of the results it brings is active academic performance management. This has led many higher education institutions to choose the universities and colleges in their own countries or countries where higher education is well developed to conduct academic cooperation and paper publication to increase the number of papers published and cited, thus improving their performance in ranking [35]. However, this approach will bring negative effects to the publicity of universities [36].

The U-Multirank was first published in 2014, combining the WOS citation data from the Leiden Ranking and students' survey as from the QS and THE ranking [28, 37]. Yet, the U-Multirank still has a problem with indicator redundancy. Too many indicators are also one of the main problems in the current university rankings. The overdetailed indicators make it hard for stakeholders to understand and make decisions based on the U-Multirank.

In addition to the above deficiencies, current university rankings still fail to reflect the dynamic mechanisms of the university innovation ecosystem. These problems have largely caused certain obstacles to the choices of institutions for stakeholders. For the colleges themselves, it also caused a lopsided pursuit of academic performance neglecting the quality of teaching, which has a certain negative impact on the healthy development of higher education [38]. Therefore, it is necessary to propose a new method of university ranking with simple indicators, which can effectively and dynamically measure the actual quality and performance of universities with robust results [21, 29, 39, 40].

2.3. The "Winning and Losing" Relationship in the Complex University Innovation System. This study proposes a new ranking method called the "winning and losing" relationship, which will take the undergraduate, postgraduate, and doctoral students' career progression or employment tendencies as the main indicators to measure the performance of universities in education. Our indicators include the net inflow of talents in each university's talent flow, the university's level of competitiveness, and the relative talent flow at each stage. The factors that affect the flow of academic talents are usually diverse, including various uncertain factors, such as the impact of epidemics on the flow of talents. Historically, pandemics may indeed affect the flow of talents, including the current COVID-19 and the closure of higher education institutions in some countries after the outbreak, which will affect people's mobility choices to a certain extent and partly affect the university ranking's accuracy. However, the data for this study were collected in 2019. The data on academic talents are mainly those born after 1950. The epidemic which has the impact that is similar to the pandemic and can change the trajectory of academic talents on a large scale does not exist in the interval. Thus, the influence of pandemics will not be taken into the consideration in this research.

In addition to the disorderly flow of talents that may be caused by government intervention, epidemics, and education agreements, which affect the scientific nature of this evaluation, there are many other factors that affect the flow of academic talents. However, the innovation of this article is precise that it does not specifically consider these traditional factors of the flow of academic talents. Instead, it starts with the final selection of academic talents for ranking construction. In fact, there are many uncertain factors (not mentioned in the previous literature) that may affect the flow of talents, but usually, the impact is partial, small-scale, and periodic. The study based on the large database still has the positive value of scientific research and method innovation.

The main theoretical basis of the research is the rational choice theory, which has been widely used in economics, sociology, law, and other fields for many years as a theory of research on the choice of human behavior strategies [41, 42]. In rational choice theory, rationality is the instrumental rationality that explains the connection between an individual's purposeful action and the outcome it can achieve. The rational choice theory generally considers that the individual is the rational person, that is, the pursuer of his own best interests, and intellectually believes that different choices will lead to different results [43]. There are different behavioral strategies to choose from in a particular situation. At this time, subjectively, people will have different preferences for different selection results [44]. And people generally tend to choose the optimal strategy, that is, the strategy with the lowest cost or the highest benefit [45]. Of course, there are people who criticize the scientific nature of rational choice theory. Criticism of this theory mainly focuses on assumptions. Many believe that rational choice theory has flaws in assumptions, and its basic assumption, that is, the hypothesis of "economic man," does not conform to reality. They believe that rational choice theory pays too much attention to the influence of psychological factors on the continuity of behavioral choices, making this theory well received. However, in this study, students' choice of further studies and employment is largely influenced by psychological factors, especially the expectations about the target colleges and universities. Students are obviously more inclined to be within the range of choices to go to better colleges to conduct further studies [46].

Based on the research ideas of this theory, we analyze the behavioral orientation of students' choice of school and propose a method of the "winning and losing" relationship.

The "winning and losing" relationship means the comparison of the trend of talent flow between the two universities, which university is more preferred by talents. Educational agreements between countries, especially agreements on mutual recognition of credits, enrollment quotas, scholarships, etc., can affect the flow of academic talents greatly. Even so, education agreements still contain students' mobility options. If the quality or reputation of the counterparty is lower than the student's previous degree, the mobility is still difficult to occur on a large scale. However, there may indeed be reverse inflow situations. For example, in China, a small number of undergraduates from Peking University choose Wuhan University or Fudan University to study for a master's degree. However, the number is very small, and the influence of a small number of small samples on the research results can be avoided through increasing sample size.

As mentioned above, there is indeed a small number of nonregular mobility of academic talents, which may be related to human intellectual factors or other factors that are not related to the quality of higher education, such as the ability of people to obtain information. Even so, a large database can still reflect the mobility choices of the vast majority of people, rational choice theory is still applicable, and university rankings based on the large database and rational choice theory are still highly applicable.

In this research, we apply a two-to-two comparison to all of the universities we surveyed, which will provide the "winning and losing" relationship of each university and the net inflow of talents. Then, we add the results together, and based on that, we calculate the total net inflow of talents. This methodology aims to rank colleges and universities by measuring the trend of the talents of colleges and universities. Our method can reflect the system dynamics in the university innovation system [47, 48], with relatively stable and simple indicators and objective data sources.

As for reputation, the reputation of a university directly reflects its public image [49] and perception [50]. As a very important indicator of university rankings, which is mentioned above, reputation is very difficult to quantify. There are plenty of methods to evaluate the reputation of universities, such as questionnaire and survey, which are mentioned above. Chen put forward 24 criteria for evaluating the reputation of universities [51], which are of great value. However, the innovation of this article lies in that the traditional reputation evaluation is more partial, and various indicators are used to try to calculate the reputation of the university. Meanwhile, it is easily ignored that value creation behaviors of talents and college students [52] also play an important role in promoting the reputation of universities. This article follows the idea of "gestalt," emphasizes the overall evaluation plan of the university reputation, and applies large database analysis of academic talents "voting with their feet" to quantify the reputation, which is fundamentally different from previous research, including Chen's.

3. Model Construction

This study is based on Coleman's analysis of rational choices, starting with the students' individual choice behaviors and constructing university metrics from the perspective of students' choices of colleges [41, 42]. With the development of the internationalization of higher education, students' choices of colleges are mainly a kind of individual behavior; students can freely choose to study or work in different institutions and are basically not bound by social systems. In addition, students who choose to continue their studies or work are the choices for graduation. The preferences of students who choose the same kind of destination are basically the same, so the connection between student preferences and social choices can be ignored.

One theoretical basis of this research is derived from the basic concept of "Man struggles upwards" in traditional Chinese culture to explore new university ranking. The basic assumption is that universities are in a generally stable political and ecological environment. In countries and regions currently in conflicts of war, extreme religious conflicts, or extreme climates, the flow of academic talents is usually more restricted by other nonacademic factors, which may lead to a decline in the scientific level of university rankings based on academic mobility.

Another assumption is that there is a relatively complete global academic labor market and a country's academic labor market in which academic talents can flow freely, but generally speaking, some countries may still have government supervision and control over the flow of academic talents for various purposes. Take China as an example; in recent years, in order to curb the flow of academic talents from the west to the east, the Chinese government has introduced a large number of policies and measures to try to restrict the flow of scholars who have received specific honors. However,this part of the flow restriction is enhanced when the students graduated from school and become academic faculties, and the object of this research is the first employment behavior of the academic talent after graduation, which is usually subject to less government intervention.

Therefore, this study will explain the student's choices of schools from the perspective of cost benefit. Based on the purpose of rational choice theory, the following formula explains the specific conditions for the emergence of rational choice theory:

$$V = BP - P'C. \quad (1)$$

If $V_i > V_j$, then V_i is chosen.

B represents the expected benefit, that is, the actor's expectation of the possible income of choice; C represents the expected cost, that is, the subjective judgment of the actor's cost of taking human and material resources for taking action; P and P', respectively, represent subjective judgments of the actor's likelihood of expected benefits and expected costs; V represents the net profit that the actor's choice may bring; and i and j represent different options.

When using this formula to analyze students' choices of schools, students' choices for further studies have a fixed scope. Because of differences in cultural capital, social capital, and economic capital of different students, each student's optimal solution V_i and opportunity cost V_j are not the same. Under the assumption of rational people, students will choose the one with the highest net benefit, the best choice. Therefore, the selected colleges can be considered as the most attractive colleges for the students, which is why we use the net flow of talents as the basis for calculating the "winning and losing" relationship.

> Hypothesis: students tend to choose institutions with better teaching quality when they enter into the next education stage, and students are free to move

3.1. The Stage of Undergraduates. Let a be the number of schools used to compare the winning and losing relationship. Taking school i as an example, calculate the "winning and losing" relationship of i school (W_i). The number of undergraduate students in i school who go to j school to study for a master's degree is x_{ij}. The number of undergraduate students who are enrolled in j school but go to the i school to study for a master's degree is x_{ji}. Then, $W_{ij} = x_{ij} - x_{ji}$ is the winning and losing relationship between the i school and the j school (in terms of the number of students), $i, j = 1, 2, 3, \ldots, a$.

Then, the comprehensive winning and losing relationship of i school is

$$W_i = \sum_{j=1}^{a} W_{ij} = \sum_{j=1}^{a} x_{ji} - x_{ij}. \quad (2)$$

Description of W_{ij}:

$W_{ij} > 0$, i school net victory (that is, i school is a university with a net inflow of talents)

$W_{ij} = 0$, i school and j school are of the same level

$W_{ij} < 0$, i_{school} net loss, i school is a university with a net outflow of talents

Compare $W_1, W_2, W_3, \ldots W_a$

The ranking rule is as follows:

If $W_1 > W_2 > W_3 > \ldots > W_a$, then $R_1 = 1$, $R_2 = 2$, $R_3 = 3$, $\ldots$, $R_a = a$ (R_i is the school ranking, $i = 1, 2, 3, \ldots, a$)

As shown in Figure 1, taking i school as an example, it shows the process of its winning and losing relationship.

3.2. The Stage of Postgraduates. Let a be the number of schools used to compare the winning and losing relationship. Taking school i as an example, calculate the "winning and losing" relationship of i school (I_i). The number of graduate students in i school who go to j school to study for a doctor's degree is y_{ij}. The number of doctoral students who are enrolled in j school but go to the i school to study for a doctor's degree is y_{ji}, and I_{ij} is the winning and losing relationship between the i school and the j school (in terms of the number of students), $i, j = 1, 2, 3, \ldots, a$.

Then, the comprehensive winning and losing relationship of i school is

$$I_i = \sum_{j=1}^{a} I_{ij} = \sum_{j=1}^{a} Y_{ji} - Y_{ij}. \quad (3)$$

Description of I_{ij}:

$I_{ij} > 0$, i school net victory

$I_{ij} = 0$, i school and j school are of the same level

$I_{ij} < 0$, i school net loss

Compare $I_1, I_2, I_3, \ldots I_a$

The ranking rule is as follows:

If $I_1 > I_2 > I_3 > \ldots > I_a$, then $R_1 = 1$, $R_2 = 2$, $R_3 = 3$, $\ldots$, $R_a = a$ (R_i is the school ranking, $i = 1, 2, 3, \ldots, a$)

3.3. The Stage of the Employment of Doctoral Students. Let a be the number of schools used to compare the "winning and losing" relationship. Taking school i as an example, calculate the "winning and losing" relationship of i school (E_i). The number of doctoral students in i school who go to j school to work is z_{ij}. The number of doctoral students who are enrolled in j school but go to the i school to work is z_{ji}, and E_{ij} is the "winning and losing" relationship between the i school and the j school (in terms of the number of students), $i, j = 1, 2, 3, \ldots, a$.

Then, the comprehensive winning and losing relationship of i school is

$$E_i = \sum_{j=1}^{a} E_{ij} = \sum_{j=1}^{a} z_{ij} - z_{ij}. \quad (4)$$

Description of E_{ij}:

$E_{ij} > 0$, i school net victory (that is, i school is a university with a net inflow of talents)

$E_{ij} = 0$, i school and j school are of the same level

$E_{ij} < 0$, i school net loss, i school is a university with a net outflow of talents

Compare $E_1, E_2, E_3, \ldots, E_a$

The ranking rule is as follows:

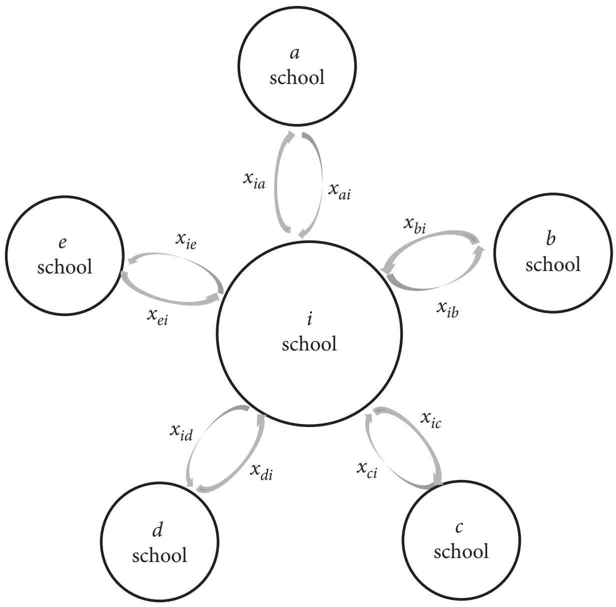

Figure 1: Talent mobility diagram.

If $E_1 > E_2 > E_3 > \ldots > E_a$, then $R_1 = 1$, $R_2 = 2$, $R_3 = 3$, …, $R_a = a$ (R_i is the school ranking, $i = 1, 2, 3, \ldots, a$)

4. Data Collection

We collect the resumes of the faculties of the universities in the BRI countries, using Python language. Specifically, the main indicators selected by the winning and losing relationship approach are the attractiveness of further studies and employment competitiveness. The attraction of the study and employment competitiveness represent the level of recognition and recognition of students in colleges. According to the theory of rational choice, students tend to choose institutions that are most beneficial to them. Therefore, the attractive indicators can reflect the educational performance and industry reputation of the university to a certain extent so that they can be used as the basis for ranking.

In the analysis section of this paper, we mainly select the data from the universities in the BRI countries to implement the above methodology. The BRI is the first two-multilateral mechanism that China has proposed to rely on China and related countries and, at the same time, leverage existing cooperation resources to establish an effective regional cooperation platform [53, 54]. The platform aims to use the historical symbols of the ancient Silk Road to actively develop economic partnerships with countries along the line from the formation of political mutual trust, economic integration, culturally inclusive community of interests, a community of destiny, and a community of responsibility [55, 56]. As global strategic cooperation, higher education research in countries along the BRI has gradually gained great attention in recent years [57]. Cooperation in education has also led to an increase in the level of higher education in the BRI countries. However, most universities along the BRI countries are difficult to rank in the mainstream rankings. The BRI countries have performed poorly on the global university rankings, and there are characteristics of "less quantity" and "quality difference." Not only the number of countries on the list and the top 500 universities in the list are small but also the ranked universities are ranked lower. There are internal and external factors in this phenomenon. The internal aspect is that most countries, along with the BRI countries, still have a certain gap between higher education and developed countries due to their economic and social development level. Therefore, the overall strength and international competitiveness of universities along the BRI countries are not strong. The external reasons are mainly reflected in the fact that the existing mainstream universities basically have some institutions in developed countries to carry out ranking work. The ranking index system formulated by these institutions is compatible with the mainstream development direction education system of universities in developed countries. The focus of such systems is different from the development trend and current situation of universities in the countries along the BRI, which may also affect their ranking results. Therefore, the universities in the countries along the BRI need a ranking system which is more suitable for their actual development, and the "winning and losing" relationship method is an effective solution to solve this problem.

Based on the above theory and practice, we collected the resumes of more than 20,000 faculties from 286 universities or higher education institutions in 35 BRI countries from the official website of the universities (the resumes of faculties not published on the official website of the university are not included) by Python and descendant collector. There are only 4 English-speaking countries among the 64 countries along the "Belt and Road." There are indeed problems such as slow update of websites in non-English-speaking countries and missing resumes of a few young scholars. However, 4 English-speaking countries also have problems with lagging resumes. And because the original data come from the official websites of higher education institutions in countries along the "Belt and Road," some schools' official websites have missing data, and the number of "Belt and Road" countries is increasing every year, so the study does not include all the countries along the "Belt and Road."

The distribution of institutions is presented in Table 1.

5. Model Results

We extract information about undergraduate, postgraduate, and doctoral programs of universities in the BRI countries. We then apply our methodology using MATLAB to calculate the "winning and losing" relationship of each university or higher education institution. The results are reported in the following.

5.1. The Attraction for Undergraduates to Continue Their Studies. Table 2 presents the ranking of the top 10 universities in terms of attractiveness for undergraduates to continue their studies. From the BRI universities we surveyed, the gap between the "winning and losing"

Table 1: The distribution of universities across countries.

Countries	The number of universities
Bangladesh	31
India	27
Bulgaria	24
Greece	20
Cyprus	18
Indonesia	16
Romania	14
Pakistan	13
Czech Republic	13
Russia	11
Malaysia	11
Azerbaijan	8
Croatia	8
Armenia	8
Albania	7
Bahrain	5
Philippines	5
Iran	5
Egypt	4
Poland	4
Georgia	4
Cambodia	4
Jordan	4
Turkey	3
Ukraine	3
Iraq	3
Vietnam	3
Afghanistan	2
Lithuania	2
Macedonia	2
Lebanon	1
Saudi Arabia	1
Uzbekistan	1
Yemen	1
Montenegro	1

relationships between universities is not very large. In terms of the attractiveness of undergraduate progression, the best-performing institution is the University of Bahrain from Bahrain, with a net inflow of talent of 4. The worst-performing institution is Beni-Suef University from Egypt, with a net outflow of talent of 8. There is only a difference of 12 units of measure between the net inflows of talent in these two institutions. Among the 286 colleges and universities, only 11 colleges and universities belong to the net inflow of talents, accounting for 3.8% of all ranked universities. Only 12 colleges and universities belong to the net outflow of talents, accounting for 4.2%. The other 264 colleges and universities are basically the same in terms of the number of inflows and inflows of higher education talents, accounting for 92%. This shows that most of the universities in the BRI countries have little difference in the attractiveness of postgraduate studies, and they have no outstanding influence.

According to the "winning and losing" relationship approach, the University of Bahrain, Nahda University, North South University, and the University of Cyprus are more attractive to undergraduates. Among the top 10 universities, four universities are from Bangladesh, and others are from Bahrain, Egypt, Cyprus, Pakistan, Ukraine, and the Czech Republic. This phenomenon shows that there are specific differences in the attractiveness of undergraduate students in different countries, along with the BRI countries.

Table 3 and Figure 2 present the distribution of net talent flows of undergraduates. Of the 12 universities with a net outflow of talents, three are from India, two are from Bahrain, and two are from Cyprus. Other institutions are from the Czech Republic, Iran, Malaysia, Georgia, and Egypt.

The rankings of colleges and universities calculated by this method essentially reflect the relatively balanced attraction of undergraduate students in most BRI countries, and only a few universities are more prominent. Such a result may be due to the fact that most of the BRI countries are developing countries, and the level of education development is not high. Many countries concentrate limited educational resources on one or several key universities, leading to general education in ordinary universities. Therefore, these colleges are not attractive. Many schools have a low turnover of talents. It is also possible that many students in the BRI universities cannot enter higher universities for further study due to information asymmetry, narrow channels for further studies, and high barriers to entry. Information asymmetry is mainly reflected in the significant cultural and linguistic diversity of the BRI countries. Therefore, in the internationalization of talent mobility, many students may not be able to obtain information about universities in other countries because of language and cultural barriers. The narrowing of the channels for further studies and the high threshold for progression are reflected in the fact that many students in the BRI universities are mainly oriented to elite groups because of their insufficient economic and social development, limited educational resources, and information asymmetry. These factors, in fact, have affected the undergraduate students' further study choices.

As for the difference in net talent inflows between institutions in different countries, there are two different interpretation angles. The first is that the countries along the BRI have both developed and developing countries. In essence, the level of economic and social development between countries is quite different. Therefore, institutions from countries with a high degree of economic and social development may have greater advantages in the level of higher education and the attractiveness of further studies. The other angle is that the BRI countries have large differences in language and culture, and students tend to move within a certain area. Therefore, the geofigureical factors, that is, the degree of active talent flow in the region, will also affect the degree to a certain extent. Thus, the scores of the "winning and losing" relationship of regional universities can show differences in rankings of universities.

5.2. The Attraction for Postgraduate Studies. In terms of the attractiveness of postgraduates, the absolute gap between the universities is unchanged. The flow of talents in the

Table 2: The ranking of the attractiveness for undergraduates to continue their studies (top 10).

University	Country	The net inflow of talents
University of Bahrain	Bahrain	4
Nahda University	Egypt	3
North South University	Bangladesh	3
University of Cyprus	Cyprus	2
Gomal University	Pakistan	1
Kharkiv National University of Radio Electronics	Ukraine	1
Masaryk University	Czech Republic	1
Northern University	Bangladesh	1
Shahjalal University of Science and Technology	Bangladesh	1
University of Dhaka	Bangladesh	1

Table 3: The distribution of net talent flows of undergraduates.

Net inflow	The number of universities
4	1
3	2
2	1
1	6
0	264
−1	11
−8	1

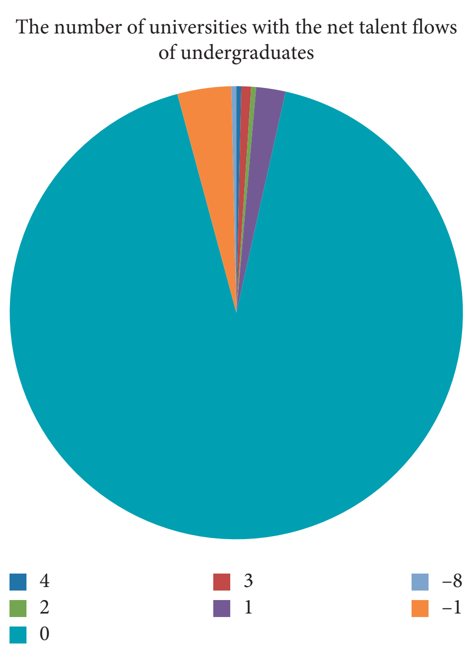

Figure 2: The distribution of net talent flows of undergraduates.

postgraduate period is still small, but the internal changes in the rankings are very obvious. The best and worst universities for the entry of graduate students are from Azerbaijan. As presented in Table 4, the best-performing university is Baku State University, with a net inflow of 6. Table 4 shows the top ten colleges and universities in terms of the attractiveness of graduate students using the winning and losing relationship method. Among the ten universities, three universities are from Bangladesh, and two are from Pakistan; other universities are from Azerbaijan, Bahrain, Egypt, India, and Cyprus, respectively.

Table 5 and Figure 3 present the distribution of the net talent flows of postgraduates. Among the 23 institutions with a net outflow of talent, seven are from India, accounting for 30.4% of all net outflows of colleges and universities, with the highest proportion. Three are from Pakistan, two from Bahrain, two from Malaysia, and two from Cyprus, and other institutions are from the Czech Republic, Iran, Bangladesh, Georgia, Egypt, Romania, and Azerbaijan. The worst performer is Khazar University, whose net inflow of talent is −6. Compared with the undergraduate entrance degree, the absolute difference between the best and the worst institutions is the same, but the structure of the whole ranking has changed a lot. The number of institutions with a net inflow of talents has changed from 11 to 19, accounting for 6.7%. The number of colleges with a net outflow of talents has changed from 12 to 23, accounting for 8%. The number of universities with basically the same level of talent inflows and outflows decreases from 264 to 244, accounting for 85.3%. It explains that, to a certain extent, in the postgraduate entrance examination stage, the number of institutions with basically the same level of talent inflow and outflow is decreasing, indicating that some institutions have changed from a college with a flat flow of talents to a net inflow of talents or a net outflow. There are certain differences in the attractiveness of undergraduate and postgraduate students within each university, and the mobility of talents is also increasing.

The result shows that, during the master's degree, the educational performance of the BRI universities has changed significantly. The higher education stage needs more abundant educational resources to support, and the distribution of educational resources makes the overall performance of colleges and universities and the attractiveness of further studies appear to be different, which makes the discrimination between universities increase. Although the absolute gap has not changed, most students generally prefer colleges with better teaching level in the choice of colleges. Therefore, the reduction of colleges with more balanced talents indicates that the mobility of talents between universities is higher. This may be due to the fact that there are fewer talents who tend to continue to pursue academic

Table 4: The ranking of the attractiveness for postgraduate studies (top 10).

University	Country	The net inflow of talents
Baku State University	Azerbaijan	6
University of Bahrain	Bangladesh	6
Nahda University	Egypt	3
North South University	Bangladesh	3
Rajshahi University	Bangladesh	3
University of Dhaka	Bangladesh	3
Aligarh Muslim University	India	2
Gomal University	Pakistan	2
Institute of Business Administration	Pakistan	2
University of Cyprus	Cyprus	2

Table 5: The distribution of net talent flows of postgraduates.

Net inflow	The number of universities
6	2
3	4
2	4
1	9
0	244
−1	15
−2	5
−4	1
−6	2

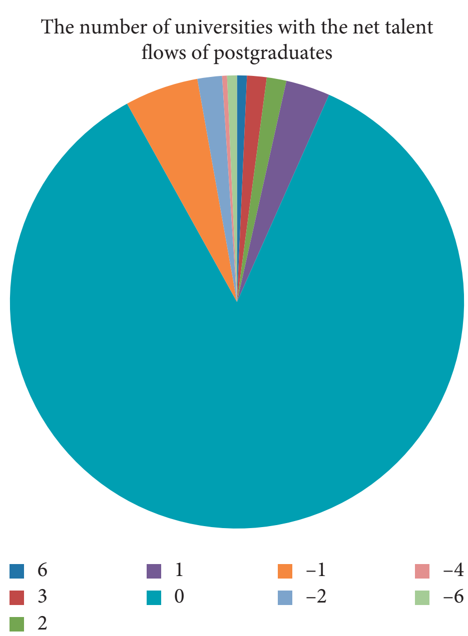

Figure 3: The distribution of net talent flows of postgraduates.

research at the doctoral level compared to the postgraduate level. These people are more likely to concentrate on stronger institutions and lead to more frequent talent flows.

5.3. The Attraction for Doctoral Students. Table 6 presents the ranking of the top ten universities in terms of attraction to doctoral students. Among the ten institutions, two institutions are from India, and other institutions are from

Table 6: The ranking of the attraction of doctoral students (top 10).

University	Country	The net inflow of talents
Anna University	India	37
University of Dhaka	Bangladesh	24
Aligarh Muslim University	India	17
Yerevan State University	Armenia	17
Baku State University	Azerbaijan	14
University of Zagreb	Croatia	14
University of Athens	Greece	14
University of Georgia	Georgia	13
Beni-Suef University	Egypt	12
University of Malaya	Malaysia	12

Bangladesh, Armenia, Azerbaijan, Croatia, Greece, Georgia, Egypt, and Malaysia. The country diversity of the top ten institutions in the employment competitiveness of doctoral students has increased compared with the previous two lists, which also shows that the mobility of talents in the doctoral degree is further enhanced. Of the ten institutions with the largest net outflow of talent, three are from India, and the other institutions are from Croatia, Romania, Egypt, Azerbaijan, Armenia, Pakistan, and Indonesia.

Table 7 and Figure 4 present the distribution of net talent flows of doctoral students.

As shown in Table 7, at the doctoral level, the mobility of talents has been further enhanced, and the absolute gap between universities expands. Compared with the attractiveness of undergraduate and postgraduate students, the absolute gap in the number of graduates' employment competitiveness rankings has further widened, from 12 to 112, with a large difference. The number of universities with a net inflow of talents has changed from 19 in the master's degree to 33, accounting for 11.5%. The number of universities with a net outflow of talents changes from 22 in the master's degree to 97, accounting for 34%, which is a significant increase compared with the undergraduate and postgraduate rankings. There are 156 institutions with equal inflows and outflows, accounting for 54.5%. Among the universities we surveyed, the best-performing institution for the employment attractiveness of doctoral students is Anna University from India, with a net inflow of talents of 37; the worst-performing institution is Airlangga University from Indonesia, with a net inflow of talent of −75. It not only shows that the gap in the employment attractiveness of

Table 7: The distribution of net talent flows of doctoral students.

Net inflow	The number of universities
37	1
24	1
17	2
14	3
13	1
12	2
11	1
9	1
8	1
6	1
5	1
4	3
3	4
2	5
1	6
0	156
−1	35
−2	23
−3	10
−4	5
−5	4
−6	3
−7	4
−8	2
−9	2
−11	1
−12	1
−13	2
−14	1
−20	1
−21	1
−52	1
−75	1

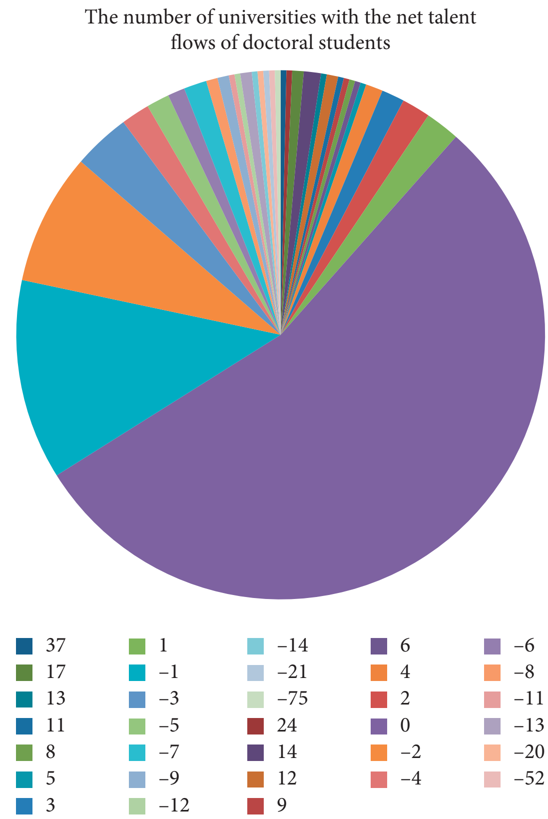

Figure 4: The distribution of net talent flows of doctoral students.

doctoral students in colleges and universities is relatively large but also shows that many doctoral students in the BRI universities are more concentrated in a certain number of universities after graduation. Therefore, a small number of universities have much higher competitiveness and attractiveness than other colleges and universities, so more graduate students tend to go to such colleges and universities. For example, Nahda University has performed well in the undergraduate and postgraduate progression competitiveness rankings, but it has a net outflow of talents in the doctoral degree, which affects the overall education level of the school.

In addition to the difference in the quality of education between universities in the postgraduate degree, this difference also reflects the disconnection of higher education at all levels in higher education, that is, the level of education at all levels has significant differences. Many colleges and universities have different performances at different levels of higher education. The large fluctuations in the attractiveness of higher education or employment also reflect the differences in education levels. For example, Anna University has a net outflow of talents for undergraduate and postgraduate students. However, in the employment competitiveness of doctoral students, it has become the university with the largest net inflow of talents. One of the reasons is due to different educational priorities of different universities, such as the difference in the importance of academic research and student training and the diversity of teaching quality requirements at different levels of higher education lead to large differences in the quality of education at all levels. The second reason is that due to the economic and social development level of the BRI countries, the academic research resources are limited, and the distribution of scientific research resources has led to great differences in the scientific research performance of universities. The employment trend of doctoral students is more concentrated in some universities with strong academic research strength, which leads to the high frequency of doctoral students. The third is that employment is different from that of further studies. In addition to the teaching level, the employment choices for doctoral students are also affected by salary and academic research. The influence of this type of factor does not exist in the ranking of the attractiveness of the study, so the role of more factors may also be the reason for the difference between the doctoral student's mobile ranking and the first two rankings.

6. Discussion and Conclusion

Based on the above ranking results of the BRI universities, we propose three major conclusions.

First, at the undergraduate and postgraduate levels, the talent mobility preferences of the universities are not obvious, and the absolute difference between the "winning and losing" relationship is small. It shows that, in the cognition of students, the gap in attractiveness between universities is not large. The concentration of student choice is low, and there is no university that shows outstanding advantages in the ranking of these two stages.

Second, from the rankings of undergraduates to doctoral students based on the "winning and losing" relationship, the actual gap score between universities is constantly expanding; especially, in the attraction of doctoral students, the gap is particularly prominent.

Third, at different stages of education, the attraction of certain universities varies greatly between universities. Some universities even change from a net inflow at the undergraduate stage to a net outflow at the doctoral students' stage.

All in all, the rankings based on the "winning and losing" relationship are somewhat different from the existing mainstream ranking results, indicating that the existing rankings include factors other than the quality of teaching in the evaluation indicators. In fact, this makes the stakeholders' understanding of the teaching level of each university have a great deviation from the actual situation. Among them, the most similar to the existing university ranking results are the results of the employment attraction ranking of doctoral students, indicating that the existing university ranking method with the status of scientific research as the main measure can reflect the quality of education in the doctoral degree to a certain extent. The requirements for higher education for doctoral students are mainly reflected in academic research. Therefore, this ranking is similar to some mainstream rankings based on scientific research. In the undergraduate and postgraduate stages, the main emphasis is on the level of teaching. This may be the reason why the "winning and losing" relationship rankings in these two stages are different from the mainstream ranking results.

This paper, for the first time, systematically evaluates and ranks universities in the BRI countries. By introducing a new method of university ranking based on complex system models, we contribute to the complex system research and university ranking research, respectively. By applying the new method of university ranking in the BRI countries, we contribute to the BRI research.

We apply the "winning and losing" relationship ranking method to 286 universities in 35 BRI countries. We find that the gap in the scores of the "winning and losing" of universities is constantly increasing with the improvement of higher education in these countries. At the undergraduate and postgraduate levels, the scores of the "winning and losing" relationship of the universities are not much different, but there is a big difference in the employment stage of doctoral students. At the same time, there are certain differences in the scores of the "winning and losing" relationship between different universities at different levels of higher education. Current major university rankings lack robust results, sometimes even produce controversial results [58–62]. Our research answers the call for solid methodology and objective measurements in the university ranking field [29, 37, 61].

Moreover, with the continuous development of higher education, the free flow of higher education talents is becoming more and more frequent, and its globalization trend is deepening [63, 64]. University rankings are playing an increasingly important role as an important reference for talents and educational mobility. In recent years, the attention and influence of university rankings in both higher education and social life are rising. However, there are still many problems in the current mainstream university rankings, especially in measuring the quality of education [29, 38]. This paper proposes a new method based on students' choice behaviors of colleges to measure the attraction and competitiveness of colleges and universities, thus demonstrating the level of college education, that is, the method of the "winning and losing" relationship. This approach complements the existing mainstream ranking gap. This method can innovatively provide stakeholders with reference and guidance for decision-making and improve the validity and accuracy of university rankings.

In conclusion, through the above research conducted by the "winning and losing" relationship method, this paper quantifies the metrics of university rankings and applies the method in universities in the BRI countries. Our research offers an alternative reference for students' school choice and can also guide policymakers to make interuniversity collaboration policies and decisions. Future research can use our research as a starting point to study the relative status and competitiveness between universities in the BRI countries.

Data Availability

The data used to support the findings of this study have not been made available because they are collected by our research group with a lot of manpower, material, and financial resources. Now sharing the data will affect the subsequent publication.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Research on the Coordination Mechanism of Value Cocreation of Innovation Ecosystems: Evidence from a Chinese Artificial Intelligence Enterprise

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This paper models the game process of the value cocreation of enterprises based on evolutionary game theory (EGT). The factors influencing value cocreation are found through mathematical analysis. Taking iFLYTEK as an example, a representative enterprise of artificial intelligence (AI) in China, six factors affecting value cocreation are verified, which are the excess return rate, the distribution coefficient of the excess return rate, coordination costs in the system, the cost-sharing coefficient, imitation costs, and penalties. These six factors have a profound impact on value cocreation in the ecosystem. Through the case study of iFLYTEK, it is concluded that innovation ecosystems can enable small- and medium-sized AI enterprises to grow. In order to build a sound ecosystem, we need to establish a mechanism to select partners, reduce the costs of cooperation, and strengthen the protection of intellectual property. At the beginning of the cooperation, it is necessary to establish a mechanism with clear responsibilities, rights, and interests. The conclusion is of great significance to the development of AI enterprises.

1. Introduction

The fourth industrial revolution is coming, and AI is beginning to penetrate all aspects of social production. AI will be the focus of the next industrial revolution in science and technology. Major developed countries are also actively deploying frontier research in AI. AI is a historic opportunity, which plays an important role in alleviating the pressure of population aging, promoting the transformation of the industrial structure, and coping with the challenges of sustainable development ("Artificial intelligence has developed into a national strategy in many countries," ChinaByte, October 21, 2016, http://server.chinabyte.com/432/13932932.shtml). Lichtenthaler [1] pointed out that, against the background of this rapid technological progress, machines may have a certain degree of technological innovation ability and participate in the creation of new products, systems, and services. Therefore, the impact of AI on business mainly involves knowledge development and utilization. AI can recognize text information and transform images and voices into understandable information, which enriches the data stream. AI is also regarded as an entity that can imitate human thinking via computers [2]. An AI innovation ecosystem has similar characteristics to a natural ecosystem. In the AI ecosystem, enterprises, universities and scientific research institutions, intermediary institutions, governments, and financial institutions offer their respective advantages and professional expertise and exchange flows of material, energy, and information with the external environment. The innovation aggregation effect of interdependence and interaction in the ecosystem continuously improves the overall innovation ability of the AI ecosystem. The AI innovation ecosystem includes two parts: the innovation population of biological components and the environment of nonbiological components. In the innovation population, the boundaries of producers, consumers, and decomposers are not so clear, and there are often interactions or overlaps. For example, producers include enterprises, universities, scientific research institutions, and other organizations that develop and apply AI technology. Consumers include enterprises and institutions that apply AI technology to various industries. The decomposer is the users who purchase relevant AI products and provide feedback information to the producer. Through the cooperation among producers, consumers, and decomposers, the ecosystem can develop continuously and improve its operation efficiency.

Botha [3] addressed the possible future evolution of innovation from a human-only initiative to human-machine coinnovation and then autonomous machine innovation, arriving at a conceptual mind model that outlines the role of innovation regimes and innovation agents. Wauters and Vanhoucke [4] provided a nearest neighbor-based extension for project control forecasting with earned value management and selected an AI method to reduce the training set to predict the real duration of a project. Lichtenthaler [5] discussed the interplay between humans and AI. Using AI at IBM Research for product composition, McCormick is transforming workflow processes for product developers, enabling them to create more innovative flavor products faster and to significantly improve their success rates [6]. This has shed light on how companies can create value through AI and highlights the strategic decisions IBM makes to create value in two dimensions: internal development and external collaborations [7]. Research of AI technology applications in business is just beginning. In the existing literature, the AI research pays more attention to AI technology, policy-making, and comparisons of international development, but rarely from the perspectives of value cocreation and innovation ecosystems. In fact, every AI enterprise experiences the ecological cycle from start-up to growth and needs to work out how to cooperate with other business partners in the ecosystem. In the growth process, AI enterprises have to face the important decision of deciding whether to cooperate or not. These problems regarding how to obtain the most favorable resources in an AI ecosystem, how to build cooperation mechanisms with other business partners, and how to find dynamic cooperation strategies are very important for the healthy development of AI enterprises, but the current research is not deep enough.

This paper analyzes the dynamic game process of platform-leading enterprises and related cooperative enterprises in innovation ecosystems of AI by establishing the replication dynamic equation. Through seeking stable solutions for the duplicated dynamic equation, six main factors affecting value cocreation are found using a calculus derivation method. Then, taking the example of iFLYTEK, a leading AI enterprise in China, the game model and the experience of value cocreation between iFLYTEK and its partners are verified. Finally, a strategy for more AI enterprises is suggested. The main contribution of this paper is to explore coordination mechanisms so as to jointly benefit and promote the development of an innovation ecosystem between platform-leading enterprises and related cooperative enterprises and to discuss the factors affecting the value cocreation of such enterprises. Because the coordination process between the two sides has to go through many repeated games in order to establish a relatively stable cooperative relationship, the learning process also shows evolution from a low level to a high level so as to achieve the maximum benefit under limited rationality. It is appropriate to use EGT to analyze the coordination mechanism of value cocreation. By solving the equilibrium of the replication dynamic equation, it is found that both sides choose to cooperate or not, depending on the location of the saddle point, and the saddle point is determined by six factors, which are the excess return rate, the distribution coefficient of the excess return rate, coordination costs in the system, the cost-sharing coefficient, imitation costs, and penalties. Taking iFLYTEK as an example, China's leading AI enterprise, these six factors are verified as affecting value cocreation in an AI ecosystem. The conclusion enriches the research on the value cocreation of innovation ecosystems.

The rest of the paper is arranged as follows. Section 2 reviews the existing studies. Section 3 establishes the theoretical model. Section 4 discusses the factors that may influence the result of the game. Section 5 analyzes the case of iFLYTEK to discuss the application of game evolution. Section 6 concludes the paper and proposes policy implications and future research.

2. Literature Review

2.1. Innovation in the AI Industry. With the rapid development of the AI industry, innovation management at the theoretical level has aroused a heated discussion among scholars around the world [8]. The evolution of the AI industry can be divided into three stages. In the first stage, it focuses on perceptual intelligence represented by the deep convolution neural network, which relies on big data. It has achieved success comparable to human intelligence in visual recognition, speech recognition, and natural language understanding. In the second stage, it focuses on cognitive intelligence, including reasoning, planning, memory, decision-making, and knowledge learning. In the third stage, it focuses on creative intelligence; that is to say, AI is required to have super abilities, like the insight and inspiration of human beings. At present, the development of the AI industry is facing many challenges, such as the economy, security, and supervision. Many countries pay special attention to the policies in this field and successively create national policies regarding AI. All kinds of innovative products, systems, and services are created by AI, thus promoting production transformation and social progress. Compared with traditional technological innovation, AI innovation has significantly improved in terms of industry, technology, and social value [9]. On the one hand, AI gradually brings new products to the market, such as computer vision and voice, semantic recognition, and intelligent robots. On the other hand, it helps to transform and upgrade traditional manufacturing and service industries, such as intelligent manufacturing, intelligent logistics, intelligent transportation, and intelligent education. AI can greatly improve the efficiency of research and development (R&D). It has a far-reaching impact on innovation performance and global manufacturing output and provides customers with personalized services, thus creating greater economic and social value.

To understand the impact of choice complexity and cognitive perceptions on the willingness to delegate a strategic decision to an algorithm, an experiment with 310 participants was conducted and found that, although choice complexity has no effect, participants with low levels of situational awareness are more likely to delegate [10]. Boyd and Holton [11] focused on the economic, political, and historical dynamics of technological innovation and its consequences for employment and economic restructuring and mediated through sovereign and discursive power. Elliott [12] pointed out that, as technological innovation has eliminated many types of jobs over the past few centuries, economies have evolved to create new jobs, which have kept workers well employed. Fujii and Managi [13] also applied a decomposition framework to clarify the determinants of AI technology invention and found that the priority has shifted from biological and knowledge-based models to specific mathematical models and other AI technologies. Hengstler et al. [14] explored how firms systematically foster trust regarding applied AI. Based on empirical analysis using nine case studies in the transportation and medical technology industries, their study illustrates the dichotomous constitution of trust in applied AI.

2.2. Research on Coordination Mechanisms in Innovation Ecosystems. In the modern society, the competition among enterprises has changed from individual to platform competitors. The complexity of the economic environment also causes enterprises to form more diversified ecological relationships, which are competitive and symbiotic. Moore [15] has put forward the concept of the innovation ecosystem for the first time and then proposed the concept of a business ecosystem, which is more conducive to value creation. Scholars have also studied innovation ecosystems from various perspectives. For example, Leten et al. [16] have put forward the intellectual property (IP) model of the coordinating mechanisms of an innovation ecosystem. The model analyzed knowledge sharing between partners, which can promote the development of the ecosystem. Policy is very important for the innovation ecosystem, and the behaviors of all participants in the ecosystem should be consistent with the strategic objectives of national policies [17]. Liu and Rong [18] took complex products in the mobile Internet industry ecosystem as an example for exploring the coevolution mechanism of enterprise self-renewal. Kapoor and Furr [19] discussed the solar photovoltaic industry to analyze the complementary capabilities of enterprises and the driving mechanism of complementary assets on technology. Lee et al. [20] illustrated the determinants of ICT innovation with a transnational empirical study, which showed that the cooperation of universities, enterprises, and governments effectively promoted knowledge sharing. Spigel [21] believed that a successful innovation ecosystem is a good supporting environment created by the complementary cooperation of all parties involved in the system. Spigel [21] also indicated that the relationship between the parties is an important guarantee for the competitiveness of the system. She constructed different game models using Bayesian networks and game theory, which were helpful in understanding stakeholders' behaviors in the ecosystem service. Mulazzani et al. [22] found that the number of human agents, management actions, and economic activities might largely affect the value of ecosystem service benefits. Madsen [23] provided a foundation for studying a new framework within the cooperation of the global ecosystem for sustainable development and clarified the types of organizational capabilities, practices, and routines that can strengthen both internal value processes and external networks and ecosystems. Moreover, Masucci et al. [24] investigated how firms can orchestrate outbound open innovation strategically to accelerate technological progress among the firms they collaborate with, thus removing technological bottlenecks in their business ecosystems. Xie and Wang [25] explored the causal recipes of how open innovation ecosystem modes promote product innovation by using both grounded theory and fuzzy-set qualitative comparative analysis (fsQCA).

2.3. Research on Cooperation Mechanisms in Value Cocreation. From the perspective of literature development, the research on the coordination mechanism of value cocreation is mainly carried out on three aspects. Firstly, research is mainly focused on the contributions of all parties involved in value creation from a systematic level. For example, Vargo and Lusch [26] placed special emphasis on the impact of institutions in the service ecosystem. Secondly, research is focused on coordination mechanisms, which can help participants obtain more knowledge, information, and public resources from the perspective of participating individuals. Vargo and Lusch [27] proposed that the foundation of value cocreation is determined by a binary relationship, which referred to the service interaction between enterprises and customers. Thirdly, the paper discusses coordination mechanisms including excess returns, the costs incurred for coordination, and the possible risks. It is found that opportunities, competition levels, and demand preferences are the driving factors of reverse innovation. Selective disclosure is indicated as a strategic mechanism for reshaping the cooperative behavior of other participants in the innovation ecosystem. Alexy et al. [28] pointed out that selective disclosure may provide an effective alternative, especially in the case of high uncertainty, high coordination costs, and the unwillingness of partners. Leclercq et al. [29] investigated the impact of two gamification mechanics' cooperation and competition, highlighted the existence of four user profiles, and then assessed their emotional, cognitive, and behavioral engagement with the gamified cocreation platform over time. Niesten and Stefan [30] reviewed literature on paradoxical tensions between value cocreation and capture in interorganizational relationships. Su and Li [31] pointed out internal mechanisms of knowledge transfer in a knowledge alliance and showed that the number of enterprises in the knowledge alliance, knowledge transfer frequency, and knowledge transfer effects is positively correlated.

2.4. Application of Evolution Game Theory in Industrial Dynamic Evolution. In recent years, EGT has been widely used in the study of industrial dynamic evolution. Wood et al. [32] used an agent-based model to provide detailed results and demonstrated the importance of natural resources for the outcome of the model. Yang et al. [33] analyzed government-industry-university-research (GIUR) intellectual property cooperation behavior and its influencing factors, including market mechanisms and administrative supervision mechanisms. Hafezalkotob et al. [34] used an integrated Cournot duopoly equilibrium and evolutionary game theory (EGT) approach to model the situation where a wholesale pricing strategy is determined by a manufacturer acting as a leader, while retailers who make order quantity decisions are acting. Mekki et al. [35] studied the vehicular cloud access problem and modeled it as an evolutionary game where the vehicles choose to cooperate or to access the conventional cloud.

In summary, although much research has been carried out on coordination mechanisms in innovation ecosystems and value cocreation, there are still gaps in the existing research. First, because of the regional imbalance in the AI industries in many countries such as China, coordination mechanisms may be different. Therefore, this study explores the coordination mechanisms of innovation ecosystems based on an evolutionary game model. Second, although there are several studies on the contributions of all parties involved in value creation and coordination mechanisms, only few studies have focused on the coordination mechanisms of AI industries from the perspective of game theory. Third, AI is an emerging industry in China, and research on the AI innovation ecosystem has just started. It is of great theoretical and practical value to analyze the composition, cooperation, and evolution of Chinese AI innovation ecosystems in terms of their healthy development. This study incorporates these three perspectives.

3. Model and Analysis

Many AI enterprises are faced with the pain of transformation from laboratory achievements to product marketization due to large initial technology investment and market risk. However, there is little research on the business model of AI enterprises, how they create value together with their partners, and how they build an innovation ecosystem to empower themselves. Ma and Ji [36] pointed out the synergetic development of regional ecological communities had an important impact on ecosystem evolution, in which the evolution process was gradual, including four stages: synergetic construction, synergetic expansion, synergetic cooperation, and synergetic innovation. Abiodun and Ivan [37] presented a model of interfirm cooperation driven by cognitive distance, appropriability conditions, and external knowledge and found that a firm chooses to cooperate and selects a partner conditional on the investments in absorptive capacity. Brice et al. [38] highlighted how ecosystem creation was a systemic process driven by coupled feedback loops, which organizations must try to control dynamically. Ron [39] followed the flow of inputs and outputs in the ecosystem to distinguish between upstream components that were handled by the local firm and downstream complements that were bundled by the firm's customers. Therefore, the key point of this paper is to explore the coordination mechanism of value cocreation in the innovation ecosystems of AI enterprises. EGT abandons the assumption that participants are completely rational. It regards the behavior of all participants in an ecosystem as contributing to a dynamic system; that is, the actors always aim at fulfilling their own interests. Moreover, it assumes "bounded rationality" for the behavior of participants in the system and pays more attention to the process of reaching an equilibrium. Therefore, EGT is an appropriate method for analyzing the cocreation mechanism between leading enterprises and cooperative enterprises in an AI ecosystem. Time is an important factor in the changes in the relationship between leading enterprises and related cooperative enterprises. Only through games can the two sides achieve a dynamic balance process. By means of EGT, we can clearly depict the dynamic path of equilibrium between leading enterprises and cooperative enterprises in AI innovation ecosystems.

3.1. Assumptions. In order to analyze the problem of the cocreation mechanism in innovation ecosystems, this paper makes the following assumptions:

(1) AI enterprise innovation ecosystem includes competitors, operators, technology intermediaries, and research institutions. There is a platform-leading enterprise A and a related cooperative enterprise B.

(2) The AI innovation ecosystem includes two parts: biological components and the environment. Among them, biological components include producers, consumers, and decomposers. The producer refers to the enterprise engaged in the R&D and production of AI technology. The consumer refers to many kinds of application that apply AI technology to specific industries, including enterprises, universities, and scientific research institutes. The decomposer refers to the users that purchase relevant AI products.

(3) In the AI innovation ecosystem, the platform-leading enterprise and other enterprises may have a possible cooperative relationship, but this relationship is not permanent, and it may be broken at any time, or a new cooperative relationship may be generated. The choice of cooperative or noncooperative behavior is real-time. Because of the distribution of interests, they play games with each other and determine the game strategy in their interaction, showing the characteristics of the evolutionary game.

(4) Leading enterprise tries to cooperate with other enterprises in the ecosystem with a certain probability at the initial stage and generates excess returns in the process of cooperation. The change of decision-making in the game process essentially stems from the pursuit of higher interests, so the allocation

of excess returns is the driving force for the development of the AI ecosystem.

(5) When the platform-leading enterprise A and the related cooperative enterprise B are in a state of cooperation, the two sides create value together, and the innovation ecosystem is developing towards a virtuous path. When one performs noncooperative behavior, it is difficult for both to create value together, and there will be many contradictions, even dissolution [40].

(6) The response of a relevant cooperative enterprise B is crucial to the choice of a platform-leading enterprise A. Therefore, the strategic choice of both is a dynamic game process, and the best strategy is cooperation, which can maximize benefits, increase the overall profit of the innovation ecosystem, and minimize the total costs and risk [41]. However, both A and B have limited rational. In decision-making, they only consider the maximization of their own interests and adopt a strategy of noncooperation.

(7) The dynamic game process is a mixed strategy game and the diversification of strategy selection. Under certain probability conditions, the game process is adjusted according to the strategy of the other one [42].

(8) As AI enterprises, their technical threshold is very high. In the early stages, they need to invest a lot of energy and cost in developing technology. Their technical threshold is also their core competitiveness in the commercial economy. However, during cooperation, there is also the problem of "hitchhiking" or "stealing" technology [43]. If such a situation occurs, the cost paid by both parties will be much higher than the benefits from cooperation. If the core technology is imitated, the imitator will obtain a technological imitative income. Therefore, in order to protect independent R&D participants, both of them need to introduce reward and punishment measures when cooperating. If the core technology is imitated or "stolen," one party will give the other a certain amount of compensation and will be punished accordingly.

3.2. Evolutionary Game Model

3.2.1. Variables. There are several variables that have positive values in the game, and they are defined as follows:

P_1: leading enterprise A can independently obtain maximum profit, which can be obtained from the respective market when there is no cooperative relationship with B.

P_2: enterprise B can independently obtain maximum profit, which can be obtained from the respective market when there is no cooperative relationship with A.

ΔR: when both A and B cooperate to create value together, it is beneficial for the whole innovation ecosystem and can create additional benefit ΔR.

α: A and B will be assigned the additional benefit, and α is a distribution coefficient which A obtains. $\alpha \in (0,1)$.

$1-\alpha$: $1-\alpha$ is a distributor coefficient of the additional benefit that B obtains.

C: the transaction costs of the ecosystem, which are the negotiation costs and management costs incurred in order to coordinate the behavior of A and B.

β: β is the cost-sharing coefficient for A. $1-\beta$ is the cost-sharing coefficient for B. $\beta \in (0,1)$.

M_1: if the core technology is imitated, then A will pay M_1 in terms of imitation costs.

M_2: if the core technology is imitated, then B will pay M_2 in terms of imitation costs.

F: if the core technology is imitated or "stolen," one party will give the other a certain amount of compensation and will be punished accordingly. F represents penalties. The introduction of penalties is also to protect the cooperation between the two sides.

3.2.2. Payoff Matrix. In the process of the dynamic game, there are four strategies. Figure 1 shows the payoff matrix of the players in the evolutionary game.

3.2.3. Evolutionary Stable Strategy Applying a Replication Dynamic Equation. The parameters of x and y are used to indicate the probabilities of platform-leading enterprise A and cooperative enterprise B choosing different strategies, respectively. E_a represents the average expected payoffs of enterprise A. E_b represents the average expected payoffs of enterprise B. Table 1 shows the specifications of all the parameters.

(1) Replication Dynamic System. According to the framework of EGT, we can observe the payoffs of players under different combinations of strategies. For platform-leading enterprise A, in the coordination mechanism of value cocreation, the expected return from cooperation is E_{a1}. The expected return from noncooperation is E_{a2}. The average expected return is E_a. Then, the corresponding formula is as follows:

$$\begin{aligned} E_{a1} &= y\left(P_1 + \alpha\Delta R - \beta C\right) + (1-y)\left(P_1 - \beta C + F\right) = y\alpha\Delta R \\ &\quad + (1-y)F + P_1 - \beta C, \\ E_{a2} &= y\left(P_1 - M_1 - F\right) + (1-y)P_1 = P_1 - yM_1 - yF, \\ E_a &= xE_{a1} + (1-x)E_{a2} = xy\alpha\Delta R + (x-y)F + P_1 \\ &\quad - y(1-x)M_1 - x\beta C. \end{aligned} \tag{1}$$

For enterprise B, in the coordination mechanism of value cocreation, the expected return from cooperation is E_{b1}. The expected return from noncooperation is E_{b2}. The average expected return is E_b. Then, the corresponding formula is as follows:

Platform-leading enterprise A \ Cooperative enterprise B	Cooperation (y)	Noncooperation ($1-y$)
Cooperation (x)	$P_1+\alpha\Delta R-\beta C$ $P_2+(1-\alpha)\Delta R-(1-\beta)C$	$P_1-\beta C+F$ P_2-M_2-F
Non cooperation ($1-x$)	P_1-M_1-F $P_2-(1-\beta)C+F$	P_1 P_2

Figure 1: The payoff matrix of the two players in the evolutionary game.

Table 1: The specifications of variables in the tripartite evolutionary game.

Variables	Description
E_{a1}	The expected return from the cooperation of enterprise A
E_{a2}	The expected return from the noncooperation of enterprise A
E_a	The average expected return from the cooperation and noncooperation of enterprise A
E_{b1}	The expected return from the cooperation of enterprise B
E_{b2}	The expected return from the noncooperation of enterprise B
E_b	The average expected return from the cooperation and noncooperation of enterprise B

$$\begin{aligned}E_{b1} &= x\left[P_2+(1-\alpha)\Delta R-(1-\beta)C\right] \\ &\quad +(1-x)\left[P_2-(1-\beta)C+F\right] = x(1-\alpha)\Delta R+(1-x)F \\ &\quad +P_2-(1-\beta)C, \\ E_{b2} &= x\left(P_2-M_2-F\right)+(1-x)P_2 = P_2-xM_2-xF, \\ E_b &= yE_{b1}+(1-y)E_{b2} = xy(1-\alpha)\Delta R+P_2-x(1-y)M_2 \\ &\quad -(1-\beta)yC.\end{aligned} \tag{2}$$

The replication dynamic equations of both A and B are as follows:

$$\frac{\mathrm{d}x}{\mathrm{d}t} = x\left(E_{a1}-E_a\right) = x(1-x)\left[E_{a1}-E_{a2}\right] = x(1-x)\left[y\left(\alpha\Delta R+M_1\right)+F-\beta C\right], \tag{3}$$

$$\frac{\mathrm{d}y}{\mathrm{d}t} = y\left(E_{b1}-E_b\right) = y(1-y)\left[E_{b1}-E_{b2}\right] = y(1-y)\{x\left[(1-\alpha)\Delta R+M_2\right]+F-(1-\beta)C\}. \tag{4}$$

(2) Evolutionary Stable Strategies for A. If $(\mathrm{d}x/\mathrm{d}t)=0$, there are three stable solutions to equation (3), $x_1^*=1$, $x_2^*=0$, and $x_3^*=((\beta C-F)/(\alpha\Delta R+M_1))$.

If formula (3) is a derivative and $(\mathrm{d}^2x/\mathrm{d}^2t)=0$, then the formula can be obtained as follows:

$$\frac{\mathrm{d}^2x}{\mathrm{d}^2t} = (1-2x)\left[y\left(\alpha\Delta R+M_1\right)+F-\beta C\right]. \tag{5}$$

Next, we discuss the stable solutions of A under different probabilities in three cases.

(a) When $y>((\beta C-F)/(\alpha\Delta R+M_1))$, $x_1^*=1$ is a stable solution, which means that platform-leading enterprise A will choose to cooperate with relevant enterprise B. The evolution results are shown in Figure 2.

(b) When $y<((\beta C-F)/(\alpha\Delta R+M_1))$, $x_2^*=0$ is a stable solution, which means that platform-leading enterprise A will choose noncooperation. The evolution results are shown in Figure 3.

(c) When $y=((\beta C-F)/(\alpha\Delta R+M_1))$, $(\mathrm{d}x/\mathrm{d}t)=0$, which means that any point is stable. The evolution results are shown in Figure 4.

(3) Evolutionary Stable Strategies for B. If $(\mathrm{d}y/\mathrm{d}t)=0$, there are three stable solutions to equation (4), $y_1^*=1$, $y_2^*=0$, and $y_3^*=(((1-\beta)C-F)/((1-\alpha)\Delta R+M_2))$. There are still

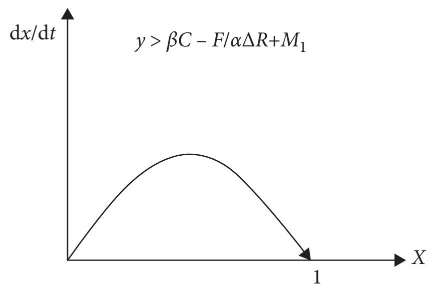

Figure 2: Stable solution for $y > ((\beta C - F)/(\alpha \Delta R + M_1))$.

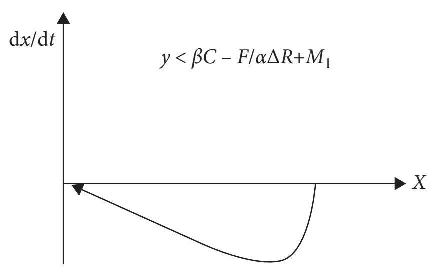

Figure 3: Stable solution for $y < ((\beta C - F)/(\alpha \Delta R + M_1))$.

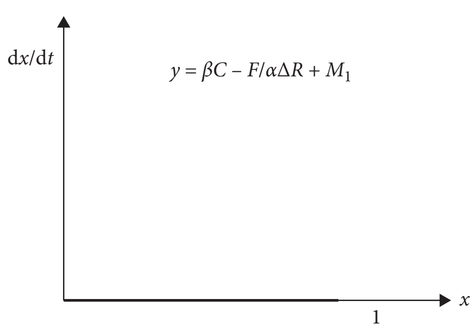

Figure 4: Stable solution for $y = ((\beta C - F)/(\alpha \Delta R + M_1))$.

three cases for discussing the stable solution of B under different probabilities.

(a) When $x > (((1-\beta)C - F)/((1-\alpha)\Delta R + M_2))$, $y_1^* = 1$ is a stable solution, which means that enterprise B will choose a strategy of cooperation. The evolution results are shown in Figure 5.

(b) When $x < (((1-\beta)C - F)/((1-\alpha)\Delta R + M_2))$, $(dy/dt) > 1$. $y_2^* = 0$ is a stable solution, which means that enterprise B will choose noncooperation. The evolution results are shown in Figure 6.

(c) When $x = (((1-\beta)C - F)/((1-\alpha)\Delta R + M_2))$, $(dy/dt) = 0$, which means that any point is stable. The evolution results are shown in Figure 7.

(4) Combination Evolutionary Stable Strategies for Both A and B. We analyze the combination evolution strategies of A and B. First, we analyze the responses of B when A adopts different strategies.

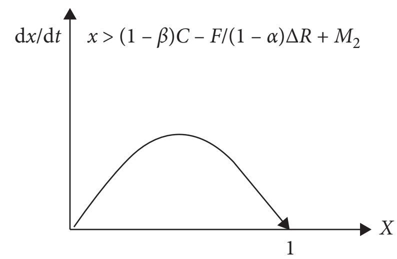

Figure 5: Stable solution for $x > (((1-\beta)C - F)/((1-\alpha)\Delta R + M_2))$.

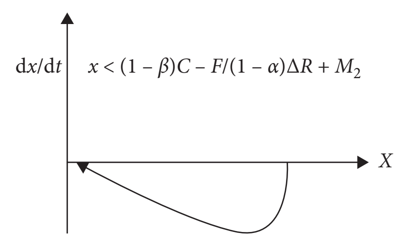

Figure 6: Stable solution for $x < (((1-\beta)C - F)/((1-\alpha)\Delta R + M_2))$.

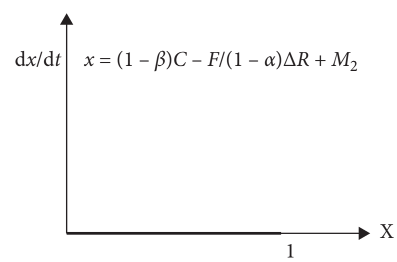

Figure 7: Stable solution for $x = ((1-\beta)C - F/(1-\alpha)\Delta R + M_2)$.

(1) When $((\beta C - F)/(\alpha \Delta R + M_1)) < 0$, $y > ((\beta C - F)/(\alpha \Delta R + M_1))$, which means that no matter what B's reaction is, A will choose a cooperative strategy without hesitation.

(2) When $((\beta C - F)/(\alpha \Delta R + M_1)) = 0$, $y = 0$. Any value of X is a stable solution, which means there is no special motivation for A to choose cooperation or noncooperation.

(3) When $((\beta C - F)/(\alpha \Delta R + M_1)) > 1$, $y < ((\beta C - F)/(\alpha \Delta R + M_1))$. No matter how B reacts, A will adopt a strategy of noncooperation.

Similarly, let us analyze the responses of A when B adopts different strategies.

(4) When $(((1-\beta)C - F)/((1-\alpha)\Delta R + M_2)) < 0$, $x > (((1-\beta)C - F)/((1-\alpha)\Delta R + M_2))$. This means that no matter what A's response is, B will only adopt a cooperative strategy.

(5) When $(((1-\beta)C - F)/((1-\alpha)\Delta R + M_2)) = 0$, $x = 0$. Any value of y is a stable solution, which means that B has no particular incentive to cooperate or not to cooperate because both results are similar for B.

(6) When $(((1-\beta)C-F)/((1-\alpha)\Delta R+M_2))\geq 1$, $x<(((1-\beta)C-F)/((1-\alpha)\Delta R+M_2))$. This means that no matter how A reacts, B only adopts a strategy of noncooperation.

The results of these comprehensive games are shown in Figure 8.

In Figure 8, there are five equilibrium points, which are $O(0,0)$, $B(1,1)$, $A(1,0)$, $C(0,1)$, and $Q(((\beta C-F)/(\alpha\Delta R+M_1)), (((1-\beta)C-F)/((1-\alpha)\Delta R+M_2)))$.

In the region $OAQC$, the result of the game evolution tends to be $O(0,0)$. This means that both sides choose a noncooperative strategy. In the region $ABCQ$, both sides tend to choose cooperative strategies; then, $B(1,1)$, $A(1,0)$, and $C(0,1)$ are unstable because if one party does not cooperate, there will be no stable equilibrium point. $Q(((\beta C-F)/(\alpha\Delta R+M_1)), (((1-\beta)C-F)/((1-\alpha)\Delta R+M_2)))$ is the saddle point.

Therefore, the evolutionary game strategy is that both sides choose to cooperate or both sides choose not to cooperate. The combination of one party cooperation and the other party noncooperation is unstable. Whether the two parties choose to cooperate at the same time or not depends on the location of the saddle point Q. The closer the Q point is to the B point, the higher the probability of both parties choosing cooperation. The closer the Q point is to the O point, the higher the probability of noncooperation.

4. Factors Influencing the Result of the Game

The position of point Q is observed, which is composed of two triangles, ΔOQC and ΔOQA. Therefore, the discussion of the position of point Q can be transformed into the discussion of quadrilateral $\square OAQC$:

$$S_{\square OAQC}=S_{\Delta OQC}+S_{\Delta OQA}=\frac{1}{2}\left[\frac{\beta C-F}{\alpha\Delta R+M_1}+\frac{(1-\beta)C-F}{(1-\alpha)\Delta R+M_2}\right]. \tag{6}$$

The evolution results of the three situations are discussed as follows:

(A) When $S_{\square OAQC}>S_{\square QABC}$, it evolves to O, and neither side cooperates

(B) When $S_{\square OAQC}<S_{\square QABC}$, it evolves to B, and both sides cooperate

(C) When $S_{\square OAQC}=S_{\square QABC}$, there is an equal probability of it evolving towards O or B

We can understand the influence of each factor on evolution in more detail through calculus derivation.

(1) Excess distribution coefficient α

$$\frac{\mathrm{d}s}{\mathrm{d}\alpha}=\frac{1}{2}\left\{\frac{(1-\beta)C-F}{[(1-\alpha)\Delta R+M_2]^2}-\frac{\beta C-F}{(\alpha\Delta R+M_1)^2}\right\}, \tag{7}$$

where $(\mathrm{d}^2s/\mathrm{d}^2\alpha)>0$ when α solves the second derivative, and $S_{\square OAQC}$ has a minimum value.

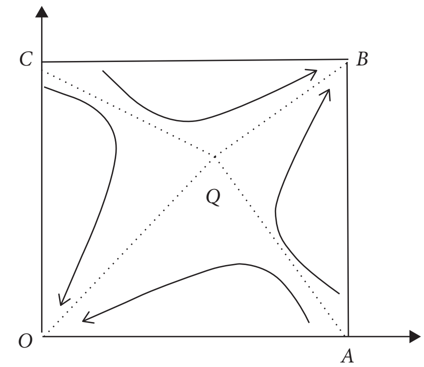

Figure 8: Comprehensive game process of A and B.

Therefore, when α is large, the evolutionary direction is that both sides adopt cooperative strategies.

(2) Excess return ΔR

$$\frac{\mathrm{d}s}{\mathrm{d}\Delta R}=-\frac{1}{2}\left\{\frac{\alpha(\beta C-F)}{(\alpha\Delta R+M_1)^2}+\frac{(1-\alpha)[(1-\beta)C-F]}{[(1-\alpha)\Delta R+M_2]^2}\right\}<0, \tag{8}$$

where $(\mathrm{d}s/\mathrm{d}\Delta R)$ is a minus function and ΔR and $S_{\square OAQC}$ change in reverse. That is to say, the larger the value of ΔR is, the stronger the willingness of both sides to cooperate and create value together is.

(3) Imitation costs M_1 and M_2

$$\frac{\mathrm{d}s}{\mathrm{d}M_1}=-\frac{1}{2}\left[\frac{(\beta C-F)}{(\alpha\Delta R+M_1)^2}\right],\quad \frac{\mathrm{d}s}{\mathrm{d}M_2}=-\frac{1}{2}\left\{\frac{(1-\beta)C-F}{[(1-\alpha)\Delta R+M_2]^2}\right\}. \tag{9}$$

This shows that if the cost of "piracy" technology is very low for technology imitators, they will adopt a noncooperative strategy, which is not conducive to the evolution of an innovation ecosystem. If the cost of "piracy" technology is high, they will cooperate with platform-leading enterprises.

(4) Cost-sharing coefficient β

$$\frac{\mathrm{d}s}{\mathrm{d}\beta}=\frac{1}{2}\left[\frac{C}{\alpha\Delta R+M_1}-\frac{C}{(1-\alpha)\Delta R+M_2}\right]. \tag{10}$$

When $(C/(\alpha\Delta R+M_1))<(C/((1-\alpha)\Delta R+M_2))$, $(\mathrm{d}s/\mathrm{d}\beta)$ is a minus function. In this case, the greater the value of $\beta$is, the less likely the evolution of mutual cooperation will be.

When $(C/(\alpha\Delta R+M_1))>(C/((1-\alpha)\Delta R+M_2))$, $(\mathrm{d}s/\mathrm{d}\beta)$ is a monotone-increasing function. In this case, the larger the value of $\beta$is, the more noncooperative the two sides will evolve to be.

(5) Coordination costs C

$$\frac{\mathrm{d}s}{\mathrm{d}C} = \frac{1}{2}\left[\frac{\beta}{\alpha\Delta R + M_1} + \frac{1-\beta}{(1-\alpha)\Delta R + M_2}\right] > 0, \quad (11)$$

which indicates that $(\mathrm{d}s/\mathrm{d}C)$ is a monotone-increasing function. This means that, with increasing cooperation costs, both parties will be more willing to adopt the strategy of noncooperation. If the costs of cooperation are reduced, both sides will be more willing to cooperate.

(6) Penalties F

$$\frac{\mathrm{d}s}{\mathrm{d}F} = -\frac{1}{2}\left[\frac{1}{\alpha\Delta R + M_1} + \frac{1}{(1-\alpha)\Delta R + M_2}\right] < 0, \quad (12)$$

which indicates that $(\mathrm{d}s/\mathrm{d}F)$ is a monotone-decreasing function. The smaller F is, the larger $S_{\square OAQC}$ is and the more noncooperative the two sides are, so the degree of the penalty also affects cocreation in the ecosystem. Fewer penalties will increase the free riding of technology and the "piracy" of technology, which will affect the cooperation mechanism. High penalties and the effective protection of technology can promote cooperation and cocreation in the ecosystem.

5. Case Analysis of an AI Enterprise: Taking iFLYTEK as an Example

According to the model of game theory, we took a leading Chinese AI enterprise, iFLYTEK, as an example to verify the hypothesis. iFLYTEK was founded in 1999. Following years of development, iFLYTEK has many world-class patents in speech recognition, speech synthesis, and other fields. In 2008, iFLYTEK was listed in the A-share market. iFLYTEK released the "iFLYTEK Voice Cloud Platform" in 2010 and launched the "iFLYTEK Super Brain Plan ("Super Brain Plan" is a major forward-looking project for advanced artificial intelligence (i.e., cognitive intelligence) initiated by iFLYTEK. It is also a key project supporting iFLYTEK's goal of "making computers understand and think" on the basis of "making computers listen and speak")" in 2014 [44]. The human-computer interface AIUI (AIUI is a new generation of human-computer intelligent interactive open platform of iFLYTEK, which aims to realize the barrier-free interaction between human and machine and make the communication between human and machine natural through voice, image, gesture, and other ways) was released in 2015. After many years, iFLYTEK has become the absolute leader in the field of intelligent voice. iFLYTEK is now a firm leader in China, accounting for more than 60% of the market share in the intelligent speech industry and more than 70% in the speech synthesis market (source: China securities net. http://stockdata.cnstock.com/stock/sz002230.html). Table 2 shows the development of iFLYTEK.

The establishment of the iFLYTEK voice ecosystem has gone through three stages. iFLYTEK's initial stage was from 1999 to 2003. In 1999, during the wave of entrepreneurship among Chinese college students, Qingfeng Liu, the founder of iFLYTEK, started to implement the idea of commercializing the intelligent voice products. However, in the early days of entrepreneurship, iFLYTEK experienced the dilemmas of poor product sales and difficult operations. Under great pressure to survive, the founding team held a meeting in Chaohu, Anhui Province to discuss the strategic development of the company in the future, which was also an opportunity to change the fate of iFLYTEK. After the conference, iFLYTEK seized the huge business opportunity offered by China's call-center market and created value together with telecom operators and external partners (including key customers and international leading intelligent voice companies). iFLYTEK first chose to occupy the market through external cooperation (with Nuance, an international voice provider specializing in speech recognition) and began to provide services for Huawei and other enterprises. In the second stage of growth, iFLYTEK seized the new business opportunity offered by 3G, developed new products, cooperated deeply with the education industry, and actively promoted the business of voice technology in oral examinations. In 2008, iFLYTEK entered the capital market and was listed on Shenzhen Stock Exchange, with a revenue of RMB *257 million yuan* in the same year (http://stock.hexun.com/2009-01-15/113455316.html). In its maturity stage, iFLYTEK realized its transformation from a single voice provider to an ecological voice platform. During the wave of AI, iFLYTEK adjusted its strategy to become the pioneer of the AI industry, and its "Super Brain Plan" came into being against this backdrop. iFLYTEK focuses on practical product functions, such as calling, texting, and listening to music. At the same time, with the development of AI technology, the "iFLYTEK Voice Cloud" has evolved into the "iFLYTEK Open Platform" and has formed an integrated voice ecosystem. iFLYTEK encourages employees to incubate new businesses within the company, cooperates with big enterprises, and has penetrated the fields of mobile phones, education, home furnishings, and cars, forming a voice ecosystem. Ranked in the first place in China on the 50 Smartest Companies 2017 list, which was announced by MIT Technology Review ("50 Smartest Companies 2017", MIT Technology Review, June 27, 2017, https://www.technologyreview.com/lists-tr50/what-are-the-50-smartest-companies/), iFLYTEK is increasingly influential with its superior voice technology in the AI industry.

iFLYTEK has gradually established a voice innovation ecosystem and cooperated with many enterprises in the system to create value together so as to realize its transformation from a small voice technology provider to a leading voice ecosystem enterprise. iFLYTEK's coordination mechanism of value cocreation and its experience of establishing a voice ecological innovation system are very representative. Its growth path and the puzzles encountered

Table 2: A chronicle of iFLYTEK over the years.

Year	iFLYTEK innovation event	iFLYTEK business event
1999	Speech-synthesis evaluation scored more than 3.0	IFLYTEK was founded
2001	iFLYTEK undertook the national voice high-technology industrialization demonstration project and set up a postdoctoral research workstation	iFLYTEK completed its second round of financing and cooperated with Nuance, which is the world's leading voice company, to provide an automatic response scheme
2004	In the international evaluation of Chinese speech synthesis, iFLYTEK ranked first for all indicators	iFLYTEK achieved profit and loss balance for the first time, and its sales exceeded 100 million yuan for the first time
2005	The iFLYTEK Research Institute of Science and Technology was officially established and won the "major technological invention award of information industry"	iFLYTEK's voice product revenue reached 150 million yuan, driving the industry by about 1 billion yuan
2008	iFLYTEK won first prize in the International Speech Synthesis Competition and first prize in the Global Speaker Competition, becoming a "China's national innovative pilot enterprise"	iFLYTEK was listed on the Shenzhen Stock Exchange, and the construction of the voice industry base was started, with a revenue of 257 million in 2008
2010	iFLYTEK won first prize in the International Competition of English Speech Synthesis and became one of the top ten independent innovation brands of intellectual property rights in China's software industry	iFLYTEK released "iFLYTEK Voice Cloud" and "Voice Input Method" and established a national intelligent voice high-tech industrial base
2012	iFLYTEK's first-generation speech recognition system, which uses deep trust network technology, improved its performance in telephone transcribing and speech dictation Breakthroughs were made in a number of core technologies to effectively solve technical problems such as antinoise, accent adaptation, and personalized vocabulary	iFLYTEK's Voice Cloud end users exceeded 150 million, with it becoming the largest voice-listed company in the Asia Pacific region and the software company with the highest market value in the Shanghai and Shenzhen stock markets of China ("New generation of 'voice cloud' released by iFLYTEK," NetEase News, March 23, 2012, http://news.163.com/12/0323/12/7T9G6BI700014AEE.html)
2013	iFLYTEK's multivoice synthesis products covered 25 major languages in the world, filled gaps in China, and overcame the key technologies of voice recognition, such as digital voice code and deep learning language recognition	iFLYTEK established a comprehensive strategic cooperative relationship with the three major telecom operators. iFLYTEK had over 350 million voice cloud downloads and activations and over 100 million voice input users
2014	iFLYTEK launched the "iFLYTEK Super Brain Program"	iFLYTEK released 3.0 smart voice products and the iFLYTEK Voice Cloud, with an annual revenue of 1.77 billion, more than 600 million end users of the iFLYTEK Voice Cloud, and more than 55,000 development cooperation projects
2015	iFLYTEK released the human-computer voice interface, defining the new standard of human and voice interaction technology in the era of the Internet of Things	iFLYTEK and JingDong performed strategic cooperation and released the DingDong smart speaker. The total number of users of iFLYTEK's open platform was 700 million, with 300 million users of iFLYTEK's input method and 18 dialects supported (https://xueqiu.com/2143043140/135269696)
2017	iFLYTEK launched "AI education," entered the medical field, and released its "intelligent medical assistant"	iFLYTEK's open platform had more than 3 billion online daily services, 250,000 partners, and 910 million users (https://www.yicai.com/news/5424180.html). iFLYTEK accounted for more than 60% of the market share in the field of Chinese speech technology and more than 70% of the market share in the field of speech synthesis products
2019	iFLYTEK deeply explored the new combinations of voice AI in the fields of medical treatment, media, education, politics, and law	

(Data sources: shown as table S1 in appendix and sorted by authors)

are the epitome of China's AI enterprises. There are six factors that affect the coordination mechanism of value cocreation of the iFLYTEK voice ecosystem, which will be discussed in following.

5.1. Distribution Coefficient α. With the development of Internet technology, iFLYTEK has invested a lot of money to build a developer platform, whatever the cost, sharing more benefits with its partners and sharing relevant technologies with the open platform. iFLYTEK's business philosophy in its innovation ecosystem has been "working together to share industrial achievements," always adhering to the principle of not directly competing with partners and sincerely cooperating with many partners in the ecosystem to jointly promote the rapid growth of the voice industry. For example, iFLYTEK continues to reduce the threshold of innovation and promote applications in the field of voice interaction technology. In 2010, before Echo and Alexa were launched, iFLYTEK launched its first Chinese voice developer platform, the "iFLYTEK Voice Cloud," which provides partners with free speech recognition technology. The construction of this intelligent voice platform had a win-win effect: for entrepreneurs, huge investments in servers were avoided, and for iFLYTEK, a broad market for small- and medium-sized enterprises with strong growth potential was obtained. During this period, Tencent QQ, Gaode, Ctrip, and other Internet companies were iFLYTEK's customers. Just five years later, iFLYTEK AIUI successfully went online, sharing rich open resources, strong customization ability, and complete personalized functions for partners, putting forward new scenarios and concepts of human-computer interaction and using its own source innovation technology to achieve the dreams of more innovative entrepreneurs (Yicai, "iFLYTEK has released a new version of its $2.1 billion open-platform AIUI," Baidu, May 18, 2018, http://baijiahao.baidu.com/s?id=1600781656523033242&wfr=spider&for=pc). iFLYTEK has also cultivated a number of enterprises in the voice ecosystem, such as Taoyun Technology Co. Ltd., Yunji Technology Co. Ltd., Lieju Technology Co. Ltd., and Yundong Technology Co. Ltd., through internal entrepreneurship and strategic investment mechanisms.

By distributing more benefits to the partners, iFLYTEK innovation ecosystem has gathered more than 1.12 million AI developers and developed more than 750,000 software applications. In 2019, iFLYTEK's consumer business achieved an operating revenue of 3.625 billion, an increase of 43.99%, and its gross profit was 1.708 billion, an increase of 31.81% (data is from the iFLYTEK annual report in 2019). Through technology empowerment, market empowerment, and investment empowerment, the iFLYTEK innovation ecosystem provides all-round technical cooperation and operation services for the partners from budding to growing and continues to create a win-win ecosystem.

5.2. Excess Return ΔR. Adhering to the concept of "working together to share industrial achievements," iFLYTEK actively cooperates with universities and scientific research institutions to establish a joint laboratory for cooperative research and development and insists on not competing directly with development partners in terms of cooperation. iFLYTEK and relevant enterprises form strategic alliances to carry out innovation activities together to promote the progress of voice technology in China and realize its industrial development. Table 3 shows the details. In the era of knowledge sharing, based on iFLYTEK's technology innovation platform, each cooperative enterprise has promoted the formation and evolution of the intelligent voice industry innovation ecosystem, which is "market-oriented, enterprise-oriented, and industry university research-combined." In this process, iFLYTEK always plays the role of the core enterprise and has a key role in the development of the innovation ecosystem of the intelligent voice industry in China.

In the cooperation with partners, iFLYTEK has always maintained the dominant position in the ecosystem and designed a mutually beneficial mechanism. By 2019, the iFLYTEK ecosystem has 1.6 million ecological partners. Due to the numerous partners in the ecosystem, iFLYTEK has made an in-depth layout in education, consumer, medical, urban management, and other industries. iFLYTEK has established a nationwide marketing channel and service network. For example, in the field of education, aiming at the market demand of personalized learning, iFLYTEK has cooperated with partners in the ecosystem to deeply tap the value of data and helped schools improve the effectiveness of students' learning. Its products have covered more than 16,000 schools across the country. In the field of intelligent medicine, iFLYTEK intelligent medical assistant of HKUST has provided 25 million times of auxiliary diagnosis suggestions, with an average of more than 200,000 pieces of data per day, serving more than 30,000 grassroots' doctors and benefiting more than 40 million residents. In terms of smart city governance, iFLYTEK has built a new AI capability platform "City Super Brain" and built urban smart applications around urban governance, so as to realize scientific government decision-making, fine social governance, and efficient public service. The relevant products have been launched in nearly 30 cities in 10 provinces in China (data is from the iFLYTEK annual report in 2019).

5.3. Imitation Costs M_1 *and* M_2. A big risk faced by many technology-based companies in the initial stage is that their core technology is imitated by competitors, and the cost of this imitation is much lower, so they lose competitiveness. For example, iFLYTEK builds the Intelligent Voice Industry Alliance Center to increase the imitation cost of competitors in the early stage. In March 2000, iFLYTEK cooperated with a large number of voice experts and scientific research institutes to launch the project "Voice Entrepreneurship Alliance in China." iFLYTEK has established the knowledge cooperation network with nearly 100 units including China University of Science and Technology, Institute of Acoustics of Chinese Academy of Sciences, Institute of Automation of Chinese Academy of Sciences, Institute of Language of Chinese Academy of Social Sciences, Huawei, IBM, and Intel and jointly established the joint laboratory, namely, "iFLYTEK Alliance Center" [45]. In 2014, the "Super Brain Program" was launched to attract the world's top voice experts to join in (annual speech of the head of the internal team of iFLYTEK "Super Brain Project," [2016-02-01], https://www.sohu.com/a/57533728_336009). In 2016, the core research platform was established, and the human-computer interaction AIUI system was developed, which expanded AI technology to the fields of smart cities, education, and finance. Secondly, iFLYTEK increases the imitation cost of competitors, which is to use the patent map to monitor the technology trends of competitors. The patent map is a kind of patent analysis and research method. It processes and analyzes patent information, reflects the information hidden in patent data through various interpretable charts, number of patents, annual growth chart, etc., so as to analyze the technology distribution situation and provide more intuitive information for decision makers. iFLYTEK uses the patent map to monitor the technology dynamics of competitors, so as to guide iFLYTEK's technology development and strategic layout and effectively prevent competitors from imitation. iFLYTEK sets a high technical threshold, which was difficult for rivals to imitate.

Table 3: iFLYTEK's cooperation events.

Year	Partners	Cooperation project	Excess returns from cooperation
2000	Huawei, IBM, Intel, Analog, etc.	Establishment of the iFLYTEK Alliance Center	Partners obtained voice service products. iFLYTEK held the main voice market share
2006	Multimedia Signal and Intelligent Information Processing Laboratory, Department of Electronic Engineering, Tsinghua University	Joint establishment of Tsinghua iFLYTEK Speech Technology Joint Laboratory	Tsinghua-iFLYTEK cooperation achieved major technological breakthroughs in speech recognition, audio content analysis, speech retrieval, language understanding, data mining, and other fields
2011	University of Science and Technology of China	Establishment of National Engineering Laboratory for Intelligent Speech and Language Information Processing	Cooperation accelerated technological breakthroughs in human-computer interaction, AI, and massive information processing
2012	Cooperation with 19 companies, including Huawei, Lenovo, China Mobile, China Telecom, and China Unicom	Joint establishment of the China Speech Industry Alliance	Cooperation integrated industrial resources, building a healthy industrial ecosystem, and promoting the development of the Chinese speech industry
2014	Harbin Institute of Technology	Joint establishment of "Harbin Institute of Technology-iFLYTEK Cognitive Language Computing Joint Laboratory"	The cooperation strengthened long-term and in-depth research in the field of cognitive language computing
2015	York University	Establishment of the iFLYTEK Neural Computing and Deep Learning Laboratory	Cooperation promoted breakthroughs in neural computing, deep learning, and AI technology
2018	MIT Computer Science and AI Lab	AI Alliance	Cooperation in speech processing, reasoning, cognition, and AI

It is also an important factor for iFLYTEK becoming a leader in the voice ecosystem.

5.4. Cost-Sharing Coefficient β. With the arriving of mobile Internet, iFLYTEK realized that this would be a huge business opportunity. At the same time, iFLYTEK received application demands from small- and medium-sized enterprises and developers. Before that, iFLYTEK's customers were mainly large- and medium-sized enterprises, and the development costs were too high. After turning to the market of small- and medium-sized enterprises, the coordination costs were able to be greatly reduced. In 2010, iFLYTEK released the world's first "iFLYTEK Voice Cloud Platform" for mobile Internet intelligent voice interaction and, simultaneously, released the "Voice Input Method" experience version to re-enter the consumer market. The launch of this platform greatly reduced the coordination cost between the partners in the voice ecosystem. For entrepreneurs, the products can be developed directly based on iFLYTEK's Voice Cloud Platform and can provide services to the outside world, reducing huge investment on the computer server. For iFLYTEK, it not only provides a "Voice Cloud Platform" for small- and medium-sized enterprises but also explores a new market for itself. Through the voice ecosystem, iFLYTEK has developed more than 50,000 partners in recent years, and iFLYTEK is also transforming from a single core technology provider to an open-platform enterprise. IFLYTEK's voice innovation ecosystem not only supports the entrepreneurial team but also cooperates with Ctrip, Sina Weibo, and other large companies to develop APPs. While spreading voice interaction functions, iFLYTEK has also won a wide range of users. iFLYTEK directly obtains income through cooperation with large companies, and after supporting small- and medium-sized companies to a certain scale, it will also share the income with them, thus generating economic benefits for iFLYTEK. iFLYTEK plays an important role in the voice ecosystem, leads the key process of the value chain, and constantly creates more new technologies. The reduction of the cooperation cost has also improved iFLYTEK's operating income and earnings' per share. Figure 9 shows iFLYTEK's net profit from 2008 to 2019.

5.5. Cooperation Costs C. When the intelligent voice market was not mature, iFLYTEK resolutely focused on business-to-business (B2B) application scenarios, grasping the needs of *B*-end users with an open mind and accumulating technical resources. For example, Huawei, ZTE, Digital China, and other domestic smart networks, call centers, and business systems needed to use voice engines to buy iFLYTEK. iFLYTEK provided the core competence of voice to partners at a lower cost, and the partners performed specific applications, which not only helped the partners reduce their R&D costs but also gave iFLYTEK more business opportunities. This was the establishment of the "iFLYTEK Inside" model. When the intelligent voice market was experiencing explosive growth, the industry competition was gradually increasing. iFLYTEK was determined to develop the platform and use cloud technology. Based on the needs of small- and medium-sized enterprises, it continued to iterate the voice recognition algorithm. For small- and medium-sized enterprises, the use of the "iFLYTEK Voice Platform" can significantly reduce huge investments in the server. For iFLYTEK, it has gained a broader voice cloud market for

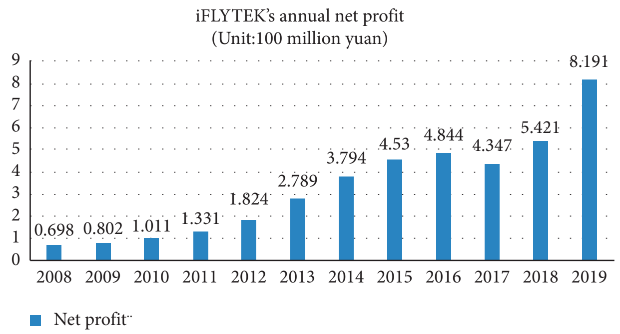

Figure 9: iFLYTEK's annual net profit (the data in Figure 9 are compiled by the author according to iFLYTEK's annual reports over the years).

small- and medium-sized enterprises. By reducing the cost of cooperation, leading enterprises and cooperative enterprises can closely strengthen cooperation.

In order to reduce the cooperation cost in the ecosystem, iFLYTEK has established a layout in three aspects. Firstly, iFLYTEK has cooperated with universities and research institutes extensively. The research institute is responsible for the applied technology research of products, while iFLYTEK is responsible for turning laboratory achievements into products. Secondly, iFLYTEK is also actively building an innovative industrial platform. On the one hand, it took the opportunity of the "National 863 Plan Achievements' industrialization base" in May 2000. Through the organization of capital, market, talent, and other resources, the industrial operation support platform is constructed, and the technical advantages are rapidly transformed into industrial advantages. On the other hand, iFLYTEK enables domestic and foreign enterprises to create new products on the basis of the iFLYTEK voice ecosystem and applies voice technology to various industries, so as to realize all-round penetration of the voice market. Thirdly, iFLYTEK has built the voice ecosystem, which has attracted leading enterprises in various industries to join in. iFLYTEK has also penetrated into the application fields of various industries, providing a variety of voice products. There are more than 1500 cooperative development partners in the ecosystem, including not only leading domestic enterprises such as Lenovo, Huawei, and Haier but also international IT giants such as Intel, Epson, and Siemens VDO.

5.6. Penalties F. The protection of intellectual property rights is very important for AI enterprises. Patent protection exists to protect the core competitiveness of product research. iFLYTEK conducts wide property rights' exploration and the monitoring of important businesses, adds intellectual property protection to the assessment system, and formulates incentive measures for protection. iFLYTEK has established a patent monitoring and early warning system for competitors. According to the analysis results, the enterprise is divided into three levels of early warning: red, orange, and blue. If the patent layout and technology direction are influenced, the red patent warning is issued urgently, and relevant technical managers are called together to discuss the response plan, so as to flexibly adjust the patent strategy. If there is an obvious but not serious impact on the enterprise, the orange patent warning can be issued, and the infringement situation can be reported to the intellectual property department. If the patent status is normal, the system will detect and display a blue warning. The patent report is published quarterly or biannually. iFLYTEK has established a set of patent monitoring and early warning system to punish imitators and ensure that its dominant market position can be maintained. Using the exclusive advantage of patent to punish imitators, IFLYTEK can use patent litigation to prohibit the sale of products of defaulting enterprises, so as to protect the sound ecosystem.

6. Discussion

6.1. Conclusions. Based on EGT, this paper constructs the value cocreation mechanism of the innovation ecosystem of an AI enterprise and discusses the factors that affect such value cocreation. Taking iFLYTEK as an example, China's leading AI enterprise, six factors are verified that affect the value cocreation in the ecosystem. The results show that obtaining an excess return rate, the distribution coefficient of the excess return rate, coordination costs, the cost-sharing coefficient, imitation costs, and penalties will affect value cocreation in an innovation ecosystem. The main conclusions are as follows:

First, the cooperation mechanism of leading enterprises in an AI ecosystem depends on the position of the saddle point. By establishing the replication dynamic equation, the stable evolutionary strategy is found. The evolution results show that there are only two stable results of the game: both sides choose to cooperate or not to cooperate. The combination of one party cooperating and the other not cooperating is unstable. Whether the two sides choose to cooperate or not at the same time depends on the location of the saddle point. The closer the saddle point is to (1,1), the higher the probability of both sides choosing cooperation. The closer the saddle point is to (0,0), the higher the probability of noncooperation.

Second, the location of the saddle point is determined by six factors, which are the excess distribution coefficient, excess returns, imitation costs, the cost-sharing coefficient, coordination costs, and penalties. The higher the values of the excess distribution coefficient, the excess returns, the imitation costs, the cost-sharing coefficient, and the penalties, the more likely leading enterprises and partners are to cooperate. The lower the value of the coordination costs, the higher the probability of both sides' cooperation.

Third, the paper analyzes the establishment process of the iFLYTEK innovation ecosystem and the value cocreation mechanism at different stages of iFLYTEK's growth, and it then discusses the role of six factors in iFLYTEK's ecosystem. For example, regarding the distribution coefficient, iFLYTEK adheres to the principle of not directly competing with partners and sincerely cooperates with many partners in the ecosystem to jointly promote the rapid growth of the voice industry. Concerning excess returns, iFLYTEK and relevant enterprises form a strategic alliance to carry out innovation activities together to promote the progress of voice technology in China and realize its industrial development. With regard to imitation costs, iFLYTEK set a high technical threshold and made it difficult for rivals to imitate its technology. In terms of the cost-sharing coefficient, the launch of the "iFLYTEK Voice Cloud Platform" project has greatly reduced the coordination costs between the partners in the voice ecosystem. Concerning cooperation costs, iFLYTEK provides the core competence of voice to its partners at a lower cost, and the partners perform the specific applications, which not only helps the partners reduce their R&D costs but also provides iFLYTEK with more business opportunities. With regard to penalties, iFLYTEK conducts wide property rights exploration, adds intellectual property protection to the assessment system, and formulates incentive measures for protection.

6.2. Contributions. The significant theoretical contributions of this work are threefold. First, our findings contribute to AI research by providing new insights through the discussion of dynamic cooperation mechanisms in AI innovation ecosystems. By solving the equilibrium solution of a replication dynamic equation, the paper analyzes the dynamic game process between leading AI enterprises and partners. There are two kinds of equilibrium strategies in the evolutionary game, either both parties cooperate or both parties do not cooperate. The combination of one party cooperating and the other party not cooperating is unstable. Whether the two sides cooperate depends on the location of the saddle point. Our research expands the application of innovation ecosystems in AI enterprises and explains the dynamic equilibrium process of AI enterprise value cocreation through EGT.

Second, the value cocreation mechanism of an AI enterprise is constructed, and the six factors affecting value cocreation are also discussed. Previous studies mainly focused on AI technology, but less on the cooperation mechanism between AI enterprises. The research in this paper is helpful in terms of opening the "black box" of the value cocreation mechanism and discussing the influencing factors in different situations for the growth of AI ecosystems.

Third, combined with the case study, the paper discusses how AI's leading enterprises and partners can create value together in order to obtain maximum benefits. The paper takes iFLYTEK as an example to illustrate the six factors that influence the cooperation of AI enterprises and to explain how to establish a suitable cocreation mechanism between leading enterprises and partners.

6.3. Managerial Implications. This study provides managerial implications for AI enterprises in terms of formulating strategies for participating in AI ecosystems. First, it is very important to find suitable partners and establish long-term cooperation mechanisms in an AI ecosystem. Most of the founding teams of AI enterprises have a certain technical threshold, but it also leads to the misunderstanding of relying too much on technology and ignoring the market. From technology to product commercialization to industrialization, the process has a long way to go. Therefore, we should break down the narrow understanding of "technology-based independence" and establish a broad cooperation mechanism. In the coordination mechanism of value cocreation, the choice of partner selection is very important. The key to long-term cooperation between ecological partners in the ecosystem is to find suitable partners who can complement each other, share risks and benefits, improve the distribution mechanism of benefits, institutionalize the proportion of excess income distribution, and establish reasonable standards. Value cocreation can promote the healthy development of an innovation ecosystem and benefit all the members of such a system. The basis of value cocreation is a reasonable cooperation mechanism and partner selection criteria.

Second, platform-leading enterprises play a key role in the development of innovation ecosystems, especially at the key moment of system development. Partners can participate in the ecosystem by reducing their cooperation costs. The way to reduce the costs of cooperation is based on specialization. In this way, participants only focus on their best business, not only to improve the scale of their core business but also to provide more opportunities for their partners. In this process, platform-leading enterprises need to be cultivated and supported, improving the coordination and service of their partners. Moreover, there is inevitably "hitchhiking" and "technology theft" in cooperation, which affects the sound operation of the system. This requires increasing the punishment and supervision mechanisms for the members involved in the system, strengthening the protection of intellectual property rights, and restraining the opportunistic behavior of the participants. Before cooperation, responsibilities, rights, and interests, restrictions with effective legal contracts and punishments for "technology theft" should be clearly outlined. Only by establishing restraint mechanisms for the sound operation of the system can we form effective protection for all participants and establish a suitable environment for an innovation ecosystem of AI enterprises.

Third, when the development of AI enterprises reaches a certain stage, there are more types of products and a wider range of businesses. It is necessary to optimize the ecosystem effect through value cocreation. For example, iFLYTEK set up an ecological voice platform to realize a huge transformation from a product provider to a platform provider and extensively connected consumers, education, city, finance, and other businesses on this platform. In the further development of innovation ecosystems, leading enterprises' innovation ability and resource allocation ability will help to clarify the synergy among the species involved. Value cocreation can accurately grasp the current and future technological needs, provide products and services with market prospects, improve the stability and innovation efficiency of the ecosystem, and accelerate its maturity.

6.4. Limitations and Future Research. This paper constructs the coordination mechanism of value cocreation in AI enterprise innovation ecosystems based on EGT. However, there are still some limitations to be considered in further research.

First, the paper focuses on the ecosystem development of AI enterprises from the perspective of value cocreation. The exit mechanism in innovation ecosystems can be further studied. For example, in the process of ecosystem evolution, the possible reasons for the quits of partners are as follows: inappropriate partners, violation of the original intention of cooperation, and unreasonable distribution of interests. Second, the paper considers value cocreation from the perspective of platform-leading enterprises. Value cocreation can also be considered from the perspective of partners. Third, although iFLYTEK has experienced great success in the field of voice, it has also gone through numerous detours in terms of its growth. The failures of AI enterprises are also worthy of further study. With the emergence of more and more AI enterprises in China, it is of great significance to study how to build an innovation ecosystem to enable the development of AI enterprises.

Data Availability

The data used to support the findings of this study are included within the article. Also, these data 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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Supplementary Materials

The information about iFLYTEK in this paper mainly comes from iFLYTEK's official website, iFLYTEK's annual report, and interviews with iFLYTEK's senior managers by mainstream media. There are also some literature information from China National Knowledge Infrastructure (CNKI) and Web of Science. (*Supplementary Materials*)

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Research Article

Member Selection for the Collaborative New Product Innovation Teams Integrating Individual and Collaborative Attributions

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As the first stage of the formation of a collaborative new product innovation (CNPI) team, member selection is crucial for the effective operation of the CNPI team and the achievement of new product innovation goals. Considering comprehensively the individual and collaborative attributions, the individual knowledge competence, knowledge complementarity, and collaborative performance among candidates are chosen as the criteria to select CNPI team members in this paper. Moreover, using the fuzzy set and social network analysis method, the quantitative methods of the above criteria are proposed correspondingly. Then, by integrating the above criteria, a novel multiobjective decision model for member selection of the CNPI team is built from the view of individual and collaborative attributions. Since the proposed model is NP-hard, a double-population adaptive genetic algorithm is further developed to solve it. Finally, a real case is provided to illustrate the application and effectiveness of the proposed model and method in this paper.

1. Introduction

In order to adapt to the dramatic, changing market environment, enterprises are paying more and more attention to the adoption of a collaborative new product innovation (CNPI) mode for collaboration development advantages [1]. By adopting the CNPI mode, it is advantageous for enterprises to expand organization scale, improve utilization efficiency of internal and external resources, and decrease the costs and risks of new product development [2]. The CNPI team is the major and core organization to implement new product innovation and development activities, in which the complementary knowledge resources are shared by team members from various organizations in a more effective way, so as to inspire the thought of new product innovation [3–6]. At the formation stage of the CNPI team, member selection is an important decision-making issue. Selecting competent team members is of much significance to achieve knowledge complementarity, efficient collaboration and mutual inspiration, and maximize the collaborative performance of the team around the new product innovation goals [7, 8].

Currently, individual attribution of candidate member is much more considered as the decision-making information in most researches concerning member selection [9, 10], with less consideration on knowledge complementarity and collaborative attribution among team members. Actually, pursuing maximization of individual competence of team members will bring in a lot of disadvantages, among which the worst is the ignorance of collaborative performance and synergy among team members [10]. As a result, in order to stimulate the team synergy and collaboration performance, this paper focuses on member selection of CNPI team based on the individual and collaborative attributions of members, to construct a member selection decision model integrating individual knowledge competence, knowledge complementarity, and collaboration ability among members. In this paper, a new study perspective and method is expected to be provided for decision-makers in enterprises to select competent team members, so as to form a CNPI team with better performance.

2. Related Works

Member selection is a complicated decision-making issue and requires systematic consideration of multiple member selection attributions and indicators [11]. As proposed by [12], indicators such as individual traits, expertise, experience, knowledge learning and sharing abilities, communication skills and problem-solving skills, etc., should be taken into account as the major factors in taking a decision to select any member into the new product development team. Similarly, it is indicated in Antoniadis's [13] research that working experience, knowledge and skills, and individual traits of candidates should be deemed as the major indicators in selecting members for the project team. Chen and Lin [14] consider the knowledge domain width, teamwork ability, and good interpersonal relationship as the key indicators for team member selection. In addition, Leenders et al. [15] state that an efficient new product development team should consist of members with a sufficient knowledge reserve and a strong pioneering spirit. Wi et al. [11] insist that to better satisfy knowledge needs of projects or tasks, individual knowledge competency should be treated as the primary indicator for project team member selection. In all of the above researches, significance of individual attribution or indicators of candidates is emphasized for team member selection, especially the significance of individual knowledge competence. However, from the perspective of team synergy, it should not only emphasize individual knowledge competence but also the collaborative attribution among members, which is also a critical factor in the process of member selection. In the CNPI team, team members can break the traditional limit of organization to enter into a public and open platform for sharing and discussion of ideas and opinions. Besides, well complemented knowledge and cross collaboration play a significant role in improving team performance, since organizational performance relies on organic combination of knowledge and experience of all members [16]. What should be pointed out is that the collaboration involves not only co-work, complementarity, and consistency among members but also the effectiveness and depth of their collaboration relationships. Based on the above analysis, the collaborative attribution among members should be also taken as crucial indicator and be given sufficient importance in making decisions to select the desired member for the CNPI team. In this paper, the collaborative attributions among members are summarized as knowledge complementarity and knowledge collaboration performance.

Today, we step into a new era of knowledge explosion, where each individual can only master a very small part of human knowledge with the continuous refinement of social division of labor. The realization of the innovation goal is more and more inseparable from human knowledge division and collaboration. Knowledge complementarity has become a critical component for people to consider in knowledge collaborative innovation [17, 18]. In the collaborative environment of innovation alliance, [19] have proposed two dimensions of knowledge complementarity, relatedness and differences, and explored the role played by knowledge complementarity in the process of innovation alliance formation and member selection. Baum et al. [20] state that proper knowledge complementarity is helpful to establish efficient collaborative partnership. Besides, as proposed by [21], in the innovation cooperation network of industrial clusters, the main purpose of cross-level and cross-organization cooperation among nodes is to realize complementary advantages of innovation knowledge resources among organizations. Moreover, they've also investigated the influence of knowledge complementarity on the generation and change rules of innovation network structure. Meanwhile, it has been shown in a large number of researches that complementary knowledge resources among members are also of much help to stimulate members' enthusiasm for collaboration, bring about new product ideas and improve new product development performance [17, 22, 23].

Currently, collaborative innovation has become a major trend in new product development [1, 24, 25]. To complete a CNPI project or task, joint efforts and cooperation are required for members with different knowledge and expertise. Collaboration level and performance among team members are important considerations in CNPI team building and member selection. Scholars have conducted some researches on knowledge collaboration performance among members. For instance, Emden et al. [26] have shown that for member selection of cooperative research and development alliance, the good collaboration condition among members, such as nonconflict objectives, harmonious culture, etc., is conducive to communication, knowledge sharing, and mutually beneficial information exchange in the future alliance cooperation. Jiang et al. [27] point out that an excellent team is not a simple combination of team members, but rather requires deep collaboration of team members to integrate complementary advantages of all members and stimulate synergy. Furthermore, as Fan et al. [28] emphasized, good collaboration performance of members is able to promote communication among members effectively; enhance cohesion; improve mutual understanding, trust, and satisfaction; reduce conflicts and uncertainties in cooperation; shorten the time of mutual adaption; and ultimately lead to a great organizational cooperation performance. Meanwhile, the good collaboration performance among members is able to integrate interdisciplinary knowledge, which is quite critical for new product development, since such integration can decrease costs and risks of new product research and development, increase application opportunities of new technologies, and accelerate the speed of entering new markets. In summary, based on the perspective of individual and collaboration attributions of members, not only the individual knowledge competence of members but also the knowledge complementarity and knowledge collaboration performance among members should be taken into consideration in the selection of suitable and competent members for the CNPI team.

In current researches, the quantitative decision-making method is mainly used to solve the problems of member selection. Among them, Chen and Lin [14] have established a mathematical model and a five-stage decision-making method to support the formation of the team, wherein they compared the competitiveness of team members using the AHP method, to select the desired members. Jiang et al. [27] have put forward a transformation method that can reduce the complexity of the member selection model and improve the solution efficiency of the member selection problem. In addition, Jian et al. [29] have proposed a nondominated sorting genetic algorithm II to solve the multi-objective partner selection problem in the context of collaborative product innovation. However, the decision-making methods proposed in the above works are mainly used to solve the member selection model based on individual attribution or indicator; however, it is difficult to directly use them for solving the member selection problem based on the individual and collaborative attributions. Therefore, a proper and effective member selection model is required to be proposed along with the solution algorithm to solve the member selection problem of a CNPI team based on individual and collaborative attributions.

3. Member Selection Model Integrating Individual and Collaborative Attributions

3.1. Problem Description. This paper aims to investigate the decision-making problem of member selection for the CNPI team based on individual and collaborative attributions of candidates, and construct a multi-objective decision model for member selection comprehensively integrating individual knowledge competence, knowledge complementarity, and knowledge collaboration performance among members. Firstly, the member selection problem of the CNPI team can be described as follows: in order to form a CNPI team, m members need to be selected from the candidate group $P = \{p_1, p_2, \ldots, p_i, \ldots, p_n\}$, where p_i represents the ith candidate, KC_i represents the individual knowledge competence of candidate p_i, while C_{ij} and CP_{ij} represent knowledge complementarity and knowledge collaboration performance among candidates p_i and p_j, respectively. The overall goal of this paper was to form a team with optimal individual and collaborative performance, under which three subgoals are considered: the first one is to optimize the individual knowledge competence of m members; the second one is to achieve proper knowledge complementarity among members; and the third one is to optimize the knowledge collaboration performance among members.

3.2. Individual Knowledge Competence of Members. CNPI is inherently a kind of knowledge-intensive activity. The individual knowledge competence of team members plays a key role in the success of product innovation [30–32]. A series of quantitative methods for individual knowledge competence has been put forward by many scholars, such as AHP, fuzzy mathematics, and text semantic method, etc [14, 33, 34]. Based on the existing researches, it has been found that direct monitoring and measuring of human knowledge competence are usually hard to be performed, and there are much fuzziness and uncertainty in the evaluation of individual knowledge competence. For these reasons, the fuzzy language variables are preferred for evaluation, such as "good knowledge competence," "moderate competence," and "poor competence." In order to deal with the fuzzy and uncertain information in the evaluation of individual knowledge competence, the fuzzy set theory [11, 35–37] is adopted in this paper for the evaluation of candidates' individual knowledge competence. For the purpose of determination of fuzzy evaluation results, the joint evaluation by candidates and experts from enterprises is considered in this paper to measure the individual knowledge competence of candidates under various attributions, with synthesis of evaluation results. Reasons for joint evaluation are listed as follows: firstly, members have the best understanding of their own knowledge competence under various attributions. Evaluation by members themselves not only reduces the impact of information "stickiness" generated by organizations in acquisition of individual information and knowledge competence but also decreases the work complexity and workload by direct self-evaluation of members compared with a series of works such as collection, acquisition, transformation, and quantification of members' information and knowledge competence. Secondly, in comparison with candidates, experts from enterprises are more aware of the knowledge requirements of product innovation projects or tasks, and thus are capable of providing necessary information support and professional assistance for candidates. Meanwhile, it is conducive to avoiding unreasonable evaluation results generated by candidates in their independent subjective evaluations. The fuzzy evaluation process of individual knowledge competence of candidates is shown in detail as follows:

Given that fuzzy language variables are mostly applied by candidates and experts from enterprises in the evaluation of individual knowledge competence, the triangular fuzzy data method is utilized in this paper for fuzzy quantification of the evaluation language variables. Assume a triangular fuzzy datum as $\widetilde{M} = (d^L, d^M, d^R)$, in which d^L, d^M, d^R represent the minimum value, the middle value, and the maximum value, respectively. The correspondence between language variables and fuzzy quantized values is shown in Table 1.

In addition, in order to meet the requirements of quantitative analysis of the problem, the fuzzy data converted from language variables are usually to be mapped to crisp scores. To this end, Oprcovic and Tzeng et al. [38] have proposed a method of converting the fuzzy data into crisp scores. As for the result obtained through this method, fuzzy data with a larger degree of membership functions will correspond to larger crisp scores, with two symmetrical triangular fuzzy data consistent with crisp scores after mapping. The triangular fuzzy datum $\widetilde{M} = (d^L, d^M, d^R)$ corresponds to a crisp score M, which can be defined as follows:

$$M = L + \frac{\Delta\left[\left(d_k^M - L\right)\left(\Delta + d_k^R - d_k^M\right)^2\left(R - d_k^L\right) + \left(d^R - L\right)\left(\Delta + d^M - d^L\right)^2\right]}{\left(\Delta + d^M - d^L\right)\left(\Delta + d^R - d^M\right)^2\left(R - d^L\right) + \left(d^R - L\right)\left(\Delta + d^M - d^L\right)^2\left(\Delta + d^R - d^M\right)}, \quad (1)$$

wherein $L = \min\{d^L\}$, $R = \max\{d^R\}$, $\Delta = R - L$.

Assume the set of knowledge points required for a CNPI project or task as $K = \{k_1, k_2, \ldots, k_\alpha, \ldots, k_U\}$ in which k_α represents the αth knowledge point, the set of candidates as $P = \{p_1, p_2, \ldots, p_i, \ldots, p_n\}$, and the set of experts from enterprises as $E = \{e_1, e_2, \ldots, e_k, \ldots, e_T\}$, in which e_k means the kth expert. Evaluations are conducted by candidates and experts from enterprises, respectively, using language variables to tacit knowledge competence under different attributions, which are assumed as the set $S = \{s_1, s_2, \ldots, s_\beta, \ldots, s_O\}$, wherein s_β means the βth evaluation attribution.

Then, based on the correspondence between language variables and the triangular fuzzy data as shown in Table 1, language evaluations by candidates and enterprise experts to knowledge point k_α under various attributions are converted into triangular fuzzy data, which are further converted into crisp scores for synthesis. Thus, the knowledge competence value of candidate p_i on knowledge point k_α is calculated as follows:

$$\mathrm{KC}_i^\alpha = w_C \sum_{\beta=1}^{O} w_{s_\beta} M_{i\alpha\beta} + w_E \sum_{\beta=1}^{O} \sum_{k=1}^{T} w_{s_\beta} M_{ki\alpha\beta}, \quad (2)$$

In the above formula, KC_i^α indicates knowledge competence value of candidate p_i on knowledge point k_α, $M_{i\alpha\beta}$ represents evaluation value of competence from candidate p_i on knowledge point k_α based on attribution s_β, $M_{ki\alpha\beta}$ represents evaluation values from expert e_k to the competence of candidate p_i on knowledge point k_α based on attribution s_β, w_C and w_E indicate the relative importance of candidates and experts, respectively, in the process of evaluation, where $w_C + w_E = 1$, and w_{s_β} indicates the relative importance of evaluation attributions, wherein, $\sum_{\beta=1}^{O} w_{s_\beta} = 1$.

Furthermore, the individual knowledge competence value of candidate p_i can be calculated by the following formula:

$$\mathrm{KC}_i' = \sum_{\alpha=1}^{M} \mathrm{KC}_i^\alpha. \quad (3)$$

To ensure that the individual knowledge competence of candidates is within the range of $[0, 1]$, the following formula is used for normalization:

$$\mathrm{KC}_i = \frac{\mathrm{KC}_i'}{\mathrm{KC}_{\max}'}, \quad (4)$$

where in $\mathrm{KC}_{\max}' = \max\{\mathrm{KC}_i' | i = 1, 2, \ldots, n\}$.

3.3. Knowledge Complementarity among Members. It is obvious that managers of enterprises expect, from their perspective, team members equipped with optimal individual knowledge competence to deal with the difficulties and challenges in CNPI. However, from the perspective of teamwork, the method to simply pursue the maximization of members' individual knowledge competence has brought about an obvious defect. In the CNPI team, too much similarity on knowledge or competence among members indicates too much overlap, which will hinder the mutual learning and collaboration performance among them. On the other hand, if there exist over-differences on knowledge or ability among members, they will find it hard to understand the knowledge of each other, leading to a great divide of knowledge communication and collaboration [20, 39]. Obviously, the synergy among team members is hard to be stimulated under the above two circumstances. As shown in the existing researches, whether a collaboration will be successful or not depends on to what extent the members' individual knowledge competence is matched and complemented [19]. In this paper, knowledge complementarity is measured from the perspective of comparative advantages of knowledge competence among members. Firstly, assume S_{ij} as the comparative advantages of the knowledge competence of candidate p_i over p_j, and $Sk^\alpha(ij)$ as the comparative advantages of knowledge competence of candidate p_i over p_j on knowledge point k_α. $Sk^\alpha(ij)$ can be calculated by the following formula:

$$Sk^\alpha(ij) = \begin{cases} \mathrm{KC}_i^\alpha - \mathrm{KC}_j^\alpha, & \text{if } \mathrm{KC}_i^\alpha \geq \mathrm{KC}_j^\alpha, \\ 0, & \text{if } \mathrm{KC}_i^\alpha < \mathrm{KC}_j^\alpha, \end{cases} \quad (5)$$

wherein, KC_i^α and KC_j^α represent knowledge competence of candidates p_i and p_j on knowledge point k_α, respectively.

Then S_{ij} can be figured out through the following formula:

$$S_{ij} = \sum_{\alpha=1}^{M} Sk^\alpha(ij), \quad i, j = 1, 2, \ldots, n. \quad (6)$$

Assume C_{ij} as knowledge complementarity coefficient between candidates p_i and p_j. Since the knowledge complementarity coefficients are symmetrical between them, then $C_{ij} = C_{ji}$. Thus, the knowledge complementarity between candidates p_i and p_j can be obtained by the following formula:

$$C_{ij} = C_{ji} = S_{ij} + S_{ji}. \quad (7)$$

It is obvious that C_{ij} is within the range of $[0, U]$, and U denotes the number of knowledge points. If $C_{ij} = 0$, candidates p_i and p_j have completely identical knowledge background and competence as expressed; if $C_{ij} = U$, it is indicated that candidates p_i and p_j have completely different knowledge background and competence. In accordance with the aforementioned analysis, neither the over-similarity nor the over-difference should appear among members on

Table 1: Correspondence between Language variables and Triangle fuzzy data.

Language variable	Triangle fuzzy data
Very poor (VP)	(0, 0, 0.2)
Poor (P)	(0, 0.2, 0.4)
Moderate (M)	(0.3, 0.5, 0.7)
Good (G)	(0.6, 0.8, 1.0)
Very good (VG)	(0.8, 1, 1)

knowledge background and competence. Hence, the appropriate knowledge complementarity among members should satisfy the following conditions:

$$\underline{\theta} \le C_{ij} \le \overline{\theta}, \tag{8}$$

wherein $\underline{\theta}$ and $\overline{\theta}$ represent the upper limit and lower limit of the reasonable knowledge complementarity interval, respectively.

3.4. Formal Knowledge Collaboration Performance. Typically, the formal knowledge collaboration relationship appears as the formal working relationship among candidates based on tasks or projects. As shown in many researches, the partner with whom we have cooperated once will be preferred to establish the next collaboration relationship, because the sound historical cooperation experience may decrease the uncertainty of understanding the competence of partners [40–42]. Therefore, it is assumed that partners with more sound cooperation experiences behave better than those with less cooperation experiences, with respect to collaboration performance. In reference to the method of Newman [43], the formal knowledge collaboration performance among candidates is measured using the task cooperation information and is calculated as FC_{ij} with the following formula:

$$\mathrm{FC}_{ij} = \sum_k \frac{\sigma_i^k \sigma_j^k}{n_k - 1}, \tag{9}$$

wherein σ_i^k is a Boolean variable used to determine if candidate p_i is involved in task k. If candidate p_i is involved in the task k, $\sigma_i^k = 1$; otherwise $\sigma_i^k = 0$. n_k refers to the number of members involved in task k. What needs to be noted in particular is that tasks undertaken by one single man are excluded here, for they do not work for a collaboration relationship among members and their introduction will lead to failure of the formula (9).

To ensure that the value of formal knowledge collaboration performance among members is within the range of $[0, 1]$, FC_{ij} should be normalized:

$$\mathrm{FC}_{ij}' = \frac{\mathrm{FC}_{ij}}{\mathrm{FC}_{ij\max}}, \tag{10}$$

where in $\mathrm{FC}_{ij\max} = \max\left\{\mathrm{FC}_{ij} | i = 1, 2, \ldots, n; j = 1, 2, \ldots, n\right\}$.

3.5. Informal Knowledge Collaboration Performance. The informal knowledge collaboration relationship mainly appears as social relations among candidates in information and knowledge communication. Currently, no unified quantification criteria have been developed for the measurement of informal knowledge collaboration relationship. The commonly used method is to measure by the frequency of communication among individuals or their joint participation [5]. However, to count the communications or activities among individuals is hard to achieve and involves a huge workload. Thus, based on the social network theory, the social relationship influence of team candidates is proposed to measure the informal knowledge collaboration performance among members in this paper. By this method, the social relationship influence of candidates with collaboration relationship is taken as the major reference. That is, the stronger the social relationship influence the candidates have, the stronger is the informal knowledge collaboration relationship among them.

To measure the social relationship influence of candidates, the commonly used indicators in social network analysis are intensity, closeness, and betweenness. Among them, the indicator of intensity is the simplest way. Used to describe the direct influence among network nodes in the static network, it reflects the direct social relationship strength of this member in a social network [44]. The indicator of closeness is utilized to illustrate the difficulty degree for a node to reach other nodes through the network, reflecting the indirect social relationship strength of this member in the social network [45]. As an indicator for measuring overall influence, the betweenness indicator reflects the importance of member position in the network and its influence in network information and knowledge flow [46]. In comprehensive consideration of direct and indirect relationship influence of members, the betweenness indicator is of great practical significance. As a result, the betweenness indicator is selected to evaluate the social relationship influence of candidates in social network, and is defined as the influence strength of informal knowledge collaboration relationship of candidates in this paper.

The betweenness of candidate p_i in the social network, also the influence strength of informal collaboration relationship, is represented by Be_i which is calculated as follows:

$$\mathrm{Be}_i = \sum_{s \ne i \ne t \in G} \frac{\xi_{\mathrm{st}}(i)}{\xi_{\mathrm{st}}}. \tag{11}$$

wherein ξ_{st} refers to the number of the shortest paths between candidates p_s and p_t, $\xi_{\mathrm{st}}(i)$ for the number of the shortest paths between candidates p_s and p_t that pass through candidate p_i. Then, Be_i should be normalized to ensure it within [0, 1]. If all of the shortest paths between any other candidates' nodes pass through candidate p_i, candidate p_i will get the highest value for the influence strength of the informal collaboration relationship, as shown in the following:

$$\mathrm{be}_{\max} = \frac{(n-1) \times (n-2)}{2}. \tag{12}$$

Thus, the normalized influence strength of informal collaboration relationship of the candidate is as follows:

$$\mathrm{Be}_i = \frac{\mathrm{be}_i}{\mathrm{be}_{\max}} = \frac{2b_i}{(n-1)\times(n-2)}, \quad 0 \le \mathrm{Be}_i \le 1. \tag{13}$$

Researches show a significant correlation between the relationship strength among nodes and the influence of nodes at both ends [47, 48], which can be expressed as $w_{ij} \sim (o_i o_j)^{\theta}$, wherein o_i and o_j stand for influence of nodes at both ends, respectively, and θ for the accommodation coefficient of a specific network. Therefore, the influence strength of informal knowledge collaboration relationship IC_{ij}' between candidates p_i and p_j is defined as:

$$\mathrm{IC}_{ij}' = \sqrt{\mathrm{Be}_i \cdot \mathrm{Be}_j}, \quad 0 \le \mathrm{IC}_{ij}' \le 1. \tag{14}$$

Combining the abovementioned formal and informal knowledge collaboration performance, the knowledge collaboration performance CP_{ij} between candidates p_i and p_j can be shown as follows:

$$\mathrm{CP}_{ij} = \mu \times \mathrm{FC}_{ij}' + \nu \times \mathrm{IC}_{ij}', \tag{15}$$

wherein μ and ν refer to the weights of formal and informal knowledge collaboration performance, respectively, with $\mu + \nu = 1$.

4. Decision-Making Model of Member Selection for the CNPI Team

Based on the above analysis, the attribution indicators including the individual knowledge competence, knowledge complementarity, and knowledge collaboration performance among candidates are integrated in this paper, so as to solve the member selection problem of the CNPI in comprehensive consideration of both individual and collaborative attributions. Then, a 0-1 multi-objective decision model is built as follows for the CNPI team member selection:

$$\mathrm{Max}\, Z_1 = \sum_{i=1}^{n} \mathrm{KC}_i \cdot x_i, \tag{16}$$

$$\mathrm{Max}\, Z_2 = \sum_{i=1}^{n} \sum_{\substack{j=1 \\ j\ne i}}^{n} \mathrm{CP}_{ij} \cdot x_i x_j, \tag{17}$$

$$\text{s.t. } \underline{\theta} \le C_{ij} \le \overline{\theta}, \quad i, j = 1, 2, \ldots, n, \tag{18}$$

$$\sum_{i=1}^{n} x_i = m, \tag{19}$$

$$x_i = \begin{cases} 1, & \text{candidate } p_i \text{ is selected}, \\ 0, & \text{otherwise}. \end{cases} \tag{20}$$

In models (16)–(20), objective (16) refers to the optimal individual knowledge competence of the member; objective (17) refers to the optimal knowledge collaboration performance among members; constraint (18) suggests that knowledge complementarity among members should be within the appropriate range, and constraint (19) indicates selection of m members from n candidates to form a team. Meanwhile, the member selection model is a 0-1 quadratic programming optimization model, similar to the difference maximization model of Kuo et al., which has proved that this problem is NP-hard [49]. Moreover, the member selection model proposed in this work comprehensively considered the individual knowledge competence, knowledge complementarity, and knowledge collaboration performance among candidates, which is more systematic and reasonable in the context of the CNPI than other member modes of selection or partner selection models [12, 29, 35]. Specifically, Zhang and Zhang's [12] member selection model considered the two goals of team members' personality and interpersonal relationships. Jian et al. [29] established an evaluation index model integrating knowledge matching degree and overall revenue of innovation alliance. The above models are difficult to deal with the complex requirements for the CNPI team member selection, while it is the advantage of the proposed member selection model of this work. Then, to solve the member selection problem in a more effective way, a Double-Population Adaptive Genetic Algorithm is proposed in this paper.

5. Improved Double-Population Adaptive Genetic Algorithm

As discussed in the last section, to solve the member selection model proposed in this paper is NP-hard. It is not possible to promptly and effectively get the optimal solution of a NP-hard problem using the traditional optimization algorithm, such as the minimum–maximum boundary method, weighted sum method, ε-constraint method, etc. [10]. For NP-hard problems, genetic algorithm is a common solution. However, the traditional genetic algorithm tends to fall into a dilemma such as local optimum, poor local optimization ability, and prematurity [12]. Thus, improvement of the standard genetic algorithm is required in the application process, and double-population genetic algorithm and adaptive genetic algorithm are two major improvement solutions. In terms of the former algorithm, two different populations evolve at the same time, where excellent individuals in the different populations exchange genetic information to achieve a higher equilibrium, so as to increase the probability of jumping out of the local optimum. With respect to the adaptive genetic algorithm, adaptive adjustment is performed to the crossover and mutation probability of individuals in accordance with the fitness of the individuals, so that the problems existing in the traditional genetic algorithm, such as a slow rate of convergence and poor local optimization ability caused by the fixed crossover and mutation probability of individuals, can be better handled. In the paper, the advantages of these two algorithms are combined, and a Double-Population Adaptive Genetic Algorithm (DPAGA) is proposed to solve the team member selection problem.

5.1. Chromosome Encoding. In accordance with the characteristics of member selection model, the chromosome is encoded with 0-1 binary coding method. Thus, each individual (e.g. member selection scheme) in a population is encoded as $[1, 0, 0, \ldots, 1, 0]$ in form, with total n-loci in the coding (gene). However, 1 indicates that candidates are selected, while 0 indicates that candidates are not selected. m members need to be selected from n candidates to form a knowledge network, so m genes should be encoded as 1 in each chromosome. According to the above encoding rules, multiple feasible chromosomes are randomly generated after n and m are defined, and two initial populations are formed.

5.2. Construction of a Fitness Function. Since team member selection is a nonlinear, multi-objective combination optimization problem, it's difficult to give the optimal values of two objectives simultaneously. However, the maximum and minimum values of the two objectives are easy to acquire. Thus, the ideal point method is used to convert the multi-objective into a single objective in this paper, so that the fitness function is constructed for the member selection model.

In terms of the ideal point method, a decision scheme is evaluated through the gap between its actual objective value and its ideal objective value. Namely, the smaller the gap is, the better the scheme is. As the set of ideal solutions of each objective, the ideal point can be subjectively determined by decision-makers or in accordance with the optimal value of a single objective [50]. Therefore, by using the ideal point method, the evaluation function for member selection is obtained as follows:

$$\min Z = \sqrt{\left(Z_1 - Z_1^*\right)^2 + \left(Z_2 - Z_2^*\right)^2}, \qquad (21)$$

wherein (Z_1^*, Z_2^*) = ideal point; it consists of optimal values of two sub-objectives, Z_1^* for the optimal value of the first objective function and Z_2^* for the optimal value of the second objective function. (Z_1, Z_2) = current objective value, wherein Z_1 represents the current value of the first objective function and Z_2 means the current value of the second objective function. Z = gap between current objective value and the ideal point.

Moreover, considering that the two objective functions have different dimensions and importance, it is necessary to normalize the two objectives and allocate them different weights, so as to construct the fitness function as follows:

$$\text{Fitness} = H - \sqrt{\gamma_1 \left(\frac{Z_1 - Z_1^*}{Z_1^*}\right)^2 + \gamma_2 \left(\frac{Z_2 - Z_2^*}{Z_2^*}\right)^2}, \qquad (22)$$

wherein H is a sufficiently large positive integer, γ_1 and γ_2 refer to the weight of objective Z_1 and Z_2, respectively, with $\gamma_1 + \gamma_2 = 1$.

5.3. Selection Operation. The Roulette method is used as the selection strategy for algorithms. Firstly, the fitness value of each individual is obtained in accordance with the fitness function, followed by selection operation to both populations using the Roulette method. Based on the fitness value, each generation of individuals is determined for its probability of being selected to enter the next generation. Assume ψ_i as the probability of individual i to be selected to enter the next generation, then:

$$\psi_i = \frac{\text{Fitness}(i)}{\sum_{i=1}^{n} \text{Fitness}(i)}. \qquad (23)$$

5.4. Adaptive Crossover and Mutation Operations. DPAGA is an algorithm where two populations evolve independently and synchronously, with different crossover and mutation operations for different populations who will communicate mutually with certain rules at the right time. Independent evolution, crossover, and mutation operations of two populations ensure their diversity, while exchange of excellent individuals among populations ensures the rate of convergence of feasible solutions. For the population construction in the DPAGA algorithm, the method proposed in reference [51] in this paper refers to: assume population 1 as a detection sub-population, used for local search and providing new hyperplanes in the evolution process to avoid premature convergence; assume population 2 as a development sub-population, used for local search and retention of outstanding individuals. In relation to crossover and mutation operations between the two populations, the two-point crossover and two-point mutation are adopted, respectively.

With regard to the two-point crossover, two individuals are chosen randomly from the selected populations as crossover objects, with random generation of two intersection location points. Then, genes at these two intersection location points are exchanged with the rest remaining unchanged, as shown in Figure 1.

By using the two-point mutation operation, two location points with different gene values are generated randomly for an individual, followed by the exchange of gene values at these two location points using their alleles, as shown in Figure 2.

For the problem that fixed crossover and mutation probability might lead to prematurity and local optimum, the adaptive selection method is adopted in this paper to optimize the crossover and mutation probability of the two populations. The fitness values are to be compared when two chromosomes are performing the crossover operation. If the larger fitness value between them is less than or equal to the average fitness value of the population, the crossover probability will increase adaptively; otherwise, it will decrease in an adaptive way. Similarly, if the fitness value of chromosomes performing mutation operation is less than or equal to the average fitness value of the population, the mutation probability will increase adaptively; otherwise, it will decrease in an adaptive way. In this way, individuals of each generation have varied crossover and mutation probabilities, and adaptive crossover and mutation are achieved. The adaptive crossover and mutation probabilities are obtained, respectively, as follows:

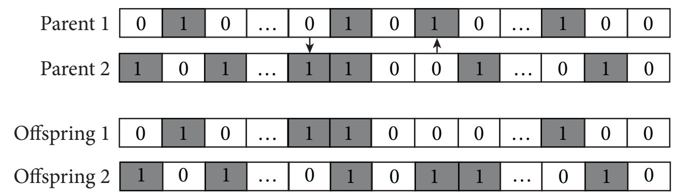

Figure 1: Two-point crossover operation.

$$p_c = \begin{cases} p_{c_{\min}} - \dfrac{f_{\max} - f}{f_{\max} - f_{\min}}\left(p_{c_{\max}} - p_{c_{\min}}\right), & f > \overline{f}, \\[2ex] p_{c_{\min}} + \dfrac{f_{\max} - f}{f_{\max} - f_{\min}}\left(p_{c_{\max}} - p_{c_{\min}}\right), & f \le \overline{f}, \end{cases}$$

$$p_m = \begin{cases} p_{m_{\min}} - \dfrac{f_{\max} - f}{f_{\max} - f_{\min}}\left(p_{m_{\max}} - p_{m_{\min}}\right), & f' > \overline{f}, \\[2ex] p_{m_{\min}} + \dfrac{f_{\max} - f}{f_{\max} - f_{\min}}\left(p_{m_{\max}} - p_{m_{\min}}\right), & f' \le \overline{f}, \end{cases} \quad (24)$$

wherein p_c, p_m refer to the adaptive crossover and mutation probabilities, respectively, $p_{c_{\max}}$, $p_{c_{\min}}$ indicate the maximum and minimum crossover probability, respectively, $p_{m_{\max}}$, $p_{m_{\min}}$ indicate the maximum and minimum mutation probability, respectively, $f_{\max}$, $f_{\min}$, $\overline{f}$ represent the maximum, minimum, and average fitness values in a population, respectively, and f, f' refer to the fitness values of individuals performing the crossover and mutation operations, respectively.

5.5. Migration Operation. After the next generation of population is produced through selection, crossover, and mutation of two populations, a random number num is generated. Then, the optimal solution is taken out from the two populations and hybridized with num chromosomes to integrate into counterpart population, so as to achieve an exchange of genetic information carried by outstanding individuals between populations and break the balance within the populations to avoid local optimal solution.

6. Case Study

To illustrate the feasibility and effectiveness of the method and the model proposed in this paper, a member selection decision for a team of smart phone appearance design project in X Technology Co., Ltd is taken as the case. X is one of the most creative companies in China, focusing on the development of intelligent electronic products. It has made great success in designing, manufacturing, and developing smartphones. X adopts the CPIN as important strategy to hold on to its core competence in NPD. Through CPIN, X aims at: (i) decreasing the NPD cost, (ii) reducing the NPD risk, and (iii) integrating partners' complementary competence to fill the knowledge gap.

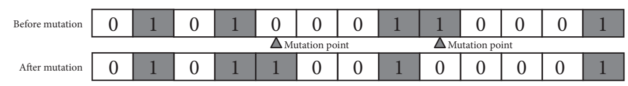

Figure 2: Two-point mutation operation.

To form a CNPI team for smart phone appearance design project, 18 members are to be selected from 42 candidates. Knowledge points of the smart phone appearance design project are mainly body style design (k_1), size design (k_2), color design (k_3), material design (k_4), and artistic design (k_5). Evaluation attributions shown in Table 2 are to be used for the measurement of individual knowledge competence of candidates. Three experts in the product innovation field are organized by X for the evaluation of individual knowledge competence of candidates, represented as $\{e_1, e_2, e_3\}$. The original data and fuzzy evaluation information of individual knowledge competence attribution of candidates are obtained as shown in Tables 3–8:

With regard to individual knowledge competence, decision-makers set the weights of self-evaluation and expert evaluation as (0.5, 0.5), respectively, and the weights of indicator s_1, s_2, and s_3 as (0.3, 0.4, 0.3), respectively. With formulas (1)–(4), the individual knowledge competence of members is obtained. On this basis, the knowledge complementarity coefficient is further obtained by formulas (5)–(7) (see Table 9). Comprehensively considering the requirements of knowledge complementarity among members and enough qualified candidates, decision-makers determine the appropriate interval of knowledge complementarity as $(\underline{\theta}, \overline{\theta}) = (1.00, 2.50)$. Accordingly, based on data in Table 9, it is derived that a set of 37 pairs of candidates incompliant with knowledge complementarity requirements are represented as $\text{INF} = \{(p_1, p_3), (p_1, p\ 13), (p_1, p_{33}), \ldots, (p_{37}, p_{42}), (p_{41}, p_{42})\}$.

Based on the task cooperation information of candidates, the formal knowledge collaboration competence among candidates can be obtained by formulas (9) and (10). With formulas (11)–(15), the informal knowledge collaboration performance among candidates is acquired. Furthermore, decision-makers confirm the relative importance weights of formal and informal collaboration performances as $\mu = 0.65$, $\nu = 0.35$. Thus, the knowledge collaboration performance among candidates is further obtained, as shown in Table 10.

Table 2: Indicators for member selection of CPIN team.

	Attribution	Description
Individual knowledge competence	Working experience (s_1)	Working experience in specific knowledge field
	Ability to solve problem (s_2)	Ability to solve practical problems with specific knowledge
	Ability to acquire help (s_3)	Ability to get help from others in specific knowledge field

Table 3: Fuzzy information of self-evaluation under attribution S_1.

	k_1	k_2	k_3	k_4	k_5		k_1	k_2	k_3	k_4	k_5
p_1	G	G	P	P	G	...	...	...	...	...	...
p_2	G	G	P	M	VP	p_{39}	P	P	VG	M	G
p_3	P	P	M	M	G	p_{40}	P	P	VP	G	G
p_4	M	G	G	P	M	p_{41}	P	VP	VG	VP	M
...	...	...	...	...	...	p_{42}	G	M	P	VG	G

Table 4: Fuzzy information of expert evaluation under attribution S_1.

	k_1	k_2	k_3	k_4	k_5		k_1	k_2	k_3	k_4	k_5
p_1	G/M/G	M/G/M	VP/P/M	P/P/M	M/G/G	...	...	...	...	...	...
p_2	M/P/M	G/M/G	VP/P/P	M/M/M	P/P/M	p_{39}	P/P/P	VP/P/P	G/M/G	M/G/G	G/G/M
p_3	P/M/P	VP/P/P	M/G/G	M/M/G	M/P/M	p_{40}	P/M/P	P/P/M	VP/P/P	G/M/G	G/G/M
p_4	M/M/P	M/M/M	G/M/G	VP/P/P	G/M/G	p_{41}	P/P/M	P/P/VP	G/M/M	VP/P/P	M/M/P
...	...	...	...	...	...	p_{42}	G/G/G	G/M/M	P/P/M	G/M/G	G/M/G

Table 5: Fuzzy information of self-evaluation under attribution S_2.

	k_1	k_2	k_3	k_4	k_5		k_1	k_2	k_3	k_4	k_5
p_1	VG	G	M	G	M	...	...	...	...	...	...
p_2	G	G	M	G	VG	p_{39}	G	VP	M	G	VG
p_3	G	P	VG	M	G	p_{40}	M	VP	P	G	M
p_4	G	G	M	P	VG	p_{41}	M	M	G	P	VP
...	...	...	...	...	...	p_{42}	VG	G	M	G	G

Table 6: Fuzzy information of expert evaluation under attribution S_2.

	k_1	k_2	k_3	k_4	k_5		k_1	k_2	k_3	k_4	k_5
p_1	P/P/M	M/G/G	P/P/VP	P/M/M	M/M/G	...	...	...	...	...	...
p_2	P/P/VP	M/M/M	M/M/P	M/P/P	G/M/M	p_{39}	VP/P/P	M/P/M	G/G/G	G/M/G	G/G/M
p_3	G/M/G	VG/G/G	M/M/G	P/M/P	G/M/M	p_{40}	P/M/P	P/M/M	P/P/M	G/G/G	P/P/M
p_4	P/P/VP	G/M/M	G/G/G	M/G/G	M/M/P	p_{41}	P/M/M	P/P/VP	G/G/M	P/P/P	M/P/P
...	...	...	...	...	...	p_{42}	M/P/M	G/G/G	P/M/M	P/M/P	P/M/M

Table 7: Fuzzy information of self-evaluation under attribution S_3.

	k_1	k_2	k_3	k_4	k_5		k_1	k_2	k_3	k_4	k_5
p_1	G	G	P	VG	G	...	...	...	...	...	...
p_2	G	VG	M	G	G	p_{39}	G	P	G	G	VG
p_3	G	P	VG	M	VG	p_{40}	M	VP	M	VG	M
p_4	G	G	VG	VP	G	p_{41}	G	G	VG	P	G
...	...	...	...	...	...	p_{42}	VG	G	M	M	G

Table 8: Fuzzy information of expert evaluation under attribution S_3.

	k_1	k_2	k_3	k_4	k_5		k_1	k_2	k_3	k_4	k_5
p_1	M/M/M	P/P/P	G/M/M	P/M/P	M/M/P	…	…	…	…	…	…
p_2	M/P/M	G/G/VG	VP/P/P	M/M/M	P/P/M	p_{39}	P/P/P	VP/P/P	G/M/G	M/G/G	G/G/M
p_3	P/M/P	VP/P/VP	M/G/G	M/M/G	M/P/M	p_{40}	P/M/P	P/M/M	VP/P/P	G/M/G	G/G/M
p_4	M/P/P	M/M/M	G/M/G	P/P/P	G/M/G	p_{41}	P/M/P	P/M/M	P/M/M	G/M/G	P/M/M
…	…	…	…	…	…	p_{42}	G/M/G	G/G/G	M/M/G	P/M/P	G/M/G

Table 9: Individual knowledge competence and knowledge complementarity.

	p_1	p_2	p_3	p_4	…	…	…	p_{39}	p_{40}	p_{41}	p_{42}
p_1	**0.79**	0.84	3.07	1.87	…	…	…	1.67	0.77	0.68	3.01
p_2	0.84	**0.91**	2.01	1.98	…	…	…	1.44	1.31	0.62	2.27
p_3	3.07	2.01	**0.75**	1.23	…	…	…	0.69	2.00	1.87	0.58
p_4	1.87	1.98	1.23	**0.88**	…	…	…	0.89	1.86	1.65	1.52
…	…	…	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…	…	…
p_{39}	1.67	1.44	0.69	0.89	…	…	…	**0.59**	1.35	1.60	1.21
p_{40}	0.77	1.31	2.00	1.86	…	…	…	1.35	**0.86**	1.24	1.80
p_{41}	0.68	0.62	1.87	1.65	…	…	…	1.60	1.24	**0.94**	3.21
p_{42}	3.01	2.27	0.58	1.52	…	…	…	1.21	1.80	3.21	**0.63**

Note: Data on the diagonals represent individual knowledge competence values of candidates.

Based on models (16)–(20), the member selection model in the case is obtained as:

$$\begin{aligned} \text{Max } Z_1 &= 0.79x_1 + 0.91x_2 + 0.75x_3 \\ &\quad + 0.88x_4 + \cdots + 0.59x_{39} \\ &\quad + 0.86x_{40} + 0.94x_{41} + 0.63x_{42}, \\ \text{Max } Z_2 &= 0.67x_1x_2 + 0.32x_1x_3 \\ &\quad + 0.66x_1x_4 + \cdots + 0.51x_{42}x_{39} \\ &\quad + 0.79x_{42}x_{40} + 0.54x_{42}x_{41}, \\ \text{s.t. } & 0.40 \le C_{ij} \le 1.00, \\ & \sum_{i=1}^{42} x_i = 18, \\ & x_i = 1 \text{ or } 0, \\ & i, j = 1, 2, \ldots, 42. \end{aligned} \tag{25}$$

Subsequently, the DPAGA is applied to solve the above member selection model. In DPAGA, the initial population size is generally made as 10~200, and 0.4~0.99 and 0.0001~0.1 as crossover and mutation probabilities, respectively. Moreover, population 1 differed from population 2 in terms of crossover and mutation probabilities, with larger crossover and mutation probabilities for the former while less for the latter. By considering the fact that population size is of direct influence in the calculation efficiency and rate of convergence of an algorithm (too large a size will lead to excessively long calculation time, while too small a size will cause more of a chance to fall into the local optimum), the initial population size of the two populations is made as 100 in this chapter with the maximum number of iterations as 300 and $H = 100$. The maximum and minimum crossover and mutation probabilities of population 1 are made as $p_{c_{1\max}} = 0.9$, $p_{c_{1\min}} = 0.7$, $p_{m_{1\max}} = 0.08$, $p_{m_{1\min}} = 0.06$, respectively. The maximum and minimum crossover and mutation probabilities of population 2 are made as $p_{c_{2\max}} = 0.6$, $p_{c_{2\min}} = 0.4$, $p_{m_{2\max}} = 0.05$, $p_{m_{2\min}} = 0.03$, respectively. Decision-makers attach the same importance to the two objective functions, namely, setting $\omega_1 = \omega_2 = 0.5$. The optimal values of the two single objective functions are calculated, respectively, and regarded as the ideal point of the final objective function (13.89, 21.77). Matlab R2010a is used to program and run the abovementioned algorithm, and the optimal scheme of team member selection is as follows upon the 103th iteration:

$$[0, 1, 0, 1, 1, 0, 1, 0, 1, 0, 0, 1, 1, 0, 1, 0, 1, 1, 0, 1, 0, 1, 0, 0, 1, 0, 1, 0, 0, 1, 0, 0, 1, 0, 0, 0, 0, 0, 1, 1, 0, 0,]. \tag{26}$$

Table 10: Overall values of knowledge collaboration performance among candidates.

	p_1	p_2	p_3	p_4	...	...	...	p_{39}	p_{40}	p_{41}	p_{42}
p_1	–	0.67	0.32	0.66	...	...	...	0.53	0.91	0.43	0
p_2	0.67	–	0.93	0.72	...	...	...	0.67	0.42	0.53	0
p_3	0.32	0.93	–	0	...	...	...	0	0.71	0.66	0.55
p_4	0.66	0.72	0	–	...	...	...	0.41	0.60	0.40	0.75
...	...	...	...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...	...	...	...
p_{39}	0.53	0.67	0	0.41	...	...	...	–	0.74	0.70	0.51
p_{40}	0.91	0.42	0.71	0.60	...	...	...	0.74	–	0	0.79
p_{41}	0.43	0.53	0.66	0.40	...	...	...	0.70	0	–	0.54
p_{42}	0	0	0.55	0.75	...	...	...	0.51	0.79	0.54	–

Note: The mark "–" on the diagonals represents that no knowledge collaboration exists between candidates and themselves.

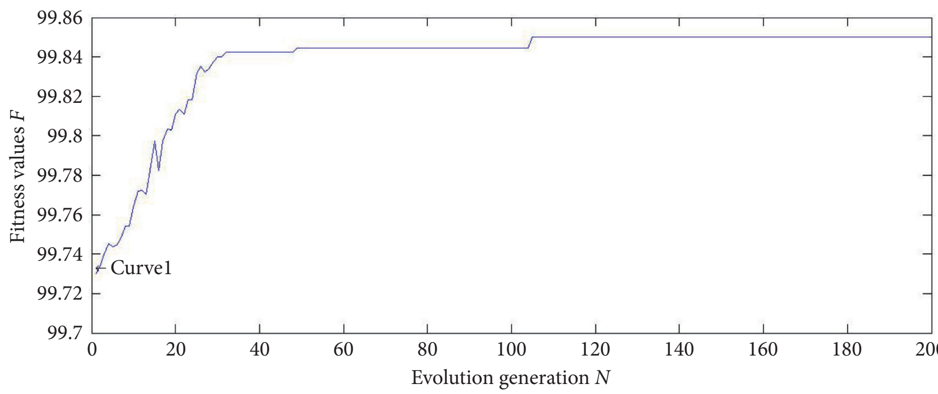

Figure 3: Optimal fitness value of each iteration of DPAGA

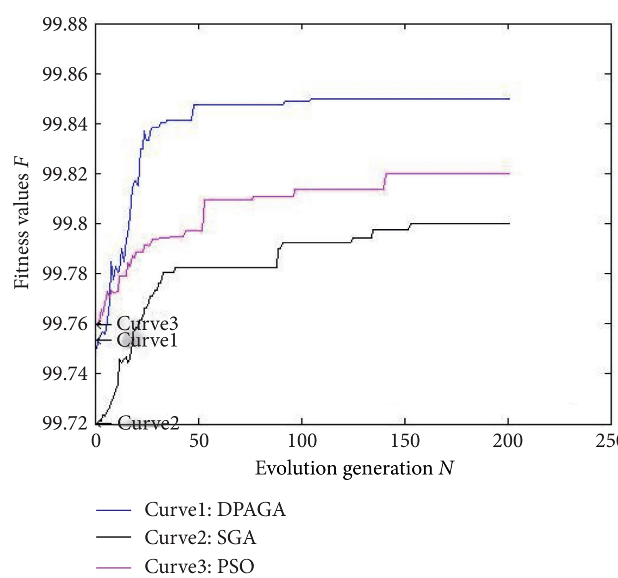

Figure 4: Comparison of DPAGA, SGA, and PSO.

Table 11: Comparison of DPAGA, SGA, and PSO.

Algorithm	Optimal result	Computing frequency	Computing time
DPAGA	99.8529	105	1.13
SGA	99.8177	156	2.24
PSO	99.7914	145	2.07

Namely, candidates $\{p_2, p_4, p_5, p_7, p_9, p_{12}, p_{13}, p_{15}, p_{17}, p_{18}, p_{20}, p_{22}, p_{25}, p_{27}, p_{30}, p_{39}, p_{40}\}$ are selected to form the smart phone appearance design team, wherein the overall knowledge competence of members selected by the scheme is 12.35, and the total knowledge collaboration performance among members is 19.18, with running results shown as Figure 3.

Moreover, for the purpose of verifying the effectiveness and advantage of DPAGA as proposed in solving the team member selection problem, DPAGA is compared with Standard Genetic Algorithm (SGA) and Particle Swarm Optimization (PSO) for analysis. The same population number and parameter of maximum iteration number are applied for all of the three algorithms which run for 30 times each, with the running results shown in Figure 4 and Table 11. It can be seen from Figure 4 and Table 11 that compared with SGA and PSO, DPAGA is capable of generating a better result with a faster solution speed. Its average iteration number is 105, less than SGA of 156 and PSO of 145; DPAGA also takes less time to get the optimal solution than SGA and PSO. In summary, the proposed DPAGA performs better than SGA and PSO in solving the member selection problem for the collaboration of new product innovation teams.

7. Conclusions

For the purpose of forming an efficient CNPI team, this paper suggests a member selection decision model and method for CNPI teams by integrating individual and collaborative attributions. The indicators for team member selection used in the method, including individual knowledge competence of candidates, knowledge complementarity, and knowledge collaboration performance among candidates, are quantified by the fuzzy theory and social network method. Then, a multi-objective optimization model is established by integrating those indicators for member selection of the CNPI teams and a double-population adaptive genetic algorithm (DPAGA) is proposed to solve the model. Meanwhile, real cases and comparative studies have confirmed the feasibility and effectiveness of the proposed member selection model and method in this paper.

It requires to be noted in particular that circumstances where might be short of individual and collaborative information of members should be taken into consideration in future researches. In addition, how to extend the research method proposed in the paper to other types of teams such as concurrent engineering teams, cross-functional teams, etc., should also be emphasized in future studies.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Fractal Characteristics of Discontinuous Growth of Digital Company: An Entrepreneurial Bricolage Perspective

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Digital companies exhibit discontinuous growth in the process of shifting from their existing core business to a newer and less familiar business. This pattern of growth often ends in failure mainly because companies invest most of their resources in maintaining the value network of their existing core business, which ultimately results in a “lock-in” effect. The fractal theory assumes that there are similarities among fractals within companies. These similarities may reduce the threats posed by the value network lock-in effect and increase the chances of successful discontinuous growth. In this study, we applied fractal theory to consider the following questions: (1) in what aspects does the successful discontinuous growth of digital companies exhibit fractal characteristics? (2) What strategy does digital companies use to ensure these fractal characteristics? We adopted an exploratory single-case study method and chose ByteDance as the case company to analyze its successful shift from Toutiao (a media platform) to Douyin (a short-video sharing platform). Our results show that (1) a necessary condition for the successful discontinuous growth of digital companies is that similarities exist (e.g., in technology or customer base) between the existing core business and the new business and (2) entrepreneurial bricolage is a strategy used by digital companies to ensure the existence of fractal characteristics of similarities. We discuss the theoretical contributions and practical implications of this finding.

1. Introduction

Disruptive innovation theory states that, to adapt to a dynamic environment, companies should pay attention to growth opportunities in emerging markets and create opportunities to grow new types of business [1]. Although these findings are very important, they do not explain how companies can successfully shift from the existing core business to the new business.

Fractal theory [2] can explain the successful shift from the existing core business to the new business. Fractal theory emphasizes similarity between the part and the whole: any relatively independent part of a fractal system can be considered a reduced-scale image of the whole [2], which can ensure overall stability. Scholars have put forward the concept of a “fractal company” based on fractal theory [3] and proposed that a fractal company develops fractals in response to its changing environment. The key to the successful development of such fractals lies in the similarities between the fractals and the whole company, including the structural characteristics of organizational design, how services are performed, and the formulation and pursuance of goals [4]. Discontinuous growth can be regarded as the successful development of fractals. The new business shares some fractal characteristics with the existing core business, which may reduce the threat posed by the value network lock-in effect in discontinuous growth [5].

We used an exploratory single-case study method to analyze the discontinuous growth of a digital company (ByteDance) to consider two related research questions: (1) in what aspects does the successful discontinuous growth of digital companies exhibit fractal characteristics? (2) What strategy do digital companies use to ensure these fractal characteristics? A “digital company” is a company that uses information technology as a competitive advantage in its business [6]. The growth of digital companies is characterized by discontinuity [7], which provides an ideal research object for exploring discontinuous growth in a dynamic environment. Based on fractal theory, this study provides a new theoretical perspective to explain the discontinuous growth of digital companies, which has important theoretical value for understanding the shift from the existing core business to the new business and has important practical implications for digital companies aiming to realize discontinuous growth in a dynamic environment.

2. Literature Review

Theories about the growth of firms are divided into endogenous and exogenous growth theories, according to the different forces driving firm growth. Endogenous firm growth theories emphasize the logic that firms realize growth through the effective use of existing resources [8, 9]. Exogenous firm growth theories emphasize the integration of new resources for market expansion as a motivation for firm growth [10–12]. Although classical theories of firm growth are very important, they cannot explain the discontinuous growth of digital companies. Endogenous growth theories focus on explaining how companies use existing resources to achieve continuous growth [8]. Few studies have considered discontinuous growth. Theories of exogenous growth also cannot provide a complete explanation for discontinuous growth. Although these theories emphasize that the key to company growth relies on identifying potential growth opportunities [10], there is still an unresolved resource allocation conflict between the existing core business and the new business [13]. Organizational ambidexterity theory assumes that the integration of exploration and exploitation activities can achieve a smooth shift from the old business to the new business, aiming to provide an explanation for discontinuous growth [14, 15]. However, in a dynamic environment, companies experience rapid and unpredictable environmental changes [16, 17] and it is difficult for them to predict the future based on the past. In this context, an ambidextrous decision-making strategy based on prediction will fail [18].

Disruptive innovation theory suggests that it is difficult for companies to achieve discontinuous growth because the value network of the existing core business locks in resources [19]. First, the powerful customers of the existing core business require companies to invest more resources to meet their needs [20]. Second, to obtain a lasting competitive advantage, companies will continue to optimize the technological paradigms of their existing core business [21]. The more successful a company's existing core business is, the more likely it is that the company will encounter value network lock-in problems when it shifts to the new business [22]. The successful realization of discontinuous growth not only requires finding new businesses in emerging and fringe markets [23], but also realizing the shift from its core business to a new business. In a highly dynamic environment, how can a company shift from its existing core business to the new business and realize discontinuous growth? This question is a widespread concern.

In this study, we apply fractal theory [2] to explain the discontinuous growth. Mandelbrot proposed the novel mathematical concept of fractals to describe how parts are obtained from the whole by similarity. Fractals are widely used to explain the self-similarity of evolving objects in nature [24]. Scholars have also put forward the concept of "fractal company" based on fractal theory [3] and proposed that the main characteristic of a fractal company is the structural similarity between fractals and the whole company in terms of organizational design, how services are performed, and the formulation and pursuance of goals [4]. A fractal structure has many advantages for companies. First, self-similarity ensures that all support mechanisms are available to all fractals through the sharing of company resources. Second, although company fractals may enjoy a large degree of autonomy, self-similarity ensures that the goals of all fractals are similar; it is in fact guaranteed that all fractals can blend together to support the goals of the whole company, maintaining overall stability [3]. The problem of discontinuous growth is that the value network lock-in effect in existing core business limits the resources available to develop new businesses. The self-similarity characteristic emphasized by fractal theory can provide a useful perspective for addressing this problem. The new business retain some aspects of the value network that are similar to those of the existing core business, which means that to some extent the new business can leverage the resources of the existing core business. This can reduce the value network lock-in effect in the existing core business.

The second research question of this study asks, if discontinuous growth exhibits fractal characteristics, what kind of strategy do companies adopt to realize these characteristics? We introduce entrepreneurial bricolage theory [25] to answer this question. Although entrepreneurial bricolage emphasizes breaking through resource constraints to achieve innovation outcomes [26], bricolage solutions exhibit some underlying similarities [25]. First, entrepreneurial bricolage relies on the resources at hand rather than searching for new resources, meaning that although the output of bricolage is new [27], the input is similar [28]; as the company finds a new way to use existing resources, the solutions arising from entrepreneurial bricolage display similarities. Second, entrepreneurial bricolage is greatly influenced by the cognition of entrepreneurs [29]. An entrepreneur's use of the resources at hand to cope with environmental upheaval is not always improvisational behavior; there is also the possibility of planned action [25]. Although bricolage emphasizes make-do, the cognition of the entrepreneur plays a leading role in the content and direction of bricolage. Therefore, bricolage solutions are manifestations of the will of individual entrepreneurs, which may lead to similarities among solutions designed by the same entrepreneur.

Digital companies are suitable research objects to investigate the characteristics of discontinuous growth. First, the discontinuous growth of digital companies is prominent [7], and they are undergoing rapid and unpredictable environmental changes in terms of technology and market competition [30]. Relying on the development of digital technologies and platforms, digital companies constantly find new opportunities to meet changing market demand [7]. Second, digital companies are good at resource integration [31]. They use low-cost and reusable information resources as factors for identifying and developing new entrepreneurial opportunities and the affordance characteristic of digital technology helps such companies to realize "technology + domain" resource reorganization [32].

3. Methods

3.1. Research Setting. This study explores the questions of why and how discontinuous growth occurs. We adopted a case study methodology because it is appropriate for this type of exploratory research [33]. Furthermore, research on how companies achieve discontinuous growth is still in the early descriptive and unstandardized stage [1, 34] and is not yet sufficiently developed to explain the complex phenomenon of discontinuous growth. In this context, a case study can provide new and key insights and suggest directions for more in-depth research [35].

We followed the principle of theoretical sampling to select our case company [35]. The selected case was required to meet the following three criteria. First, as our research questions concern the discontinuous growth of digital companies, the case company had to be a digital company. We chose Beijing ByteDance Technology Co., Ltd. (hereinafter referred to as "ByteDance"). Founded by Zhang Yiming in March 2012, ByteDance is now regarded as one of the most outstanding digital firms worldwide. ByteDance has set up its own artificial intelligence (AI) lab that focuses on machine learning and embedding technology learning into its products and services. ByteDance products are all based on AI technology. Second, the selected case company should have achieved discontinuous growth. The discontinuous growth of ByteDance is striking (see Figure 1). It created two successful digital products, Toutiao and Douyin, in 2012 to 2016 and successfully realized the shift from Toutiao (the existing core business) to Douyin (the new business). Founded in 2012, Toutiao, meaning "headline" in Chinese, was the first product of ByteDance. It is an online platform that aggregates, recommends, and delivers news and content based on users' interests. Douyin, released by ByteDance in September 2016, is an online short-video mobile application that allows users to create, post, and share self-created videos. It has become one of the leading social network applications in terms of downloads and active users. Third, the selected case company should be able to provide detailed evidence of discontinuous growth. ByteDance has attracted a lot of attention and relevant data are conveniently available from multiple channels for verification by data triangulation. Table 1 displays the basic information of Toutiao and Douyin.

3.2. Data Collection and Analysis. We opted for a case in which the phenomenon of discontinuous growth was present to a high degree and was easily observable. We had been tracking the case company since 2018. Based on the multisource data collection method [36], we collected extensive primary and secondary data related to the case company to form an evidence triangle [33]. The data came from a compilation of company information, semistructured interview, and field observations (see Table 2). First, we collected information from newspapers, periodicals, publicly released executive statements, websites, forums, social media, and some internal materials related to the research issue and transcribed them for coding and archiving. As the development of the case company had received extensive public attention, second-hand data from various sources were abundant, which made up for the shortage of in-depth interviews with the founder, Zhang Yiming. The main sources of primary data were field observations and semistructured interviews with main managers, employees in various departments, and key stakeholders. Semistructured interviews were divided into in-depth interviews and information interviews. Before conducting an in-depth interview, we sent an interview outline to the interviewees. We also conducted an online preparatory interview of no more than 10 minutes with each interviewee in advance to enhance familiarity and confirm the formal interview time. Each interview lasted for 1 to 2 hours. During the interview, we asked the interviewee to provide detailed information. If the interviewee did not consent to recording, we wrote up our notes soon after the interview and combined them with our on-site records. The interview records were compiled and completed within 48 hours of the interview and were mutually confirmed by multiple researchers. Informal interviews were also conducted with experts in this field of research (such as at academic conferences) and other relevant personnel of the case company. The core points made in the informal interviews were coded and archived.

We applied the inductive analysis method of Miles and Huberman [37]. The primary coding came from repeated combining of the original material and the secondary coding involved combining the primary codes; then, through cross-analysis of the original data, secondary coding, and existing literature, the aggregate dimensions were summarized. We established a four-person case study term, including two professors and two doctoral candidates. First, the two students sorted the original material and obtained multiple key sentences by clustering similar content. Then, the two professors each formed an independent analysis team with a student to analyze the key sentences, repeatedly comparing the key sentences against the reference theory. Each coding step was repeated and refined until a consensus was formed.

4. Results and Discussion

4.1. Fractal Characteristics in Discontinuous Growth. By coding the data related to ByteDance's shift from Toutiao (the existing core business) to Douyin (the new business), we revealed that the company's discontinuous growth exhibited fractal characteristics. Specifically, Toutiao and Douyin showed self-similarity characteristics in four aspects: organizational structure, technology, goal, and market.

As shown in Table 3, in technology, Douyin still uses Toutiao's recommendation engine algorithm (A1) and

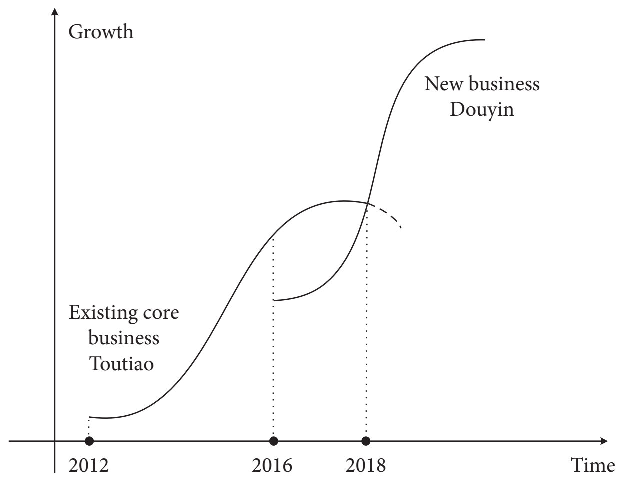

Figure 1: Discontinuous growth of ByteDance.

Table 1: Basic information about Douyin and Toutiao.

Category	Toutiao	Douyin
Domains	Media information	Short social video
Release year	2012	2016
Business scale	700 million registered users by 2016 By 2018, with fewer than 800 million users, the scale of growth was no longer significant	250 million daily active users by 2018 Over 400 million daily active users as of early 2020

Table 2: Summary of the process used to obtain information about the case company.

Data source	Data type	Interviewee/main content	Number of items
Company information compilation	Public interviews and external speeches by executives	Videos and textual material of ByteDance executives	35,000 words
	Direct materials	Douyin and Toutiao's product development information, ByteDance official websites, forums, media reports, etc.	10.1 million words
	Newspapers and periodicals	Search results from China Academic Journal's Network and China's Core Newspaper Full-Text Database (online version)	More than 600 studies
Semistructured interview	In-depth interview	Company executives, employees in various departments, and key stakeholders	9 participants
	Informal interview	Experts in this field and other relevant people in the case company	Several participants
On-the-spot investigation	—	Observations of ByteDance's workplaces and project meetings	2 times

personalized recommendation algorithm to conduct the information distribution (A2). The user tags in Douyin and Toutiao are also shared (A3). In terms of organizational structure, Douyin and Toutiao both have a middle platform, which includes three key departments: technology, user growth, and commercialization (A4). A microteam is adopted when developing new products (A5). Douyin and Toutiao both take pursuing user growth as the primary goal (A6) and attach great importance to user experience (A7). The original intentions of Douyin and Toutiao were to develop functions that distinguished them from similar products (A8). In the market, Douyin and Toutiao both focus on the high-quality needs of customers (A9) and use immature technology to expand emerging markets (A10). Self-similarity characteristics emphasize the similarity between the parts and the whole [3], which can explain the value network lock-in of a digital company when it shifts from the existing core business to the new business. Therefore, we propose the following.

Proposition 1. *A necessary condition for the discontinuous growth of digital companies is that similarities exist between the existing core business and the new business in terms of organizational structure, technology, goal, and market.*

4.2. The Effect of Entrepreneurial Bricolage on Fractal Characteristics. By coding the data of ByteDance's shift from Toutiao (the existing core business) to Douyin (the new business), we found evidence of entrepreneurial bricolage in

Table 3: Fractal characteristics of discontinuous growth.

Evidence	Primary coding	Secondary coding	Aggregate dimensions
A1 Douyin benefits from Toutiao's recommendation algorithm, which is a notable known ability of Toutiao. Specifically, Toutiao's mature recommendation engine algorithm is directly used in the development of Douyin. Therefore, it can be said that Toutiao's recommendation engine algorithm supported the development of Douyin. Douyin had a solid technical foundation when it was launched, which quickly made it a hot product in the field of short video.	Douyin adopts Toutiao's recommendation engine algorithm	Similarities in technology	Self-similarity
A2 Toutiao and Douyin both use the mode of "personalized recommendation algorithm + domain." Toutiao's mode is "personalized recommendation algorithm + text," and Douyin's mode is "personalized recommendation algorithm + short video." Both these modes address the issue of content distribution.	Douyin and Toutiao both use personalized recommendation algorithm to distribute information		
A3 User tags are shared in Toutiao and Douyin, supporting Douyin to conduct a cold start smoothly. Each app that splits off from Toutiao retains some similarities with Toutiao. Even so, Douyin, under the unified account system and user data tag mechanism, it continuously forms a huge app matrix with continuous internal segmentation together with other apps.	Douyin adopts Toutiao's accumulated user tags		
A4 Like Toutiao, Douyin's middle platform has three key departments—technology, user growth, and commercialization—which are responsible for retention, acquisition, and monetization, respectively. Although the foreground system operates more than a dozen apps, at the same time, much of the research and development work is supported by the middle platform.	Douyin and Toutiao's middle platform both contain three key departments	Similarities in the organizational structure	
A5 A lean team can quickly trial and error different areas to find opportunities for growth. Douyin's development team is an entrepreneurial team of fewer than 10 people. Zhang Yiming spent more than three months developing the initial version of Toutiao with a team of a dozen engineers.	Douyin and Toutiao both use microdevelopment teams		
A6 Toutiao attaches great importance to user growth at all levels. For example, at the product level, it pays attention to what functions can improve user retention and transformation. Douyin's strategic goal is to improve user retention, which is highly related to user scale. The ultimate goal is to improve daily active user (DAU), duration, and other scale data to achieve user's growth.	Douyin and Toutiao regard user's growth as a top priority	Similarities in the goal	
A7 ByteDance designs Toutiao and Douyin based on the logic of traffic realization, gives users more choice rights, increases their choice area and autonomy, and achieves the purpose of immersing users and occupying more of users' time.	Douyin and Toutiao attach great importance to a high-quality product/service experience		
A8 Douyin and Toutiao's teams both hope to develop something different. Toutiao's team wants to become a search engine and wants to let ordinary people use the internet. Douyin's team wants to develop it as a young, trendy, and fashionable creation and communication platform.	Douyin and Toutiao both want to differentiate themselves from competitors		
A9 Douyin incisively and vividly shows the "essence and beauty" of life. Toutiao pays more attention to removing "low-brow" content from the platform than its peers and never actively pushes "low-brow" content.	Douyin and Toutiao both aim to meet users' high-level, high-style, and high-standard demands	Similarities in the market	
A10 ByteDance used a new logic (namely, a recommendation engine algorithm) to distribute information. The founder of Yi-Dao and founder of Douban both thought they had seen the potential for personalized recommendation technology for a long time, but they thought the recommendation technology was not mature and there was not enough content for distribution.	Douyin and Toutiao both exploited immature technology to develop emerging markets		

the discontinuous growth of ByteDance, including labor bricolage, physical bricolage, skills bricolage, market bricolage, and institutional bricolage (see Table 4). Entrepreneurial bricolage ensured the case company's fractal characteristics during its discontinuous growth. In the development stage of Douyin, ByteDance lacked labor and technical resources. In this situation, ByteDance used labor bricolage and physical bricolage to provide resources for Douyin. For instance, nonprofessional personnel and customers became labor to support Douyin's development (B1–B5). Toutiao used accumulated resources, including user tags, a recommendation engine algorithm, and a middle platform to support its development (B6–B8). In the update stage, the Douyin team used skills bricolage to learn

Table 4: Entrepreneurial bricolage in discontinuous growth.

Evidence	Primary coding	Secondary coding	Aggregate dimensions
B1 Douyin team members were thrown together from the Toutiao team. Zhang Yi had been responsible for the operation for three years; he has no experience of being a product manager. Jia Liang, a new intern, has little knowledge of the content operation work. Li Jian, a junior majoring in broadcasting and hosting, has never worked in the internet industry.	Organize nonprofessionals when developing Douyin	Labor bricolage	Entrepreneurial bricolage
B2 The startup team of Douyin was not strong. After the style of Douyin was determined, nearly 10 engineers were drawn from the Toutiao team in less than a week to develop this new product. Among them, the most senior had three years of work experience; the others were fresh graduates and intern students.			
B3 At that time, similar domestic products generally had a music and image syncing problem. "Xue Laoshi," an early user, had made comments about these products, but they were unable to be changed. Douyin decided to solve this problem and organized a video conference with Xue Laoshi, adjusting the product version by version. They are constantly thinking about how to solve new problems.	Douyin integrates the customers of Toutiao into the labor force		
B4 To improve the rate of demand response of users, the Douyin operation department set up a technical Q&A group to enable employees in the technology department to communicate directly with users. If the problem was unclear online, users were invited to the office to chat face to face.			
B5 "We treat users well and communicate with them every day. We listen to their feedback, and it will eventually be reflected in the products." Early users contributed a lot to the product and grew together with Douyin.			
B6 In May 2016, the user retention rate of the Toutiao short-video column went beyond the graphic content column; then, ByteDance began to develop the short-video product, Douyin. With Toutiao's accumulation of customer data, Douyin adopted the same user tags as Toutiao and improved user traffic through Toutiao's recommendation.	Develop Douyin to use resources previously accumulated by Toutiao	Physical bricolage	
B7 The daily active user (DAU) of Toutiao has just gone beyond 50 million. . .our accumulation in multimedia technology is weak, everything is still in the initial state. When developing Douyin, we used Toutiao's mature recommendation engine algorithm. The algorithm derived from Toutiao directly supported the incubation of Douyin.			
B8 ByteDance adopted Toutiao's middle platform organizational form to operate Douyin, including the departments of user growth, technology, and commercialization. Different members were selected from various departments to form Douyin teams.			
B9 The early team members of Douyin were unfamiliar with video or photography skills. Everyone can quickly learn unfamiliar skills with patience.	Members of the Douyin development team try to learn unfamiliar things	Skills bricolage	
B10 The Douyin team established a creator conference to encourage creation. The short-video format of Douyin has brought innovation to a wide range of industries, including gourmet foods, make-up, beauty, tourism, and others.	Douyin provides customers with products/ markets that were previously unavailable	Markets bricolage	
B11 Douyin's live broadcast platform has helped more and more farmers out of poverty, enabling them to increase their income and get rich.			
B12 The trend of mobile live broadcasting appeared in 2016. Short videos were not yet popular at that time. There were many short-video products in the market. Most of them were in the horizontal format; portrait format was rare. Douyin displays a video in full screen and automatically plays as soon as it is opened.	The positioning of Douyin has broken through the conventional cognition	Institutional bricolage	
B13 A group of young people gathered in the Douyin community, where they can find freedom of self-expression and self-identification. Douyin broke the fixed mindset that the original application was only used to watch videos. It has become a popular cultural social community.			

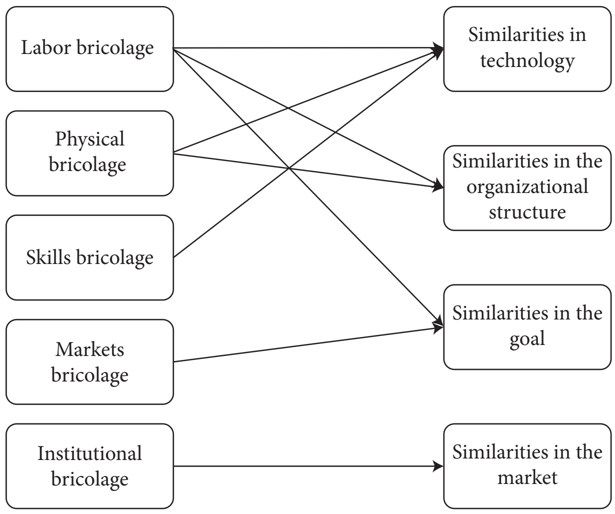

Figure 2: Entrepreneurial bricolage and its effect on fractal characteristics in discontinuous growth.

unfamiliar skills in the short-video field (B9). By using market bricolage, Douyin provided experience that had never been offered by other short-video platforms, attracting more users (B10-B11). By using institutional bricolage, Douyin broke through the existing impression of the short-video field and developed it into a popular cultural community (B12-B13).

Our analysis reveals that through physical bricolage, Douyin used Toutiao's recommendation engine algorithm and user tags to bricolage a personalized recommendation algorithm and short-video content, maintaining technology similarity with Toutiao. Douyin also used Toutiao's middle platform, transferring staff from Toutiao's technology, user growth, and commercialization departments to quickly form a microteam to develop Douyin. Therefore, Douyin and Toutiao have similar organizational structures. In terms of labor bricolage, ByteDance incorporated some of Toutiao's technical staff and old users into Douyin's workforce, ensuring that Douyin and Toutiao are similar in organizational structure, technology, and goal. Through skills bricolage, technicians from Toutiao learned short-video skills. This bricolage ensures the technology similarity between Toutiao and Douyin. Through market bricolage and institutional bricolage, Douyin and Toutiao have realized goal similarity (see Figure 2). Therefore, we propose the following.

Proposition 2. *Digital companies adopt entrepreneurial bricolage to maintain fractal characteristics in discontinuous growth.*

5. Conclusion

This study provides new insights into two important questions that are key to the underresearched issues of discontinuous growth. Research on the discontinuous growth of companies is still at the early descriptive and unstandardized stage [1, 34] and few studies have considered this issue in depth. Addressing the question of what aspects of successful discontinuous growth of digital companies exhibit fractal characteristics, we first identified that a necessary condition for discontinuous growth of digital companies is that fractal characteristics are shared between the existing core business and the new business. Specifically, these fractal characteristics are reflected in similarities between the existing core business and the new business in organizational structure, technology, goal, and market, which can reduce the threat of a value network lock-in effect brought by the existing core business. A technology lock-in effect in the value network will lead a company to continuously strengthen its technological paradigms [38], making it difficult for it to achieve discontinuous growth. The case company, ByteDance, fully developed and optimized the technology of its existing core business to support the development of the new business. The technology of the new business shares some similarities with the technology of the existing core business. Technology similarity gave the case company two advantages during the process of discontinuous growth. First, technology similarity enabled the low-cost development of technology suitable for the new business. Second, technology similarity prevented the new business from being completely separated from the technological paradigm of the existing core business, which reduced the switching cost of technological paradigm transformation. This solves the technology lock-in problem in the value network of the existing core business. Some industry-leading companies aiming at a customer lock-in effect have suffered because their major decisions are influenced by their powerful customers, meaning it is difficult to make changes. The case company integrated customers of its existing core business into the labor force when developing the new business and directed user traffic from the existing core business during the user acquisition stage of the new business. All of these factors make the new business similar to the existing core business in terms of customers. The similarity of customers enables the customers of the existing core business to accept the new business, reducing the resistance to the transformation of old to new business caused by customer demands.

Addressing the question of what kind of strategy companies adopt to realize fractal characteristics in its discontinuous growth, we propose that entrepreneurial bricolage ensures that companies possess such characteristics. Entrepreneurial bricolage is an important pathway by which digital companies can use the resources at hand to achieve novelty while maintaining some underlying similarities in outcomes [26]. From the case company, we find that a digital company can find a new way to use existing resources such that the solutions arising from entrepreneurial bricolage show similarities. We therefore propose that entrepreneurial bricolage is a strategy that a digital firm can use to obtain fractal characteristics in discontinuous growth. Importantly, we identify the necessary condition for the discontinuous growth of digital companies (answering the first question) and reveal the entrepreneurial bricolage process through which digital companies can foster fractal characteristics (answering the second question). Although some classic theories of firm growth and the theory of organizational ambidexterity have paid attention to discontinuous growth, they fail to provide an adequate explanation for the successful discontinuous growth process. We are the first to use fractal characteristic and entrepreneurial bricolage to reveal the process of successful discontinuous growth. We also respond to the "black box" problem of discontinuous growth of companies raised by Christensen [1] and Handy [34].

In addition, our findings expand entrepreneurial bricolage research by providing insights into a new function of entrepreneurial bricolage. The literature on entrepreneurial bricolage describes recombining resources for new or novel purposes for which they were not originally planned [27]. It emphasizes that entrepreneurial bricolage may create some unexpected results [28]. By studying the fractal characteristics in the discontinuous growth of companies, we find that, due to entrepreneurial bricolage, there exist similarities between the existing core business and the new business. This finding provides a new understanding of the entrepreneurial bricolage function. The solutions brought about by entrepreneurial bricolage can not only be unpredictable and novel but also similar.

Finally, this study also provides the following contributions to fractal research in two important ways. First, we apply fractal theory to explain the firm growth problem, addressing the problem of discontinuous growth from the perspective of fractals. Such interdisciplinary approaches are still rare [39, 40]. Second, we explain how to realize fractal characteristics from the perspective of entrepreneurial bricolage. Previous studies have defined the characteristics of fractal companies, including self-similarity, self-organization, dynamics, and goal-orientation [3], but they have not provided in-depth explanations of how companies should form these characteristics in the development process. This study considers the manifestation of fractal characteristics during the discontinuous growth of digital companies. We discovered that, due to entrepreneurial bricolage, companies can successfully shift from the existing core business to the new business, during which fractal characteristics are embodied.

Our study has some limitations, which offer opportunities for future research. The first limitation of this study lies in our research object. The phenomenon of discontinuous growth is relatively common in digital companies [7], so we chose a typical digital company as our research object. However, discontinuous growth does not occur only in digital companies. Future studies could analyze companies in other industries, broadening the applicable conditions for discontinuous growth. The second limitation is the research content: we focused on research questions and conducted process exploration research, but lacked attention to the dynamic environment. Nowadays, companies in all industries are experiencing dynamic environments marked by strong competitive pressure [41]. In the future, the dynamic environment faced by companies, as well as the mechanisms of effects of the dynamic environment on the discontinuous growth of companies, should be further described. Moreover, we conclude that the results of entrepreneurial bricolage exhibit similarity characteristics, but this conclusion is based on a single case. Various data from different companies, industries, or counties can be exploited to replicate our findings in future studies to improve the generalizability of these findings.

Data Availability

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

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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Research Article

Evolutionary Game Analysis of Firms' Technological Strategic Choices: A Perspective of the Behavioral Biases

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To reveal the mechanisms of firms' technological strategic choices between innovation and imitation, an evolutionary game model is proposed from the perspective of the behavioral biases. First, behavioral biases such as reference point dependence, loss aversion, and probability weighting can be defined and modeled based on the prospect theory. Second, according to the firm theory, a Cournot or Stackelberg game modeled with a technology spillover effect and intellectual property protection is applied to portray the interaction between firms. Third, an improved evolutionary game model is provided by incorporating behavioral biases into the framework of the decision-making process. Finally, the simulation analysis of some important factors, such as intellectual property protection, patent fees, innovation risks, decision-making attitudes, and consumers' price preference on firms' technological strategic choices, is presented. The corresponding results show that (1) innovation risk is an important factor affecting the technological strategic choices of firms, (2) increasing the intellectual property protection and the patent fee for technology transfer can effectively control the spillover effect of technology, (3) there is a partial U-shaped relationship between the consumers' price preference and innovation, and (4) the behavioral biases such as reference point dependence, loss aversion, and probability weighting will change the perception of payoff and risk and will eventually induce firms to adopt the innovation strategy.

1. Introduction

Firms' technological strategic choice in the market is complex and dynamic. First, after entering the market, firms will often face the choice of binary strategies, i.e., whether to choose incremental innovation strategy or radical innovation strategy, sustaining innovation strategy or disruptive innovation strategy, imitation innovation strategy or original innovation strategy, close innovation strategy or open innovation strategy, substantive innovation or strategic innovation, etc [1]. Each strategy is closely linked with the competitive environment, market structure, and innovation ability [2–4]. Second, firms will still face the problem of acting first or acting later in terms of investing in R&D (Research and Development). The first mover may become a technology leader and gain a large market share but at the same time also face high R&D costs and higher innovation risks, while the later entrants may avoid the corresponding risks and obtain new business benefits through technological upgrading [5]. Third, the strategic choice is an interactive dynamic process. Firms will continue to adjust their strategic choices based on previous returns and competitors' strategic choices [6].

Firms' strategic choices can be roughly divided into two types: innovation and imitation. (1) Innovation is an influential factor for firm survival and growth [7]. On the one hand, innovation can help a firm to build strong barriers and be the first to bring a brand-new technology to market and gain a large market share. On the other hand, a firm with an innovation strategy can achieve leapfrog development and form core competitiveness through continuous technological development. In particular, innovation can be divided into process innovation and product innovation [8, 9]. Process innovation is defined as a reduction in a firm's marginal costs (i.e., cost-reducing R&D innovation), while product innovation is interpreted as an improvement in the quality of the product (i.e., quality-improving R&D innovation). Zhou et al. established a dynamic two-stage Cournot duopoly game with an R&D spillover effect and noted that R&D is a creative activity of firms that increases their knowledge and further reduces their production costs [10]. Takashima and Ouchida considered a quality-improving R&D and merger policy in a differentiated duopoly and found that a merger can better encourage R&D investment than the R&D competition [11]. In addition, Sun analyzed both the cost-reducing R&D and quality-improving R&D activities in a Hotelling model with an endogenous spillover effect and noted that these two R&D activities will have the same strategic properties and that the equilibrium strategy of the quality-improving R&D model can be derived from the cost-reducing R&D model [12]. It can be seen that process innovation affects marginal production costs, while product innovation affects product prices. (2) Imitation is a strategy that prefers the intentional copying of the innovator's existing technology, design, and business models as well as organizational practices [13]. The concept of imitation is the extent related to the concept of late entrants, and the imitators can seem as the followers with the passive suitability. Under an imitation strategy, imitators can reduce R&D costs through spillover from the innovators, but it is difficult to formulate long-term technology accumulation in the process of technology development. However, according to Golder and Tellis [14], the failure rates of innovators and imitators are 47% and 8%, respectively. Imitators can exploit the innovators' efforts to develop the technology or products and as late entrants can even overtake pioneers in various markets. To date, the role of innovation and imitation strategies is widely recognized, such as they can both improve the firm productivity, but there is still no consensus on which is better.

According to the recent studies, whether firms choose innovation or imitation is related not only to external factors, such as innovation risks, intellectual property protection, and technology spillover, but also to the behavioral biases of decision makers, such as reference point dependence, loss aversion, and probability weighting [15, 16]. For example, the innovative, strategic, and risk-taking traits of CEOs will positively relate to entrepreneurship and can improve firm performance [17]. Some scholars further consider that firms are no longer considered simple actors with a stress-response style but rather as agents with perception, interest trade-offs, and complex decision-making ability [18, 19]. For example, reference point dependence is an important benchmark for the firm to judge whether a strategy will eventually bring gains or losses [20], which indicates that firms may pay more attention to the change in wealth than to the final level of wealth in the process of decision making [21]. In addition, loss aversion describes the situation that firms or investors will tend to continue to hold a loss or assets in anticipation of a rebound phenomenon when suffering a loss or asset depreciation [22, 23]. It can be seen that behavioral biases will greatly affect the process of strategic choices.

Hence, this article continues with this line of thought and mainly investigates the following research questions. (1) What are the behavioral biases of firm decision makers? (2) How can behavioral biases be modeled into the process of decision making? (3) How do behavioral biases influence the firms' technological strategic choices between innovation and imitation?

Analyzing the relationship between behavioral biases and strategic choices at the firm's behavior level presents two challenges. First, it is necessary to properly define and model behavioral biases, such as reference point dependence, loss aversion, and probability weighting. Second, behavioral biases should be incorporated into the interactive process among firms. Therefore, to address the above challenges, this article fuses prospect theory and evolutionary game theory to reveal the influence of behavioral biases on strategic choices.

The main contributions of this paper can be summarized as follows. (1) A new evolutionary game model based on prospect theory is proposed, which comprises behavioral biases such as reference point dependence, loss aversion, and probability weighting. (2) In terms of the sequence of actions for innovation and imitation, a Cournot or Stackelberg game model with technology spillover effects and intellectual property protection is applied to portray the competition between firms. (3) The mechanisms of behavioral biases on the firms' technological strategic choices are revealed based on the prospect theory.

The remainder of this paper is organized as follows. In Section 2, we conduct a literature review on the behavioral biases. Section 3 presents a basic evolutionary game model and an improved evolutionary game model based on prospect theory. In Section 4, the simulation analysis and the results are presented. Finally, the conclusions and discussions are discussed in Section 5.

2. Literature Review

In addition to focusing on the impact of intellectual property protection, patent fees, and other factors on innovation decisions [24], we follow the studies that explain firms' different systematic behavioral biases from the perspective of cognition. Early studies analyzed behavioral biases from the perspectives of bounded rationality, farming, inconsistent risk aversion, certain effects, etc [25]. It is difficult to form a unified analysis framework based on these theories. It is worth mentioning that prospect theory may provide an analytical framework comprising the following elements to capture the behavioral biases [26, 27]:

(1) *Reference Point Dependence*. The reference point plays a critical role in the decision-making process. Decision makers care about the final returns as well as the changes in returns concerning a reference point [28]. That is to say, the reference point determines how firms frame the returns of a strategy. A large number of studies have confirmed this

conclusion. For example, Greve found evidence from shipbuilding that the R&D intensity is related to the distance between the performance and aspiration level and pointed out that the high performance will reduce R&D intensity, while performance below aspiration level will increase R&D intensity [29]. Accordingly, they perceive a given return as a gain (loss) when above (below) the reference point. This shows that the core issue here is the selection of the reference point because the same outcome may be evaluated differently under different reference points. Most researchers measured a common reference point by the industry median or mean of returns. Wiseman and Catanach used average performance as the reference point and found that below-average firm performance will create a loss frame and stimulate risk-seeking behavior [30]. Additionally, Short and Palmer argued that firms use many reference points and that they may change over time [31].

(2) *Loss Aversion*. According to classical economic theory, the basic assumption of risk return is a positive relationship. However, much evidence shows that when returns are below their expectations, decision makers in firms may perceive greater dissatisfaction than satisfaction when returns exceed their expectations [32–34]. A typical example is the endowment effect experiment, in which decision makers are more simulated to changes that are considered as losses than equal-sized changes that are regarded as gains. This phenomenon is called Bowman's paradoxical negative risk return or loss aversion [35]. Some scholars consider it a paradox of human cognition that while people are risk-averse, they also tend to be optimistic [36]. In particular, the strategic choice behavior will be risk-averse when firms perceive gains and risk-seeking when perceiving losses. In the empirical studies, Kliger and Tsur examined the relationship between the returns and risk level by using the COMPUSTAT data and showed that firms with returns above their expectations will assume less risk than those firms with returns below their expectations [37]. Situmeang et al., in a study of 362 game developer firms, further found that a stable market will negatively influence new market entry while a high-degree variable market will positively influence new market entry [38]. This conclusion is also supported by a study that examined the 379 firms in India [35].

(3) *Probability Weighting*. Probability weighting is the decision maker's perception of the probability of an event, which is traditionally considered as a linear function. However, an abundance of evidence shows that the individuals do not use objective probabilities to evaluate the possibility of an event but rather the transformed probabilities obtained from objective probabilities via mental processing [39–41]. A recent empirical study by Stearns shows that innovation will may fail fast as a result of overconfidence by a firm's managers, which indicates that the cognitive biases may affect investment decisions [42]. The most important feature of the probability weighting is that low probabilities are overweighted and high probabilities are underestimated [43]. That is, decision makers more accurately simulate the probability of rare events than typical events. Many mechanisms have been proposed to explain probability weighting, such as anchoring bias [44], probability estimation error [45], and salience-based theory [46]. In the financial markets, probability weighting is applied to explain the underdiversification of household portfolios [47], stock prices, and asset prices [48–50]. For example, probability weighting may matter in merger and acquisition deals. The reason for this is that investors may overestimate the true probability of deal failure, which results in a lower willingness to pay for deals with small failure probabilities.

The above studies suggest that the behavioral biases of the decision maker will affect the decision-making behavior to a certain extent. However, previous studies have paid less attention to the firms' technological strategic choices; most of these studies use only one or two elements of prospect theory, and few studies treat it as a coherent whole. Therefore, to reveal the influence of behavioral biases on strategic choices, behavior with prospect theory is applied. First, behavioral biases such as reference point dependence, loss aversion, and probability weighting can be defined and modeled based on the prospect theory. Second, according to the firm theory, a Cournot or Stackelberg game model with a technology spillover effect and intellectual property protection is applied to portray the interaction between firms. A Cournot game is mainly used to describe the competition situation when two firms adopt the same strategy (imitation or innovation) simultaneously. A Stackelberg game portrays the orderly competition with one firm as the first mover to adopt an innovation strategy and another firm as a later entrant to adopt an imitation strategy. Third, an improved evolutionary game model is provided by incorporating behavioral biases into the framework of the decision-making process. Therein, it mainly uses the perception payoff formed by the value function to replace the final payoff formed by the utility function and replaces the objective probabilities with the transformed probabilities. Finally, the simulation analysis of some important factors, such as intellectual property protection, patent fees, innovation risks, decision-making attitudes, and consumers' price preference for strategic choices, is presented.

3. The Model

3.1. Assumptions

Assumption 1. To simplify the problem, this article assumes that there are two alternative strategic choices, namely, innovation strategy (C) and imitation strategy (M), that can be adopted by each firm to compete in the market, and each firm will make optimal production decisions to maximize profits [51–53]. Firms that adopt innovation strategies are called the *innovation-leading firms*, while those that adopt imitation strategies are called the *imitation-following firms*. In terms of the *innovation-leading firms*, intellectual property protection is a very important way to protect their vested interests by curbing technology spillover. *Imitation-following firms* can achieve innovative technology by paying a certain patent fees to the *innovation-leading firms*.

Assumption 2. In general, when the *innovation-leading firms* increase the intellectual property protection, other *imitation-following firms* have difficulty free riding on innovative technology by technology spillover [6]. The stronger the intensity of property protection, the greater extent to which the technology spillover effect will be contained. Here, we assume that there is a negative correlation between intellectual property protection and technology spillover [54–56]. The specific relationship is set as follows:

$$\theta = 1 - \beta, \tag{1}$$

where θ represents the extent of intellectual property protection, $\theta \in [0, 1]$, and β denotes the technology spillover, $\beta \in [0, 1]$, in which $\beta = 0$ indicates that there are no spillovers and $\beta = 1$ means that the firm can obtain the same technology as a rival.

Assumption 3. A constant marginal cost A can be reduced by investing in R&D. The R&D investment allows a firm to reduce its marginal cost A by the amount s, where $s \in [0, 1]$, and s can also be regarded as the R&D investment level. In addition, due to the technology spillover effect, the marginal cost of a firm is still reduced by the rival's R&D outcomes. However, subject to intellectual property protection, the unit cost reduction for firm i is $(1-\theta)s_j$.The total cost of production generally includes unit marginal cost and fixed R&D cost [57], namely,

$$C_i(q_i, R, \theta) = \left[A - H(w)s_i - (1-\theta)H(w)s_j\right]q_i + H(w)R_i, \tag{2}$$

where $H(w)$ is the indicator function. $H(w) = 1$ stands for the firm's decision to engage in R&D and $H(w) = 0$ means that the firm abstains from innovation. R_i is the fixed R&D cost.

The R&D cost is assumed to be quadratic, which reflects the diminishing returns to levels of R&D efforts [58, 59]. The relationship is shown as follows:

$$R_i = \frac{\gamma s_i^2}{2}, \tag{3}$$

where γ represents the R&D cost coefficient. Therefore, the total marginal cost of the firm can be rewritten as follows:

$$C_i(q_i, R, \theta) = \left[A - H(w)s_i - (1-\theta)H(w)s_j\right]q_i + H(w)\frac{\gamma s_i^2}{2}. \tag{4}$$

Assumption 4. The linear inverse demand function has been widely adopted in the research concerning oligopolistic competition [60], which can be described as follows:

$$p_i = a - q_i - q_j, \tag{5}$$

where p_i is the price, a is the market potential capacity, and q_i and q_j represent the quantity of firm i and quantity of firm j, respectively.

Furthermore, evidence indicates that R&D investment cannot only reduce the cost of production of the product but also improve the quality of the product, thereby affecting the product's price [61, 62]. Holcombe argues that quality is implicit in product differentiation, and the differentiated products may result in different prices [63]. It can be seen that R&D investment achieves product differentiation through improved production technologies, thereby affecting the market equilibrium price. Specifically, firms that choose an innovation strategy will obtain high-quality differentiated products through R&D investment, and the improvement of quality is reflected in consumers' price preferences for products. Therefore, to reflect the consumer's price preference for differentiated products, this article introduces a parameter φ, so the product price of the firms that choose the innovation strategy is

$$p_{i,c} = a - q_i - \varphi q_j. \tag{6}$$

For firms that choose the imitation strategy, because they have not invested in R&D, consumers' price for this product will decrease. At this time, the price is

$$p_{i,M} = \varphi\left(a - q_i - q_j\right), \tag{7}$$

where φ measures the price preference between the differentiated products and $\varphi \in (0, 1]$. When φ is set as 1, there is no difference in consumers' price preference between innovation products and imitation products. While $0 < \varphi < 1$, it shows that consumers have a price preference, and the smaller the value φ, the greater the difference between imitation products and innovative products for consumers' price preference. And $p_{i,C}$, $p_{i,M}$, and $p_{i,M}$ satisfy $p_{i,M} < p_i < p_{i,M}$. That is, consumers pay more for innovation products than for the imitation products.

3.2. The Basic Evolutionary Game Model. The market competition between two firms can seem like a typical game process [64], which could be composed of four stages. (1) The first stage is the selection of the strategy. When they both adopt the innovation strategy or the imitation innovation strategy at the same time, they play a Cournot game. When they adopt different strategies, they play a Stackelberg game with an order of action. (2) The second stage is the R&D investment. A firm that adopts an innovation strategy will determine its optimal R&D investment level, while a firm that adopts an imitation strategy will not carry out this process. (3) The third stage is production decision making. Firms will make optimal production decisions under the optimal R&D investment level and optimal prices. (4) The fourth stage is the strategy adjustment. In the process of continuous market competition, firms adjust the next strategy according to the previous payoff to obtain higher returns in the future.

The payoff matrix owing to different strategies adopted by firm i and firm j is shown in Table 1.

Under the different combinations of two strategies chosen by two firms, three market situations will be constructed as follows: (1) when two firms adopt an innovation strategy simultaneously, they carry out a Cournot game [65]; (2) when one firm adopts the innovation strategy and another adopts the imitation strategy, it means that there is an orderly competition in production and they carry out a Stackelberg game [66]; and (3) when two firms adopt an imitation strategy, they carry out a Cournot game without the R&D investment. The payoffs from the different situations are presented as below.

Table 1: The payoff matrix of the basic evolutionary game model.

		Firm j	
		Innovation strategy (C)	Imitation strategy (M)
Firm i	Innovation strategy (C)	$\pi_{i,C}^{C}$, $\pi_{j,C}^{C}$	$\pi_{i,C}^{S}$, $\pi_{j,M}^{S}$
	Imitation strategy (M)	$\pi_{i,M}^{S}$, $\pi_{j,C}^{S}$	$\pi_{i,M}^{C}$, $\pi_{j,M}^{C}$

Situation 1. Firm i and firm j both adopt an innovation strategy.

In this situation, the Cournot game model between two *innovation-leading firms* is applied to construct the model. During the R&D investment stage, both firms can share the benefits of technology spillovers and then compete with each other in terms of production. Since both firms choose an innovation strategy at the same time, the price of innovation products is $p_{i,C}$. Therefore, the objective of the firm is to choose an innovation strategy that maximizes profits:

$$\begin{cases} \max\limits_{q_i} \pi_{i,C}^{C} = \left[a - q_i - \varphi q_j - \left(A - s_i - (1-\theta)s_j\right)\right]q_i - \dfrac{\gamma s_i^2}{2}, \\ \max\limits_{q_j} \pi_{j,C}^{C} = \left[a - q_i - \varphi q_j - \left(A - s_j - (1-\theta)s_i\right)\right]q_j - \dfrac{\gamma s_j^2}{2}. \end{cases} \quad (8)$$

The solution concept is the subgame perfect Nash equilibrium, and the game is solved by backward induction. First, firms determine their optimal R&D investment level s_k^* according to the best response to production. Second, the optimal equilibrium productions q_k^* are solved based on the given R&D investment level s_k^*. Then, firms' profit maximization is derived:

$$\begin{aligned} \pi_{k,C}^{C^*} &= \left[\frac{(2-\varphi)(a-A) + (4 - 2\varphi - 2\theta + \varphi\theta)s_k^*}{4-\varphi^2}\right] - \frac{\gamma}{2}s_k^{*2}, \quad k = i,\ j, \\ s_k^* &= \frac{2L_1L_2}{\gamma - 2L_2^2 - 2L_3L_2}, \\ L_1 &= \frac{a-A}{2+\varphi}, \\ L_2 &= \frac{2-\varphi+\varphi\theta}{4-\varphi^2}, \\ L_3 &= \frac{2-\varphi-2\theta}{4-\varphi^2}. \end{aligned} \quad (9)$$

Situation 2. Firm i adopts an innovation strategy, and firm j adopts an imitation strategy.

In this situation, the strategy selection is in order. The first mover may become an *innovation-leading firm* while the later entrants may become an *imitation-following firm*. Therefore, the Stackelberg game with an orderly competition is applied. In general, when the *innovation-leading firms* increase the intellectual property protection, other *imitation-following firms* have difficulty free riding on innovative technology by technology spillover, but they can acquire the technology by technology transfer. According to the research of Žigić [67], licensing trade as a simple and easy approach to operate technology transfer is widely used. On the one hand, for the *innovation-leading firms*, the high innovation investment in the early stage can be quickly recovered through licensing trade, and the innovation risk in the future can be reduced. On the other hand, the *imitation-following firms* can acquire new technology as quickly as possible by paying certain patent fees, which reduces the unit cost of production to a certain extent. In addition, since firm i chooses an innovation strategy and enterprise j chooses an imitation strategy, the product price of firm i and firm j is $p_{i,C}$ and $p_{i,M}$, respectively. Therefore, the firms' profit maximization is transformed into

$$\begin{cases} \max_{q_i} \pi_{i,C}^{S} = \left[a - q_i - \varphi q_j - (A - s_i)\right] q_i - \dfrac{\gamma s_i^2}{2} + f, \\ \max_{q_j} \pi_{j,M}^{S} = \left[a - q_j - \varphi q_i - (A - (1-\theta) s_i)\right] q_j - f, \end{cases}$$
$$f = \rho \pi_{j,M}^{S} = \rho\left[\varphi\left(a - q_j - q_i\right) - (A - (1-\theta)s_i)\right] q_j, \tag{10}$$

where f represents the patent fees. The patent fees is the royalty payment based on the total payoff. This article uses ρ as a percentage of the total payoff, which can also be regarded as the bargaining power of the *innovation-leading firm* [68].

The backward induction method is used to solve the problem [69], and the optimal payoff of the *innovation-leading firm* and the *imitation-following firm* is shown below:

$$\begin{aligned}
\pi_{i,C}^{S*} &= \left[a - q_i^* + \frac{\varphi}{2} q_i^* - A + s_i^* - \varphi V\right] q_i^* - \frac{\gamma}{2} s_i^{*2} + \rho\varphi\left[V - \frac{q_i^*}{2}\right]^2, \\
\pi_{j,M}^{S*} &= (1-\rho)\varphi\left[V - \frac{q_i^*}{2}\right]^2, \\
V &= R_1 + R_2 s_i^*, \\
R_1 &= \frac{\varphi a - A}{2\varphi}, \\
R_2 &= \frac{1-\theta}{2\varphi}, \\
q_i^* &= M_1 + M_2 s_i^*, \\
M_1 &= \frac{2a - 2A - (1+\rho)(\varphi a - A)}{4 - 2\varphi - \rho\varphi}, \\
M_2 &= \frac{2 - (1+\rho)(1-\theta)}{4 - 2\varphi - \rho\varphi}, \\
s_i^* &= \frac{M_1\left[1 + ((\varphi/2) - 1)M_2 - \varphi R_2\right] + M_2\left[a - A + ((\varphi/2) - 1)M_1 - \varphi R_1\right] + 2\rho\varphi\left(R_2 - (M_2/2)\right)\left(R_1 - (M_1/2)\right)}{\gamma - 2M_2\left[1 + ((\varphi/2) - 1)M_2 - \varphi R_2\right] + 2\rho\varphi\left(R_2 - (M_2/2)\right)^2}.
\end{aligned} \tag{11}$$

Situation 3. Firm i and firm j both adopt an imitation strategy.

In this situation, the Cournot game between two *imitation-innovation firms* is utilized to construct the model. Without R&D investment, there is no benefit of sharing technology spillover between each other, and it is not possible to reduce their own unit production cost. Since both firms choose an imitation strategy at this time, the price of imitation products is $p_{i,M}$.Therefore, the firms' profit maximization is transformed into

$$\begin{cases} \max_{q_i} \pi_{i,M}^{C} = \left[\varphi\left(a - q_i - q_j\right) - A\right] q_i, \\ \max_{q_j} \pi_{j,M}^{C} = \left[\varphi\left(a - q_i - q_j\right) - A\right] q_j. \end{cases} \tag{12}$$

By the backward induction method, the optimal production q_k^* is solved. The optimal payoff of firm i and firm j can be obtained by substituting the profit function as follows:

$$\pi_{k,M}^{C^*} = \pi_{k,M}^{C^*} = \frac{(\varphi a - A)^2}{9\varphi}, \quad k = i,\ j. \tag{13}$$

In general, a new technology to reduce marginal costs is always subject to risks [14, 60]. This suggests that the *innovation-leading firm* will encounter all sorts of uncertainty risks that may result in a decrease in profit, such as the difficulty of technology research and development, the alternative technology risk, policy risk, and the risk of changes in market demand. Therefore, an innovation risk factor δ is introduced. The greater the innovation risk is, the lower the innovation payoff will be. Innovation payoffs can be expressed as

$$\begin{aligned}
\pi_{i,C}^{C} &= (1-\delta)\pi_{i,C}^{C^*}, \\
\pi_{j,C}^{C} &= (1-\delta)\pi_{j,C}^{C^*}, \\
\pi_{i,C}^{S} &= (1-\delta)\pi_{i,C}^{S^*}, \\
\pi_{j,C}^{S} &= (1-\delta)\pi_{j,C}^{S^*}.
\end{aligned} \tag{14}$$

According to the evolutionary game theory, the replicator dynamic equation can be constructed to analyze the evolutionary stability of the strategies. The evolutionary game framework of a single group is applied for analysis. We assume that there are many firms paired to compete for production in the market, and the actual proportion of firms in the group choosing innovation strategy and imitation strategy is x and $1-x$, respectively. Therefore, the expected payoff of innovation strategy and imitation strategy adopted by any firm k in the group is as follows:

$$\begin{aligned} U_{k,C} &= x\pi_{k,C}^{C} + (1-x)\pi_{k,C}^{S}, \\ U_{k,M} &= x\pi_{k,M}^{S} + (1-x)\pi_{k,M}^{C}, \\ \overline{U}_k &= xU_{k,C} + (1-x)U_{k,M}. \end{aligned} \tag{15}$$

According to the above analysis, the replicator dynamic equation can be obtained:

$$F(x) = \frac{\mathrm{d}x}{\mathrm{d}t} = x\left(U_{k,C} - \overline{U}_i\right) = x(1-x)\left(U_{k,C} - U_{k,M}\right). \tag{16}$$

The evolutionary stability of innovation and imitation strategy can be obtained by solving the replicator dynamic equation.

3.3. The Improved Game Model Based on Prospect Theory. According to prospect theory, the decision-making behavior of the firm highly depends on the perception of returns [69]. That is, the firm often tends to maintain the previous decision when perceiving gain but changes the decision when perceiving loss. This can be represented by the gain-loss utility, and the shape of the function is S-shaped, as suggested by Tversky and Kahneman [43], as shown in Figure 1.

According to Figure 1, the gain-loss utility $f(\Delta\pi)$ has the following characteristics. $\Delta\pi$ can be seen as the difference between the final payoff π and the reference point r. When $\Delta\pi > 0$, which means that the perception of choosing this strategy is gains, the firms will show satisfaction and continue to tend to adopt this strategy. When $\Delta\pi < 0$, which indicates that the perception is losses, the firms will show loss aversion and will not be inclined to adopt this strategy in the future.

$$f(\Delta\pi) = \begin{cases} (\pi - r)^{\alpha}, & \pi > r, \\ -\lambda(r-\pi)^{\beta}, & \pi < r. \end{cases} \tag{17}$$

In addition, $f(\Delta\pi) < 0''(\Delta\pi > 0)$ and $f(\Delta\pi) > 0''(\Delta\pi < 0)$ mean that firms show risk aversion in the face of gains and risk-seeking in the face of losses, respectively. α and β $(0 < \alpha, \beta < 1)$ represent the marginal diminishing degree of gains and losses. $\lambda\,(\lambda \geq 1)$ refers to the coefficient of loss aversion, meaning that the decision-making firm is more sensitive to losses for the same degree of gains.

However, in reality, this type of decision-making behavior that mainly focuses on the gain-loss utility cannot reflect the real decision-making process of the firm [70]. For example, when a firm makes a strategic investment decision, it will affect both the payoff gap with other firms and its

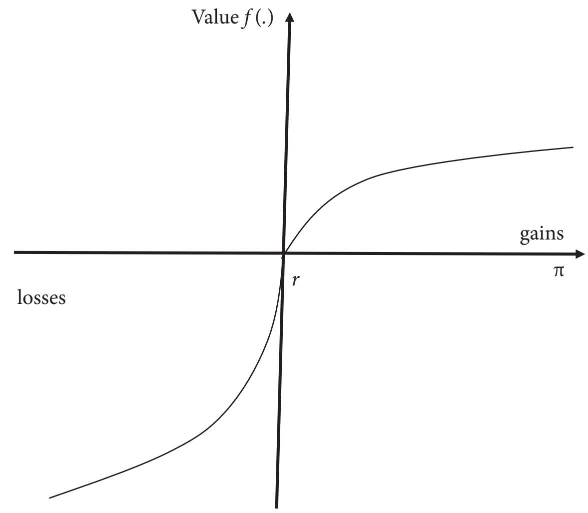

Figure 1: The curve of an S-shaped value function. Note: $f(\Delta\pi)$ is the gain-loss utility, r is the reference point, and π is the final payoff.

aspiration level. It is worth noting that because the strategy selection of the rival firm is based on incomplete information, there will be a variety of different strategy combinations. That is, the aspiration level (i.e., reference point) of the firm is not unique and will be adjusted according to the competition model formed by the combination of strategies of both firms. We assume that there are M different situations in which the reference point in the j-th situation is represented by r_j, and the probability of each situation is represented by p_j. Therefore, to analyze the decision-making behavior of firms more reasonably, this paper introduces an improved utility function, which considers both rational expected and gain-loss utility. The utility function specifically is expressed as

$$V = \sum_{i=1}^{N} \chi_i \pi_i + \sum_{i=1}^{N} \chi_i \left[\sum_{j=1}^{M} p_j f\left(\pi_i - r_j\right)\right]. \tag{18}$$

The first term in the equation is rational expected utility, and the second term is gain-loss utility.

In addition, it is worth noting that the probability weighting function of the utility function proposed by Köszegi and Rabin [21] is still linear, and a large number of studies have confirmed the universality of the nonlinear probability weighting function [71]. One commonly used function form for a probability weighting function $w(\cdot)$ is given by

$$w(\chi) = \frac{\chi^{\phi}}{\left[\chi^{\phi} + (1-\chi)^{\phi}\right]^{(1/\phi)}}. \tag{19}$$

The probability weighting function has the same inverted S shape, as shown in Figure 2, which maps the true probabilities χ on to the unit interval. Generally, $w(\chi)$ satisfies $w(0) = 0$, $w(1) = 1$, with $w(\chi) > \chi$ for all $\chi < \overline{\chi}$ and $w(\chi) < \chi$ for all $\chi > \overline{\chi}$. This indicates that there is a general tendency to overestimate the low probability events and underestimate

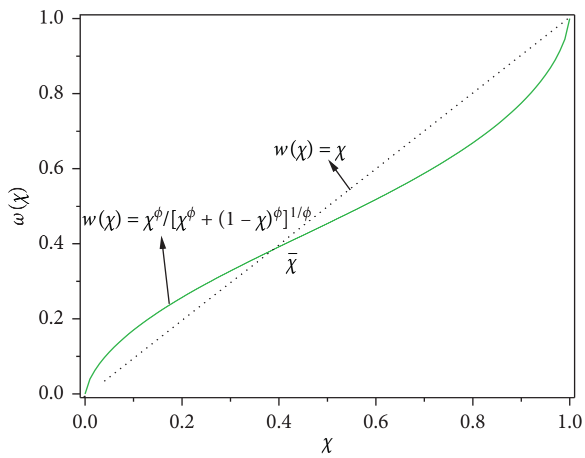

Figure 2: The curve of the probability weighting function.

the high probability events. ϕ is an adjustable parameter that controls the curvature of the probability weighting function.

Therefore, this paper replaces the linear probability weighting function in the gain-loss utility with the nonlinear probability weighting function:

$$V = \sum_{i=1}^{N} \chi_i \pi_i + \sum_{i=1}^{N} w(\chi_i) \left[\sum_{j=1}^{M} p_i f\left(\pi_i - r_j\right) \right]. \tag{20}$$

3.4. The Payoff Matrix Based on Prospect Theory. According to prospect theory, perception payoff is described as the change in relative payoff compared with their current reference point rather than upon final payoff. By comparing the actual payoff with the reference points, the difference reflects the gains or losses. For example, when firm i adopts the innovation strategy since it is unknown which strategy the firm j will adopt, there may be two possible payoff results, as shown in Table 1, $\pi_{i,C}^{C}$ and $\pi_{i,C}^{S}$. If the firm i adopts $\pi_{i,C}^{C}$ as the reference point, the perception payoffs are 0 and $\pi_{i,C}^{S} - \pi_{i,C}^{S}$, while if the firm i adopts $\pi_{i,C}^{S}$ as the reference point, the perception payoffs are $\pi_{i,C}^{C} - \pi_{i,C}^{S}$ and 0, respectively. Similarly, when the firm i adopts the imitation strategy, there may be two possible payoff results, $\pi_{i,M}^{S}$ and $\pi_{i,M}^{C}$, then the perception payoffs are 0 and $\pi_{i,M}^{C} - \pi_{i,M}^{S}$ under the reference point $\pi_{i,M}^{S}$, and the perception payoffs are $\pi_{i,M}^{S} - \pi_{i,M}^{C}$ and 0 under the reference point $\pi_{i,M}^{C}$. Furthermore, we assume that the probabilities of two possible reference points in the case of innovation strategy or imitation strategy are p and $1-p$. The selection of the preference point under uncertain conditions can be regarded as the decision-making attitude [61], that is, p and $1-p$ represent the degree of pessimism and optimism of the decision maker, respectively. When the value of p is large, it means that the firm believes that its rival will adopt the same strategy and pessimistically considers that it will compete fiercely with its rival in the market. In contrast, when p is smaller, it means that the firm believes that its rival will adopt a different strategy and expects optimistically to obtain a greater payoff. Therefore, by comparing the payoffs of firm i and firm j with their corresponding possible reference points, respectively, a new perception payoff matrix can be obtained, as shown in Table 2.

According to the prospect theory that considers rational expectation and gain-loss utility, the prospect value of the innovation strategy or imitation strategy can be obtained. Assume that the actual proportions of firms in the group choosing an innovation strategy and imitation strategy are x and $1-x$, respectively. Owing to the information and subjective judgment bias, the firms in the group will subjectively think that the proportions of choosing an innovation strategy and imitation strategy in the group are $w(x)$ and $w(1-x)$. Therefore, the prospect values of the innovation strategy and the imitation strategy adopted by any firm i in the group are as follows:

$$\begin{aligned}
V_{k,C} &= x\pi_{k,C}^{C} + (1-x)\pi_{k,C}^{S} - w(x)\left[(1-p)\lambda\left(-\left(\pi_{k,C}^{C} - \pi_{k,C}^{S}\right)\right)^{\beta}\right] + w(1-x)\left[p\left(\pi_{k,C}^{S} - \pi_{k,C}^{C}\right)^{\alpha}\right], \\
V_{k,M} &= x\pi_{k,M}^{C} + (1-x)\pi_{k,M}^{C} - w(x)\left[(1-p)\lambda\left(-\left(\pi_{k,M}^{S} - \pi_{k,M}^{C}\right)\right)^{\alpha}\right] + w(1-x)\left[p\lambda\left(-\left(\pi_{k,M}^{S} - \pi_{k,M}^{S}\right)\right)^{\beta}\right], \\
\overline{V}_{k} &= xV_{k,C} + (1-x)V_{k,M}.
\end{aligned} \tag{21}$$

According to the above analysis, the duplicator dynamic equation can be obtained:

$$F(x) = x\left(V_{k,C} - \overline{V}_{k}\right) = x(1-x)\left(V_{k,C} - V_{k,M}\right). \tag{22}$$

The evolutionary stability of firm innovation and imitation strategy can be obtained by solving the replicator dynamic equations.

4. The Simulation Results

Simulation analysis is used to analyze the evolution stability results by setting different parameter scenarios. Based on the research of Tversky and Kahneman [43] and Dhami [70], the loss aversion coefficient λ is set as 2.25, the risk preference coefficients α and β are set to 0.89 and 0.92, the curvature of the probability weighting function ϕ is set to 0.69, the R&D

Table 2: The payoff matrix based on the prospect theory.

		Firm j	
		Innovation strategy (C)	Imitation strategy (M)
Firm i	Innovation strategy (C)	$\prod_{i,C}^{C} = \{0, \pi_{i,C}^{C} - \pi_{i,C}^{S}\}$, $\prod_{j,C}^{C} = \{0, \pi_{j,C}^{C} - \pi_{j,C}^{S}\}$	$\prod_{i,C}^{S} = \{\pi_{i,C}^{S} - \pi_{i,C}^{C}, 0\}$, $\prod_{j,M}^{S} = \{0, \pi_{j,M}^{S} - \pi_{j,M}^{C}\}$
	Imitation strategy (M)	$\prod_{i,M}^{S} = \{0, \pi_{i,M}^{S} - \pi_{i,M}^{C}\}$, $\prod_{j,C}^{S} = \{\pi_{j,C}^{S} - \pi_{j,C}^{C}, 0\}$	$\prod_{i,M}^{C} = \{\pi_{i,M}^{C} - \pi_{i,M}^{S}, 0\}$, $\prod_{j,M}^{C} = \{\pi_{j,M}^{C} - \pi_{j,M}^{S}, 0\}$

cost coefficient γ is set to 2, the market potential capacity a is set to 10, and the marginal cost A of production is set to 8. In addition, the initial actual proportion of firms in the group choosing the innovation strategy is $x = 0.5$. This article further reveals the mechanisms of the behavioral biases on firms' technological strategic choices through simulation analysis of important factors such as intellectual property protection, patent fees, and decision-making attitudes. To compare and analyze the influence of the behavioral biases such as reference point dependence, loss aversion, and probability weighting on firms' technological strategic choices, the corresponding results of the basic game model are also presented.

4.1. The Effect of Intellectual Property Protection Intensity. The mechanism of intellectual property protection on firm decision-making behavior is analyzed first. The intensity of intellectual property protection describes the efforts of firms to implement patent protection and modularization to protect their interests from infringement. The stronger the intensity of intellectual property protection, the less knowledge the other firms will acquire through technology spillover. This paper divides the strength of intellectual property protection into five levels: $\theta = 0$ $\theta = 0.3$, $\theta = 0.5$, $\theta = 0.8$, and $\theta = 1$; the innovation risk is divided into three levels: $\delta = 0.3$, $\delta = 0.5$, and $\delta = 0.8$. The patent fees are fixed as $\rho = 50\%$, the consumers' price preference is set as $\varphi = 1$, and the decision-making attitude of the firm is set as neutral, $p = 0.5$. The simulation results are shown in Figures 3 and 4.

As can be seen from Figure 3, with the increase in intellectual property protection θ, the proportion of firms that choose the innovation strategy will also increase, and the lower the innovation risk ($\delta = 0.3$ and $\delta = 0.5$), the greater the proportion of firms that choose the innovation strategy. This shows that intellectual property protection can effectively improve firms' innovation initiative.

Compared with the results in Figure 3, as can be seen from Figure 4, with the increase in the intellectual property protection, there is a general trend that the strategy selection of firms will change from an imitation strategy to an innovation strategy even with the high innovation risks ($\delta = 0.8$). This phenomenon can be further inferred; in addition to improving intellectual property protection, the new mechanism to promote the innovation lies in the behavioral biases such as reference point dependence and loss aversion. By analyzing the perception payoff caused by different strategy selections, it can be found that firms are more sensitive to the loss caused by imitation strategy, as shown in Figure 5.

As can be seen from Figure 5, taking firm i as an example, there are two possible results $(\pi_{i,C}^{C}, \pi_{i,C}^{S})$ or $(\pi_{i,M}^{C}, \pi_{i,M}^{S})$ under the conditions that firm i adopts the innovation strategy or adopts the imitation strategy, respectively. The differences $(\Delta V^{C} = \pi_{i,C}^{S} - \pi_{i,C}^{C},\ \Delta V^{M} = \pi_{i,M}^{S} - \pi_{i,M}^{C})$ between the two results are the perception payoff. A positive value $(+\Delta V^{C},\ +\Delta V^{M})$ represents the perception of gain, and a negative value $(-\Delta V^{C},\ -\Delta V^{M})$ represents the perception of loss. It can be seen that if the firm adopts the imitation strategy since it does not need to pay the R&D cost, it can gain technology spillover by paying a certain patent fees to reduce its own production cost. Thus, it can be reasonably inferred that $|\pi_{i,M}^{S} - \pi_{i,M}^{C}| > |\pi_{i,C}^{S} - \pi_{i,C}^{C}|$. Furthermore, when both $|\pi_{i,C}^{S} - \pi_{i,C}^{C}|$ and $|\pi_{i,M}^{S} - \pi_{i,M}^{C}|$ are in the gain domain, the gap of the difference $+\Delta V^{C}$ and $+\Delta V^{C}$ is small, but when both $|\pi_{i,C}^{S} - \pi_{i,C}^{C}|$ and $|\pi_{i,M}^{S} - \pi_{i,M}^{C}|$ are in the loss domain, the gap of difference $-\Delta V^{C}$ and $-\Delta V^{M}$ is relatively obvious. Therefore, the losses caused by the imitation strategy are relatively larger than the gains brought by the innovation strategy, so under the influence of loss aversion, firms will eventually tend to adopt the innovation strategy.

4.2. The Effect of Patent Fees. Next, the effect of patent fees on firm decision-making behavior will be analyzed. The value of patent fees ρ can be set as three levels: $\rho = 30\%$, $\rho = 50\%$, and $\rho = 80\%$. The innovation risk can be set as three levels: $\delta = 0.3$, $\delta = 0.5$, and $\delta = 0.8$, the intellectual property protection intensity is set as $\theta = 0.5$, the consumers' price preference is set as $\varphi = 1$, and the decision-making attitude of the firm is set as neutral, $p = 0.5$. The simulation results are shown in Figures 6 and 7.

As can be seen from Figure 6, under the lower level of innovation risks ($\delta = 0.3$, $\delta = 0.5$), increasing patent fees can significantly increase the proportion of firms that choose innovation strategies. Even in a high innovation risk environment ($\delta = 0.8$), increasing patent fees can delay the time to finally adopt an imitation strategy to a certain extent. The results show that under the combined effect of high patent fees and lower innovation risk, firms are more inclined to adopt an innovation strategy instead of an imitation strategy.

Compared with the results in Figure 6, it can be seen from Figure 7 that when firms consider the behavioral biases in the process of strategy selection, increasing patent fees can significantly promote the proportion of innovative firms even under higher innovation risk conditions ($\delta = 0.8$). There are two main reasons for this: (1) a higher patent fee can stimulate the enthusiasm of firms to adopt an innovation strategy and protect the innovation interests of firms; and (2) relying on behavioral biases, such as reference points dependence and loss aversion, a higher patent fees will make

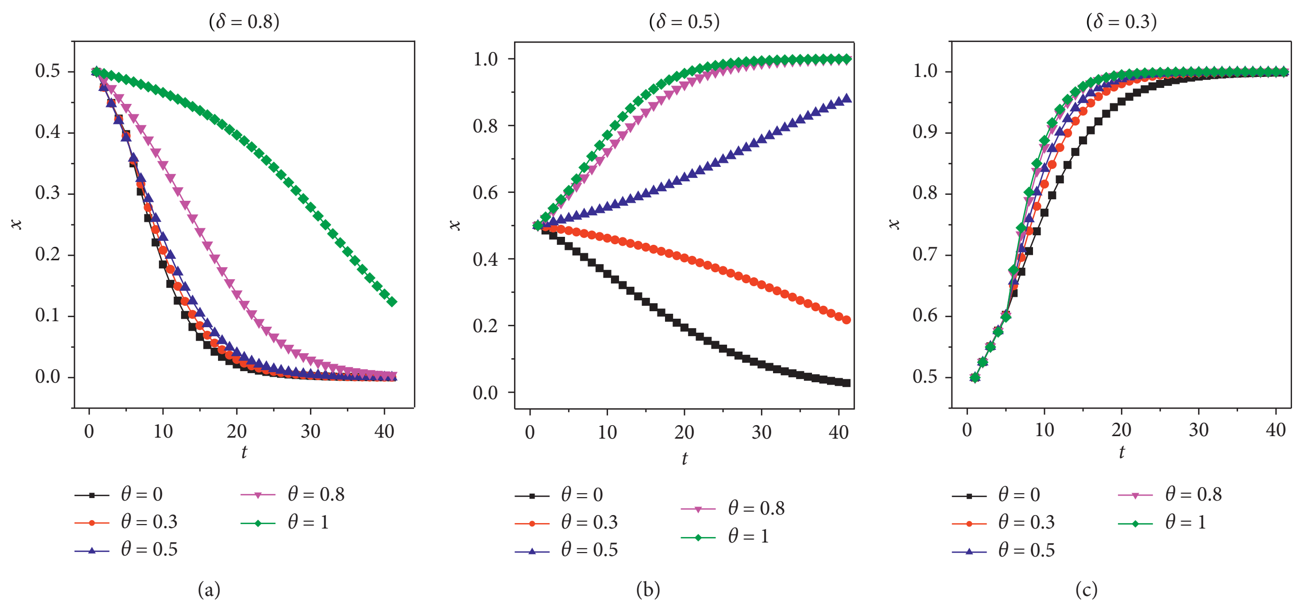

FIGURE 3: The proportion of innovation-leading firms in the group for different intellectual property protection intensity θ on three levels of the innovation risk δ based on the basic game model.

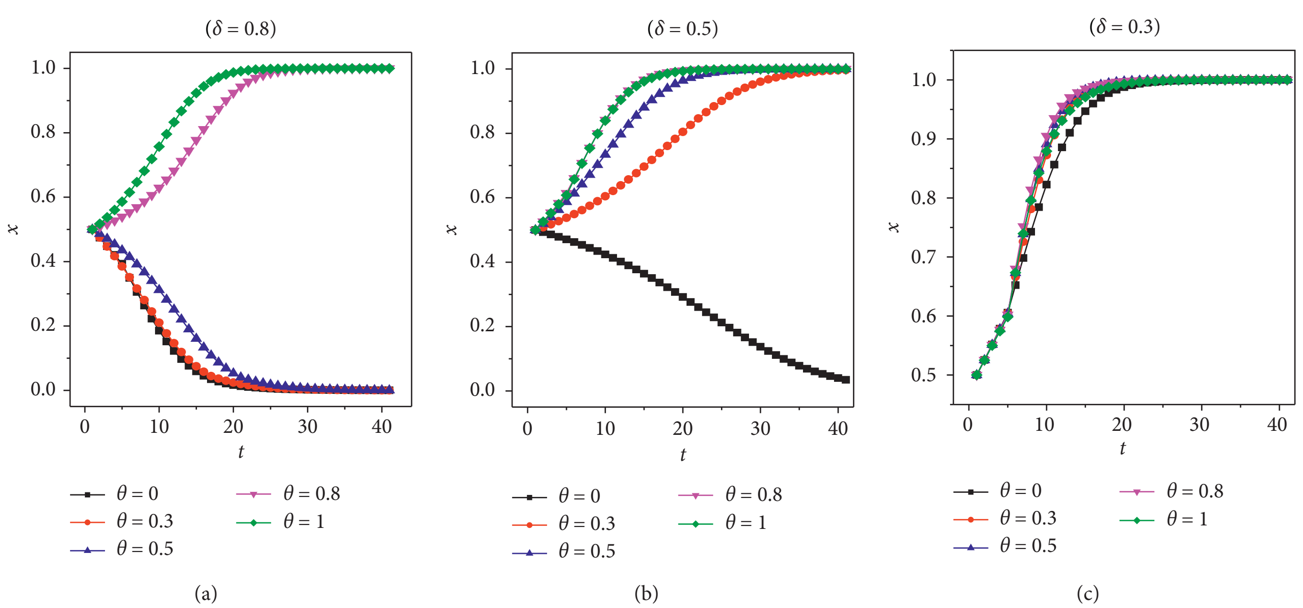

FIGURE 4: The proportion of innovation-leading firms in the group for different intellectual property protection intensity θ on three levels of the innovation risk δ based on the improved game model.

firms perceive that the loss of the imitation strategy will exceed the gain of the innovation strategy to a great extent, as shown in Figure 6. Therefore, the effect of loss aversion will eventually force the firm to adopt the innovation strategy.

4.3. The Effect of Decision-Making Attitudes. The mechanism of the firm's decision-making attitude on strategic choices is analyzed further. The decision-making attitude of firms is divided into five levels: complete pessimistic ($p = 1$), partial pessimistic ($p = 0.3$), neutral ($p = 0.5$), partially optimistic ($p = 0.8$), and completely optimistic ($p = 0$). The innovation risk is divided into three levels: $\delta = 0.3$, $\delta = 0.5$, and $\delta = 0.8$. The intellectual property protection intensity is fixed as $\theta = 0.5$, the consumers' price preference is set as $\varphi = 1$, and the patent fees are fixed as $\rho = 50\%$. The simulation results are shown in Figure 8.

As can be seen from Figure 8, under different conditions of innovation risk with the firm's decision-making attitude changing from complete pessimism ($p = 1$) to complete optimism ($p = 0$), the firm's enthusiasm for choosing the innovation strategy will increase. Especially under high risk

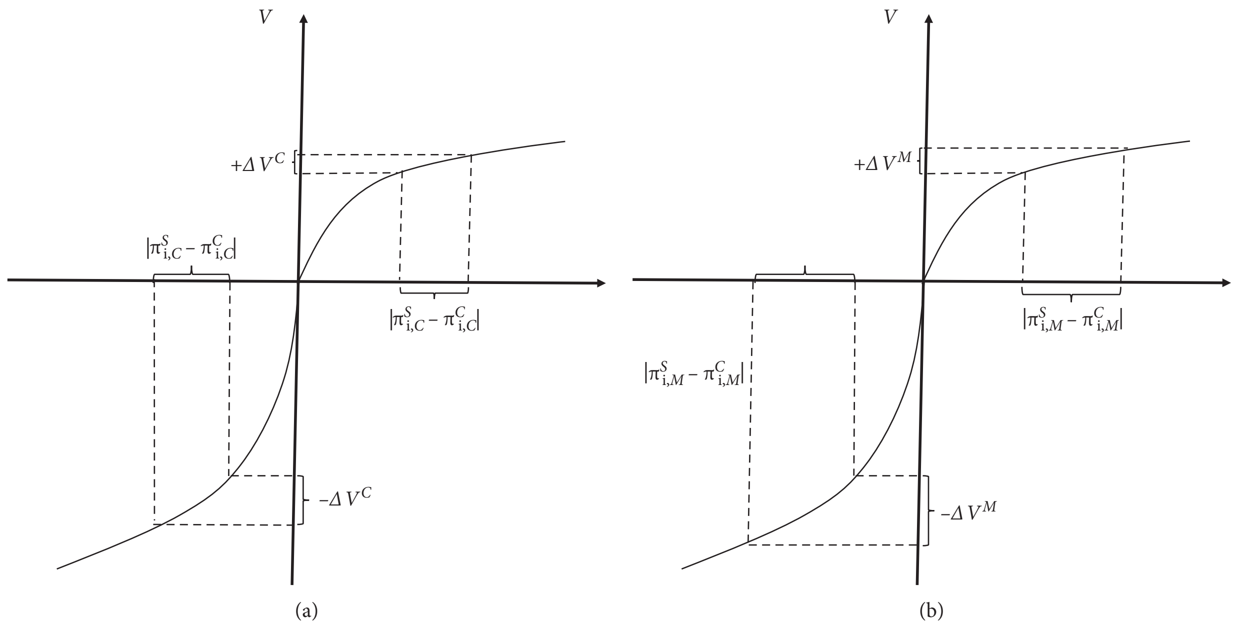

FIGURE 5: The difference of perception payoff between innovation (a) and imitation (b).

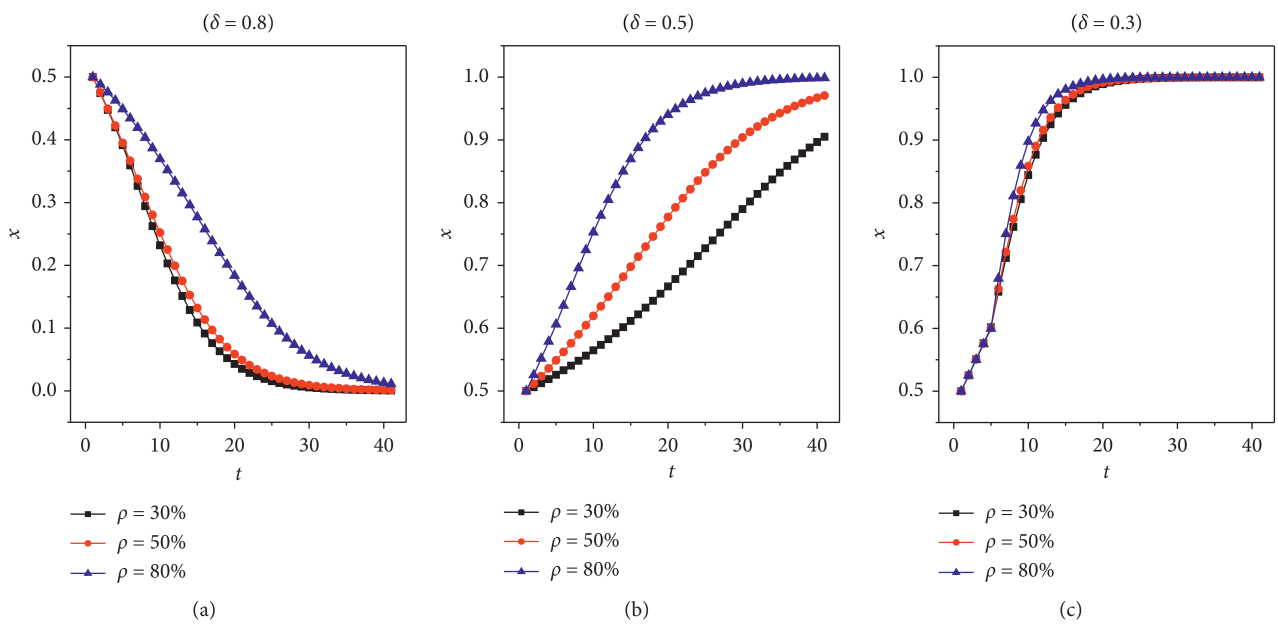

FIGURE 6: The proportion of innovation-leading firms in the group for different patent fee intensity ρ on three levels of the innovation risk δ based on the basic game model.

conditions, the more optimistic the firm's decision-making attitude is, the higher the proportion of firms that choose the innovation strategy is. The principal reason for this is that in the process of strategic choices, if the firm optimistically believes that the other firm will adopt a different strategy from its own, it will to some extent adopt an innovation strategy with a first-mover advantage to obtain more market opportunities. Additionally, the firm perceives that the loss of imitation strategy will far exceed the gain of the innovation strategy. Therefore, under the effect of loss aversion, the firm will eventually tend to adopt the innovation strategy.

4.4. The Effect of the Consumers' Price Preference. Finally, this study analyzes the mechanism of the consumers' price preference on strategic choices. Consumers' price preferences are divided into five levels: $\varphi = 0.1$, $\varphi = 0.3$, $\varphi = 0.5$, $\varphi = 0.7$, and $\varphi = 0.9$. The innovation risk is divided into three levels: $\delta = 0.3$, $\delta = 0.5$, and $\delta = 0.8$, the intellectual property

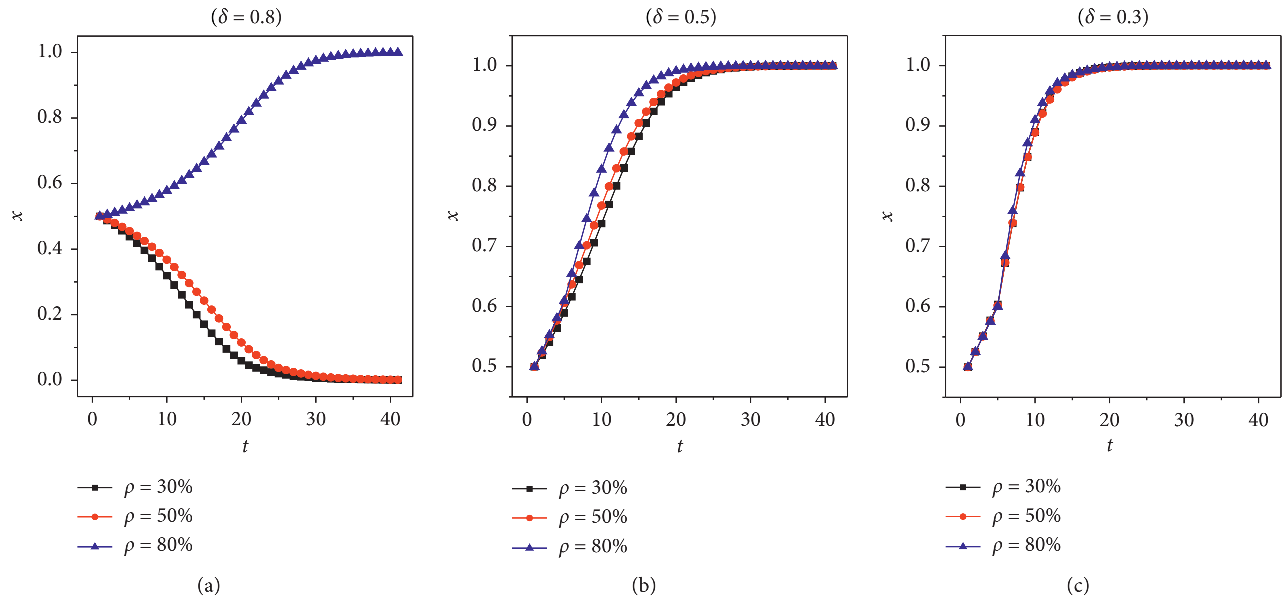

Figure 7: The proportion of innovation-leading firms in the group for different patent fee intensity ρ on three levels of the innovation risk δ based on the improved game model.

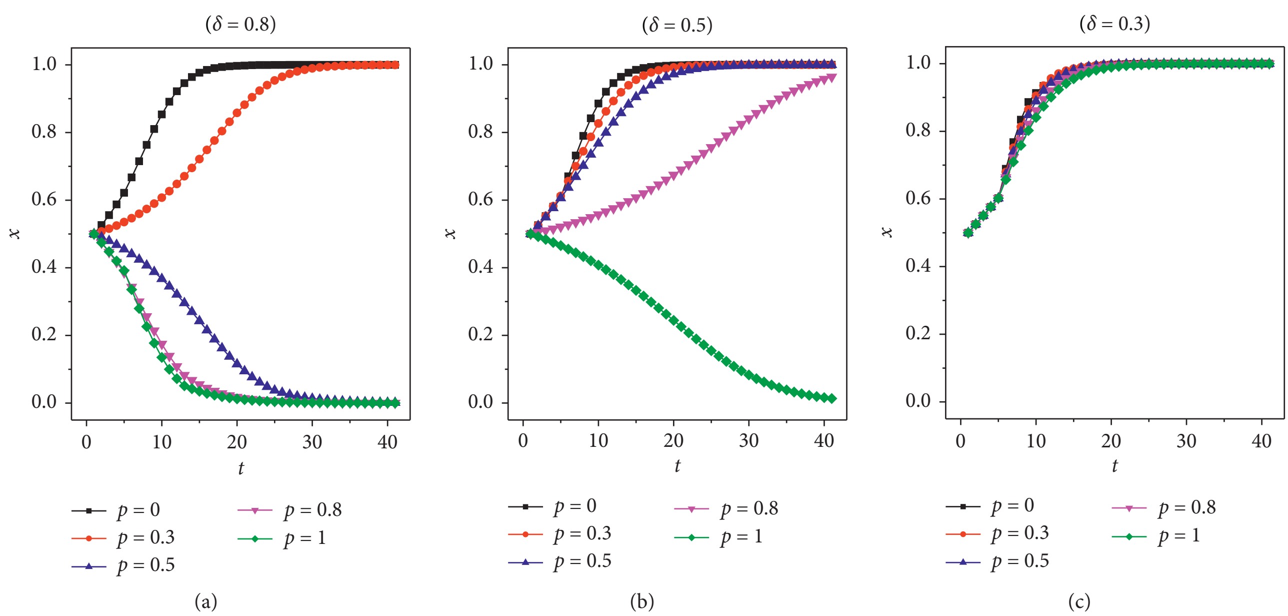

Figure 8: The proportion of innovation-leading firms in the group for different decision-making attitude p on three levels of the innovation risk δ based on the improved game model.

protection intensity is fixed as $\theta = 0.5$, the patent fees are fixed as $\rho = 50\%$, and the decision-making attitude of the firm is set as neutral, $p = 0.5$. The simulation results are shown in Figure 9.

It can be seen from Figure 9 that when consumers' price preference for choosing innovative products and imitating products decreases (that is, as φ increases), the number of firms that choose innovation strategy increases. The reason for this situation can be obtained by further observing the prices of products between *innovation-leading firms* and *imitation-following firms*. From Figure 10(a), it can be seen that as φ continues to increase, there will be no difference in consumers' price preference for these two products, but because firms that choose the innovation strategy can obtain new profit growth by charging patent fees, more firms will choose the innovation strategy. However, this does not mean that consumers' price preference has no effect on innovation. To further understand the reason for this outcome, we observe the relationship between the smaller φ and x in the steady state, as shown in Figure 10(b).

Through Figure 10(b), it can be identified that there is a partial U-shaped relationship between the smaller φ and x in

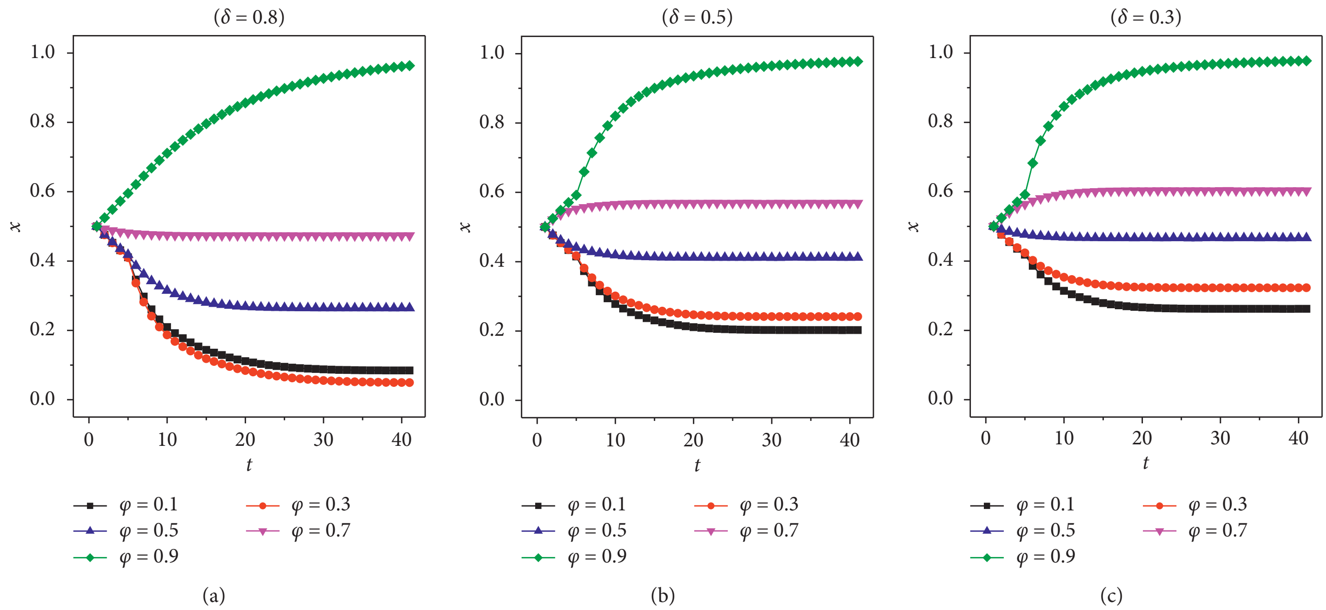

Figure 9: The proportion of innovation-leading firms in the group for different consumers' price preference φ on three levels of the innovation risk δ based on the improved game model.

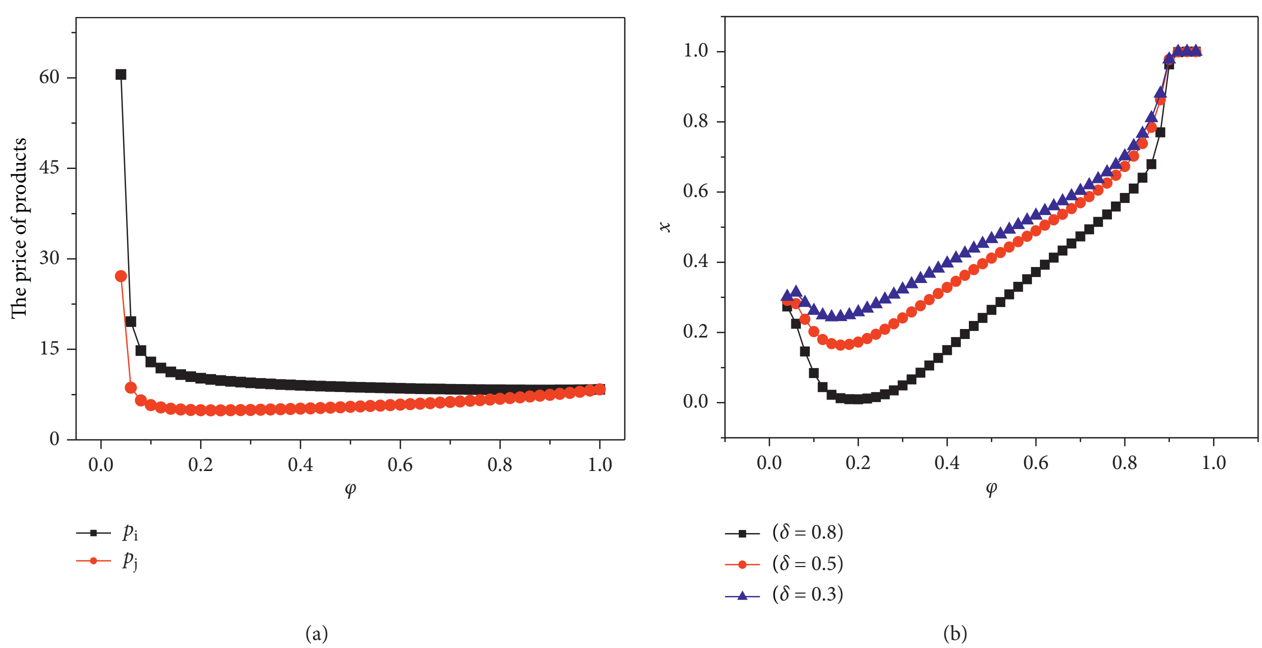

Figure 10: (a) The prices of products between innovation-leading firms and imitation-following firms for different consumers' price preference φ with the innovation risk $\delta = 0.5$ and (b) the relationship between the proportion of innovation-leading firms in the group and different consumers' price preference φ on three levels of the innovation risk δ based on the improved game model.

the steady state under different innovation risks, indicating that a very small φ is beneficial to choosing the innovation strategy to some extent. The reason for this phenomenon is also evident. When φ is very small, consumers have a very large price preference for innovation products, and consumers are more willing to pay high prices for innovation products, as shown in Figure 10(a). Therefore, firms that choose an innovation strategy can obtain greater profit returns, which will increase the probability of firms choosing an innovation strategy. With the gradual increase in φ, a certain degree of substitution appears between innovation products and imitation products. At this time, consumers' price preference for innovation products may begin to decrease, and the price difference between innovation products and imitation products will gradually shrink. Although firms that choose an innovation strategy can obtain certain profit growth by charging patent fees, this part of the profit growth cannot offset the loss of profit caused by innovation costs and innovation risks. Therefore, firms that choose an imitation strategy at this time may obtain more profit margins. Therefore, the number of firms choosing an innovation strategy will decrease. As φ further increases, the substitution of innovation products and imitation products further improves. As a result, the price difference between innovation products and imitation products decreases, but because firms that choose an innovation strategy can obtain more profit growth by charging patent fees, the extra profit is enough to offset the loss caused by innovation costs and innovation risks. Therefore, firms that choose innovation strategies will continue to increase.

5. Conclusions and Discussion

This paper analyzes how the firms' technological strategic choices between innovation and imitation are affected by behavioral biases. First, behavioral biases such as reference point dependence, loss aversion, and probability weighting can be modeled based on the prospect theory. Second, the interactive process among firms is described by a Cournot or Stackelberg game model with a technology spillover effect and intellectual property protection. By setting different parameters and performing simulation analysis, the following important conclusions are obtained:

(1) Innovation risk, as a concentrated reflection of the technology, market, and policy environment, is an important factor affecting a firm's decision-making behavior. The higher the innovation risk, the greater its impact on the firm's innovation payoff. Once the innovation risk exceeds the range that the firm can tolerate, even under high intellectual property protection, high patent fees, and optimistic innovation decision-making attitudes, it will not arouse the firm enthusiasm for innovation.

(2) Increasing intellectual property protections and the patent fees for technology transfer can effectively control the technology spillover. By increasing the difficulty and cost of the imitation-following firms, we can maintain the enthusiasm for innovation and safeguard the benefits of innovation. Therefore, increasing the awareness of intellectual property protection and strengthening the role of intellectual property protection will be more conducive to the cultivation of firm innovation capabilities.

(3) A partial U-shaped relationship between the consumers' price preference and innovation is presented, namely, consumers' price preference for innovation products and imitation products is extremely large or smaller, which can effectively improve the innovation. This conclusion suggests that increasing the enthusiasm of firms for innovation, on the one hand, can greatly increase the difference between innovation products and imitation products such that consumers are willing to pay the higher prices of innovation products and innovation-leading firms obtain high profits. On the other hand, by increasing the substitutability of innovation products and imitation products, under the combined effect of consumers' price preference and technology transfer, firms may have a larger market share when choosing an innovation strategy. It is worth noting that through the second method, the profit growth of innovation products brought about by the combined effect of consumers' price preference and technology transfer must be enough to offset the loss caused by innovation costs and innovation risks.

(4) Compared with the results based on the basic model, the behavioral biases such as reference point dependence, loss aversion, and probability weighting will significantly affect a firm's decision-making behavior and increase the innovation enthusiasm. These behavioral biases will change the perception payoff and suggest that the losses caused by the imitation strategy will be higher than the gains brought about the innovation strategy. Therefore, under the influence of loss aversion, the firm will eventually prefer to adopt the innovation strategy. Once the innovation behavior is formed, it will be further strengthened through the positive feedback mechanism.

In summary, the driving force behind the innovation should focus not only on the role of external factors such as intellectual property protection and patent fees but also on the firm's behavioral biases.

From the above research, it can be seen that innovation risk runs through the analysis of the full text and is the key focus of this article. The conclusions have confirmed that innovation risk has become one of the decisive factors in the success or failure of innovation and interacts with factors such as property rights protection, patent fees, decision-making attitudes, consumer price preferences, and other factors to jointly determine the outcome of innovation. However, because the meaning of innovation risk in the article is relatively simple and the situation under incomplete information has not been considered, we can supplement our work from some existing research conclusions considering incomplete information. Harrison and Sunar considered a problem of investment timing with incomplete information and multiple learning modes based on a continuous-time Bayesian framework [72]. The results indicate that the optimal learning and investment policy lie on a small number of critical values in terms of the single-mode selection problem. When extended to multiple learning modes, the analysis of both investment timing and dynamic subset selection decisions is required. In addition, Sunar et al. pointed out that the customer network, business size, and investment timing will also affect the competitive investment [5, 6].

These studies show that investment decisions under incomplete information will be affected not only by the firm's learning modes but also by consumers' network, heterogeneous customer demand, business size, and investment timing. This is not only a further verification of our article but also guides us in the direction of future research. Therefore, our future research will further consider investment decision making under incomplete information, taking into account factors such as learning modes, investment timing, and consumers networks into the research model.

Data Availability

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

Conflicts of Interest

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

Acknowledgments

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Research Article

How Could Policies Facilitate Digital Transformation of Innovation Ecosystem: A Multiagent Model

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The digital transformation of the innovation ecosystem is not only an inevitable direction of innovation activities in the era of digital economy but also a highly complex and uncertain process. The way to facilitate transformation with policies has become a topic of common concern of academia and policymakers. This paper builds a multiagent model and studies the impacts of supply-side policies, demand-side policies, and environmental policies on enterprises' transformation willingness, digital level, and income level as well as the proportion of enterprises that carry out transformation in the whole innovation ecosystem and innovation network structure by numerical experiments. According to research findings, supply-side policies play the biggest role in the facilitation of transformation, demand-side policies are second important to them, and environmental policies have comparatively weak impacts.

1. Introduction

The rapid development of digital technologies has reshaped human society and given rise to the trend of digital transformation. In the field of business, digital technologies have not only generated profound impacts on contents, approaches, and organizational forms of innovation activities but also attracted extensive attention from academia and industry. Existing researches commonly believed that the application of digital technologies benefited the optimization of enterprises' innovation process and improved enterprises' innovative performance [1–3]. Accompanied with the emergence of open innovation in recent years, scholars also discussed the impacts of enterprises' IT investments on availability of external resources and performance of open innovations [4–6] and found the nonlinear interactions between those two. However, existing researches were still mainly based on the digital transformation of individual enterprises and rarely discussed the digital transformation of innovation systems as a whole.

Meanwhile, researches on innovation ecosystem transformation failures also received attention from academia in recent years [7], particularly the way to avoid transformation failure through effective policy means [8]. However, among such researches, the transformation of innovation ecosystem was neither placed under more scenario-based discussions nor specific to digital transformation.

Based on the abovementioned information, the research topic of this paper is whether and how could policies facilitate the digital transformation of the innovation ecosystem? This paper uses the concept of innovation ecosystem to depict interactions and influence relations among enterprises' innovation activities [9] and uses the digital transformation to reflect innovation ecosystem's agents' adoption of information technology as well as changes in innovation activities incurred thereby [10]. Considering the innovation ecosystem is a typical complex system [11] and digital transformation is a "bottom-up" evolution process, an agent-based model is an appropriate approach to study such complicated issues [12]. To be specific, this paper builds a multiagent model for the digital transformation of innovation ecosystem, introduces supply-side, demand-side, and environmental policies, and identifies the impacts of different types of policies on the digital transformation of innovation ecosystem through computational experiments.

2. Theoretical Background

2.1. Digital Transformation of Innovation Ecosystem. According to the latest research by Granstrand and Holgersson [13], this paper defines the innovation ecosystem as "evolving set of actors, activities, artifacts, institutions, and relations, including complementary and substitute relations that are important for the innovative performance of an actor or a population of actors." In essence, the innovation ecosystem is an organization system of integration and coordination of innovation resources. Furthermore, knowledge resources spillover, diffusion and transfer among different innovation agents [14, 15], and the corresponding absorptive capacity have important influence on innovation performance [16]. The innovation ecosystem can be divided into different levels such as enterprise, region, and industry, which play a positive role in innovation performance and sustainable development [17]. From the perspective of complex system, different levels of innovation ecosystem showed "bottom-top" and "micro-macro" ecological agglomeration relations [18].

The digital transformation of innovation ecosystem takes the digital transformation of enterprises and other innovation agents as microfoundation first. To enterprises, digital transformation refers to major changes in strategy, organizational structure, product operation, business model, and other aspects brought by digital technologies, which are characterized by their integration, span, and strong environmental dependency [19]. Meanwhile, the system attribute of innovation ecosystem means digital transformation changes in whole system structure, function, and operating mechanism arising out of correlated microtransformation activities instead of the simple accumulation of digital transformation activities of individual enterprises. To be specific, such changes are reflected in the two aspects of innovation activities and innovation organization mode in a centralized manner.

On the one hand, digital innovation has become a dominant innovation activity. Digital innovation refers to the production of new products or services, development of new processes, or creation of new business models through digital technologies, which are featured by significant characteristics of ambiguous boundaries, flexible and changeable innovation agents, as well as intertwined innovation process and innovation results [20]. Digital innovation can be also taken as a "new combination" of digital technologies with enterprises' existing products, processes, and business models [21], and this is exactly the connotation and inevitable path of digital transformation [22].

On the other hand, innovation organization mode has shown characteristics of online and offline integration. Online initiatives are dominated by an allocation of information, coded knowledge, data, and other resources, while offline initiatives are dominated by tacit knowledge exchange, production, and transportation of physical resources and products as well as other activities. This is not only the result of changes in communication methods and improvement of efficiency brought by digital technologies but also the result of increasing distribution and democratization of innovation agents [23, 24]. Online and offline integration is mainly reflected by the increasingly prominent role of digital platforms in the innovation ecosystem. From the perspective of technology, digital platform refers to extensible codebase that can embed third-party modules. From the perspective of the sociotechnical system, digital platform refers to the set of technical elements, organizational processes, and standards [22]. The digital platform has provided a space for online and offline interactions of innovation agents, and restructuring of innovation organization mode by the digital platform has become a significant characteristic of the digital transformation of an industry's innovation ecosystem.

2.2. Impacts of Policies on Digital Transformation of Innovation Ecosystem. The digital transformation of innovation ecosystem has high complexity and uncertainty, which led to transformation failures. To cope with complexity and uncertainty in transformation, policymakers would actively develop and implement a series of policy tools to facilitate transformation. Based on research on the classification of policy tools conducted by Huang and others [25] and analysis on functions of the innovation ecosystem carried out by Hekkert et al. [26], this paper divides policy tools to facilitate transformation into three categories.

The first category is the supply-side policies. Such policies mainly drive the transformation through increasing supply of technology, fund, information, and other key elements required. Consumption of different resources constitutes the main source of transformation cost, so the main function of supply-end policies is the reduction of transformation cost. The second category is the demand-side policies. Such policies mainly drive transformation through increasing market demand for transformation, such as government purchase services and adjustment of market entrance criteria. The demand-side policies can play comprehensive roles, and they can affect individuals' willingness to transform by means of reducing uncertainty and changing market structure. The third category is the environmental policies. Such policies mainly drive transformation through improving the economic, social, and institutional environments that are required by transformation. Environmental factors have indirect and common impacts on transformation activities, which can create a favorable atmosphere or "field" for transformation as a whole. Such an atmosphere can cause isomorphic pressure on individuals and thus facilitate individuals' willingness to transform.

The three aforementioned policies will eventually affect the digital transformation of innovation ecosystem from micro- and macro perspectives. From a microperspective, the first impact is individual enterprises' willingness to transform. As mentioned above, in the case of a complex system, individuals' transformation activities constitute microfoundation of the whole system's transformation, and individuals' willingness to transform is the premise of their implementation of transformation. The second impact is enterprises' digital levels, which reflect changes in the technical dimension brought by transformation to enterprises. The third impact is enterprises' economic benefits, which are both economic results of transformation and important motivation for enterprises to carry out transformation. From the perspective of the macrosystem, the first impact is the proportion of enterprises carrying out digital transformation in the system, while the second impact is the changes in network structure of the innovation ecosystem. Characteristics of the digital transformation of innovation ecosystem are reflected by those two impacts.

3. Model

Different policies will promote the digital transformation of enterprises from different aspects and increase the level of digitization of enterprises, and the level of digitization of enterprises will affect the cooperative innovation between enterprises, leading to the evolution of the innovation ecosystem. Based on this idea, this paper builds a multiagent model for the digital transformation of innovation ecosystem to study whether and how could supply-side, demand-side, and environmental policies facilitate the digital transformation of innovation ecosystem. Then, we will explain our model in this paper from four aspects: agents and their attributes, the interaction between agents, the endogenous and external environment where the model is located, and the complete simulation process of the model.

3.1. Agents. This section introduces the agents involved in our model. In order to study how can policies facilitate digital transformation of innovation ecosystem, two types of agents are designed in the simulation model. One is the enterprise, which is the main body of the innovation ecosystem, and the other is IT application, which embodies the existing digital technology in the innovation ecosystem.

An enterprise may choose whether it is going to carry out digital transformation based on the existing policies and the enterprise's revenue, choose whether to conduct cooperative innovation based on the digital level in the innovation ecosystem, and then acquire a certain market share based on existing conditions. Its attributes include the enterprise's market share, net income, digital level, and cooperative relations with other enterprises. An enterprise's market share of the present period determines its current net income, the connection between an enterprise and IT application determines the enterprise's digital level, and the connection between enterprises represents their cooperative innovation.

IT application represents digital technology, it is a 10-dimensional vector, and the value of each element of the vector is 0 or 1, which indicates the state of the digital technology on that attribute. For instance, if vector of a certain digital technology is $[1\ 0\ 0\ 1\ 0\ 1\ 0\ 0\ 0\ 1]$, then the value of 1 for the first dimension means the state of the digital technology on the first attribute is "1."

3.2. Interactions. This section introduces the interaction between agents in our model. Interactions in the simulation models can be divided into two types, which include interactions between enterprise and IT application and interactions between enterprises.

Interactions between enterprise and IT application include an enterprise's upgrading of existing IT application as well as an enterprise's building of new IT application. An enterprise is connected with a certain IT application, which means the enterprise possesses such digital technology. The number of IT applications connected with an enterprise represents the enterprise's digital level.

Interactions between enterprises refer to cooperative innovations between enterprises, and an edge will be added to connect two enterprises if they have cooperative innovation, which will eventually form a network of cooperative innovations.

3.3. Environment. This section introduces the endogenous and external environments of the simulation model in this paper. Environment in simulation system includes the endogenous environment of enterprises and the external environment of the whole innovation ecosystem. The endogenous environment of enterprises mainly refers to different rules that affect an enterprise's decision-making process, while the external environment refers to external digital demands. That is, with the development of information technology, consumers will put forward new technical demands for products every once in a while. This external market environment prompts enterprises to upgrade digitally to obtain the digital technology, and the enterprises that have acquired this kind of digital technology can apply it to innovation activities to gain an advantage in the competition. In this paper, we assume such external digital demand is also a 10-dimensional vector, and the value of each element of the vector is 0 or 1.

3.4. Process. In this section, we introduce the complete simulation process of the multiagent model in this paper. The model includes five stages: initialization stage, digital demand release stage, enterprise digital transformation stage, cooperative innovation stage, and market share redistribution stage. It simulates the processes of the creation of a new digital demand from the external environment, to the enterprises trying digital transformation to realize this new digital demand, launches cooperative innovation activities to form an innovation network, and finally rewrites the allocation of market share based on successful innovation activities:

(1) *Initialization*. Assume the market size of the whole network is MS, and there are M enterprises and N IT applications in the network. The N IT applications are connected with M enterprises randomly. Considering that the real market environment usually shows a long tail distribution, this article assumes that, among the M enterprises, few of them have relatively large market share, and most of them have comparatively small market share.

(2) The external environment releases a digital demand at a certain interval.

(3) *Stage of digital transformation*. To meet digital demands of the external environment, enterprise will consider carrying out digital transformation. Enterprise's willingness to carry out digital transformation P is affected by expected cost, expected net income, and policies. Among them, the expected cost is the decisive condition that affects whether an enterprise will choose digital transformation. It is affected by technology gaps and unit costs of transformation. Expected net income is an important factor in promoting enterprises to choose digital transformation, and it is affected by the average net income of related companies. The three kinds of policies affect the enterprise's willingness to digital transformation in different ways. Supply-side policies affect the willingness of enterprises to transform by affecting the unit cost of digital transformation, demand-side policies trigger the willingness of enterprises to transform by increasing market demand, and environmental policies encourage enterprises to carry out digital transformation through the pressure of cooperative enterprises. The following article discusses it in detail:

Expected cost. Enterprise decides whether it should consider digital transformation based on expected digital transformation cost, and the enterprise will abandon digital transformation if expected cost is greater than the enterprise's present capital, and transformation willingness $P = 0$.

The expected cost of digital transformation is related to the effort required by the enterprise for the transformation. Since this article uses a ten-dimensional vector to represent the IT application and the digital requirements of the enterprise itself, each dimension of the vector represents the capabilities required to realize the digital technology; thus, expected digital transformation cost can be estimated by the similarity between vectors of the enterprise's own IT application and digital demand. Compare the minimum number of mismatches between digital demand vector and the enterprise's IT application vector, that is, the number of elements that are 1 in the digital demand vector but are 0 in the existing IT application; the enterprise will upgrade existing IT application with an expected cost of $\mathrm{Cu} * k$ if the minimum number of mismatches k is not greater than T_k, and the enterprise will build new IT application with the expect cost of $\mathrm{Cb} * k$ if the minimum number of mismatches k is greater than T_k, among which Cu is the unit cost for the upgrading of existing IT application and Cb is the unit cost for the building of a new IT application. For instance, if $T_k = 3$, an enterprise possesses a certain digital technology $[0\ 0\ 0\ 1\ 0\ 0\ 0\ 0\ 1\ 0]$; digital demand released by the market at present is $[0\ 0\ 0\ 1\ 1\ 0\ 0\ 0\ 1\ 0]$, then number of mismatches between existing digital technology and digital demand is 1, which is less than the threshold T_k. Hence, the expected cost of the enterprise's digital transformation is Cu×1.

Expected net income. Enterprise decides whether it should carry out digital transformation based on expected net income of digital transformation, the enterprise will abandon digital transformation if expected net income is less than the enterprise's transformation cost, and transformation willingness $P = 0$.

An enterprise's expected income is estimated by the average net income of enterprises one level higher than it in the digital level at the current stage. If there is no prior knowledge, the enterprise will consider digital transformation as long as expected digital transformation cost is less than present capital.

Effects of policies. Enterprise's willingness to carry out digital transformation P is the result of the three parts of supply-side policies, demand-side policies, and environmental policies.

The main function of supply-side policies is a reduction of transformation cost, so changes in supply-side policies can be reflected by adjusting unit cost *Cu* and *Cb*. Enterprise will only consider digital transformation when the transformation cost is less than the enterprise's present capital.

The main function of demand-side policies is the facilitation of transformation through an increase in market demand, so the paper uses $p1$ to represent the enterprise's willingness to transform due to market demand and by adjusting $p1$ to achieve the role of controlling demand policies.

The function of environmental policies is the facilitation of individuals' willingness to transform through isomorphic pressure; that is, if the digital level of a company's cooperative enterprise is higher, the stronger the willingness of the company to digitally transform in order to narrow the gap between itself and the cooperative enterprise. So, this paper obtains isomorphic pressure based on digital levels of cooperative enterprises of the enterprise. To be specific, if enterprise a has k cooperative enterprises, in which digital levels are $D_1, D_2, \ldots, D_k$, respectively, and then neighbors' isomorphic pressure on enterprise a is represented as

$$p2 = \frac{\max_i (D_i - D_a)}{D_a}. \quad (1)$$

The impact of neighbors' isomorphic pressure on the enterprise is represented as $p2 \times \mathrm{pr}$. Among which, pr refers the coefficient of neighbors' isomorphic pressure; i.e., coefficient of environmental policies' influences on the enterprise's willingness to transformation. By adjusting $p2$, we can adjust the impact of environmental policies on the enterprise's willingness to transform.

To sum up, enterprise's digital transformation willingness can be represented as

$$P = \begin{cases} 0, & \text{if the expected digital transformation cost} < \text{present capital}, \\ p1 + p2 \times pr, & \text{otherwise.} \end{cases} \quad (2)$$

Upon acquirement of each enterprise's digital transformation willingness P, the enterprise will choose to carry out digital transformation or not based on probability P. An additional IT application will be added to the network if all enterprises choose to carry out digital transformation succeed at it, in which eigenvector is a digital demand released by the environment. An edge will be added to the enterprise succeed at transformation and new IT application. The actual cost of an enterprise's digital transformation is a random number within 10% fluctuation of its expected cost.

(4) *Stage of cooperative innovation*. Upon the ending stage of digital transformation, enterprises start to think about whether they should carry out cooperative innovation, and each enterprise has three choices of no innovation, independent innovation, and cooperative innovation. Assume an enterprise knows selection made by all enterprises in the innovation ecosystem in the last round and their corresponding net income, then the enterprise may help its judgment on the selection of innovation mode based on other enterprises' experiences. If an enterprise chooses to cooperate innovation, the achievement of a cooperative relationship is determined by the enterprise's current innovation strategy, the digital level of the two enterprises, and whether the two enterprises have a cooperative relationship. Both independent innovation and cooperative innovation have an innovation success rate. The following article discusses it in detail:

Selection of innovation mode. Target on each enterprise divides enterprises of similar scale in the previous period into three types of no innovation, independent innovation, and cooperative innovation, calculates the average unit net income of those three types of enterprises, respectively, and divides the values by the sum of average unit net income of those three types of enterprises, which give you probabilities for the enterprise to choose those three innovation modes. Enterprise chooses the innovation strategy of the present period based on such probabilities. If the enterprise chooses no innovation, then no operation is required. If the enterprise chooses independent innovation, then the enterprise will succeed at innovation with a certain probability.

Selection of partner. If a certain enterprise intends to conduct cooperative innovation, then the enterprise will randomly send requests for cooperative innovation to an enterprise with a digital level no lower than it, and it is more likely for it to choose an enterprise worked with it before.

The invitee may accept or reject an invitation for cooperation, and factors affecting acceptance or rejection of cooperative innovation are as follows: (1) the enterprise's innovation strategy of the present period: if the invitee also chooses cooperative innovation, then the enterprise will consider invitation for such cooperative innovation; (2) digital levels of the two parties of cooperation: the more similar the digital levels of the two enterprises are, the more likely for them to encounter the same problem and thus have cooperative innovation; (3) existence of previous cooperative relations between the two parties: if the two parties had cooperation before, then regardless of invitee's current consideration of cooperative innovation and the digital levels of the two enterprises, the invitee will agree to carry out cooperative innovation.

If the invitee agrees to carry out cooperative innovation, then the two parties of cooperation start to carry out cooperation.

Success rate of innovation. Both independent innovation and cooperative innovation have success rate of innovation. Success rate of cooperative innovation R_c is proportional to digital levels of the two parties of cooperation, to make sure success rate of cooperative innovation is a value between 0 and 1, and this paper assumes $R_c = ((\beta((D_A + D_B)/2) + \alpha_1)/(\beta((D_A + D_B)/2) + \alpha_1 + 1))$, in which D_A and D_B refer to digital levels of the two parties of cooperation, respectively. Success rate of independent innovation R_S is proportional to the enterprise's own digital level and $R_S = (\beta D_A + \alpha_2)/(\beta D_A + \alpha_2 + 1)$, in which α_1 and α_2 control minimum value of success rate of transformation, while β controls growth rate of success rate of transformation. Previous researches have shown that success rate of independent innovation is normally greater than success rate of cooperative innovation, so $\alpha_1 < \alpha_2$. An edge with weight of 1 will be added to two enterprises if they succeed at cooperative innovation.

(5) *Redistribution of market share*. The market redistributes market share based on the market share of previous period and successful innovation activities

of the present period. Enterprises that innovate successfully will gain more market share in the next round of competition. Therefore, this article designs the method of calculation of new market share as follows: assume 10% of whole market share is occupied by enterprises succeed at innovation, and the remaining 90% is occupied by all enterprises in the market based on the market share of the last round. Among enterprises succeed at innovation, the average increase in market share brought by cooperative innovation is higher than that brought by independent innovation, and enterprises choose cooperative innovation will distribute an increase in market share by business scale. To be specific, the base of an increase in market share of an enterprise chooses independent innovation is $1 \times r_1$, base of total increase in market share of two enterprises choose cooperative innovation is $2 \times r_2$, and the two parties of cooperation will further distribute the base of increase in market share of $2 \times r_2$ by business scale, in which r_1 is a random number between [0.9, 1.1] and r_2 is a random number between [1.0, 1.2].

For example, if there are 4 enterprises and the total market share is 100, the market shares of each enterprise in the previous period are 10, 20, 30, and 40. In the current period, enterprise 1 chose not to innovate, enterprises 2 and 4 chose cooperative innovation and succeeded, and enterprise 3 chose independent innovation and succeeded. The new market share allocation method is as follows:

10% of the total market share (10) is divided among companies 2, 3, and 4. Enterprises 2 and 4 choose cooperate innovation and thus randomly select a value of r_2 from [1.0, 1.2]; assume the value is 1.1, then the sum of the market share gain base of these two enterprises is $2 \times 1.1 = 2.2$, and because the ratio of the scale of enterprises 2 and 4 is 1 : 2, the market share gain base of enterprise 2 is $2.2^* (1/3) = 0.73$ and the market share gain base of enterprise 4 is $2.2^* (2/3) = 1.47$. Enterprise 3 chooses independent innovation and succeeded; thus, we take a random number from [0.9, 1.1]; assume it is 1, then the market share gain base of enterprise 2 is 1. Therefore, companies 2, 3, and 4 will share 10% of the market share at a ratio of 0.73 : 1 : 1.47, and the remaining 90% of the market share will be shared by 4 companies at a ratio of 1 : 2 : 3 : 4. The final new market shares of the four companies are as follows: 9, 20.3, 30.1, and 40.6.

Enterprise's net income is proportional to its market share; if the net income of each unit market share is UNI, then the enterprise's net income = the enterprise's market share × UNI.

3.5. Parameters and Their Initialization. Table 1 lists summarized parameters involved in the model and their values in this paper.

The four parameters of Cu, Cb, $p1$, and pr control the effects of supply-side policies, demand-side policies, and environmental policies, respectively. In experiments of this paper, we will make other parameters unchanged and adjust aforesaid four parameters to study impacts of different policies on enterprises' digital transformation and evolution of innovation ecosystem.

4. Numerical Experiments

Supply-side policies, demand-side policies, and environmental policies can all affect enterprises' digital transformation and thus affect structure of innovation ecosystem. This paper conducts contrast experiments from perspectives of transformation willingness, transformation proportion, digital level, and net income of enterprises in innovation ecosystem as well as network structure of innovation ecosystem.

4.1. Impacts of Supply-Side Policies on Transformation. Impacts of supply-side policies on digital transformation are mainly reflected by transformation cost. Digital transformation cost is controlled by parameters of Cu and Cb, among which Cu is the unit cost required for enterprise to upgrade existing IT application and Cb is the unit cost required for enterprise to create new IT application. To study impacts of supply-side policies on ecosystem, this section fixes parameters of $p1 = 0.5$, $\text{pr} = 0.5$, and $R = 60$ first, assumes (a) Cu = 2, Cb = 4, (b) Cu = 1.5, Cb = 3, (c) Cu = 1, Cb = 2, and (d) Cu = 0.5, Cb = 1 respectively, and conducts four groups of multiagent simulations. Related experiment results are as follows.

4.1.1. Enterprises' Transformation Willingness. Figure 1 shows distribution of enterprises' willingness to carry out digital transformation at different values of unit transformation cost, the x-axis shows enterprises' willingness to carry out digital transformation, and the y-axis shows number of enterprises willing to transform. If an enterprise's willingness to carry out digital transformation is 0, it means the enterprise does not want to carry out digital transformation due to limited fund, insufficient expected income from digital transformation, and other reasons.

It can be seen from the figure that when digital transformation cost is relatively high, most enterprises will be unable to carry out digital transformation due to limited fund and other factors (when Cu = 2 and Cb = 4, around 950 enterprises have transformation willingness of 0 in the present period), and only few enterprises are willing to carry out digital transformation. Accompanied with reduction in digital transformation cost, an increasing number of enterprises show relatively strong willingness to carry out digital transformation (when Cu = 0.5 and Cb = 1, only around 75 enterprises have transformation willingness of 0 in the present period).

Table 1: Parameters involved in the model and their values.

Symbol	Parameter description	Value
M	Enterprises number	1000
N	Initial IT application number	10
R	Total number of iterations	60
MS	Market size of whole network	10000
$p1$	Demand-side policies' influence on the enterprise's willingness to transformation	0.3, 0.5, 0.7
pr	Coefficient of environmental policies' influence on the enterprise's willingness to transformation	0.3, 0.5, 0.7
T_k	Threshold of the minimum number of mismatches	3
Cu	Unit cost for upgrading of existing IT application	0.5, 1, 1.5, 2
Cb	Unit cost for building of new IT application	1, 2, 3, 4
UNI	Net income of each unit market share	1
α_1	Parameter of the success rate of cooperative innovation	0.5
α_2	Parameter of the success rate of independent innovation	1
β	Parameter controlling the growth rate of success rate of transformation	0.1

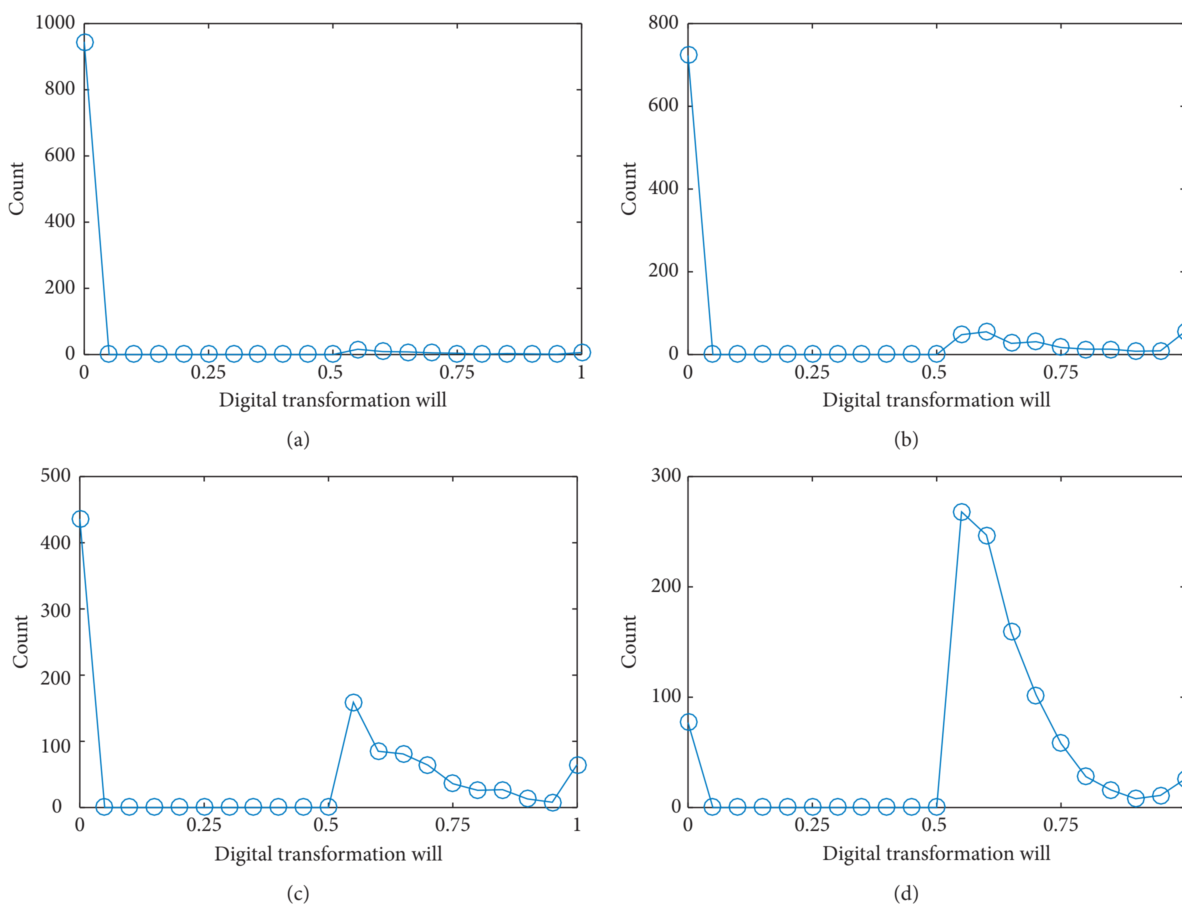


Figure 1: Enterprises' willingness to transformation at different values of unit transformation cost: (a) Cu = 2, Cb = 4; (b) Cu = 1.5, Cb = 3; (c) Cu = 1, Cb = 2; (d) Cu = 0.5, Cb = 1.

4.1.2. Enterprises' Transformation Proportion. Figure 2 shows proportions of enterprises carry out digital transformation under different transformation costs, in which the x-axis shows number of periods of digital transformation and the y-axis shows proportion of enterprises carry out digital transformation in the R period in innovation ecosystem.

It can be seen from the figure that the number of enterprises carrying out digital transformation in innovation ecosystem constantly increases with time. However, the higher the transformation cost, the slower the proportion grows. When digital transformation cost is comparatively high (Figure 2(a)), only around 65% of enterprises eventually possess digital technology. Accompanied with continuous reduction in digital transformation cost, the number of enterprises succeed at digital transformation continuously increases, and all enterprises in innovation ecosystem will accomplish digital transformation if transformation cost is low enough (Figure 2(d)).

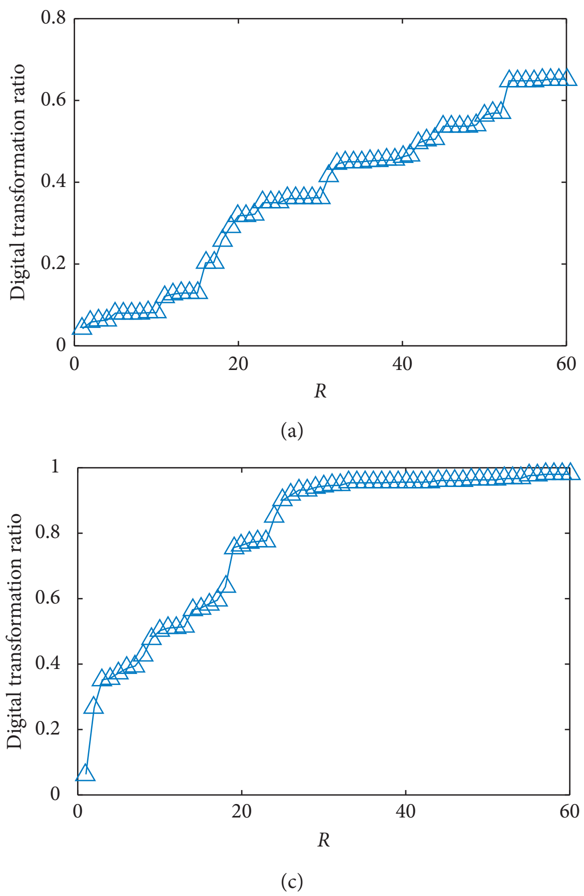


Figure 2: Proportions of enterprises carry out digital transformation under different transformation costs: (a) Cu = 2, Cb = 4; (b) Cu = 1.5, Cb = 3; (c) Cu = 1, Cb = 2; (d) Cu = 0.5, Cb = 1.

4.1.3. Enterprises' Digital Levels. Figure 3 shows the digital levels distribution of enterprises succeed at digital transformation under different transformation costs when $R = 60$, x-axis shows digital levels, and y-axis shows number of enterprises with such digital level.

It can be seen from the figure that when the transformation cost is relatively high, distribution of enterprises' digital levels is similar to a long-tailed distribution, most enterprises have very low digital level, and few enterprises have relatively a high digital level. Accompanied with constant reduction of transformation cost, distribution of enterprises' digital levels gradually leans toward inverted U-shaped distribution, most enterprises have intermediate digital level, and few enterprises have very high or low digital level. Besides, accompanied with continuous reduction of transformation cost, the peak value of the inverted U-shaped distribution gradually moves to the right. In other words, reduction of digital transformation cost can give the whole innovation ecosystem a higher digital level.

4.1.4. Enterprises' Net Income. This section discusses relations between enterprises' net income and their digital levels under different transformation costs when $R = 60$. The results are as indicated in Figure 4, in which x-axis shows digital levels of enterprises and y-axis shows net income of enterprises with such digital level. Each circle in the figure represents an enterprise; the more dense the circles in an area, the more the enterprises with such digital level and net income.

It can be seen from Figure 4 that, regardless of changes in digital transformation cost, enterprises with high digital levels tend to have a greater net income. However, when digital transformation cost is relatively high, enterprises will be more centralized at a lower left corner. In other words, most enterprises have low digital levels and net income, and there is a huge gap between enterprises with high net income and enterprises with low net income, which can easily result in monopoly. When enterprises' digital transformation cost is gradually reduced, most enterprises are gradually centralized in the middle, and the gap between net income of enterprises gradually decreases. It means when digital transformation cost is reduced, more enterprises will be able to carry out cooperative innovation through digital transformation and thus occupy market share. The ecosystem boasts of comparatively intense competition, and so-called "leading enterprise" has less obvious advantage.

4.1.5. Network Structure. Figure 5 shows the visual graph of cooperative innovation structure under four types of digital transformation costs when other parameters remain

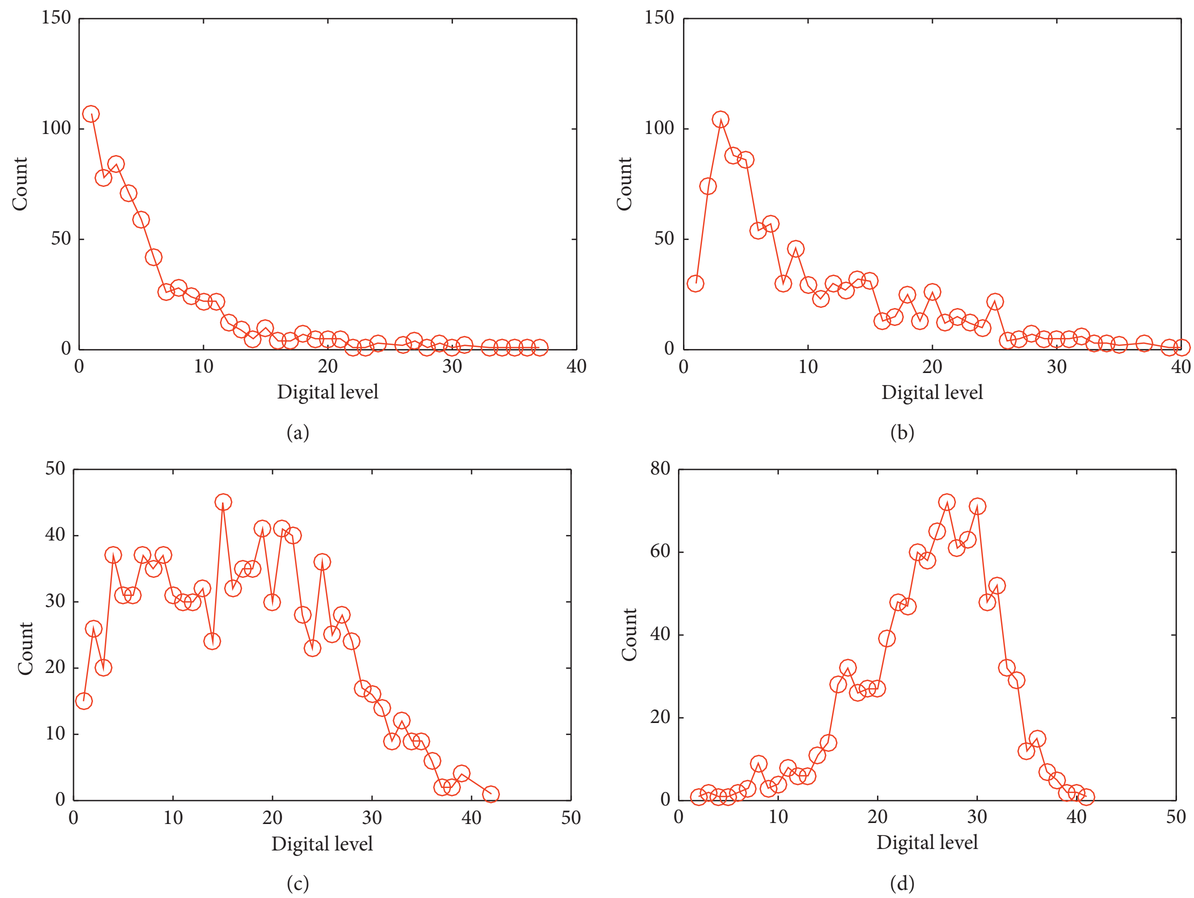


Figure 3: Digital level distribution of enterprises under different transformation costs: (a) Cu = 2, Cb = 4; (b) Cu = 1.5, Cb = 3; (c) Cu = 1, Cb = 2; (d) Cu = 0.5, Cb = 1.

unchanged and $R = 60$. Table 2 shows partial indicators of cooperative innovation network, in which islands number (N_I) indicates the number of enterprises not participating in cooperative innovation. Average number of cooperative enterprises (A_{CE}) indicates the average number of enterprises has cooperative innovation with each enterprise during evolution of whole innovation ecosystem. The average number of cooperation (A_C) indicates many successful cooperative innovations each company has carried out on average. If the average number of cooperation is greater than average number of cooperative enterprises, it means some enterprises have multiple collaborations.

It can be seen from aforesaid figure that cooperative innovation network in innovation ecosystem has an obvious core-periphery structure. In other words, only few enterprises in the network can have cooperative relations with numerous enterprises, and those enterprises connect with each other and form the "core" of the network. Most enterprises only have cooperative relations with one or two enterprises, and the sparse connections between those enterprises form the "periphery" of the network. This paper uses *K*-core [27] to gradually remove nodes and edges on the edge of network and acquires a subnetwork located at the core of network. Table 2 shows corresponding average number of cooperative enterprises (A_{CE}_S) and average number of cooperation (A_C_S) of each enterprise in those subnetworks. When digital level gradually decreases, average number of cooperative enterprises of core enterprises gradually increases at low speed, average number of cooperation between core enterprises rises significantly, and core parts of the network are connected more closely. The potential cause of this phenomena is accompanied with reduction in digital transformation cost, more enterprises have the chance to carry out digital transformation, digital levels of different enterprises in the network become more decentralized, and available cooperative partners of each enterprise intend to carry out cooperative innovation become more centralized, which makes it easier to form long-term stable cooperative relations. It is reflected by constantly strengthening cooperation between core enterprises from the perspective of network structure.

4.2. Impacts of Demand-Side Policies on Innovation Ecosystem. In the model of this paper, demand-side policies are controlled by parameter $p1$; the greater the $p1$, the more powerful the demand-side policies. To study impacts of demand-side policies on innovation ecosystem, this section fixes parameters of pr = 0.5 and $R = 60$ based on experiment results of previous section, assumes (a) $p1 = 0.3$, Cu = 1, Cb = 2; (b)

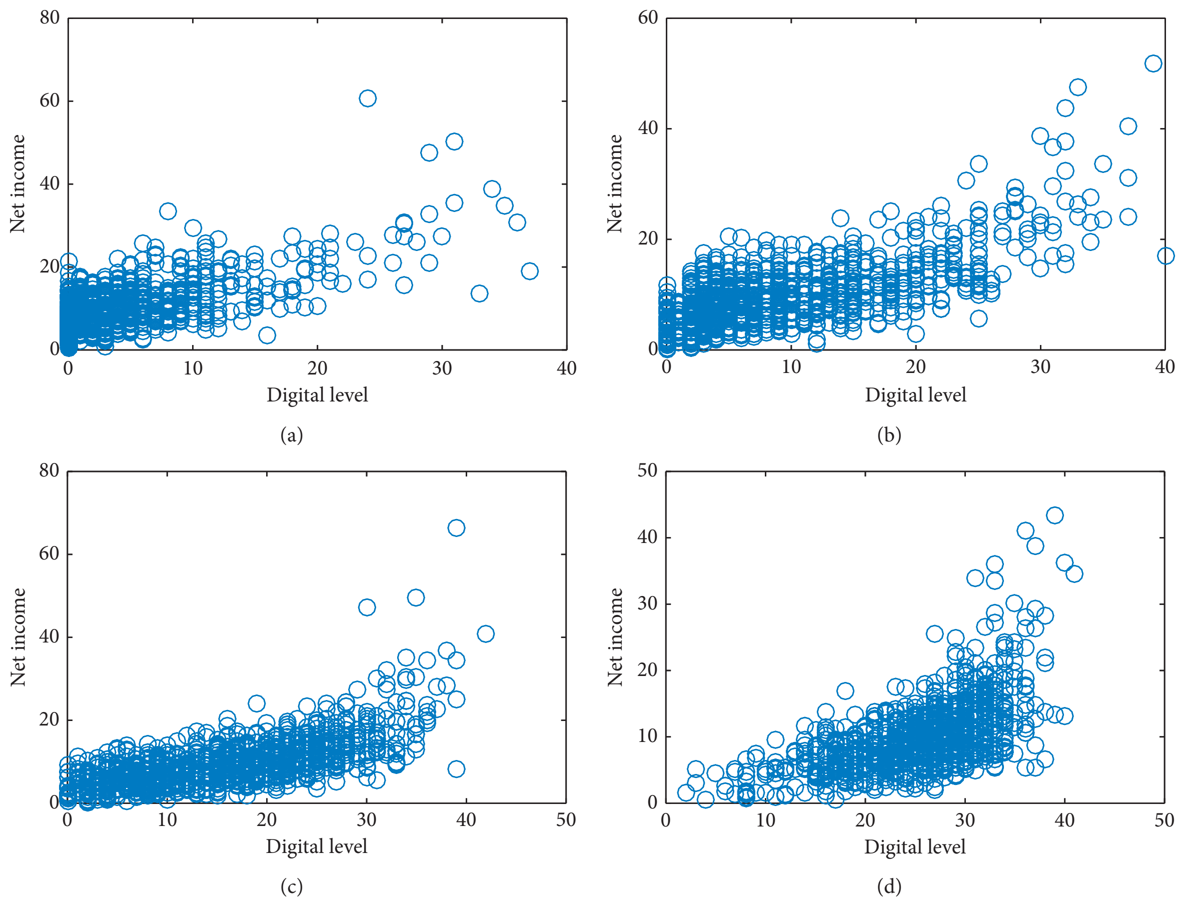


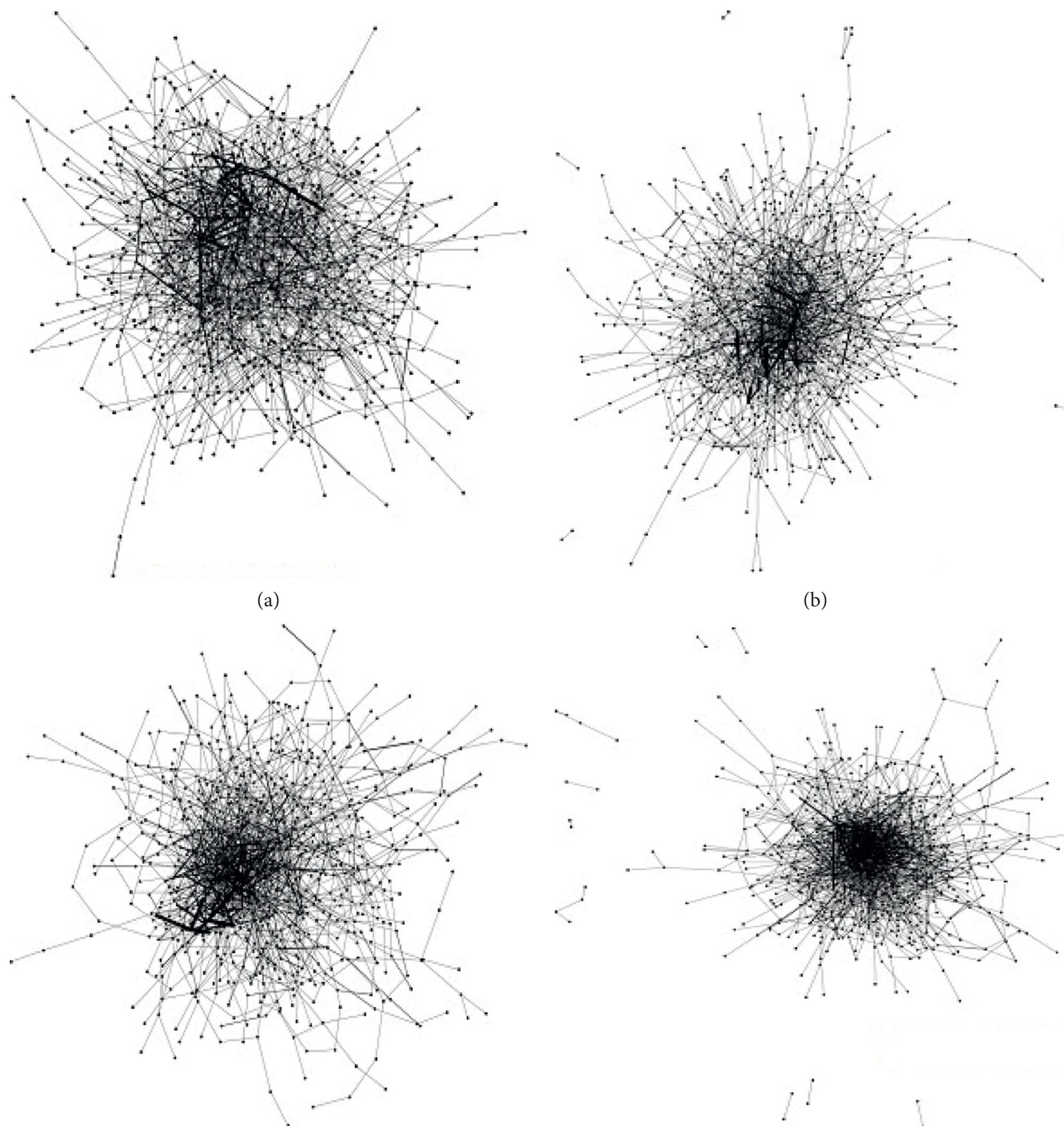
Figure 4: Enterprises' net income under different transformation costs: (a) Cu = 2, Cb = 4; (b) Cu = 1.5, Cb = 3; (c) Cu = 1, Cb = 2; (d) Cu = 0.5, Cb = 1.

$p1 = 0.5$, Cu = 1, Cb = 2; (c) $p1 = 0.7$, Cu = 1, Cb = 2; (d) $p1 = 0.3$, Cu = 2, Cb = 4; (e) $p1 = 0.5$, Cu = 2, Cb = 4; and (f) $p1 = 0.7$, Cu = 2, Cb = 4, respectively, and conducts six groups of multiagent simulations for validation of effects of demand-side policies under two conditions of relatively low transformation cost and relatively high transformation cost. Related experiment results are as follows.

4.2.1. Enterprises' Transformation Willingness. Figure 6 shows distribution of enterprises' transformation willingness under different demand-side policies when $R = 60$. The first row shows the situation when digital transformation cost is relatively low, and the second row shows the situation when digital transformation cost is relatively high. It can be seen from the figure that, at the same digital transformation cost, there is a small difference in number of enterprises willing to carry out digital transformation under different demand-side policies, but only feel enterprises have strong transformation willingness when $p1$ is relatively small. Accompanied with a gradual increase in $p1$, those willing to carry out digital transformation will all have strong transformation willingness.

Increase in digital transformation cost will lead to dramatic decrease in number of enterprises willing to carry out digital transformation, but changes in transformation cost will not change distribution of strengths of transformation willingness.

4.2.2. Enterprises' Transformation Proportion. Figure 7 show proportions of enterprises carry out digital transformation under demand policies of different strengths when $R = 60$. The first row shows the situation when digital transformation cost is relatively low, and the second row shows the situation when digital transformation cost is relatively high. Regardless of changes in transformation cost, accompanied with strengthening of demand-side policies, enterprises choosing to carry out digital transformation continuously increase. However, when transformation cost is relatively low (the first row), since most enterprises can try digital transformation, the guiding role of demand-side policies is mainly reflected by acceleration of different enterprises' digital transformation, which allows enterprises in the whole ecosystem to realize digitalization ASAP. When transformation cost is relatively high, strengthening of demand-side policies can significantly increase proportion of enterprises carrying out digital transformation in the ecosystem (from under 60% in Figure 7(d) to around 90% in Figure 7(f)).



(a) (b) (c) (d)

Figure 5: Network structures under different transformation costs: (a) Cu = 2, Cb = 4; (b) Cu = 1.5, Cb = 3; (c) Cu = 1, Cb = 2; (d) Cu = 0.5, Cb = 1.

Table 2: The partial indicators of cooperative innovation network under different transformation costs.

Costs	N_I	A_{CE}	A_{CE}_S	A_C	A_C_S
Cu = 2, Cb = 4	48	3.567	4.034	4.569	5.826
Cu = 1.5, Cb = 3	67	3.479	4.49	4.797	7.565
Cu = 1, Cb = 2	103	3.518	4.716	5.064	8.189
Cu = 0.5, Cb = 1	95	4.393	5.702	5.943	10.298

4.2.3. Enterprises' Digital Levels. Figure 8 shows distribution of digital levels of enterprises succeed at digital transformation under demand-side policies of different strengths when $R = 60$. The first row shows the situation when digital transformation cost is relatively low, and the second row shows the situation when digital transformation cost is relatively high.

It can be seen from the figure that, regardless of changes in transformation cost, strengthening of demand-side policies will lead to gradual rise in average digital level and maximum digital level of enterprises in ecosystem. When $p1 = 0.3$, 0.5, and 0.7, maximum digital levels of enterprises are around 30, 40, and 50, respectively. However, increase in

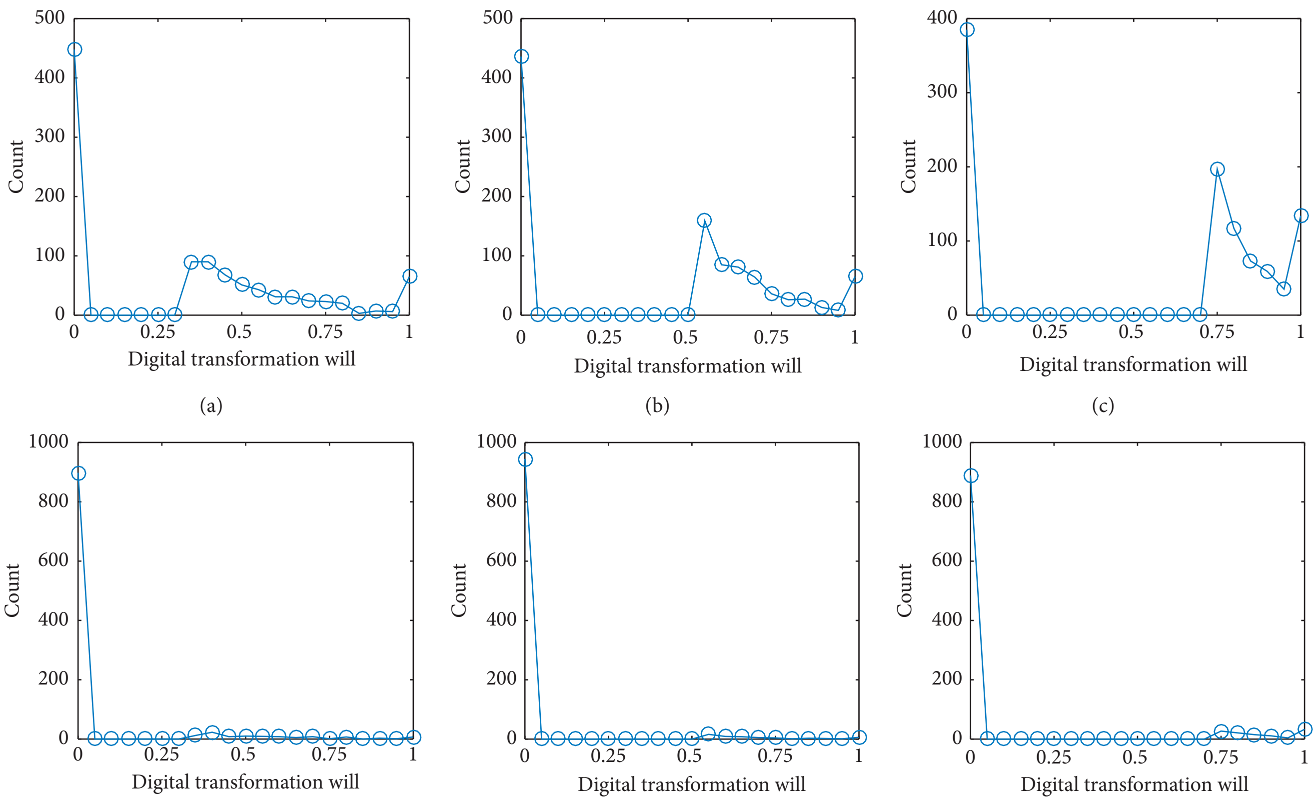


Figure 6: Enterprises' transformation willingness under different demand-side policies: (a) p1 = 0.3, Cu = 1, Cb = 2; (b) $p1 = 0.5$, Cu = 1, Cb = 2; (c) $p1 = 0.7$, Cu = 1, Cb = 2; (d) $p1 = 0.3$, Cu = 2, Cb = 4; (e) $p1 = 0.5$, Cu = 2, Cb = 4; (f) $p1 = 0.7$, Cu = 2, Cb = 4.

transformation cost will make most enterprises stay at relatively low digital levels and thus make average digital level of enterprise lower than that at low transformation cost, but maximum digital levels of enterprises remain unaffected.

4.2.4. Enterprises' Net Income. Figure 9 shows relations between digital level and net income of enterprises under demand-side policies of different strengths when $R = 60$, in which the first row shows the situation when digital transformation cost is relatively low and the second row shows the situation when digital transformation cost is relatively high.

It can be seen from Figure 9 that enterprises with high digital levels all tend to possess greater net income, and it is a ubiquitous characteristic. Besides, changes in strengths of demand-side policies mainly change distribution of digital levels on x-axis, while net income of enterprises on y-axis do not change obviously with changes in strengths of demand-side policies. The potential cause is strengthening of demand-side policies can gradually increase overall digital level of innovation ecosystem, but the market size is limited. So, when all enterprises possess certain digital level, the dividend from digital level will gradually decrease.

4.2.5. Network Structure. Table 3 shows partial indicators of cooperative innovation network under demand-side policies of different strengths when $R = 60$. The lower the digital transformation cost, the stronger the demand-side policies, the greater the digital transformation willingness of enterprises, the higher the eventual digital level of innovation ecosystem, and the more obvious the core-periphery structure in the network. When digital transformation cost is relatively high, only few enterprises can carry out digital transformation, and most enterprises' digital levels are at a relatively low level. Although the network does have core-periphery structure, enterprises' willingness to carry out digital transformation has small impact on network structure.

4.3. Impacts of Environmental Policies on Innovation Ecosystem. This section studies impacts of environmental policies on enterprises' digital transformation, enterprises' net income distribution, and network structure of innovation ecosystem. Environmental policies are controlled by parameter pr in the model of this paper; the greater the pr, the greater the impact of other enterprises' isomorphic pressure on an enterprise's digital transformation. Similar to Section 4.2, this section fixes parameters of $p1 = 0.5$ and $R = 60$, assumes (a) pr = 0.3, Cu = 1, Cb = 2, (b) pr = 0.5, Cu = 1, Cb = 2, (c) pr = 0.7, Cu = 1, Cb = 2, (d) pr = 0.3, Cu = 2, Cb = 4, (e) pr = 0.5, Cu = 2, Cb = 4, and (f) pr = 0.7, Cu = 2, Cb = 4, respectively, and conducts six groups of multiagent simulations for validation of effects of

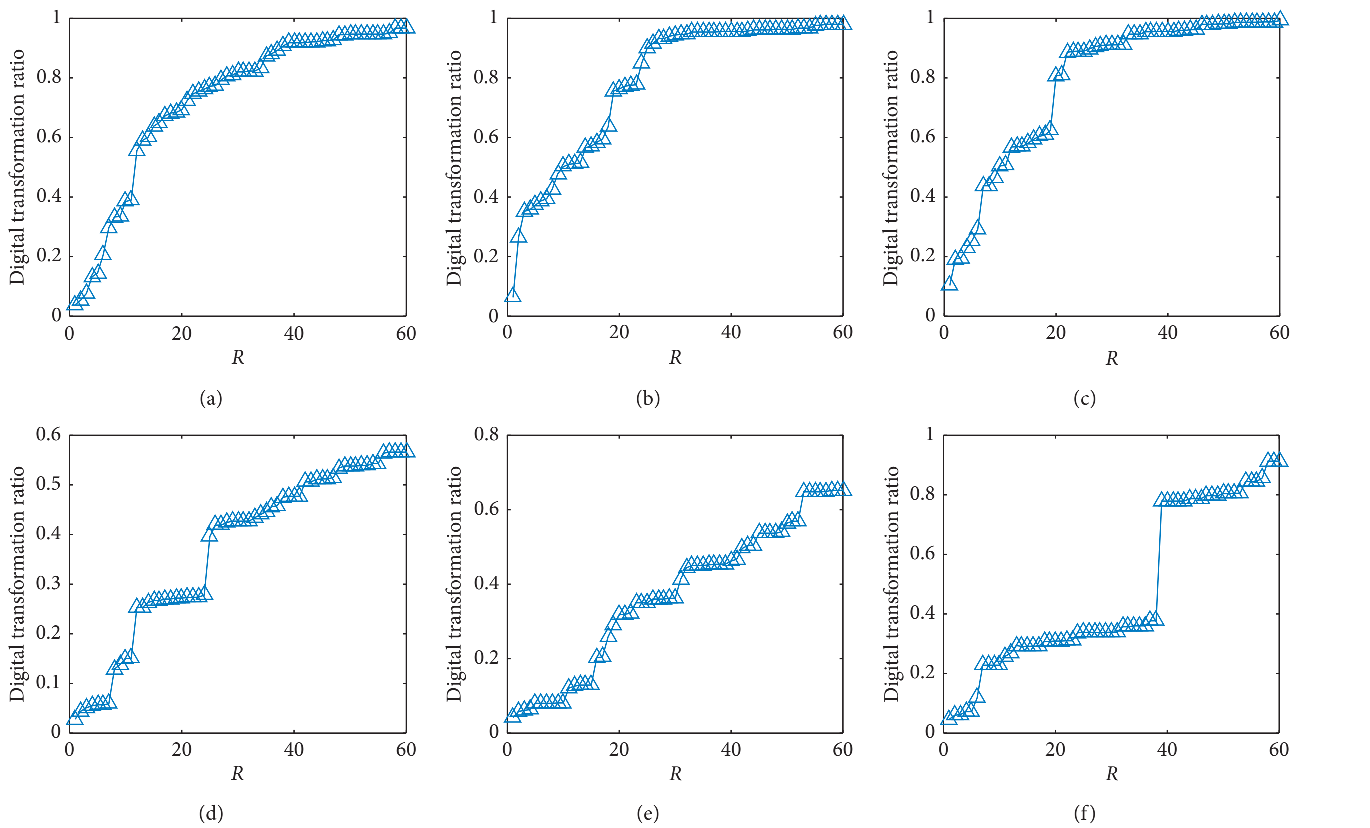


Figure 7: The proportions of enterprises carry out digital transformation under different demand-side policies: (a) $p1 = 0.3$, Cu = 1, Cb = 2; (b) $p1 = 0.5$, Cu = 1, Cb = 2; (c) $p1 = 0.7$, Cu = 1, Cb = 2; (d) $p1 = 0.3$, Cu = 2, Cb = 4; (e) $p1 = 0.5$, Cu = 2, Cb = 4; (f) $p1 = 0.7$, Cu = 2, Cb = 4.

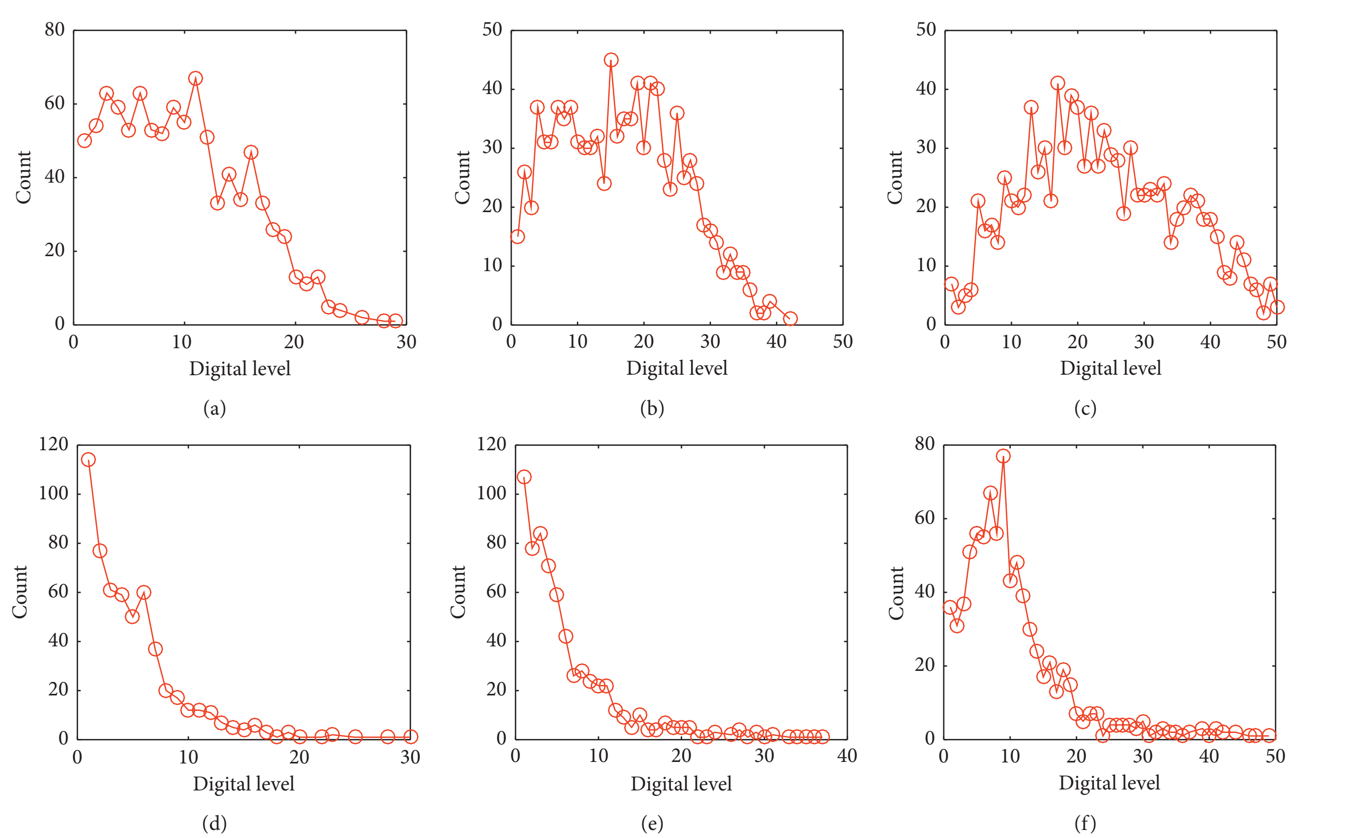


Figure 8: The digital levels of enterprises under different demand-side policies: (a) $p1 = 0.3$, Cu = 1, Cb = 2; (b) $p1 = 0.5$, Cu = 1, Cb = 2; (c) $p1 = 0.7$, Cu = 1, Cb = 2; (d) $p1 = 0.3$, Cu = 2, Cb = 4; (e) $p1 = 0.5$, Cu = 2, Cb = 4; (f) $p1 = 0.7$, Cu = 2, Cb = 4.

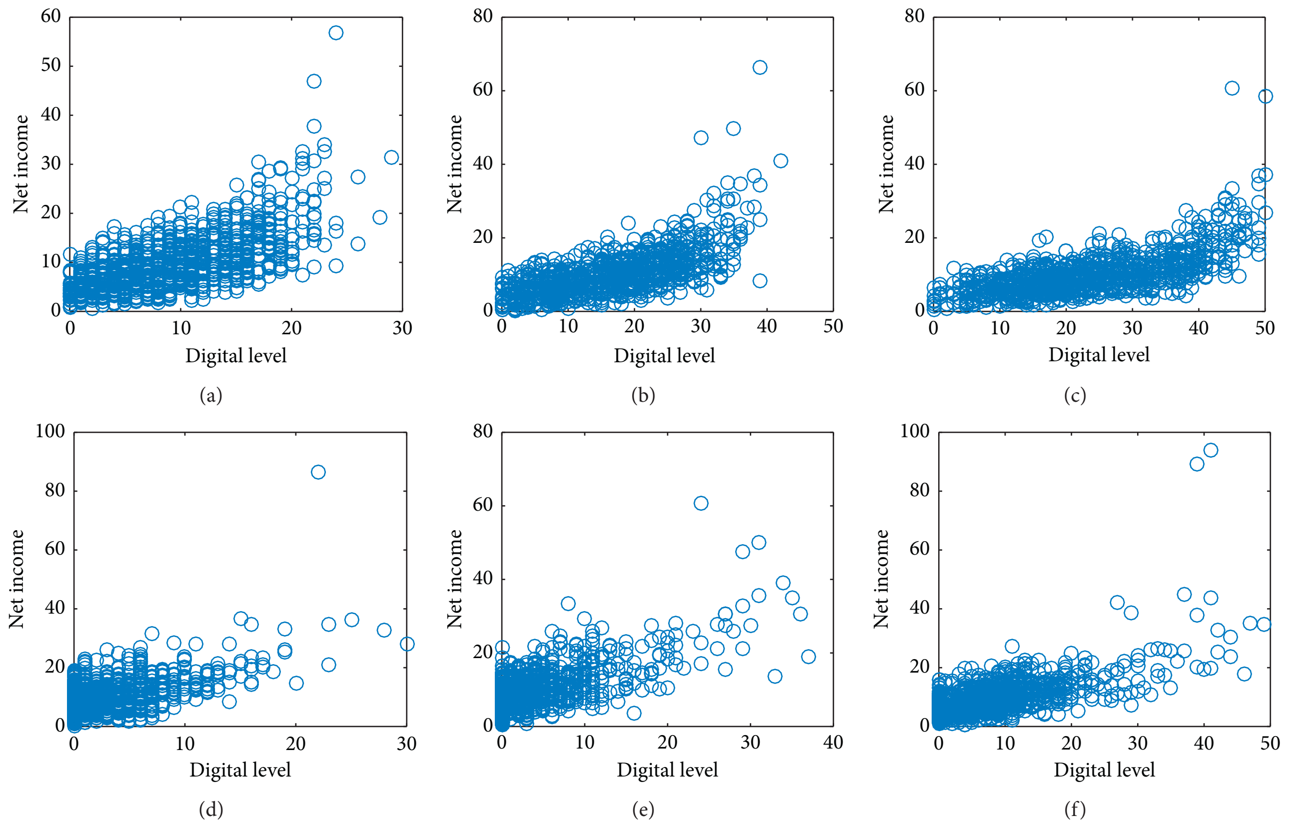


Figure 9: Enterprises' net income under different demand-side policies: (a) $p1 = 0.3$, Cu = 1, Cb = 2; (b) $p1 = 0.5$, Cu = 1, Cb = 2; (c) $p1 = 0.7$, Cu = 1, Cb = 2; (d) $p1 = 0.3$, Cu = 2, Cb = 4; (e) $p1 = 0.5$, Cu = 2, Cb = 4; (f) $p1 = 0.7$, Cu = 2, Cb = 4.

Table 3: The partial indicators of cooperative innovation network under different demand-side policies.

Costs	N_I	A_{CE}	A_{CE}_S	A_C	A_C_S
$p1 = 0.3$, pr = 0.5, Cu = 1, Cb = 2	94	4.011	4.908	5.341	7.071
$p1 = 0.5$, pr = 0.5, Cu = 1, Cb = 2	103	3.518	4.716	5.064	8.189
$p1 = 0.7$, pr = 0.5, Cu = 1, Cb = 2	111	3.386	4.743	5.093	15.829
$p1 = 0.3$, pr = 0.5, Cu = 2, Cb = 4	36	4.002	4.578	4.916	6.016
$p1 = 0.5$, pr = 0.5, Cu = 2, Cb = 4	48	3.567	4.034	4.569	5.826
$p1 = 0.7$, pr = 0.5, Cu = 2, Cb = 4	59	3.581	4.213	4.784	6.308

environmental policies under two conditions of relatively low transformation cost and relatively high transformation cost. Related experiment results are as follows.

4.3.1. Enterprises' Transformation Willingness. Figure 10 shows distribution of enterprises' transformation willingness under different environmental policies when $R = 60$. The first row shows the situation when digital transformation cost is relatively low, and the second row shows the situation when digital transformation cost is relatively high.

It can be seen from the figure that, at the same digital transformation cost, there is a small difference in number of enterprises willing to carry out digital transformation under different environmental policies, but the number of enterprises with high transformation willingness continuously increases accompanied with a gradual increase in $p1$. This impact is similar to that of demand-side policies, but what different from demand-side policies is: under low level of demand-side policies, the minimum transformation willingness of enterprises willing to transform is also at a low level. Under high level of demand-side policies, the minimum transformation willingness of enterprises willing to transform is also at a high level, as indicated in Figure 6. However, regardless of level of environmental policies, the minimum transformation willingness of enterprises willing to transform is similar around 0.55, as indicated in Figure 10, and strengthening of environmental policies only makes enterprises' transformation willingness distributed more evenly. From the perspective of innovation

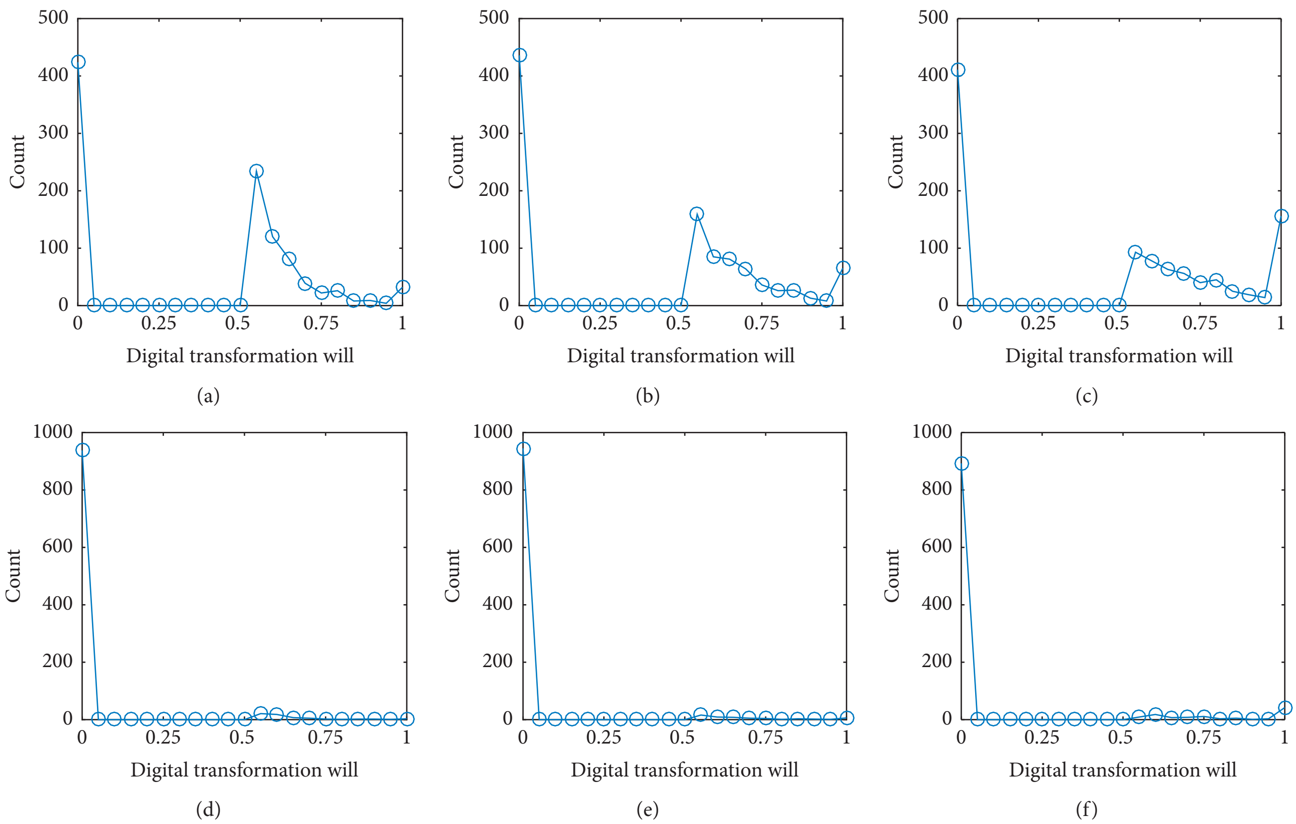


Figure 10: Enterprises' transformation willingness under different environmental policies: (a) pr = 0.3, Cu = 1, Cb = 2; (b) pr = 0.5, Cu = 1, Cb = 2; (c) pr = 0.7, Cu = 1, Cb = 2; (d) pr = 0.3, Cu = 2, Cb = 4; (e) pr = 0.5, Cu = 2, Cb = 4; (f) pr = 0.7, Cu = 2, Cb = 4.

ecosystem, it can be taken as demand-side policies' impacts on transformation willingness are more immediate and effective than environmental policies' impacts on transformation willingness.

4.3.2. Enterprises' Transformation Proportion. Figure 11 shows proportions of enterprises carry out digital transformation under different environmental policies. The first row shows the situation when digital transformation cost is relatively low, and the second row shows the situation when digital transformation cost is relatively high.

Regardless of changes in transformation cost, impacts of environmental policies on proportion of enterprises carrying out digital transformation are not as significant as impacts of demand-side policies.

4.3.3. Enterprises' Digital Levels. Figure 12 shows distribution of digital levels of enterprises succeed at digital transformation under different environmental policies when $R = 60$. The first row shows the situation when digital transformation cost is relatively low, and the second row shows the situation when digital transformation cost is relatively high.

It can be seen from the figure that, regardless of changes in transformation cost, strengthening of environmental policies will make average digital level of enterprises in ecosystem gradually increase, but the effects of environmental policies are less significant in comparison with demand-side policies.

4.3.4. Enterprises' Net Income. Figure 13 shows relations between digital level and net income of enterprises under different environmental policies when $R = 60$, in which the first row shows the situation when digital transformation cost is relatively low and the second row shows the situation when digital transformation cost is relatively high. As indicated in Figure 13, enterprises with high digital levels tend to possess a greater net income, which is in consistence with conclusions of Figures 4 and 9.

4.3.5. Network Structure. Table 4 shows partial indicators of cooperative innovation network under different environmental policies when $R = 60$. The network shows core-periphery structure under both digital transformation costs, but environmental policies have insignificant impacts on network structure.

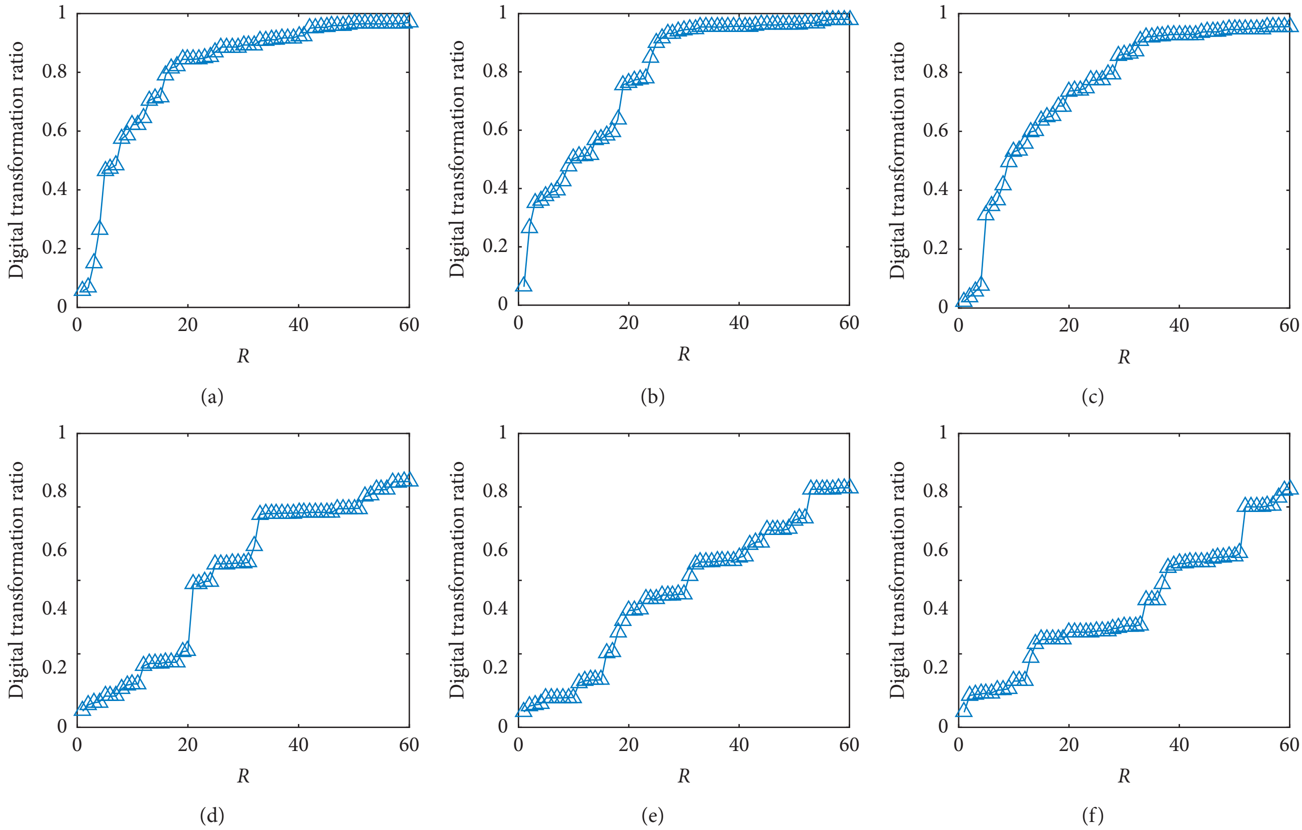


Figure 11: The proportions of enterprises carry out digital transformation under different environmental policies: (a) pr = 0.3, Cu = 1, Cb = 2; (b) pr = 0.5, Cu = 1, Cb = 2; (c) pr = 0.7, Cu = 1, Cb = 2; (d) pr = 0.3, Cu = 2, Cb = 4; (e) pr = 0.5, Cu = 2, Cb = 4; (f) pr = 0.7, Cu = 2, Cb = 4.

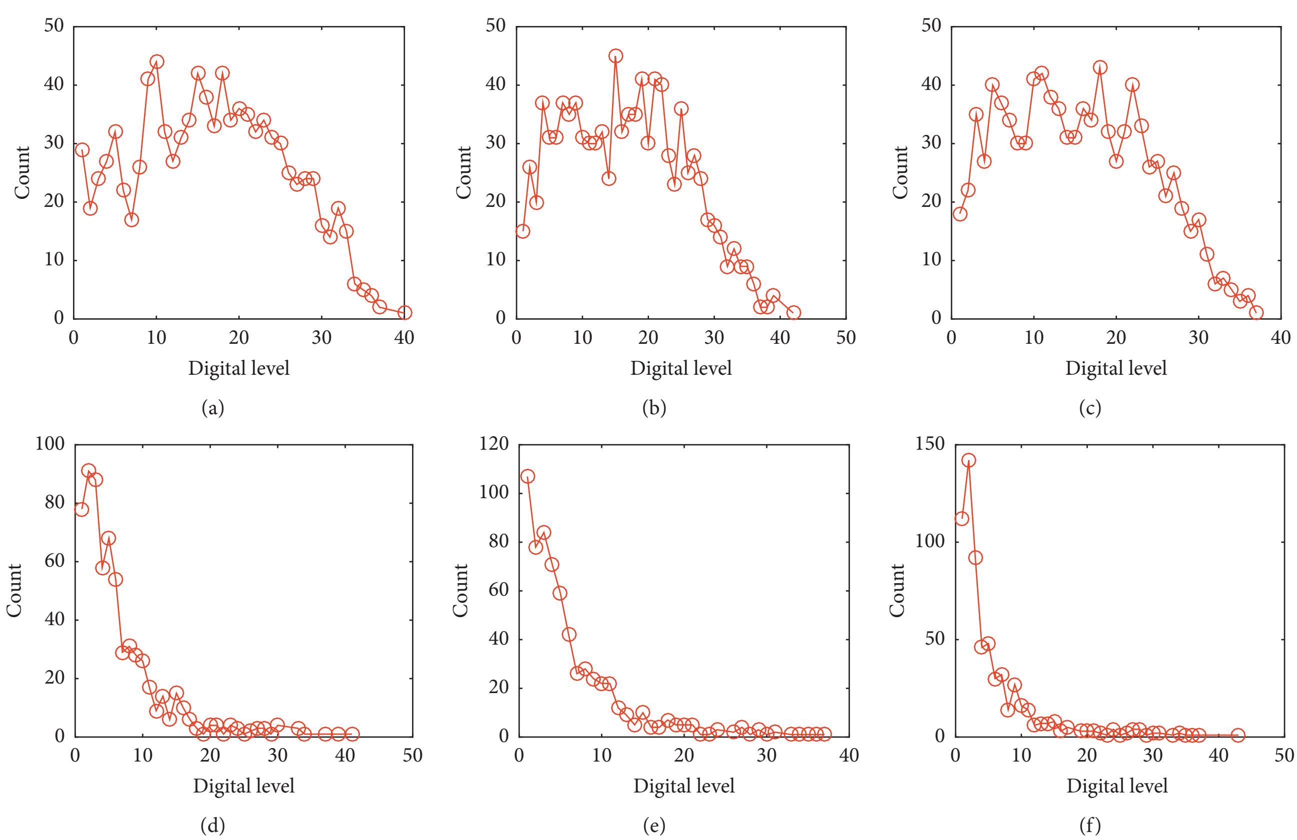


Figure 12: The digital levels of enterprises under different environmental policies: (a) pr = 0.3, Cu = 1, Cb = 2; (b) pr = 0.5, Cu = 1, Cb = 2; (c) pr = 0.7, Cu = 1, Cb = 2; (d) pr = 0.3, Cu = 2, Cb = 4; (e) pr = 0.5, Cu = 2, Cb = 4; (f) pr = 0.7, Cu = 2, Cb = 4.

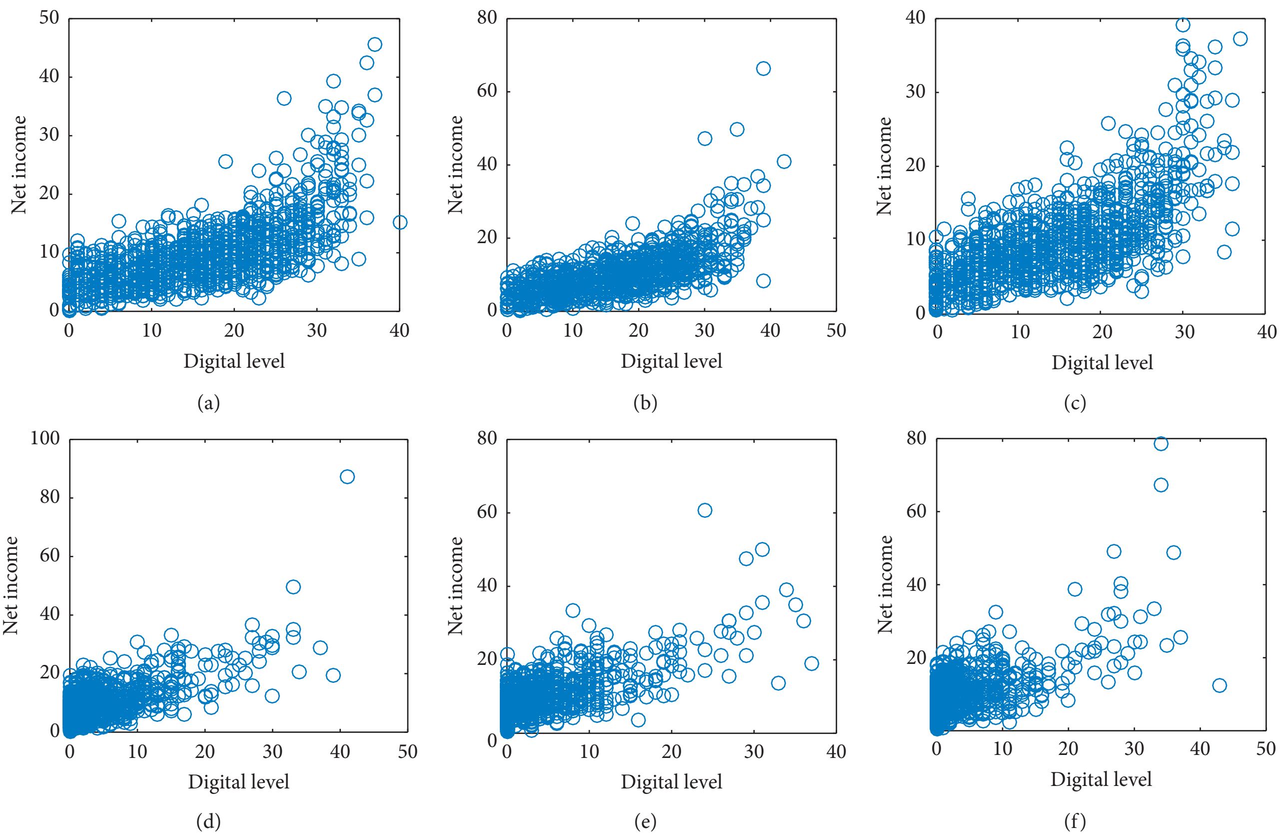


FIGURE 13: The digital level of enterprises under different environmental policies when $R = 60$: (a) pr = 0.3, Cu = 1, Cb = 2; (b) pr = 0.5, Cu = 1, Cb = 2; (c) pr = 0.7, Cu = 1, Cb = 2; (d) pr = 0.3, Cu = 2, Cb = 4; (e) pr = 0.5, Cu = 2, Cb = 4; (f) pr = 0.7, Cu = 2, Cb = 4.

TABLE 4: The partial indicators of cooperative innovation network under different environmental policies.

Costs	N_I	A_{CE}	A_{CE}_S	A_C	A_C_S
$p1 = 0.5$, pr = 0.3, Cu = 1, Cb = 2	115	3.759	5	5.39	8.376
$p1 = 0.5$, pr = 0.5, Cu = 1, Cb = 2	103	3.518	4.716	5.064	8.189
$p1 = 0.5$, pr = 0.7, Cu = 1, Cb = 2	90	3.736	4.838	5.182	7.772
$p1 = 0.3$, pr = 0.3, Cu = 2, Cb = 4	33	3.847	4.322	4.836	5.824
$p1 = 0.5$, pr = 0.5, Cu = 2, Cb = 4	48	3.567	4.034	4.569	5.826
$p1 = 0.5$, pr = 0.7, Cu = 2, Cb = 4	34	3.654	4.032	4.569	5.523

5. Discussion and Conclusions

5.1. Main Findings. Facilitation of the digital transformation of innovation ecosystem by means of policies is an important approach to develop the digital economy. This paper builds a multiagent model to study the effects of supply-side policies, demand-side policies, and environmental policies on the digital transformation of innovation ecosystem, and basic conclusions drawn from numerical experiments are as follows.

Firstly, supply-side policies, demand-side policies, and environmental policies all facilitate the digital transformation of innovation ecosystem. From the perspective of effects, the effects of supply-side policies are greater than that of demand-side policies, and the effects of environmental policies are the weakest. Secondly, the digital levels of enterprises play an important intermediate and transmission role in the transformation process. On the one hand, enterprises' digital levels show a positive correlation with their net income; the higher the enterprises' digital levels, the more likely for them to occupy a higher market share, and thus the higher the net income. On the other hand, the higher the digital levels of individuals, the more obvious the core-periphery structure in the cooperative innovation network. In other words, there are few enterprises in the system (the core of network), which have long-term stable cooperative relations.

5.2. Theoretical and Policy Implications. This paper is associated with literature in the fields of the innovation ecosystem, digital transformation, and technological policies. Research results have contributions to previous literatures from two aspects. Firstly, this paper carries research on the relationship between policy intervention and innovation ecosystem transformation [8] further. Existing researches pay close attention to the way to get rid of innovation ecosystem transformation failures with technological policies. This paper further focuses on the digital transformation of innovation ecosystem, studies effects of supply-side, demand-side, and environmental policies on digital transformation, and thus carries existing researches further. Secondly, this paper also plays an active role in the development of innovation ecosystem modeling. Theoretical analysis and case study are main research methods of innovation ecosystem at the moment, and application of modeling and computational experiments is still obviously inadequate [9], so they fail to effectively depict and represent the complex system characteristics of the innovation ecosystem. The agent-based model built by this paper can help to make up this shortage of research.

This paper also has positive implications for policy practices of digital transformation. First of all, according to the results of this study, policymakers need to choose appropriate policy tools to promote the digital transformation of innovation ecosystem. Specifically, the supply-side policy can effectively break the bottleneck in the transformation process, which should be the first choice of policy tools. Secondly, considering the diminishing marginal effect of policy tools, policymakers should make policy from the perspective of dynamic combination. We should not only consider the process of digital transformation of innovation ecosystem to adjust the policy tools in time but also enlarge the scope of different policy tools to realize the integration and optimization of effects. The concept of tentative governance emerged in recent years enlightens this practice to a huge degree [28]. Third, policymakers need to pay more attention to the microeffect of policy. According to the research of this paper, the digital level of enterprises plays a good intermediary role in the whole process of digital transformation of innovation ecosystem. Therefore, policymakers need to emphasize the role of policy tools in enhancing the digital level of enterprises, especially the leading enterprises which dominate innovation network. Fourth, to enterprises and other innovation agents, digital transformation can help enterprises getting a greater competitive advantage in the innovation ecosystem, occupying core position in the innovation network, and forming relatively stable cooperative relationships with other agents. Therefore, enterprises shall use policy conditions for the implementation of transformation in a more active manner.

Data Availability

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

Conflicts of Interest

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

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Research Article

China's Auto Industry Upgrade Process Based on Aging Chain and Coflow Model

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To protect energy resources and alleviate environmental pollution, many countries attach great importance to the transformation of traditional industries into clean energy industries. In this paper, fuel vehicles (FVs), hybrid vehicles (HVs), and electric vehicles (EVs) are included in the research. Then, based on the aging chain and coflow theory of SDs, we construct a dynamic matching model of the auto industry upgrade process and its energy consumption attributes. The simulation results of China's auto industry show that (1) the upgrading of the auto industry is an evolutionary process from high energy consumption and high pollution to low energy consumption and no pollution and the transition from FVs and HVs to EVs will undergo two adjustments; (2) simply reducing energy supply does not have the expected impact on vehicle size and vehicle energy consumption intensity and only by adjusting the energy supply and upgrade ratios together, energy utilization efficiency can be improved; (3) market screening time has an impact on auto industry upgrade speed by affecting vehicle market share and dwell time; (4) China's auto industry upgrade process should adhere to "problem-oriented" and strengthen consumer guidance, technology innovation, and infrastructure construction. The conclusions can provide references for industrial policy adjustment and industrial structure optimization.

1. Introduction

Transportation, especially autos, consumes large amounts of fossil fuels and has a significant impact on air pollution, greenhouse gas emission, and global warming [1, 2]. China Industry Information Network (CIIN) shows that auto production increased from 2.07 million to 24.5 million during 2000–2015, with an average annual growth rate of 17.92% [3]. Meanwhile, the statistics of the China Association of Automobile Manufacturers (CAAM) show that the sales of autos in 2018 reached 28.08 million [4]. The rapid growth of auto production and sales drives the overall development of the industry, but it also causes a continuous increase in traffic energy consumption and air pollution. This result is mainly related to the fact that the auto industry structure is still dominated by fuel vehicles (FVs) [5]. In order to protect energy resources and the environment, the Chinese government chooses new energy vehicles (including hybrid vehicles (HVs) and electric vehicles (EVs)) as a new strategy to achieve the green development of the auto industry [6]. In addition, the government also adopts differentiated measures for high-pollution and low-pollution vehicles. For example, a CO_2 emission tax is imposed on highly polluting fuel vehicles, while new energy vehicles are provided with incentives and subsidies [7]. With the promotion of new energy vehicles, their advantages compared to traditional fuel vehicles are increasingly apparent, and this strategy makes renewable energy resources (such as electricity and solar energy) become a new way to solve traffic problems [8].

From the perspective of industry development, the auto industry is a technology-oriented industry. Under the background of a new round of technological revolution, the development of auto products with less polluting technologies has undoubtedly become the primary goal of automakers [9, 10]. Automakers are devoted to developing eco-friendly vehicles to help reduce environmental hazards, including common HVs, plug-in HVs, fuel cell vehicles, and EVs [11]. Some or all of these vehicles are driven by renewable energy, with low pollutants and low carbon footprint. They are natural supplementary resources and can be transformed into secondary energy [12]. At present, the types of vehicles classified by energy-driven systems in the Chinese market mainly include FVs (gasoline vehicles and diesel vehicles), HVs (common HVs and plug-in HVs), and EVs [13]. It shows that technological advancement makes auto products more diversified and personalized. Therefore, the optimization of auto structure is also more urgent.

As the issue of environmental pollution has become a hot topic of great concern in many countries, industries, and fields [14, 15], scholars have successively studied the energy consumption and environmental impact of different vehicles. Wang et al. [16] analyzed environmental pollution problems caused by fuel combustion. Considering the high energy consumption and high pollution of FVs, Tang et al. [17] pointed out that the government has successively implemented a series of measures to limit the growth of FVs. These measures provide opportunities for the development of HVs and indicate that reducing emissions and improving fuel economy should be the direction of the auto industry. Research by Dextreit et al. [18] demonstrated that the energy consumption of HVs is in the range of 20–30% lower than FVs. Yu et al. [19] also believed that HVs have better power and economy than FVs, which is mainly because battery energy optimizes power efficiency. Later, Clairand et al. [1] pointed out that EVs are more eco-friendly and efficient than HVs. The development of EVs was considered to be a particularly promising strategy to promote the sustainable development of the auto industry [20, 21]. A comparative literature by Liu et al. [22] showed that energy consumption of EVs is lower than that of FVs and HVs, and under the same driving distance, HVs and EVs saved 4.4% and 19.7%, respectively, compared with FVs, that is, the promotions of HVs and EVs are more conducive to reducing the emissions of SO_2, NO_x, CO, and other pollutants. Besides, Werber et al. [23] also found that EVs can become a substitute for FVs by comparing the life cycle costs, and this replacement is highly efficient and low cost. Therefore, the upgrading of the auto industry (from FVs and HVs to EVs) has become an inevitable choice to enhance industrial international competitiveness.

The structural transformation process of the auto industry involves many factors, and each factor interacts with each other to form a complex and nonlinear evolution process. Most existing literature used modeling methods to focus on the optimization design of vehicle performance and technical innovation. For example, research studies on HVs and EVs focused on the optimal location of charging infrastructures [24, 25], optimal route scheduling and navigation strategy [26, 27], and vehicle scheduling problem [28]. Besides, some scholars also studied the auto industry using the system dynamics (SDs) method. For example, Li et al. [29] analyzed the influence factors of technological innovation capability of the auto industry and their interrelationships, which provided a new reference for technological innovation decision-making. Miao and Liu [30] studied EV's industrialization process and analyzed the impact of government policies on the auto industry chain in the short term and long term. Cheng and Mu [31] used the SD game model to discuss the new energy vehicle's subsidy mechanism, impact, and strategy, which can provide a reference for industry policy adjustment and enterprise production decisions.

However, in terms of existing literature, the research perspective and content still lack integrity and systematicness. On the one hand, scholars mostly focus on a single vehicle or a comparative study of two types of vehicles. There is no systematic analysis of the auto industry structure (from FVs and HVs to EVs) from the perspective of industrial continuous evolution. On the other hand, there is no literature focus on the good matching between the SDs method and auto industry structure transformation process, and this method is used to construct the model and predict auto industry's overall development trend. In terms of practical development, the development of China's auto industry still exists some problems: First, auto manufacturing, use, scrapping, and disposal processes consume nonrenewable energy and emit large pollutants [32]. The consumption of gasoline and diesel accounts for about 55% of total petrol and diesel consumption [33]. The shortage of resources and environmental degradation caused by excessive energy consumption inevitably affect the long-term development of the auto industry. Second, at present, FVs occupy a large market share in Chinese auto market, while the market shares of HVs and EVs are small. The unreasonable market structure is also the bottleneck for the auto industry development. Third, the auto industry upgrade process is guided by national policies and industrial goals and scholars also conduct research studies around this content. However, theoretical research still lags behind industrial development, which further verifies the gap between literature and practice. Therefore, it is of great theoretical and practical significance to study the auto industry upgrade process from a systematic perspective.

SDs is good at analyzing long-term evolution characteristics and is suitable for exploring the dynamic feedback mechanism of nonlinear and time delay [34]. An aging chain in SDs refers to the flow rate of any object (enters or exits the stock and flow system) related to the object's age. The aging chain is suitable for modeling and analyzing changes of any stock age structure, which has a wide range of applications. Coflow is a record of stock attributes in the stock and flow system, which can be any feature of stock [35]. The auto industry upgrade process includes multiple subsystems. The interaction between various subsystems and internal factors of the subsystem makes the system present characteristics such as delay and feedback, which are very suitable for research using the SDs method. Besides, the tracking surveys of auto enterprises find that the listing rate, upgrade rate, and elimination rate of different vehicles are closely related to vehicle aging. The limitation of energy supply makes vehicle energy consumption become an important characteristic affecting vehicle aging speed. Therefore, the auto industry upgrade process and its energy consumption attributes are well matched with the aging chain and coflow model of SDs.

The transformation and upgrading of the auto industry have become an inevitable trend. Based on the double gap in the literature and practice, firstly, from the two perspectives of environment and energy constraints, the scope of this paper includes FVs, HVs, and EVs. Then, using the aging chain and coflow theory of SDs, a matching model of the auto industry upgrade process and its energy consumption attributes is constructed. The model presents the evolution process of the auto industry from high emissions to low emissions and then to zero emissions from a dynamic perspective. Secondly, the listing rate is a record of the activity status of the "flow" in the auto industry upgrade process subsystem, which reflects the time change of the "flow." It is not only related to the technological innovation speed of enterprises but also closely related to the market demand. Specifically, this paper believes that the listing rate represents the "input" of various types of vehicles and is an important indicator reflecting the upgrading speed of the auto industry and the rationality of industrial structure. Therefore, to further investigate the relationship between the internal structure of the auto industry upgrade process and its dynamic behavior, this paper uses listing rate as a test function to verify the rationality of the model. Meanwhile, this paper also analyzes the influence of energy supply upgrade ratios and market screening time on the sustainable development of the auto industry through the design of different scenarios and finds the main factors that affect the upgrading speed of the auto industry. In addition, this paper further discusses the matching between the theoretical model and industrial situation. The conclusions can provide new insight and suggestions for the optimization and adjustment of industrial structure.

The remainder of this paper is organized as follows. Section 2 identifies model boundaries and constructs the causal loop diagram and stock and flow diagram of the auto industry upgrade process. Section 3 makes a detailed analysis and discussion of simulation results. Section 4 gives the conclusions and policy recommendations.

2. Methods and Model Construction

2.1. System Dynamics. Complex system science mainly focuses on the complexity phenomenon and the evolution of research objects, and all elements within the system are closely related [36]. SDs was first proposed by Professor Forrester in the 1950s, which is used to analyze complex nonlinear problems. It can explain the complex relationships between multiple elements from a macroperspective and predict the dynamic feedback of historical dimensions [35, 37]. The modeling steps of SDs mainly include clarifying problems and determining the system boundaries, proposing initial hypotheses and constructing the causal loop diagram, building the stock and flow diagram by equation design, and carrying out simulation tests [38]. In addition, SDs can optimize models and simulate reality by adjusting model boundaries, structures, parameters, and setting scenario. The aging chain in SDs refers to the flow rate of any object (individual) entering or exiting the stock and flow system (whole) related to its age, that is, the rate at which individuals leave the system is determined by their age. This characteristic determines that the aging chain theory can be applied to various fields. Coflow is a record of stock (level variable) attributes in a stock and flow system, which can be any characteristic associated with the level variable [35, 38]. Richmond [39] and Sterman [34] pointed out that when the quantity and quality of level variables have an impact on the system, the aging chain and coflow should be used together to describe the complex feedback relationship within the system.

The auto industry upgrade process is a nonlinear, complex, and dynamic system. It is difficult to reveal the upgrading rule of the auto industry by conventional analysis methods, and it is also difficult to describe the complex relationship between subsystems. Therefore, this paper uses the SDs method to study this complex system. From the government's restrictive policies (banning FVs) and supporting policies (HVs and EVs), the update of auto products has input (product R&D, listing, and upgrading) and output (product upgrading and eliminating) in each stage. This process is closely related to product life (age), showing obvious aging chain characteristics. Therefore, this paper adopts the aging chain theory to construct the auto industry upgrade model. In addition, considering the elimination of auto products is also the result of energy and environmental problems, and vehicle energy consumption records the energy demand of different vehicles, which is also an important criterion for measuring whether the industrial structure is reasonable. Therefore, based on the aging chain model, this paper further constructs the coflow model of energy consumption that matches the aging chain model. The main steps of model construction include the following:

(1) Causal loop diagram: based on the aging chain and coflow theory of SDs and combined with the empirical investigation of the auto industry, this paper identifies the three stages of the auto industry upgrade process and constructs a causal loop diagram by clarifying the relationships between variables.

(2) Stock and flow diagram: based on the causal loop diagram, the variables are divided into level variables, rate variables, and auxiliary variables, and the relationships between variables are nonlinearly processed. Then, the stock and flow diagram is constructed by equation design.

(3) Model testing and adjustment: the consistency of the model is tested with the real world. Test functions are used to check the graphical trend of output results to further adjust the model structure.

(4) Model simulation: the Vensim PLE software is used to conduct dynamic simulation analysis on the target variable by adjusting relevant parameters.

(5) Suggestions: according to the simulation results, this paper puts forward some recommendations.

2.2. Model Boundary and Basic Hypotheses. This paper uses level variables to determine system boundaries. The dynamic upgrading process of the auto industry mainly includes three major stages: FVs, HVs, and EVs. Considering that this paper aims to study the matching model between different vehicles and their corresponding energy requirements, the model's boundary involves FVs, HVs, EVs, and their energy consumption. This paper is an abstract model of the auto industry upgrade process. The following hypotheses are proposed for subsequent research:

H1: auto industry upgrade is a continuous and dynamic process. Vehicles that cannot withstand market inspection at each stage will be eliminated or withdrawn from the market.

H2: the energy supply is limited, and the industry upgrade process needs to match energy supply.

H3: the energy consumption of different vehicles is significantly different.

H4: the vehicle listing rate, market share, and energy consumption at different stages affect the whole structure of the auto industry.

H5: the impacts of the financial crisis and other unforeseen factors on the model are not considered.

2.3. Causal Loop Diagram. The causal loop diagram is a feedback analysis diagram that describes the structure of the system and the relationship between variables in the form of a causal relationship chain. It is composed of two types of elements: variables and connections, among which variables are the boundaries and influence factors of the system and the connections are represented by directional arrows and ± polarity, reflecting the relationship between variables and the direction of change. In this section, the relationships between vehicles and their energy consumption in each stage are sorted out, and a causal loop diagram is constructed. The causal loop diagram in this paper only considers the system formed by the interrelationship between variables and does not consider the influence of other possible factors on the whole system. The causal loop diagram is shown in Figure 1. Taking the dynamic changes of FVs as an example, FV upgrade rate and FV elimination rate will reduce the number of FVs. Therefore, in the stage of FVs, the closed loops based on the causal association between variables are all negative feedback loops. The main circuits of Figure 1 include the following:

(1) Total vehicle ⟶ vehicle market screening rate ⟶ vehicle listing rate ⟶ total vehicle

(2) Total vehicle ⟶ vehicle market screening rate ⟶ vehicle elimination rate ⟶ total vehicle

(3) FV ⟶ FV market screening rate ⟶ FV upgrade rate ⟶ FV

(4) FV ⟶ FV market screening rate ⟶ FV elimination rate ⟶ FV

(5) HV ⟶ HV market screening rate ⟶ HV upgrade rate ⟶ HV

(6) HV ⟶ HV market screening rate ⟶ HV elimination rate ⟶ HV

(7) FV energy consumption ⟶ FV energy consumption intensity ⟶ HV energy demand increase rate ⟶ FV energy consumption

(8) HV energy consumption ⟶ HV energy consumption intensity ⟶ EV energy demand increase rate ⟶ HV energy consumption

(9) EV energy consumption ⟶ EV energy consumption intensity ⟶ EV energy demand reduction rate ⟶ EV energy consumption

2.4. Stock and Flow Diagram. According to the causal loop diagram, this paper constructs a stock and flow diagram that matches the auto industry upgrade process with the energy consumption demand. Figure 2 is composed of the auto industry upgrade process subsystem (the aging chain model) and the energy consumption subsystem (the coflow model), and the vehicle average energy consumption intensity is an intermediary bridge connecting two subsystems. The auto industry upgrade process subsystem includes FV subsystem, HV subsystem, and EV subsystem. The energy consumption subsystem includes FV energy consumption subsystem, HV energy consumption subsystem, and EV energy consumption subsystem. The model includes 6 level variables, 12 rate variables, and 14 auxiliary variables. Among them, the level variables are determined by inflow rate and outflow rate, which are cumulative values (integral equation) and can describe the system state. The rate variables reflect the characteristics of the level variable changing with time, which are differential equations. The auxiliary variables are intermediate variables that convey information between level variables and rate variables. The equation design between variables is shown in the following section.

2.5. Equation Design and Data Collection. Figure 2 shows that the variables in the subsystem interact with each other, and the subsystems are interrelated. This paper takes the FV subsystem as an example to explain the key variables and main equations as follows:

(1) FV = INTEG (FV listing rate − FV upgrade rate − FV elimination rate, initial value). The FV is affected by the FV listing rate, FV upgrade rate, and FV elimination rate. Among them, the FV listing rate indicates R&D speed, and the faster the FV listing rate, the more the number of FVs. The FV upgrade rate indicates the rate at which the FVs are converted to HVs. The higher the FV upgrade rate, the lower the number of FVs. The FV elimination rate refers to the rate at which the FV fails to market or exits (the life is exhausted). The higher the FV elimination rate, the lower the number of FVs. The initial value is derived from the real statistics of vehicles.

(2) FV market screening rate = FV/FV screening time. The FV market screening rate is determined by FV and FV screening time. The FV market screening rate is proportional to FV and inversely proportional to FV screening time.

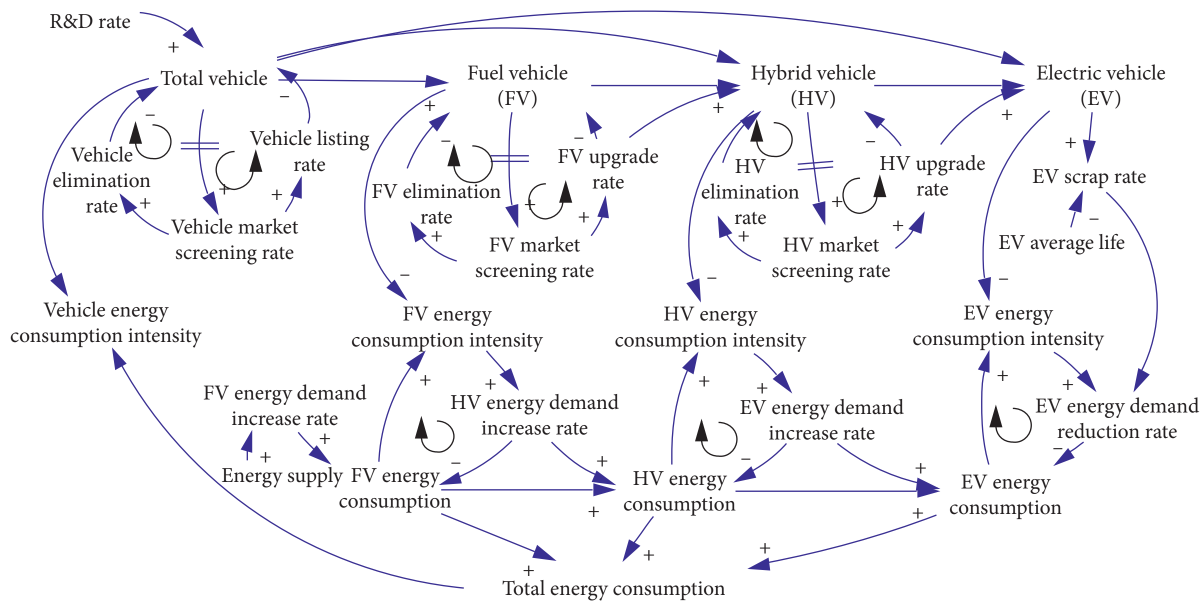

Figure 1: Causal loop diagram.

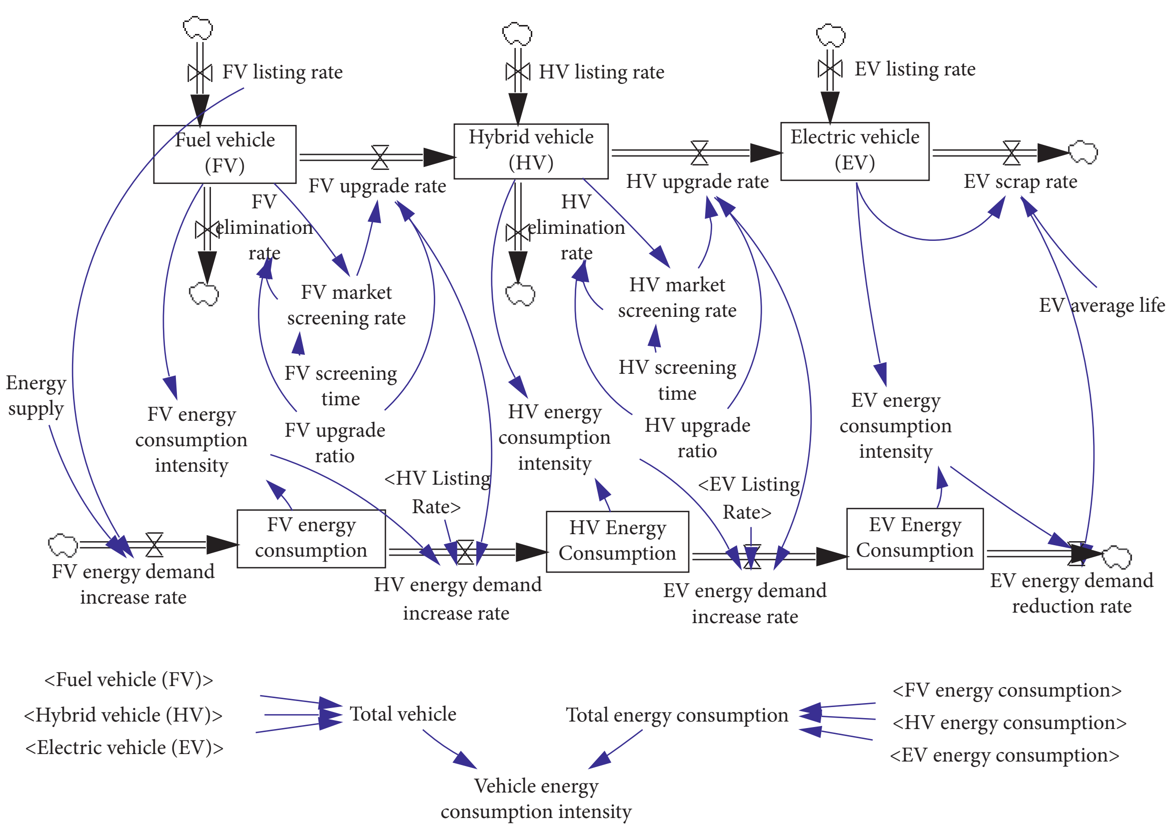

Figure 2: Stock and flow diagram.

(3) FV upgrade rate = FV market screening rate * FV upgrade ratio. The FV upgrade rate is related to FV market screening rate and FV upgrade ratio. Among them, the FV upgrade ratio is set to a constant according to expert experience data.

(4) FV elimination rate = FV market screening rate * (1 − FV upgrade ratio).

(5) FV energy consumption intensity = FV energy consumption/FV. The FV energy consumption intensity is determined by FV energy consumption and FV.

(6) FV energy consumption = INTEG FV energy (demand increase rate − HV energy demand increase rate, energy supply * FV). The FV energy

consumption is affected by FV energy demand increase rate and HV energy demand increase rate. The initial value is the energy supply multiplied by FV, which is calculated using the auto statistics data.

(7) FV energy demand increase rate = energy supply ∗ FV listing rate.

(8) HV energy demand increase rate = (FV upgrade - rate + HV listing rate ∗ FV energy consumption intensity.

(9) Total vehicle = FV + HV + EV.

(10) Total energy consumption = FV energy consumption + HV energy consumption + EV energy consumption.

(11) Vehicle energy consumption intensity = total energy consumption/total vehicle.

The initial values of vehicles are mainly derived from the statistics of China's basic passenger vehicle (sedan car), which is released by China Industry Information Network (CIIN), China Auto Information Net (CAIN), and China Association of Auto Manufacturers (CAAM). The initial data include 1,163 (ten thousand vehicles) fuel vehicles, 13 (ten thousand vehicles) hybrid vehicles, and 24 (ten thousand vehicles) electric vehicles. The initial value of energy supply is determined by the conversion formula of gasoline into standard coal and vehicle's average mileage life, which is about 45 (ten thousand tons/ten thousand vehicles). The initial energy consumptions of different vehicles are equal to the corresponding energy supply multiplied by the number of vehicles. In addition, the parameters are mainly determined by the empirical data of authoritative experts and the empirical investigation of auto enterprises. The initial values of auxiliary variables are as follows: FV market screening time is 7 years and HV market screening time is 8 years. The setting of market screening time comprehensively considers the influence of factors such as consumer preference, market demand, and average vehicle price on different vehicles. The FV upgrade ratio is 0.5, and the HV upgrade ratio is 0.6. The setting of the upgrade ratio takes into account the impact of factors such as R&D intensity, technological progress, and supporting infrastructure construction. The EV average life is 12.5 years, which is an average estimate of empirical data. The proposed control parameters: initial time = 2016, final time = 2050, and time step = 1.

3. Model Simulation and Analysis

3.1. Model Testing Analysis. This paper uses Vensim PLE for model simulation. On the basis of model construction and equation design, the validity and reliability of the model are tested. The results show that the model passed the "system boundary rationality test," "unit test," "extreme situation test," and "abnormal behavior test." It shows that the model is well constructed and can be used for further analysis.

SDs believes that setting specific variables as test functions can judge a model's ability to predict reality. This study focuses on the impact of FV listing rate, HV listing rate, and EV listing rate on vehicle size and auto industry structure. The test equations are determined by the empirical investigation of the auto industry and related statistics, including FV listing rate = 0 (FVs are gradually decreasing, no longer R&D and listing), HV listing rate = 8 + STEP (16, 2025) − STEP (10, 2035), and EV listing rate = 17.5 + STEP (35, 2025) + STEP (35, 2035). STEP (height, time) is a step function. The results are shown in Figure 3.

Figures 3(a) and 3(b) present the FV listing rate, HV listing rate, EV listing rate, and the changes of three types of vehicles, respectively. According to the statistics data of CAIN, FVs far exceed the sum of HVs and EVs at present. However, under the guidance of the national new energy vehicle policy, the FVs in basic passenger vehicles have shown a continuous downward trend since 2016, indicating that traditional vehicles are gradually withdrawing from the market. Meanwhile, according to the "A study on China's timetable for phasing-out traditional ICE-vehicles" initiated by the Innovation Center for Energy and Transportation (iCET), when the sales of FVs are banned around 2035, FV's market share will continue to decline until it is completely withdrawn from the market [40]. Therefore, this paper sets the FV listing rate to 0, which is in line with the auto industry development situation and future trend. The exit of FVs mainly includes two parts: one is natural scrapping and the other is the conversion from oil to electricity. The "oil to electricity" is the upgrading process of auto products from FVs to HVs. With the upgrade of FVs, HVs will show an increasing trend. However, as HVs still consume nonrenewable energy resources and emit pollutants, it will also show a downward trend in the future until it exits the market. This paper sets the HV listing rate based on the development of China's auto industry. The changing trend of FVs is consistent with simulation results (Figure 3(b)). The decline in HVs is accompanied by a second upgrade of the auto industry, that is, from HVs to EVs. As the main type of new energy vehicles in China, EVs will continue to expand market share and far exceed FVs and HVs due to their advantages in energy-saving and environmental protection. The model test results are consistent with the real and theoretical evolution process of the auto industry, and further simulation analysis can be continued.

3.2. Energy Supply Analysis. In order to analyze the impact of the energy supply on the auto industry upgrade process, this paper adjusts rate variables as constants. With reference to the energy supply of 45 (ten thousand tons/ten thousand vehicles), the energy supply is adjusted to 22.5 (ten thousand tons/ten thousand vehicles), and the FV upgrade ratio and HV upgrade ratio are adjusted accordingly. We use a comparative analysis method to study the effects of different energy supplies on vehicles and energy consumption intensity. The adjustment of each parameter value is determined by expert opinions and investigation results of the auto industry. The scenario designs are shown in Table 1.

Figure 4 shows that when FV listing rate, HV listing rate, and EV listing rate remain unchanged, the trends of the three types of vehicles are consistent with the actual situation (Figures 4(a)–4(c)). The simulation results support

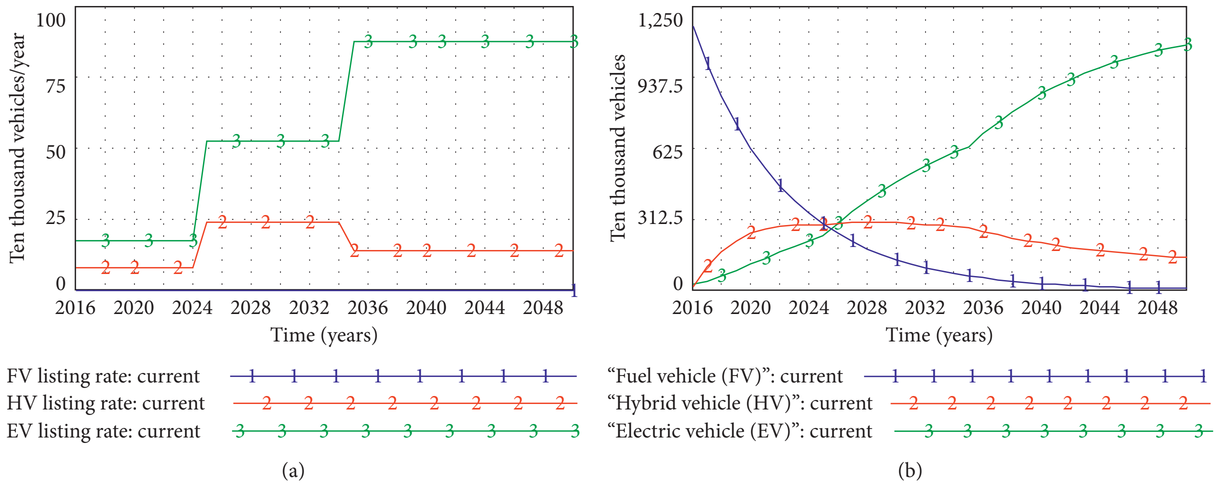

Figure 3: Test function and the number of different types of vehicles. (a) Listing rate; (b) number of FVs, HVs, and EVs.

Table 1: Design of energy supply and vehicle upgrade ratio under three scenarios.

Scenario	Variables		
	Energy supply (ten thousand tons/ten thousand vehicles)	FV upgrade ratio	HV upgrade ratio
Original scenario	45	0.5	0.6
Scenario 1	22.5	0.5	0.6
Scenario 2	22.5	0.7	0.8

Figure 3(b), indicating that the model has good stability. At present, the energy dilemma urgently requires an innovation development path for high energy-consuming industries. In order to analyze the impact of the energy supply on the structural adjustment of the auto industry, this paper designs scenario 1 (energy supply is reduced to half). By comparing the trends of different vehicles under the original scenario and scenario 1, we find that the two curves are consistent, i.e., only reducing the energy supply does not result in an expected change in FVs, HVs, and EVs. On this basis, this paper continues to design scenario 2 (adjusting energy supply and vehicle upgrade ratio). Comparing the trends of vehicles, we find that HVs and EVs show a significant increasing trend, further verifying that the model of excessive consumption of energy resources in exchange for the auto industry long-term development is not correct. Only by adjusting the upgrade ratios, the speed of auto industry upgrade can be accelerated.

In addition, vehicle energy consumption intensity represents the energy utilization efficiency of per unit vehicle, which is also a key indicator reflecting whether the auto industry structure is reasonable. Figure 4(d) shows that the vehicle energy consumption intensity curve of the original scenario coincides with scenario 1, but the energy consumption intensity is significantly reduced in scenario 2. It shows that the reduction of the energy supply does not improve vehicle's energy utilization efficiency. If we continue to maintain the auto industry structure dominated by FVs, it will not be able to fundamentally alleviate energy crisis and environmental pollution. Therefore, the improvement of energy efficiency still depends on the innovation of vehicle upgrading technology. For auto enterprises, the key to breaking through the limitations of the current development model is to improve vehicle R&D and upgrade ratio through innovative energy-saving and emission-reduction technologies.

3.3. Industry Upgrade Cycle Analysis. The industry upgrade cycle is an important criterion for measuring the healthy development of the auto industry. When FV listing rate, HV listing rate, EV listing rate, and energy supply are constant, the FV screening time and HV screening time may become the key factors affecting auto industry upgrade speed. This paper adjusts rate variables and energy supply as constants to study the impact of screening time on the auto industry upgrade process. The time parameters are determined based on real industry conditions and expert opinions. The scenario designs are shown in Table 2.

In this model, the market screening time affects vehicle upgrade rate and elimination rate, which is an important factor affecting vehicle market share, and the market share is crucial to the industrial evolution cycle. This paper designs scenario 1 and scenario 2 (adjusting FV market screening time and HV market screening time, respectively) and compares those scenarios with the original scenario to analyze the impact of screening time on the auto industry upgrade process. Figure 5(a) shows that shortening FV screening time will accelerate FV upgrade rate and elimination rate, i.e., accelerate FV's exit speed (scenario 1), which is consistent with government FV policy orientation. Figure 5(b) shows that shortening FV screening time will

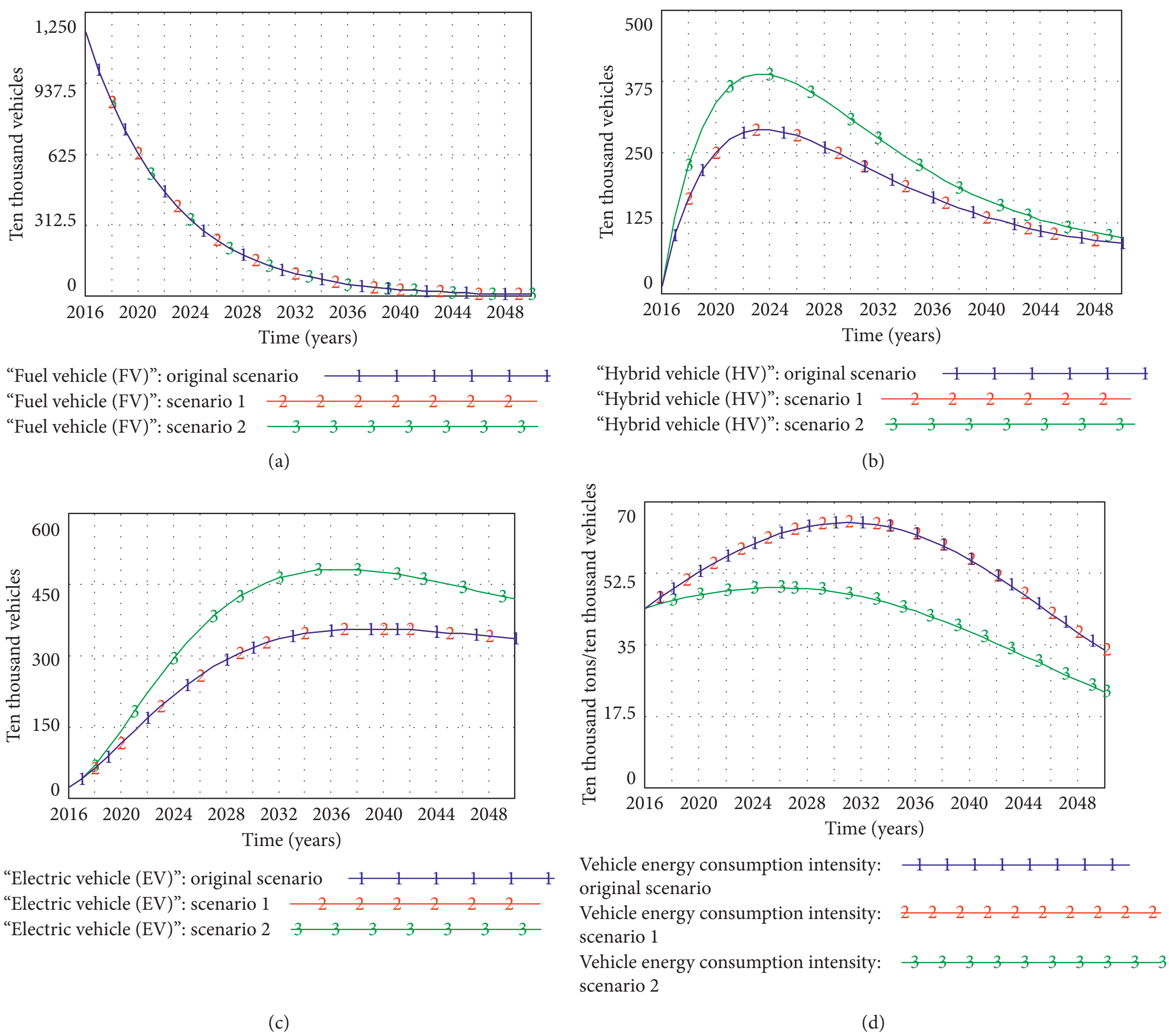

FIGURE 4: The changing trend of vehicles and vehicle energy consumption intensity under three scenarios. (a) FV. (b) HV. (c) EV. (d) Vehicle energy consumption intensity.

TABLE 2: Time changes in the auto industry upgrade process under three scenarios.

Scenarios	Variables	
	FV screening time	HV screening time
Original scenario	7	8
Scenario 1	5	8
Scenario 2	7	6

increase first and then reduce HV market share (scenario 1), but shortening HV screening time will reduce the overall HV market share (scenario 2), mainly because shortening market screening time can increase HV upgrade rate, that is, considering factors such as vehicle performance and environmental protection, consumers may scrap FVs and purchase HVs. However, with the popularity of EVs, many consumers will replace old cars (selling HVs and purchasing EVs), which will further reduce HVs market share. Figure 5(c) shows that shortening FV screening time and HV screening time will also increase EVs market share (scenario 1 and scenario 2). This trend is in line with the long-term development of the auto industry. The popularity of EVs is an important symbol of the optimization of auto industry structure. Therefore, this paper believes that the auto industry upgrade cycle is affected by market screening time.

Total energy consumption is a key index for measuring the green development of the auto industry. The traditional auto industry is a high-energy consumption and high-pollution industry. At present, under the guidance of national energy-saving and emission-reduction policy, the auto industry is undergoing a new round of technological reform. This paper analyzes the impact of time parameters on total energy consumption by adjusting vehicle market screening time, which is used as a measure of the success of auto industry upgrade. Figure 5(d) shows that shortening FV market screening time and HV market screening time

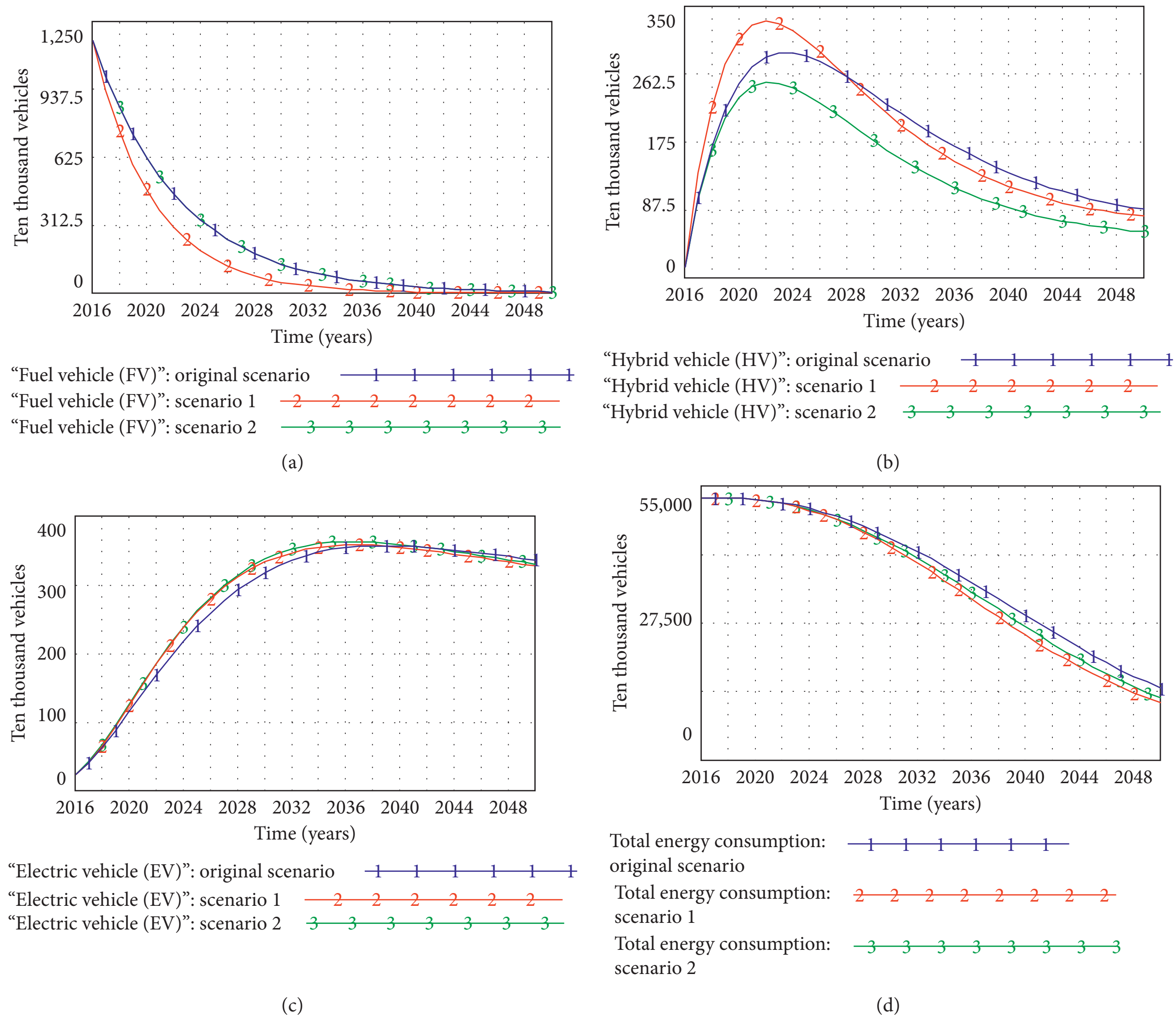

FIGURE 5: The changing trend of vehicles and total energy consumption under three scenarios. (a) FV. (b) HV. (c) EV. (d) Total energy consumption.

reduces total energy consumption (scenario 1 and scenario 2), and the rate of decline is faster than the original scenario. It indicates that market screening time will affect vehicle's market dwell time (from listing to exiting). The market dwell time is an important factor affecting auto industry life cycle. Therefore, in order to protect nonrenewable energy resources and promote the green development of the auto industry, we must pay attention to the impact of time parameters on industrial structure.

3.4. Supplementary Analysis. Section 3.1 tests the structure and validity of the model. Besides, in this section, we also select the data of basic passenger vehicles of 2016–2018 to compare the simulated values and historical values. The results show that errors are within a reasonable range, and error values (absolute value) are 0.25%, 5.52%, and 8.11%, respectively. Besides, the direction of vehicle change is also consistent with real data. For example, by the end of the simulation period (2050), there are only about 6.15 (ten thousand) fuel vehicles in the auto market, which is in line with the government's goal of achieving the complete withdrawal of FVs by 2050 [40]. Meanwhile, at the end of the simulation period, there approximately 1,083 (ten thousand) electric vehicles, consistent with the trend of new energy vehicles becoming the mainstream of the auto market. These results further verify the credibility of the model.

With the overall decline of the auto market, the productions of China's basic passenger vehicles have also shown a continuous downward trend since 2016. The statistics provided by the National Bureau of Statistics (NBS) also show that basic passenger vehicle production reached 7.324 million from January to September 2019, a cumulative decline of 15.1% [41]. The conservative productions of auto enterprises are closely related to purchasing power, as consumers are holding a wait-and-see attitude toward buying cars. Facing the sluggish auto market, how to restore market vitality is both a challenge and an opportunity. Therefore, auto enterprises should seize market opportunities, keep up with consumer demand, and eliminate outdated productivity timely. Enterprises should also expand the market share of EVs (representatives of new energy vehicles) and enhance the competitiveness of the auto industry through a new round of technological innovation.

The construction of EVs infrastructure is another bottleneck in the auto industry upgrade process. Driven by policy incentives and consumer demand, the development of EVs has driven the rapid growth of public charging infrastructure. According to the statistics released by China Industrial Economic Information Network, the possession of new energy vehicle charging piles increased from 3.3 (ten thousand) to 77.7 (ten thousand) in 2014–2018, greatly improving the difficulty of charging [41]. However, there are still some problems in EVs infrastructure construction, such as unreasonable layout, low utilization rate, and long charging time. Therefore, in the future, auto enterprises should pay more attention to the improvement of the supporting service system.

In addition, in theory, the auto industry consumes nonrenewable energy (such as gasoline and diesel) and emits large amounts of pollutants during the FV stage. When the auto industry enters the HV stage, energy consumption and pollution emissions are greatly reduced. Later, as the auto industry gradually upgraded to the EV stage, the driving of vehicles mainly relies on the motor system, which maximizes environmental protection, that is, the upgrading of the auto industry is an evolution process from high energy consumption and high pollution to low energy consumption and no pollution. However, the development situation of the auto industry shows that only about 30% of the electricity supply of EVs comes from clean energy in China, i.e., EVs still consume a lot of nonrenewable energy (main coal) and emit pollutants, which is far from the theoretical goal. At present, the Chinese government takes new energy vehicles as a strategic pillar industry and believes that developing new energy vehicles is an inevitable way from a big country to a powerful country in auto industry. Therefore, the development of EVs should continue to breakthrough in technology and accelerate the replacement of FVs and HVs through the development and application of power generation technologies such as wind, solar, and tidal energy.

4. Conclusions and Implications

4.1. Conclusions. Based on the two perspectives of environment and energy constraints, this paper divides the auto industry upgrade process into three stages: FVs, HVs, and EVs. Combined with vehicle energy consumption attributes, this study constructs an aging chain and coflow model. Furthermore, taking China's auto industry as an example, we select the statistics of basic passenger vehicles to simulate and study the impact of test function, energy supply, and time parameters on auto industry structure. The main conclusions include the following:

(1) The upgrade process of China's auto industry structure from FVs and HVs to EVs will undergo two important adjustments. The first upgrade is the natural scrapping of FVs and the conversion of "oil to electricity." The second upgrade is the gradual reduction of HVs (low-energy and low-pollution) and the overall popularity of EVs.

(2) This paper studies the impact of energy supply and upgrade ratios on auto industry structure by using vehicle size and vehicle energy consumption intensity. The scenario test results indicate that a single reduction in energy supply does not change vehicle size and vehicle energy consumption intensity, that is, the development model of excessive consumption of energy resources cannot improve energy utilization efficiency and promote the sustainable development of the auto industry. Only by adjusting energy supply and upgrade ratios together, the speed of industry upgrade can be accelerated and the energy crisis and environmental pollution can be alleviated.

(3) This paper analyzes the impact of market screening time on auto industry life cycle using vehicle size and total energy consumption. For one thing, the market screening time on the auto industry upgrade process is mainly achieved by affecting vehicle's market share. For another, the market screening time will also affect auto industry life cycle by affecting vehicle's market dwell time. Therefore, we must pay attention to the impact of time parameters on industrial structure.

(4) The upgrading of the auto industry also needs to focus on the consumer preferences of the demand side, the technological innovation of the supply side, and the improvement of the infrastructure system. The auto industry upgrade process should be designed and planned from the perspective of the whole industrial chain.

4.2. Implications. In order to accelerate the structural adjustment of China's auto industry, the following suggestions are proposed. First, China's auto industry is still in the stage of "big but not strong," and the international competitive advantage is not obvious. In the new round of industrial transformation, government and enterprises should continue to implement innovation-driven strategy and build the new energy vehicle innovation development system. On the one hand, it is necessary to build a public R&D platform to help enterprises reduce R&D threshold and improve R&D success rate and market share. On the other hand, government should improve the supporting infrastructure and service facilities of EVs, such as cross-regional power grid layout, standardized maintenance, and battery life extension, to improve EVs performance and convenience. Second, the current development model at the expense of energy resources not only fails to solve energy and environmental problems but also is not conducive to the sustainable development of the auto industry. Governments and industry organizations should strengthen market supervision, eliminate high-pollution vehicles in time, and transform the traditional auto industry into a clean energy industry. Meanwhile, government and enterprises should take energy conservation and environmental protection as development goals and increase capital investment in power generation technologies to fundamentally protect nonrenewable energy resources. Third, as a major auto manufacturing and consumption country, the upgrading of China's auto industry should pay more attention to consumer guidance. We can encourage and guide consumers to use low-carbon and pollution-free vehicles by providing consumer subsidies, creating consumption environment, and innovating marketing channels.

4.3. Limitations and Future Research Directions. This study has two limitations. First, this paper constructs a matching model of the auto industry upgrade process and its energy consumption attributes. However, due to the complexity of the factors, this paper only considers the system formed by the interrelationship between FVs, HVs, EVs, and their corresponding energy consumption. Other influencing factors, such as vehicle price and consumer preference, are only considered in the design of auxiliary variables, and the independent impact of each variable on industrial upgrading is not considered. Future research can further extend the impact of other possible influencing factors on the overall auto system. Second, this paper uses the statistical data of China's basic passenger vehicles to simulate and predict the auto industry upgrade process. However, due to the lack of industry panel data, this paper does not simulate the cross section data, which reduces the accurate prediction ability of the model. Future research can further conduct in-depth comparative studies by collecting industry panel data.

Data Availability

The data used in this study are partly from China Industry Information Network (CIIN), China Auto Information Net (CAIN), and China Association of Auto Manufacturers (CAAM), and partly from the empirical investigations of authoritative experts in the auto industry and auto companies.

Conflicts of Interest

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

Acknowledgments

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Research Article

Detecting and Visualizing the Communities of Innovation in Beijing-Tianjin-Hebei Urban Agglomeration Based on the Patent Cooperation Network

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For a deep understanding of Beijing-Tianjin-Hebei (BTH) collaborative innovation, we detected and visualized the communities of innovation in BTH Urban Agglomeration based on the patent cooperation network. China Patent Database was connected with Business Registration Database and the Tianyan Check to achieve the geographical information of organizational innovators. Spinglass algorithm was applied and ultimately 12 communities of innovation were detected. Based on the different structure characteristics, we further clustered the 12 communities into four typical structures that are hierarchical, single-center, polycentric, and flat structures. The hierarchical structure is usually large in scale and the cooperative intensity is relatively high. Single-center structure has a center with a high proportion of centrality and the cooperative intensity is relatively low. Polycentric structure has multiple centers with similar proportions of centrality. Flat structure is usually small in scale and has no obvious network center. In the patent cooperative network of BTH Urban Agglomeration, universities and state-owned enterprises occupied the centers and acted important roles to connect other organizations. Some communities of innovation showed significant industry characteristics, mainly involving six industry fields that are electric power, construction, petroleum, metallurgy and materials, municipal transportation, and railway. From the geographical perspective, some communities manifested local attributes and some demonstrated cooperation between regions. Beijing was the center of the Beijing-Tianjin-Hebei patent cooperation network. Compared with the pair of Beijing-Tianjin and the pair of Beijing-Hebei, Tianjin and Hebei were not closely connected. In the future, Beijing-Tianjin-Hebei collaborative innovation should strengthen cooperation between Tianjin and Hebei.

1. Introduction

Beijing-Tianjin-Hebei (BTH) integration plan is an important national strategy aimed for the sustainable development of the BTH Urban Agglomeration. In the past, Beijing as the capital of China abstracted the best talent, technology, and capital from all over the country while the region surrounding Beijing is somewhat overshadowed. As the unique first-tier city in the North of China, Beijing plays a role of siphonage on the region surrounding Beijing through the spillover effect [1]. Unlike the balanced development in Yangtze River Delta, the region surrounding Beijing has significantly lagging economic development levels. However, BTH integration plan will change it and aims to create the third growth pole of the Chinese economy after the Yangtze River Delta and Pearl River Delta.

Nowadays, innovation has become an important driving force for economic development. Accordingly, collaborative innovation plays an important role in the coordinated development of BTH. In recent years, some scholars have explored the cooperative innovation in BTH Urban Agglomeration from the perspective of network based on copatenting, copublications, or patent right transaction data. Liu et al. [2] portrayed the spatial dynamics of intercity technology transfer networks in China's three urban agglomerations based on patent right transaction data from 2008 to 2015. Chen et al. [3] explored the evolution of regional innovation ability based on the innovation network constructed by using the cooperation patent data of "211 universities" in Beijing, Tianjin, and Hebei regions during 2002–2016. Shi et al. [4] portrayed the scientific cooperation network of Chinese scientists and the spatial distribution characteristics. Lyu et al. [5] revealed the spatial organization and evolution characteristics of the innovation network of BTH Urban Agglomeration based on coauthorized patent data. Xing and Zhang [6] observed the innovation network evolution process of BTH Urban Agglomeration and compared the network features with Yangtze River Delta Urban Agglomeration based on the copatenting data of the World Intellectual Property Organization. The previous studies have studied the network characteristics and spatial distribution characteristics of the innovation network in BTH Urban Agglomeration constructed at the city level or microlevel. In this paper, we focused on the community structure in the innovation network of BTH Urban Agglomeration.

With the rapid development of technology, in some fields with dispersed knowledge, no one firm can lead the position in all aspects. It is difficult to create significant innovations for the entire market on its own. In this situation, firms have to seek collaboration from the outside world. Hence, the innovation cooperative network forms. In this complex network, the community structure raised the attention of Coakes and Smith [7]. They termed this kind of community structure as a community of innovation and deemed it as a special case of the more general community of practice dedicated to the support of innovation. Lim and Ong [8] further clarified the relationship between the community of innovation and community of practice. Yi and Li [9] focused on the mechanism of knowledge transfer between enterprises. Researchers have formed a consensus that a community of innovation plays a vital role in the innovation generation [10, 11]. However, the empirical research is still very rare. The current research mainly focuses on the theoretical level although Coakes and Smith had pointed out that network visualization and analysis (NVA) and social network analysis (SNA) were feasible means to detect the relationships between organizational actors and map their social networks. One of the reasons is that the empirical data of innovation cooperative networks is not available. With the availability of data and the development of methodology, researchers can detect and visualize communities of innovation in innovation cooperative networks. Gloor et al. [12] visualized the communication patterns in cooperative innovation networks constructed on e-mail archives and selected three communities. Smith [13] visualized a network map showing who goes to whom for specific information in a target community. However, these communities visualized are usually on a small scale and the community detection technique has no necessity of use in the research.

In recent years, community detection techniques have been used in the detection of technology clusters or scientific knowledge clusters based on the network of patent or scientific publications [14–17]. The community detected in the citation network of patent or scientific publications is different from the community of innovation. Community of innovation consists of innovators and their cooperation relationship; however, in the patent citation network, the nodes are patents or scientific publications and the links are the citations. The aim of detecting the community of innovation is to find who cooperates with whom and what characterizes the community; however, the aim of detecting technology clusters is to explore the technological change and predict the emerging technologies.

This paper detected and visualized the communities of innovation in BTH Urban Agglomeration based on the patent cooperation network by using community detection techniques in SNA. The patent cooperation network was constructed with organizational innovators and their patent cooperative relationship. Patent is an important form of innovation output; therefore, we use the patent cooperation network to portray innovation cooperative networks. Through community detection, we hope to have a deeper understanding of the innovation cooperative network in BTH Urban Agglomeration. From the communities of innovation, we can find the features of the innovation cooperation in BTH Urban Agglomeration.

2. Materials and Methods

2.1. Data

2.1.1. Dataset. Three data sources were used in this paper. The first was China Patent Database from the State Intellectual Property Office (SIPO) from 1985 to March 2018, which contained 19 variables including patent application time, inventor, patentee, and patent category. The second was Business Registration Database (BRD) from the State Administration of Industry and Commerce (SAIC) which contained 15 variables including enterprise name, province, city, district, 4-digit industry code, registered capital, foundation date, and address. The third was data from the TianYanCha Database (TYCD), which collected information on more than 180 million social entities (including enterprises, institutions, foundations, schools, and law firms) in the country, including listing information, enterprise background, enterprise development, judicial risk, business risk, business status, and intellectual property rights.

2.1.2. Data Processing. Data processing and matching was essential in this study and there were five steps to construct the patent cooperation network. First, we filtered out those patents that had only one patentee. Second, we split the multiple patentees into array and each patentee was the element of the array. Third, we filtered out the individual patentees because they were not valid organizations. We identified an organization as valid only if its name was contained in BRD or TYCD. BRD contained all business registration information except nonprofit organizations such as universities and research institutions. As supplementary, we used TYCD that contained information about nonprofit organizations. Forth, we constructed the data frame of patent cooperation network by reshaping the patentee array. For example, if a patent contained three organization patentees, we wrote the array as $[p_1, p_2, p_3]$, where each element stood for an organization patentee. We reshaped the array into three arrays, that is, $[p_1, p_2]$, $[p_1, p_3]$, and $[p_2, p_3]$. The pair of elements in the newly reshaped arrays constituted two nodes and one edge between them in the patent cooperation network, meaning that the two organization patentees had patent cooperation relationship. Finally, we extracted the edges with both nodes belonging to BTH Urban Agglomeration. Since BRD and TYCD supplied the geographical information of all the organizations, we could easily filter out the nodes and edges that did not belong to BTH Urban Agglomeration.

From 1985 to March 2018, SIPO received 21.7 million patent applications, 4.4% of which were cooperative patents between organizations. There were 125 thousand organizations in the patent cooperation network, of which 57% were domestic enterprises, 27% were universities and institutions, and 16% were foreign organizations. Before 2000, only few organizations cooperated in patent applications while the number has grown rapidly since then. We extracted 128 thousand cooperation relations and 9643 organizations for the patent cooperation network of BTH Urban Agglomeration from the national network. Within all the organizations which had a patent cooperation relationship in BTH Urban Agglomeration, 6093 organizations were from Beijing, 1838 from Tianjin, and 1712 from Hebei, accounting for 63.2%, 19.1%, and 17.8%, respectively. Therefore, it can be seen that Beijing played a key role in the patent cooperation network of BTH Urban Agglomeration.

2.2. Methodology. Social network analysis is a multidisciplinary emerging field based on graph theory and using statistical, computer, and visualization techniques as analysis methods. Since the later 20th century, this method has received much attention from scholars in many disciplines such as physics, mathematics, biology, sociology, and economics.

Network can be defined as a graph $G := (V, E)$. V is the collection of nodes representing cooperative organizations such as enterprise, university, and research institution. E is the collection of edges representing patent cooperative relationship with weight W. The more frequently they collaborate in patent application, the larger the weight is. Larger weight means closer connection. Since collaboration has no direction, we deem the patent cooperation network as an undirected graph.

2.2.1. Indicator Based on Network Description. Many quantitative indicators have been defined on networks. In this paper, we applied the following indicators to describe the innovation cooperation network of BTH Urban Agglomeration:

(1). Community Size. Community size refers to the number of nodes contained in the community.

(2). Degree Centrality. Degree centrality is the simplest measure of centrality, which measures how many links a node has. In a given graph $G := (V, E)$ with n vertices and m edges, the degree centrality of a vertex v is defined as

$$C_D(v) = \deg(v). \tag{1}$$

(3). Cooperative Intensity. In order to measure how many different cooperators an organizational innovator has, we defined cooperative intensity. Let L denote the number of edges without weight in graph G. Cooperate intensity is as follows:

$$\text{cooperative intensity} = \frac{2L}{n}. \tag{2}$$

2.3. Community Detection Technique. Community refers to a group of nodes with dense connections within the group and sparser connections between the groups. Community detection is crucial for the understanding of the internal organizations of complex networks. Over the last decades, community detection has become one of the most popular subfields in social network analysis. Many community detection methods have been developed and applied in a variety of fields such as sociology, biology, and statistics. Fast Greedy algorithm [18], Walktrap [19], Infomap [20], Label Propagation [21], Multilevel [22], and Spinglass [23] are the most popular and widely used algorithms in the field of community detection. Some research [24, 25] compared these algorithms and showed that Spinglass, Multilevel, and Fast Greedy performed better than other algorithms. Further, Spinglass performed more robust on community detection regarding perturbations. In this paper, we applied Spinglass community detection algorithm to identify the communities in the innovation cooperation network of BTH Urban Agglomeration. Spinglass algorithm employs a Spinglass model from statistical physics to provide a rigorous foundation for combining external knowledge into community detection processes [26]. It is a semisupervised community detection algorithm. The goal of Spinglass algorithm is not to maximize the "modularity" which is a global objective measure of how good the global community structure discovered by an algorithm is [27]. It can both obtain high-scoring modularity and meet the provided requirement.

We compared five community detection algorithms to find the best one to fit the BTH cooperative network. The summarized results (Table 1) showed that Fast Greedy and Spinglass had the highest modularity. Different algorithms varied greatly in the number of communities and the community size. Walktrap and Label Propagation had more than 500 communities with the highest coefficient of variation (CV) of community size. Although the Fast Greedy algorithm had 0.83 modularity, it generated too many communities with extremely small size. There were only 15

Table 1: Comparison of community detection algorithms in BTH patent cooperation network.

Algorithm	Fast Greedy	Walktrap	Label Propagation	Multilevel	Spinglass
Modularity	0.83	0.75	0.73	0.81	0.83
Number of communities	115	531	516	57	12
Maximal community size	1300	758	934	774	784
Mean of community size	55	12	12	111	527
Minimal community size	2	2	2	3	318
CV of community size	2.85	4.3	3.8	1.31	0.29

communities with more than 100 nodes and more than 71% of the communities were with less than 20 nodes. Therefore, in order to better understand the structure of the BTH patent cooperation network, we finally chose the Spinglass algorithm.

3. Results

3.1. Characteristic of Patent Cooperation Network. We extracted organizations of BTH Urban Agglomeration from the entire national network and constructed an innovation cooperation network of BTH Urban Agglomeration with 9643 nodes (Figure 1). In the network, the largest connected subgraph contained 6319 nodes accounting for 66% of the total. Except the largest connected subgraph, the other 1370 subgraphs were all on a small scale; most of them consisted of two nodes.

Visualizing the largest connected subgraph (Figure 2), we found that Beijing organizations (yellow nodes) dominated the patent cooperation network of BTH Urban Agglomeration. Within the top 30 organizations, 24 (80%) were from Beijing and within the top 10 organizations, and 9 (90%) were from Beijing. From the perspective of the organizational category, universities and some state-owned enterprises occupied the center of the network and acted as bridges (Table 2).

3.2. Communities of Innovation. Except the largest connected subgraph, other subgraphs were on a small scale, most of which consisted of only two nodes. Therefore, we only detected communities in the largest connected subgraph with the aim of exploring the modes of patent collaboration in BTH Urban Agglomeration.

Since the frequency of collaboration obeyed power-law distribution with few organizations collaborating frequently while the others rarely, we took logarithm transformation of the frequency in order to eliminate the huge difference. We designated the number of communities in Spinglass algorithm from 6 to 25, since too many or too few communities did not benefit the understanding of network structure. By comparing the modularity under different designated numbers of communities, ultimately we chose 12 communities of innovation (Figure 3) by using Spinglass algorithm in *R* package igraph.

We further used a hierarchical cluster algorithm to cluster 12 communities into clusters based on six clustering variables reflecting the structure characteristic of each community (Table 3). We standardized the six clustering

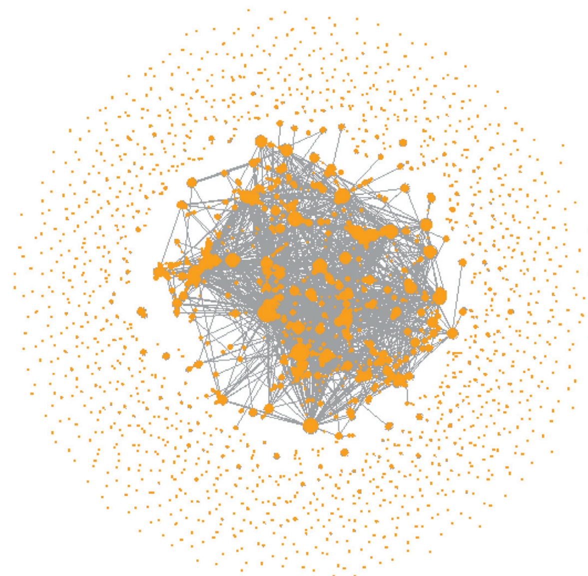

Figure 1: Patent cooperation network in BTH Urban Agglomeration.

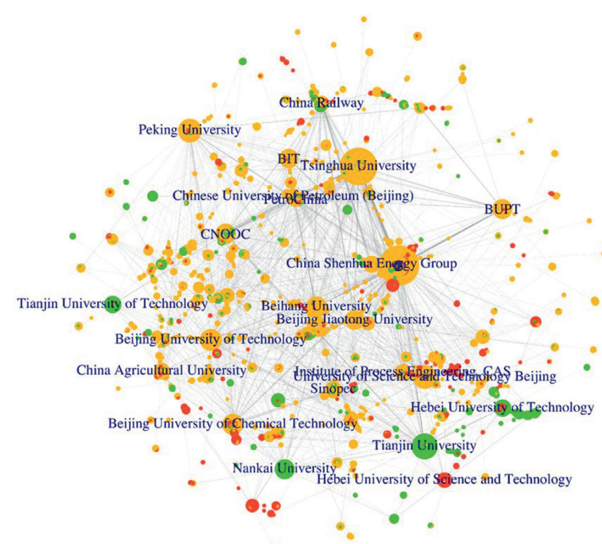

Figure 2: Visualization of the largest connect subgraph. Note: yellow nodes represent Beijing organizations, red nodes represent Hebei organizations, and green nodes represent Tianjin organizations.

variables and used ward.D2 cluster method based on Euclidean distance in the hierarchical cluster algorithm. Elbow method was used to determine the optimal number of

Table 2: The top 20 organizations with the highest degree centrality in BTH Urban Agglomeration.

Rank	Name	Centrality	Rank	Name	Centrality
1	State Grid Corporation	685	11	China National Offshore Oil Corporation	125
2	Tsinghua University	575	12	Beijing University of Posts and Telecommunications (BUPT)	117
3	Tianjin University	225	13	North China Electric Power University	116
4	Peking University	183	14	Nankai University	116
5	University of Science and Technology Beijing	181	15	Beijing Jiaotong University	112
6	Beijing University of Technology	150	16	Beijing Institute of Technology (BIT)	110
7	China Electric Power Research Institute	146	17	Hebei University of Technology	82
8	Beihang University	136	18	State Grid Electric Power Company, Beijing	81
9	Beijing University of Chemical Technology	135	19	Tianjin University of Science and Technology	81
10	State Grid Power Company in Hebei Province	126	20	China Shenhua Energy Group	79

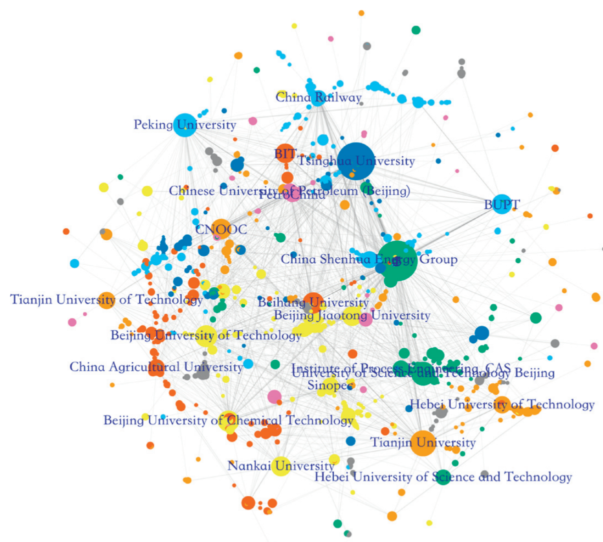

Figure 3: Visualization of the 12 communities of innovation. Note: different colors denote different communities of innovation.

Table 3: Clustering variables and description.

Variable	Description
$centr_{1st}$	The proportion of the highest degree centrality
$ratio_{12}$	The ratio of the highest degree centrality to the second high
$Ratio_{13}$	The ratio of the highest degree centrality to the third high
$ratio_{14}$	The ratio of the highest degree centrality to the fourth high
$Ratio_{15}$	The ratio of the first highest degree centrality to the fifth high
coop-int	The number of different cooperators an organizational innovator has

clusters. Figure 4 shows that the optimal number of clusters was four where the curve became flat.

Table 4 shows the group members of each cluster and their features. The mean of cooperative intensity is ranked as cluster #1 > cluster #4 > cluster #3 > cluster #2. Except for cooperative intensity, the mean of the other five variables is ranked as # 2 > cluster # 1 > cluster #3 > cluster #4. Furthermore, analysis of variance (ANOVA) showed a significant difference in the four clusters given a significant level of 0.05.

4. Discussion

Sort the 12 communities according to their size in descending order and number them no. 1–12. We will discuss the structural characteristics and industrial

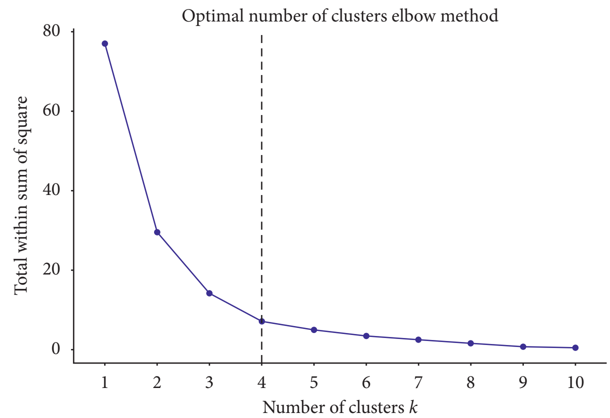

Figure 4: Plot of the total within the sum of the square with the number of clusters.

Table 4: Group members of each cluster and their features.

Cluster no.	Community no.	Mean of $centr_{1st}$ (%)	Mean of $ratio_{12}$	Mean of $ratio_{13}$	Mean of $ratio_{14}$	Mean of $ratio_{15}$	Mean of *coop-int*
1	1	16	4.69	5.44	5.91	8.46	4.86
2	2	27	11.27	14.02	19.83	21.30	2.32
3	3, 4, 5, and 7	11	1.76	3.36	4.69	5.80	2.52
4	6, 8, 9, 10, 11, and 12	7	1.45	2.02	2.45	2.89	2.88

characteristics of these 12 communities of innovation in BTH Urban Agglomeration in the following.

4.1. Structural Characteristic of Communities. According to the features of the four clusters, we summarized four typical structures of the community: hierarchical structure, single-center structure, polycentric structure, and flat structure. In the following, we will illustrate these four structures in detail.

4.1.1. Hierarchical Structure. Hierarchical structure consists of first-level central nodes, second-level central nodes, and slave nodes. The first-level central node takes the central position. The second-level central node surrounds the first-level central node and at the same time acts as the central node itself with other slave nodes surrounding it. Cluster #1, which only contains community #1, is a typical hierarchical structure. Community #1 is the largest community of innovation with 784 nodes mainly composed of universities, research institutes, and enterprises related to electricity and power grid. Therefore, we named it as the Electric Power Community of Innovation (Figure 5).

In hierarchical structure, the first-level central node usually accounted for a high proportion of degrees, and the degree ratios of the first-level central node to the second-level central nodes were high too. This feature made the structure hierarchical. Besides, we speculated that hierarchical structure encouraged more connections with different nodes since it had the highest cooperative intensity compared with the other three structures.

The first-level central node in the Electric Power Community of Innovation was the State Grid Corporate and the second-level central nodes were the China Electric Power Academy, State Grid Power Company in Hebei Province, North China Electric Power University, and State Grid Power Company in Beijing. Due to the high-tech and high-capital characteristics of the power industry, innovation cooperation in the power industry was more necessary. Meanwhile, the monopoly nature of the power industry was obvious. State Grid Corporate, the head enterprise, inevitably occupied the most important position. Most of the organizations in the Electric Power Community had close relationships with the State Grid Corporation in the form of subsidiaries, joint-stock, common industry filed, and so on, which cleared the barriers to innovation cooperation and made it the biggest community in BTH Urban Agglomeration. The number of cooperative patents in the Electric Power Community was 58 thousand accounting for 32% of the largest connected subgraph and 29% of the entire network.

From the geographical characteristics (Table 5), community #1 had the highest proportion of organizations from Hebei Province, accounting for 36%. The geographical characteristics of community #1 indicated that in the field of electric power Hebei Province had a close relationship with Beijing while it had a weak relationship with Tianjin. Within all the connections between regions in community #1, the proportions of connections between Beijing-Hebei, Beijing-Tianjin, and Hebei-Tianjin were 76.1%, 22.3%, and 1.6%, respectively. This characteristic was also true for community # 4, which was in the field of metallurgy and materials.

Actually, from the view of the whole network, we could find that there was no close relationship between Tianjin and Hebei. Strong relationships only existed between Beijing and

1 State grid corporation
2 China electric power academy
3 State grid power company in hebei province
4 North china electric power university
5 State grid electric power company, beijing
6 rth china electric power research institute
7 State grid power company in hebei province
8 State grid power company in tianjin
9 State grid jibei electic power Co., Ltd.
10 State grid jibei electric power research institute

Figure 5: Electric Power Community of Innovation with hierarchical structure.

Table 5: Geographical characteristics of communities of innovation in BTH Urban Agglomeration.

Community no.	Beijing (%)	Tianjin (%)	Hebei (%)
1	54	9	36
2	86	7	7
3	71	7	22
4	63	7	30
5	31	59	11
6	80	10	9
7	86	4	10
8	56	31	13
9	62	17	22
10	40	49	11
11	78	11	12
12	59	21	19

Tianjin or between Beijing and Hebei. To be more specific, there were 1712 nodes in the BTH network belonging to Hebei Province with 2797 edges, within which, 38% were connected inside Hebei and 53% connected Beijing and Hebei, while only 9% connected Tianjin and Hebei. For Tianjin, there were 1838 nodes in the BTH network with 2812 edges, within which, 53% were connected inside Tianjin and 38% connected Beijing and Tianjin, while only 9% connected Tianjin and Hebei. As for Beijing, 6093 nodes in the BTH network belonged to Beijing with 10038 edges, within which, 74% were connected inside Beijing, 11% connected Beijing and Tianjin, and 15% connected Beijing and Hebei. It was obvious that Beijing dominated the BTH network and connected Tianjin and Hebei, respectively. It reflected the lack of innovative connections between Tianjin and Hebei.

Some of the communities have significant geographical attributes. For example, more than 80% of organizations of communities #2, #6, and #7 were from Beijing, and about half of the organizations of communities #5 and #10 were from Tianjin. This phenomenon reflected geographical agglomeration. We speculated that geographical proximity facilitated patent cooperation.

4.1.2. Single-Center Structure. Single-center structure community consisted of one single node as core and the other nodes surrounding it. The single node occupied the dominant position and the others were subordinate status. Cluster #2, which only contained community #2, was a typical single-center structure. Since the center of community #2 was Tsinghua University, we named it as Tsinghua Community of Innovation (Figure 6). Single-center structure had two features. First, it had a single central node with very large degree centrality and other nodes with much smaller degree centrality. Second, due to

Figure 6: Tsinghua Community of Innovation with single-center structure.

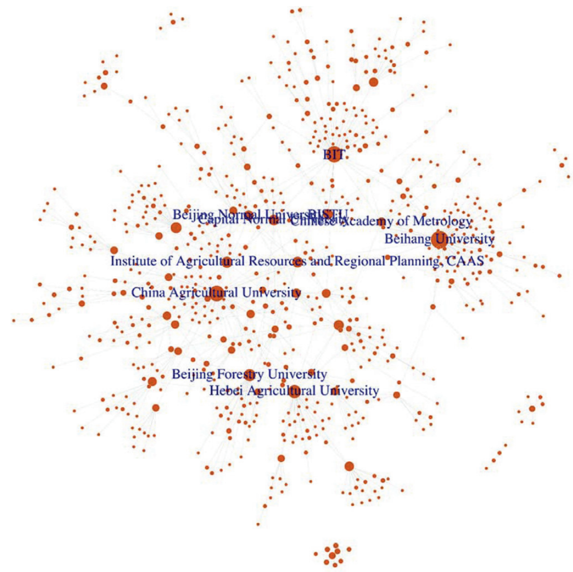

Figure 7: Community of innovation with multiple centers of Beihang University, Beijing Institute of Technology, and China Agricultural University.

the lack of connection between other nodes, the network connection is not dense. From Table 3, we can see in Tsinghua Community of Innovation that $centr_{1st}$ was the highest and $ratio_{12}$, $ratio_{13}$, $ratio_{14}$, and $ratio_{15}$ were the highest too. Nevertheless, the cooperative intensity was the lowest in the four structures, which indicated that the single-center structure was not conducive to generating innovative links.

Usually, the central node in a single enter structure should meet two characteristics. The first is depth, which requires strong R&D capability to become an ideal partner of other organizations. The second is breath, which requires broad research fields to intersect with other organizations in different fields and to form complementary technologies. Only comprehensive universities or large enterprises can meet these two characteristics. In the Tsinghua Community of Innovation, Tsinghua University acts as the central node with strong R&D capability and broad research fields connecting with other organizations. Tsinghua University dominates this community and other organizations' layout around it. The degree centrality of Tsinghua University is 575, more than 10 times of the China Institute of Water Resources and Hydropower Research, whose centrality is the second largest in this community. Meanwhile, the betweenness centrality of Tsinghua University is 8 times of the second largest node. It indicates that the cooperative relationship in the community is very dependent on the central node. Due to the lack of direct connection between each other, they need to connect through the central node, which means the central node occupies the structural hole in the network. According to the structural hole theory developed by Burt [28], the node on the structural hole can gain an important comparative advantage.

4.1.3. Polycentric Structure. Polycentric structure community has multiple central nodes whose degree centrality is even. Cluster #3, which consisted of communities #3, #4, #5, and #7, was typical polycentric structures. In the following, we will illustrate communities #3 and #7 as examples to show the polycentric structure.

Community #3 (Figure 7) had three central nodes that were Beihang University, BIT, and China Agricultural University accounting for 7%, 5%, and 4% of the total degree centrality, respectively. Beihang and BIT were local centers with many subordinate nodes surrounding them. Their structures were very like single-center structures but on a small scale. The subcommunity of China Agricultural University had a hierarchical structure with China Agricultural University as the first-level central node and Hebei Agricultural University and Beijing Forestry University as second-level central nodes forming a community of innovation in agricultural fields.

We found that the three multiple centers were not connected with each other directly but connected via an important node that was Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences (CAAS). The shortest paths between BIT, Beihang University, and China Agricultural University all passed this node.

Community #7 (Figure 8) was also a polycentric structure with Peking University and BUPT as centers whose proportions of degree centrality were 12% and 8%, respectively. Besides, there were several important organizational innovators with 2% proportion of degree centrality, such as China Mobile Communications Corporation (CMCC), Institute of Computing Technology of Chinese Academy of Sciences, and Beijing Nonferrous Metal

FIGURE 8: Community of Innovation with multiple centers of Peking University and BUPT.

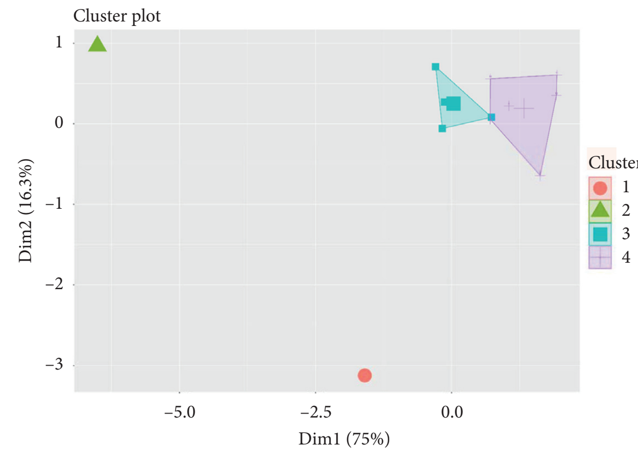

FIGURE 9: Cluster plot of hierarchical cluster algorithm.

Research Institute. Unlike the polycentric community of Beihang, BIT, and China Agricultural University, the multiple centers, Peking University and BUPT, had connections directly; namely, they had patent collaboration.

Compared with single-center structure, the proportion of the highest degree centrality in polycentric structure was relatively lower but the multiple centers had relatively uniform degree centrality.

4.1.4. Flat Structure. Flat structure had no obvious central nodes. Cluster #4, which contains six communities, was a typical flat structure. In cluster #4, the mean of $centr_{1st}$ was the lowest and the means of $ratio_{12}$, $ratio_{13}$, $ratio_{14}$, and $ratio_{15}$ were the lowest too, which meant the distribution of the degree centrality was uniformly in flat structure.

Flat structure was similar to polycentric structure. From Figure 9, we can see that cluster #4 whose structure was flat had the shortest distance to cluster #3 whose structure was polycentric. However, different from the polycentric structure, the top largest nodes in flat structure had not so large degree centrality. In the following, we will illustrate community #11 as an example to show flat structure.

Community # 11 (Figure 10) was mainly in the field of the construction industry. The top three nodes with the highest degree centrality were China Construction First Bureau Group, China Construction Corporation, and China Academy of Building Research, whose degree centrality accounted for 3%, 3%, and 3%, respectively. Different from the above three types of structure, flat structure had no obvious central nodes in the network. However, the cooperation intensity was higher than the single-center structure and polycentric structure. Flat structure was usually on a small scale. In this study, communities #6, #8, #9, #10, #11, and #12 had flat structure which were small communities while hierarchical structures usually were on a large scale. Due to fewer organizations, flat structure had less of a need for hierarchical management. The degree centrality was evenly distributed throughout the flat structure network, which meant there exited no dominant node in the network. The organizations collaborated with each other through comparative technological complementarity. Flat structure was a relatively loose innovation community structure.

FIGURE 10: Community of construction industry with flat structure.

4.2. Industry Characteristic of Communities. For better understanding the BTH network and communities, we named each community by the industrial characteristics of the top ten nodes with the largest degree centrality. Since the node degree centrality was power-law distribution, the top ten nodes could represent the overall characteristics of each community. The BRD and TYCD provided us with the industrial category attributes for each enterprise. For research institutions and some universities, we could judge their main research fields from their names. Based on the industrial category attributes of enterprises and the main

Table 6: Detailed information on the communities of innovation with industrial characteristics.

Community no.	Industry filed	Community structure	Community size	Cooperation intensity
1	Electric power	Hierarchical	784	4.86
4	Metallurgy and materials	Polycentric	582	2.44
5	Petroleum	Polycentric	559	2.75
6	Municipal transportation	Flat	537	2.73
8	Petroleum	Flat	489	2.73
9	Railway	Flat	379	3.47
11	Construction	Flat	365	2.68
12	Petroleum	Flat	318	2.92

research fields of research institutions and some universities, we labeled the communities if they showed significant industrial characteristics. Within the twelve communities of innovation, eight communities had significant industrial characteristics. Except the communities of innovation in the field of electric power (community #1) and construction (community #11) illustrated above, there were still six communities with significant industrial characteristics. They were communities #4, #5, #6, #8, #9, and #12. Table 6 shows the detailed information of the eight communities. The eight communities of innovation mainly gathered in six industries, which were electric power, metallurgy and materials, petroleum, municipal transportation, railway, and construction. From the view of community structure, five of them were flat structure, two were polycentric structure, and one was hierarchical structure. Many researches [29, 30] had shown that moderate technological distance was beneficial for innovation. Innovation had a higher chance to emerge in the same industry due to the moderate technological distance. Different organizations in the same industry took their advantage to cooperate with each other.

From the view of organization type, the communities of innovation are usually composed of universities, enterprises, and research institutes. Since universities had a wide range of research fields and they usually had fewer conflicts of interest with enterprises in the intellectual property rights, universities often cooperated with many other organizations in the network. In five of the eight communities, the node with the highest degree centrality was university. In further, we calculated the proportion of each type of organization in the eight communities (Table 7). Although only 1%–3% of organizations were universities in the communities, universities played an important role in the network with high degree centrality.

Actually, universities not only had high degree centrality themselves but also played an important role in connecting regions. We attempted to find the key nodes connecting regions, which had more potential for increasing the cooperation between regions. We extracted the nodes that connected different regions most and found that universities and state-owned enterprises played important roles in connecting among the regions. Table 8 shows the top 20 organizations connecting different regions with the largest degree across regions, which was defined as the number of connections between different regions. Within the 20 organizations, universities accounted for eight of them, indicating that universities were very important to connect organizations between different regions. Some researches [26, 32] also showed that universities had central positions in university-industry network acting as the disseminators of knowledge and technology. In addition, state-owned enterprises were more likely to cooperate with their affiliated companies.

Among the eight communities with significant industrial characteristics, communities #9, #1, #5, #12, and #8, which were in the field of railway, electric power, and petroleum, had more connections between different regions. The proportions of connection across regions in the communities #9, #1, #5, #12, and #8 were 37.0%, 32.7%, 32.0%, 28.0%, and 27.7%, respectively, ranking higher than the other 7 communities. It indicated that BTH Urban Agglomeration had more connections in patent application in the field of railway, electric power, and petroleum.

In the following, we will illustrate the other four industries reflected from the communities of innovation.

4.3. Petroleum Industry. Communities #5, #8, and #12 (Figures 11–13) were three separate communities of innovation in the field of the petroleum industry. They centered on China's three oil giants, CNOOC, Sinopec, and PetroChina, respectively. In community #5, CNOOC connected with Tianjin University and Tianjin University of Technology, acting as the three multiple centers. Community #5 had strong geographical attributes. Since CNOOC mainly engaged in offshore oil exploitation, most of the organizations (59%) were from Tianjin. This was very different from the majority of communities with most of the organizations located in Beijing. Community #8 had a flat structure with Sinopec as one of the most important nodes. This community was prominent in the chemical industry, which was consistent with the area of expertise of Sinopec. Community #12 was also a flat structure with PetroChina as an important node. The other important nodes include the Chinese University of Petroleum (Beijing), Tiangong University, Shenhua Group, and Eastern Geophysical Exploration Co., Ltd. Community #12 showed outstanding performance in oil exploration, which was also the area of expertise of PetroChina.

4.4. Metallurgy and Materials. Community #4 (Figure 14) was mainly in the field of metallurgy and materials. Shougang Group, Hebei Iron and Steel Group, and their subsidiaries were important enterprise nodes in this community. Metallurgy and materials industry occupied a large proportion in

Table 7: Industry-university-research structure of the eight communities of innovation.

Community no.	Industry	University (%)	Enterprise (%)	Research institute (%)
1	Electric power	0.8	95.3	4.0
4	Metallurgy and materials	3.4	89.2	7.4
5	Petroleum	1.8	90.0	8.2
6	Transportation	1.9	89.4	8.8
8	Petroleum	2.7	87.7	9.6
9	Railway	1.1	89.4	9.5
11	Construction	0.8	91.0	8.2
12	Petroleum	1.6	92.1	6.3

Table 8: Top 20 nodes with the largest degree across regions.

Organizations	Province	Degree across regions	Degree	Industry
State Grid	Beijing	308	685	Power
Tianjin University	Tianjin	78	225	University
China National Offshore Oil Corporation	Beijing	75	125	Petroleum
Tsinghua University	Beijing	74	575	University
University of Science and Technology Beijing	Beijing	40	181	University
State Grid Hebei Electric Power Company	Hebei	38	126	Power
CNOOC Energy Development Co., Ltd.	Beijing	37	50	Petroleum
Hebei University of Technology	Tianjin	35	82	University
China National Petroleum Corporation	Beijing	34	69	Petroleum
Beijing University of Chemical Technology	Beijing	33	135	University
State Grid Tianjin Electric Power Company	Tianjin	33	54	Power
China Electric Power Research Institute	Beijing	30	146	Institution
The Third Railway Survey and Design Institute Group Co., Ltd.	Tianjin	29	38	Railway
North China Electric Power University	Beijing	28	116	University
Institute of Process Engineering, CAS	Beijing	26	74	Institution
Nankai University	Tianjin	25	116	University
Chinese Academy of Military Medical Sciences	Tianjin	25	28	Institution
CNPC Bohai Petroleum Equipment Manufacturing Co., Ltd.	Tianjin	24	30	Petroleum
China Shenhua Energy Co., Ltd.	Beijing	23	79	Mining
North China Electric Power University (Baoding)	Hebei	21	26	University

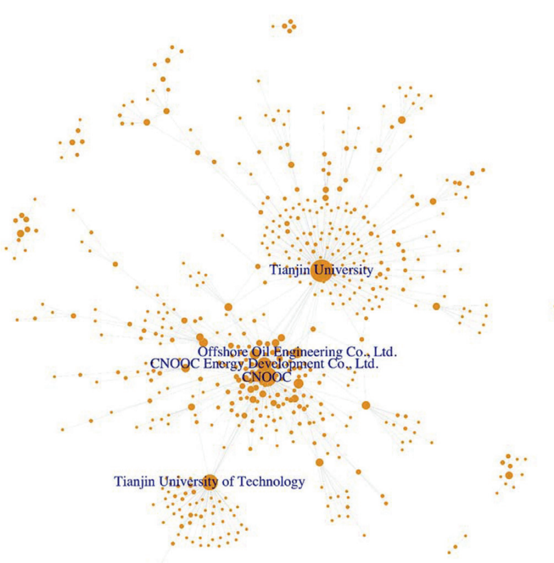

Figure 11: CNOOC community.

Figure 12: Sinopec community.

Figure 13: PetroChina community.

Figure 15: Community in the field of municipal transportation.

Figure 14: Community #4 in the field of metallurgy and materials.

Figure 16: Community in the field of railway.

the industrial structure of BTH Urban Agglomeration, especially Hebei Province. Hebei Province was an important steel production base in China. Since 2002, Hebei has been the province with the largest steel output. In 2019, Hebei's steel output was 284 million tons, accounting for 23.6% of the country. Community #4 had a close innovation cooperation relationship in BTH Urban Agglomeration. About 30% of organizations in the community came from Hebei Province. Compared with the other communities, the proportion was relatively high, which was only lower than that of the Electric Power Community of Innovation.

4.5. Municipal Transportation. Community #6 (Figure 15) was in the field of municipal transportation with flat structure. The first three important nodes in the community were all universities. Except these universities, important enterprise and research institute nodes included the Institute of Highway Science under the Ministry of Transport, Beijing Rail Transit Construction Management Co. Ltd., and Beijing Urban Construction Group Co. Ltd. These enterprises and research institutes were in the field of municipal transportation. From the geographical composition, 80% of organizations of community #6 came from Beijing, 10% from Tianjin, and 10% from Hebei Province, which reflected the significant geographical attribute of Beijing.

4.6. Railway Industry. Community #9 (Figure 16) was in the field of the railway industry. Within the top ten nodes with the highest degree centrality, eight of them had relationships with railways and the other two nodes were in the field of energy. Since the railway industry in BTH Urban

Agglomeration was mainly concerned with railway operations and electrical design, few enterprises in community #9 were involved in manufacturing.

5. Conclusions

This article studies the coordinated development of Beijing-Tianjin-Hebei from the perspective of the community of innovation, which complements the previous research. Through investigation of the communities of innovation detected from the patent cooperation network in BTH Urban Agglomeration, we summarized four typical community structures and found significant industrial and geographical characteristics in the communities of innovation. Beijing, Tianjin, and Hebei have formed a patent cooperation network centered on universities and large state-owned enterprises mainly in six industry fields. Tianjin and Hebei both have close patent cooperation relationships with Beijing; however, there is a lack of cooperation between Tianjin and Hebei. Universities and state-owned enterprises played an important role in connecting organizations among regions; especially, universities have more potential to connect organizations from different regions due to their advantages in various research fields and nonprofit attributes. In the field of railway, electric power and petroleum BTH Urban Agglomeration had more connections in patent application compared with other industries. In the future, Beijing, Tianjin, and Hebei should further strengthen innovation cooperation and remove obstacles that hinder innovation.

Data Availability

The China Patent Database and Business Registration Database used to support the findings of this study were supplied by LIIN DATA under license and so cannot be made freely available. Requests for access to these data should be made to LIIN DATA via e-mail guochunlei@liindata.com. The Tianyan check data can be obtained through the data query port: https://www.tianyancha.com/.

Disclosure

Fang Zhou and Bo Zhang contributed to conceptualization, data curation, formal analysis, methodology, software, validation, visualization, and writing the original draft. Fang Zhou contributed to writing, review, and editing.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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Research Article

How Do Innovation Network Structures Affect Knowledge Sharing? A Simulation Analysis of Complex Networks

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Knowledge has become an important resource that can help enterprises gain a competitive advantage in the market. In this regard, knowledge sharing in the process of cooperative innovation provides an important way to acquire knowledge. With the development of innovation, the innovation network has become an important carrier of knowledge sharing, which can also have an influence on knowledge sharing. Based on knowledge management theory and complex network theory, this study constructed a multilayer network environment for knowledge sharing. It then identified the network elements and knowledge-sharing paths that influence knowledge sharing from microperspectives and macroperspectives. On this basis, the effects of node cohesion and weak connection on knowledge sharing in small-world and scale-free topologies were analyzed by computer simulation. The results showed that, in an innovation network with a scale-free topology, cohesion and weak ties had a great influence on the average knowledge level and knowledge equilibrium. Meanwhile, in small-world topological innovation networks, a mixed path had the best promotion effect on network knowledge sharing.

1. Introduction

Under the ongoing "Fourth Industrial Revolution," emerging industries tend to be more knowledge intensive and less focused on the consumption of material resources [1]. The rapid development of such industries can directly affect regional and national development levels and enhance competitiveness. Specifically, emerging industries based on scientific knowledge can help developing countries catch up with technology and promote their future development [2]. Knowledge, therefore, has become a high-value asset for achieving innovation and creating wealth. The knowledge and technology that promote enterprise development require learning, sharing, and diffusion. Thus, in the era of the knowledge economy, knowledge is an important factor for economic growth; knowledge sharing's contribution to economic growth is even considered greater than that of knowledge innovation itself [3].

With the accelerated development of science and technology, cross-field knowledge is becoming increasingly integrated into emerging industries. The increasing demand for rapid, high-quality innovation creates challenges for enterprises' technological innovation. In this regard, individual innovation activities can have difficulty adapting to a changing innovation environment [4]. With the goal of sharing benefits and risks, enterprises, universities, and institutions form alliances to jointly overcome such difficulties. These innovation networks formed by industry-university-research cooperation have given rise to a new organizational form that is becoming increasingly systematic and complex [5]. Accordingly, the influence of the network structure on knowledge sharing has become an important research topic.

Knowledge sharing is a behavior that allows different types of knowledge to be shared between different subjects, resulting in new knowledge. The knowledge-sharing process has been studied from three perspectives. First, transaction theory suggests that knowledge is scarce and can be sold in an alliance to gain profits [6]. Therefore, obtaining profits through such an exchange of knowledge is a knowledge-sharing process. Second, knowledge transfer theory suggests that knowledge sharing is a process in which subjects possessing knowledge transfer that knowledge to subjects who want to use knowledge more efficiently. New knowledge is generated in this process of knowledge transfer [7, 8]. Third, according to organizational learning theory, knowledge sharing is a process in which enterprises communicate with each other and receive the knowledge they need. Through this process, enterprises promote and share their knowledge with other enterprises in the alliance and encourage member firms to continue learning to achieve knowledge sharing [9]. In this knowledge-sharing process, information technology development levels [10], organizational incentives [11], and organizational environments [12] affect knowledge-sharing efficiency. Alliance networks have become an important channel for enterprises to acquire, integrate, and utilize external knowledge resources. Knowledge networks [13], structural diversity [14], and network structures will affect the efficiency of knowledge sharing [15, 16]. Cowan found that "small-world" networks were the most conducive to knowledge sharing and diffusion, and the shorter the average network path, the more rapid and complete the knowledge-propagation process [17]. However, too much similarity in a community structure can hinder knowledge sharing [18]. Lin found that knowledge sharing performed best in scale-free networks [19]. Su and Li constructed a knowledge-transfer model for a knowledge alliance based on acoustic-wave theory and found positive correlations among the number of enterprises in a knowledge alliance, knowledge-transfer frequency, and knowledge-transfer effect [20]. Two gaps can be identified in the literature. First, most existing studies constructed a network environment for knowledge sharing and analyzed its influence from a macroperspective while ignoring the influence of strong and weak ties on knowledge sharing between micro-individuals. Second, the knowledge in the organization exists in the form of knowledge network. Thus, a traditional single-layer network model cannot describe the knowledge network owned by an actual organization in a detailed and comprehensive way.

The present study, therefore, utilized multinetworks to describe the carrier of knowledge sharing and explain its process. Moreover, complex network theory was adopted to deal with the structural characteristics of innovation networks. On this basis, this study constructed a mechanism model and analyzed how network structures influence knowledge sharing in multinetworks. We focused on two questions: Q1: which network elements affect knowledge sharing from macroperspectives and microperspectives? Q2: how do these elements affect knowledge sharing in multinetworks? This study focused, therefore, on the process of knowledge sharing among different organizations and examined the influence of network elements on knowledge sharing. Accordingly, this study's findings have implications for governments, researchers, and industries.

The rest of this paper is organized as follows: Section 2 reviews the literature, which forms the basis for the analytical framework. Section 3 analyzes the knowledge-sharing model in the innovation network that was established to explain the mechanism of knowledge sharing. Then, in Section 4, numerical simulation is used to construct the related mechanisms that can promote knowledge sharing in innovation networks. Section 5 provides conclusions and suggestions.

2. Literature Review

2.1. Knowledge Sharing. Knowledge has public goods, transfer, and agglomeration characteristics, which allow innovation subjects to smoothly transfer knowledge through cooperation and thereby obtain benefits. Polanyi and Nonaka proposed the classic division of knowledge. According to whether knowledge can be expressed and how much it can be expressed, they divided knowledge into explicit and implicit knowledge [21, 22]. Explicit knowledge is the knowledge that is clearly expressed, usually in a publicly accessible manner, such as written text, numbers, or graphics. Explicit knowledge can be effectively transmitted through media and can be received by most groups. Implicit knowledge, meanwhile, has a low degree of explicitness. It is difficult to express implicit knowledge through precise language; it can only be accessed through communication and learning between individuals [23]. Therefore, cooperation provides a good platform for the transfer of implicit knowledge. During the cooperation process, collaboration parties can learn, grasp, and transmit implicit knowledge that cannot be easily expressed through words [24].

Knowledge sharing is a process of knowledge transmission between individuals and organizations; it represents the organic unity of knowledge transfer and knowledge-absorption processes [25], as well as the acquisition, integration, and creation of knowledge and information [26]. Knowledge sharing is thus the core of knowledge production and plays an important role in knowledge inheritance and knowledge innovation [27]. Knowledge sharing enables innovative organizations to create knowledge by learning from other organizations. Efficient knowledge sharing helps implicit knowledge become more explicit and facilitates knowledge innovation through knowledge externalization, internalization, integration, and absorption [28]. Knowledge sharing, moreover, facilitates communication among members of an organization, which in turn helps innovation subjects acquire required knowledge, narrows the knowledge gap between parties, and accelerates innovation diffusion [29]. Knowledge sharing also has positive externalities

[30]. Through knowledge sharing, both parties gain knowledge from each other, pursue knowledge innovation, spread knowledge to the organizational level of the innovation network, improve knowledge exchange, and support technological innovation [31]. Therefore, knowledge sharing is a dynamic process in which knowledge acquirers contribute to the value of an organization. It is only through such means that knowledge can be absorbed, utilized, and transformed into an ascending spiral. Managing knowledge in the system can provide a fourfold value through knowledge acquisition and selection, processing and absorption, sharing and transfer, and innovation and creation. Under specific network conditions, the mechanism of knowledge flow within an organization forms a knowledge-sharing process, which ensures knowledge sharing and organizational identity among organization members with compatible knowledge structures and cultural backgrounds [32].

Based on the literature, this study defines knowledge sharing as the process of knowledge dissemination and recreation, that is, the whole process of knowledge recreation through direct or indirect communication and interaction between subjects (subject can also be a node in a network) in an innovation network, absorbing each other's knowledge advantages in the presence of differences in knowledge potential.

2.2. Innovation Networks and Complex Networks. An innovation network is an open and dynamic complex system [33]. It is a basic institutional system that serves the systemic innovation of the subjects. The innovative cooperation relationship between enterprises is the main bridging mechanism of the network frame [34]. This relationship is mostly maintained by contracts. The content of the relationship is the innovation activities between the innovation subjects, and the ultimate goal is to maximize the benefits of all participants. Under the influences of technology spillover [35], knowledge integration [36], innovation dependence [37], organization proximity [5], and other factors, nodes in the network constantly adjust strategies according to development needs in the process of activities; original innovation subjects are reintegrated, new subjects are constantly added, and the innovation network structure transitions from looseness to centralization [38]. An innovation network gradually assumes the form of a "small-world" with strong cohesion [39], evolving from a low level to a high level. It gradually forms an innovative system with the characteristics of open growth, selective connectivity, and complex multisubjectivity [40]. An innovation network contains significant innovative talent. Through collaborative cooperation, talented individuals who possess knowledge can share that information and communicate with different subjects, thus injecting knowledge. Because an innovation network has a large number of complex connected relationships, the inflow of resources, such as innovation knowledge, is broadened, and knowledge is aggregated. Therefore, the formation of an innovation network provides a platform for knowledge sharing, which in turn promotes the development of an innovation network.

In recent decades, as a kind of complex social network, innovation networks have been increasingly formed to promote innovation and knowledge sharing. Complex networks are applied to explain the formation and evolution of innovation networks [41]. A complex network is a set of graphs composed of nodes and their relationships. The nodes in a complex network are numerous and diverse. Connections between nodes can appear or disappear at any time. The fusion of multiple behaviors leads to high complexity and evolution [42], which are mainly manifested in structural complexity, network evolution, and node diversity. Analyzing the concepts and characteristics of complex networks and innovative networks reveals that the two have similarities in terms of their network attributes, as shown in Table 1.

Since innovation networks are similar to complex networks (i.e., the nodes are diversified, the connections are complex, and there are certain evolutionary characteristics), studies generally use the measurement indexes of complex networks to measure innovation networks [44].

In summary, this study defines an innovation network as the interrelated organizational structure formed by innovation subjects in the process of cooperation and communication, and it is measured using the related indexes of complex networks.

2.3. Network Structure and Its Effect on Knowledge Sharing. Knowledge sharing is a process of knowledge transfer and recreation between innovation subjects. To fill knowledge gaps, innovation subjects in a network must cooperate with other subjects to promote knowledge sharing and integrate knowledge. Only by realizing knowledge sharing can innovation subjects achieve technological innovation and improve their innovation performance. Therefore, the present analysis of knowledge sharing in innovation networks is designed to explore the knowledge transfer and creation process in an innovation network, thus helping innovators identify a better knowledge-sharing pattern. The knowledge-sharing process includes knowledge transfer and knowledge creation. Knowledge transfer emphasizes the process of knowledge transfer from provider to recipient. The knowledge provider has an absolute knowledge advantage, and the knowledge receiver, based on the subjects' innovation needs, can acquire, absorb, and utilize complementary knowledge through cooperation and exchange. Knowledge creation emphasizes the socialization and internalization of implicit knowledge, highlighting the ascending-spiral process of knowledge.

The cooperation and communication relationship between subjects in an innovation network is the link that helps them acquire and utilize complementary and heterogeneous knowledge. Innovation subjects can access cutting-edge knowledge in the process of communication and

Table 1: Attribute comparison between complex networks and innovation networks.

Main properties of complex networks [43]	Main properties of innovation networks [41]
The number and types of network nodes are varied.	The number of innovation nodes is increasing, and there are different nodes in the network (e.g., universities, institutions, and firms).
The structure of the network is complex.	There is a great deal of nonlinear positive and negative feedback between innovation subjects, which makes the innovation network a complex system with complex structures, intricate relationships, and diverse target functions.
It involves the dynamic evolution of time and space.	They have complex evolution characteristics. The innovation subject carries on the transformation connection according to resource endowment preference differences. Meanwhile, external nodes are attracted to join the network, causing the relationships between innovation subjects to change constantly, and the network evolves accordingly.

cooperation. Meanwhile, the knowledge-communication relationship established with heterogeneous subjects can help enterprises build their reputation in the network and help them form more network relations to acquire rich external knowledge [45]. Due to differences in the frequency, intensity, and number of connections between the subjects, a diversified network structure is formed, and the structural position of the subject is an important basis for measuring the knowledge capital it can obtain. With principals at the center of the network, they will have more opportunities to use and control information and resources [46]. A network with more structural holes can facilitate knowledge diffusion by promoting the adoption of nonredundant information and knowledge, carrying out middleman business, and acquiring tangible resources [47]. The popularity and activity of individuals in the network are often considered the key area regarding the function of the "structure diagram" or "bridge connection." Therefore, subjects occupying structural holes and having more bridge connections can obtain more heterogeneity and advantageous information [48]. In addition, some stable network structure relationships will be formed among individuals who have established connections, which is conducive to the acquisition and sharing of knowledge [49].

In summary, the network structure formed by an innovation network and the network locations of the innovation subject both influences the subject's knowledge acquisition. This study examined knowledge sharing in an innovation network from two aspects: microindividual network elements and macronetwork topologies. From the microperspective, subjects with direct connections can share knowledge through direct cooperation, exchange, and recreation. Therefore, the cohesion of nodes has an effect on knowledge sharing; the more subjects with direct connections, the higher the cohesion. In addition, the positive externality of knowledge sharing enables subjects without direct connections to acquire knowledge through indirect relations, such as "structural holes" and "bridge connections"; thus, the weak ties of nodes will also have effects on knowledge sharing. From the macropoint of view, different network topologies determine the sharing efficiency and knowledge paths in the network. Therefore, this study established knowledge-sharing paths, including direct, indirect, and mixed paths. A direct path reflects the influence of node cohesion on knowledge sharing, while an indirect path reflects the influence of weak ties among knowledge-sharing nodes.

3. Method

3.1. Multinetwork Model. Based on the literature review, to describe the knowledge-sharing process in innovation networks, this study constructed a knowledge network based on knowledge elements and an innovation network for knowledge sharing. It then simulated the relationship between the two networks to build a multilayer network of knowledge sharing.

3.1.1. Construction of a Knowledge Network. The basic components of a knowledge network include related knowledge in the network organization. Drawing on previous studies [50], we described the knowledge possessed by individuals in an innovation network by creating a knowledge-network tree diagram. We divided the knowledge used by an organization into a knowledge field and a knowledge unit (KU), as shown in Figure 1. In this paper, we defined the knowledge field as some kinds of knowledge in different industries or in different subjects; it can be divided into different knowledge unit. And knowledge unit refers to the knowledge with a complete expression that cannot be divided. The knowledge stock of the network node was represented at the same level, and the knowledge source at the same level did not have overlapping knowledge. Knowledge networks are represented by innovation networks, where K means nodes in the network and V means relationship in the network. Thus, we have $V_k = \{(k_i, k_j) \mid \theta(k_i, k_j)\}$. If $\theta = 1$, K_i is the subnode of K_j; otherwise, there is no connection relationship between K_i and K_j.

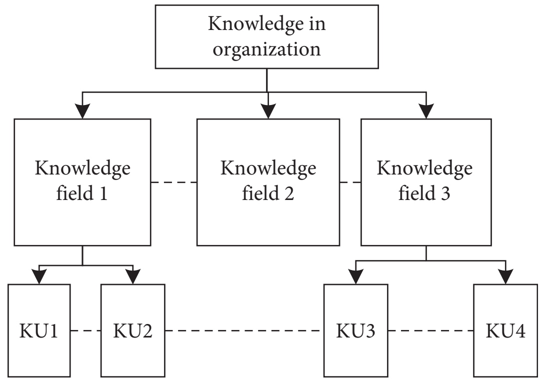

Figure 1: Diagram of a knowledge network.

3.1.2. Construction of an Innovation Network. "Innovation network" describes the relationship between each innovation subject. This study used the complex-network metaphor for the innovation-network environment. Small-world and scale-free networks are common complex networks. The small-world network is a common complex network proposed by Watts and Strogatz. The node degree of a small-world network presents Poisson distribution characteristics. This network has a high clustering coefficient and a short average path length [51]. Complex networks with a scale-free structure exhibit the following two characteristics: first, the number of nodes is constantly increasing; second, newly added nodes and original nodes are connected based on the principle of "degree preference" (higher-degree nodes are selected more often) [52]. We constructed innovative cooperation networks with these characteristics. The cooperation network expression is $\mathrm{NC} = (K_c, V_c)$, where K_c is the number of subjects in the cooperation network, and V_c is the connection relationship in the cooperation network. If $V_c = 1$, a cooperative relationship exists between the innovation nodes; if $V_c = 0$, no connection relationship exists between the innovation nodes.

In general, studies have used network average degree and average path length to describe the topology structures of complex networks. The degree of nodes refers to the number of edges that other nodes in a complex network are directly connected via a specified node, called k_i. Degree is an index for measuring the relationship between nodes in a network. The average degree of all nodes in the network becomes the average degree of the network.

Average path-length L refers to the shortest path between nodes i and j in a network as follows:

$$L = \frac{1}{(1/2)N(N-1)} \sum_{i \geq j} d_{ij}, \quad (1)$$

where N represents the number of nodes in the network and d_{ij} is the geodesic distance between two nodes. The smaller the average path length, the shorter the distance between nodes; that is, the shorter the time needed to reach the target position, the less the authenticity.

3.1.3. Multilayer Network Construction. Network members in a cooperative innovation network possess relevant knowledge in the knowledge network. Therefore, the relationship between the innovation network and the knowledge network was constructed, and the relationship formed among networks constitutes a knowledge-sharing multilayer network in the innovation network (Figure 2). This study established an array $v[n, m]$ to express the amount of knowledge owned by members of the innovation network.

3.2. Mechanism of Knowledge Sharing in Multinetworks. Innovation subjects at this stage of socialization utilize mobile resources and communicate with innovation subjects in the network to acquire implicit knowledge. The innovation network provides a communication exchange platform for innovation subjects to conduct social activities. Innovation subjects make the acquired implicit knowledge more explicit to renovate and transform the implicit knowledge of the individual into the public knowledge of the network [28]. Innovation subjects then integrate scattered knowledge into the network through a joint process and integrate the implicit knowledge acquired in the first and second stages, forming a knowledge-innovation system. In the process of internalization, innovation subjects absorb knowledge, create new knowledge through practice and learning, and continue the process of knowledge transfer, knowledge processing, knowledge integration, and knowledge innovation [53]. In addition, innovation subjects absorb useful knowledge, process knowledge based on its advantages, transfer new knowledge to the innovation system, and achieve the two-way circulation of knowledge through transferring and sharing. We can conclude, therefore, that innovation ability, learning ability, and degree of explicitness affect

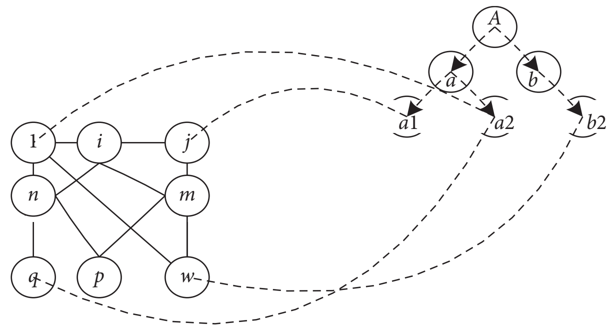

Figure 2: Multilayer knowledge network diagram.

the efficiency of knowledge sharing in a network. Knowledge is transferred, absorbed, digested, shared, and recreated among cooperative innovation organizations, achieving an ascending-spiral process of communication, coordination, cooperation, and collaboration [54].

This study focused on the process of knowledge sharing between organizations. A multilayer network structure was used to describe the carrier of knowledge sharing. Based on the analysis in Section 2.3, this study divided the knowledge-sharing path in the innovation network into three types: direct path, indirect path, and mixed path.

Direct path (DP) refers to knowledge sharing in the knowledge network via direct contact between subjects in the innovation network. Such direct contact and learning usually promote the transmission of tacit knowledge in the network. When innovation subjects in the innovation network cooperate, they communicate with each other and share knowledge with the knowledge-learning party. Since tacit knowledge is stored in the mind of the knowledge provider, it cannot be encoded with specific words; meanwhile, the knowledge receiver can acquire knowledge through the establishment of a connection relationship to enhance their own knowledge reserve and complete the process of knowledge transfer.

Under DP, it is assumed that the knowledge provider (P_a) has a certain kind of knowledge (K_{ij}). After a round of knowledge sharing, the new knowledge possessed by the knowledge-learning party is only affected by its own cohesion—that is, the influence of the subject in direct contact with it. If there is a knowledge gap between the two nodes, P_a will own some knowledge units of the other node, and the greater the degree of k, the more knowledge it will likely share. Since knowledge potential decreases with increased communication between two parties, the knowledge potential attenuation function $F(\alpha)$ is introduced. $F(\alpha)$ is a power function varying with time, and k is the degree of the node. After a round of knowledge diffusion and learning, the efficiency of knowledge sharing is

$$D_a(t+1) = I_a(t) + F(\alpha) * k. \quad (2)$$

Under the indirect path (IP), it is assumed that the knowledge provider (P_a) has a certain kind of knowledge (K_{ij}). The efficiency of knowledge sharing is only affected by the indirectly connected subject—that is, the number of weak ties. In this study, the average path length L of the innovation network was chosen to represent the weak ties of nodes. After a round of knowledge diffusion and learning, the efficiency of knowledge sharing is

$$I_a(t+1) = I_a(t) + F(\alpha)\hat{L}. \quad (3)$$

Under the mixed path (MP), the knowledge owner will select the DP according to equation (2) at probability P, and the knowledge owner will select the IP according to equation (3) at probability 1–P:

$$M_a(t+1) = pD_a(t+1) + (11p)I_a(t+1). \quad (4)$$

As shown in Figure 3, the innovation network is composed of 1–7. For example, after a round of knowledge sharing and learning, subject 2 can be shared through a DP to learn the knowledge of subject 1. Meanwhile, it can also be shared from node 3 and node 8 through the IP.

3.3. Measure of Knowledge Sharing. Assuming the initial knowledge stock $TK_{PS}(t)$ of each innovation subject in the innovative network NC is the sum of the initial stock of various types of knowledge owned by the subjects, we have

$$TK_{P_a}(t) = \sum_{k_{ij}=1}^{m} v\left(P_a, k_{ij}\right)(t). \quad (5)$$

The total amount of knowledge in the innovation network is

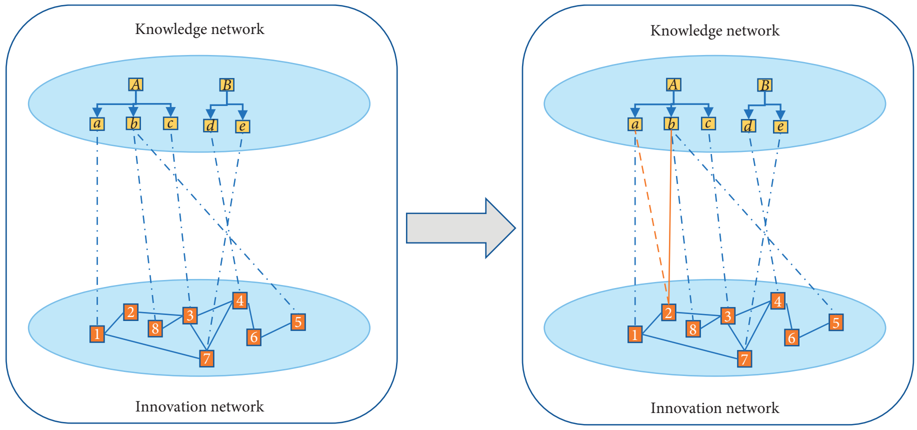

FIGURE 3: Mechanism of knowledge sharing in multilayer networks.

$$TK_{P_a}(t) = \sum_{P_a=1}^{n} v\left(P_a, k_{ij}\right)(t). \quad (6)$$

According to the relationship between the innovation network and the knowledge network, a multilayer network expression, $SN = (K, V, V_{k-k}, V_{c-c}, V_{k-c})$, is established, where V_{k-c} is the set of edges that connects the innovation nodes in the knowledge network and innovation network in the multilayer network. In the simulation, the matrix element value is set to 0 or 1 to indicate whether knowledge field i has knowledge unit j. The number of knowledge units in the network is m, which is the sum of all nonzero elements in the innovation network.

Efficient knowledge sharing can promote collaboration between innovation subjects and enhance innovation performance. Knowledge sharing is one of the goals of collaborative innovation. The level of knowledge measures the efficiency of knowledge transfer in an innovation network. In a certain period of time, the faster the knowledge level in the innovation network grows, the higher the knowledge-sharing efficiency of the network. Therefore, this study used the knowledge level to measure the knowledge-sharing efficiency of the whole network. In addition, the knowledge balance in an innovation network can measure the level of knowledge development in the overall network. The higher the balance, the stronger the cohesiveness of the network, and the more similar the knowledge acceptance ability of each innovation subject. This study selected the average knowledge level and knowledge equilibrium level to measure the efficiency of knowledge sharing in an innovation network. The equations are as follows:

$$u(t) = \frac{1}{n}\sum_{P=1}^{n} TK_P(t), \quad (7)$$

$$\sigma^2 = \frac{1}{n}\sum_{P=1}^{n} TK_P^2(t) - u^2(t). \quad (8)$$

4. Simulation and Discussion

4.1. Steps and Parameter Initialization Settings. Based on the rules of knowledge sharing in a multilayer network, we designed the following simulation steps:

Step 1. The *NC* of an innovation network and NK of a knowledge network with a certain number of nodes are constructed. To simulate the influence of different structures on knowledge sharing, innovation networks with small-world characteristics and scale-free characteristics are generated.

Step 2. Small-world and scale-free networks with 500 nodes were generated based on the literature [55]. Set the average degrees of the network as 2, 4, and 8 and the average path lengths of the network as 2, 6, and 8.

Step 3. When $t = 0$, knowledge elements are randomly assigned to nodes in the innovation network, and the initial average knowledge level and knowledge equilibrium of the network are calculated according to equations (7) and (8).

Step 4. When $t = 1$, after the knowledge sharing and learning of all nodes according to equations (2)–(4), the average knowledge level and knowledge equilibrium of the network are calculated according to equations (7) and (8).

Step 5. Repeat steps 2–4. The simulation is terminated after 10,000 times; it then generates simulation diagrams of the knowledge-sharing effects in different network topologies.

Following the given simulation steps, we used MATLAB R2019b to generate knowledge-sharing effect diagrams in the innovation network with different parameter settings.

4.2. Knowledge Sharing in a Scale-Free Network. Figures 4 and 5 show the effects of node cohesion and the number of weak ties on the average knowledge level and knowledge equilibrium in a multilayer network with a scale-free topology.

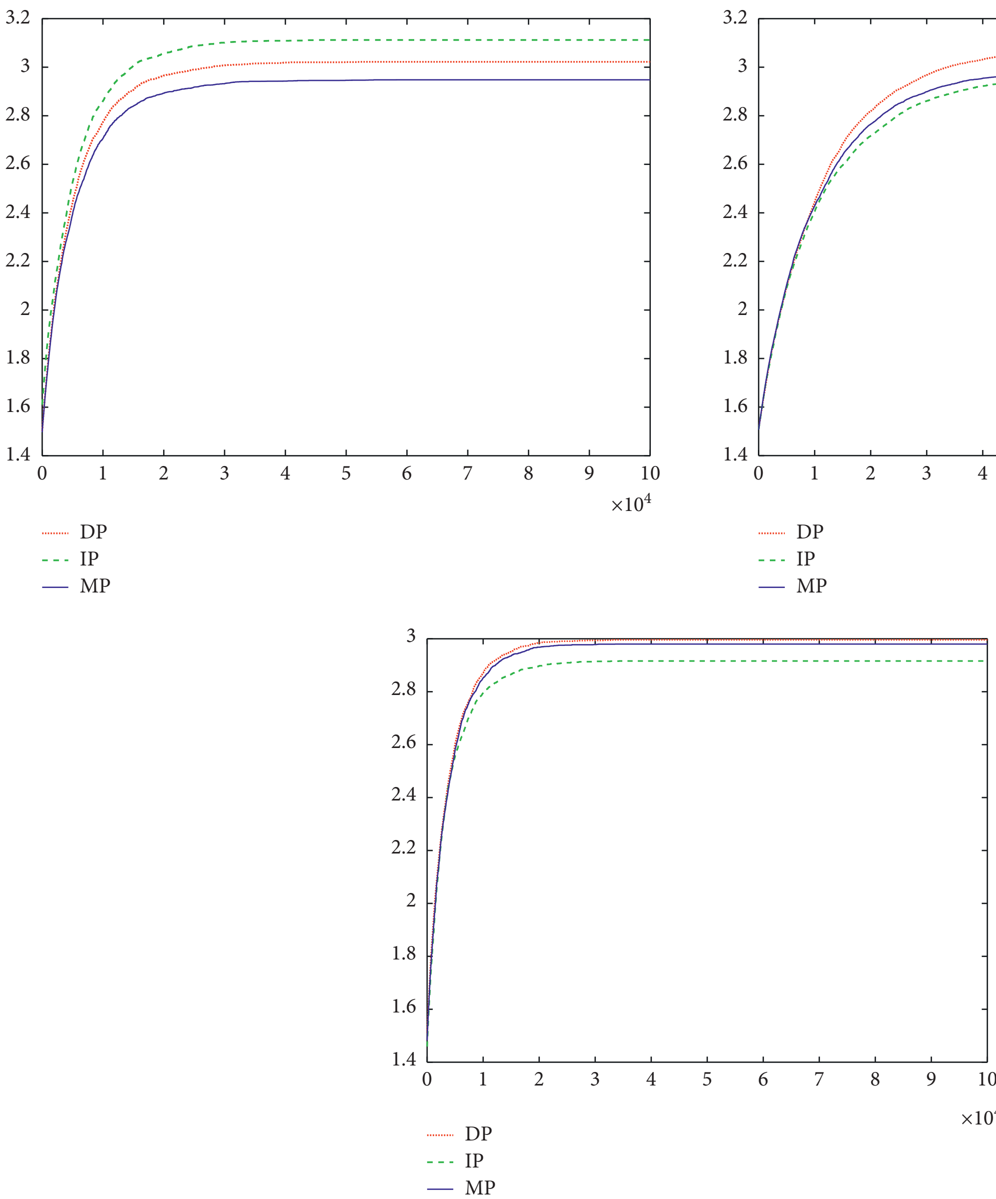

Figure 4: Levels of average knowledge in a scale-free network when $k = 2$, 4, and 8.

When node cohesion k is 2, 4, and 8, the average knowledge level and knowledge equilibrium in the innovation network under a scale-free topology are shown in Figures 4 and 5.

As shown in Figure 3, as node cohesion increased, under a scale-free network environment, the average knowledge level of the innovation network decreased gradually in the DP, MP, and IP. In a scale-free network environment and according to the "Matthew effect" of a scale-free network, as the number of innovation nodes increased, new nodes cooperated with old nodes that had stronger cohesion and more connected relationships. Existing subjects in the network acquired their partners' explicit knowledge through encoded documents and needed more implicit knowledge that could be accessed through cooperation and communication. Therefore, when innovation subjects had stronger cohesion, DP was more conducive to the sharing and creation of network knowledge.

As shown in Figure 5, as node cohesion increased, the innovation network's knowledge equilibrium gradually changed from IP to DP in the scale-free network. Knowledge equilibrium reflected the stock of knowledge owned by each subject in the network. When node cohesion was low, each subject in the IP acquired more similar knowledge through the encoded knowledge. At this time, the network balance was the strongest. As

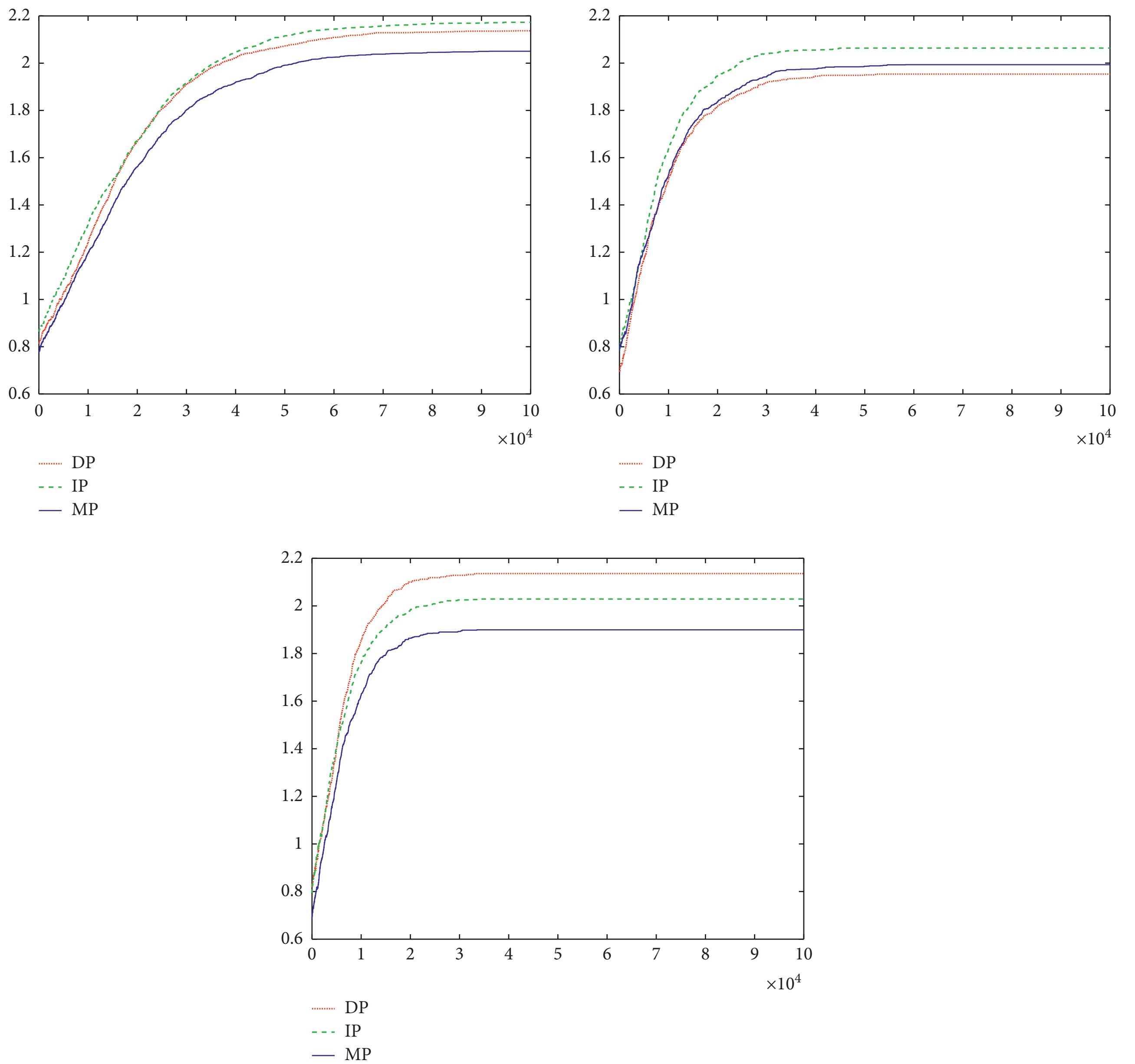

Figure 5: Knowledge equilibrium in a scale-free network when $k = 2$, 4, and 8.

subject cohesion was enhanced, subjects with a relatively high value in the scale-free network acquired implicit knowledge through direct communication. Under the joint catalysis of implicit and explicit knowledge, the collaboration and equilibrium of subjects under DP were gradually enhanced. Therefore, in the process of collaborative innovation, innovation subjects should constantly self-evaluate, master their innovation ability, select appropriate knowledge-sharing channels according to their ability, and improve collaboration efficiency.

When the learning ability of innovation subjects L is 2, 6, and 8, the average knowledge level and knowledge equilibrium in the innovation network under a scale-free topology are shown in Figures 6 and 7.

As shown in Figure 6, MP and IP influenced the effect of weak ties on the level of knowledge sharing, whereas MP

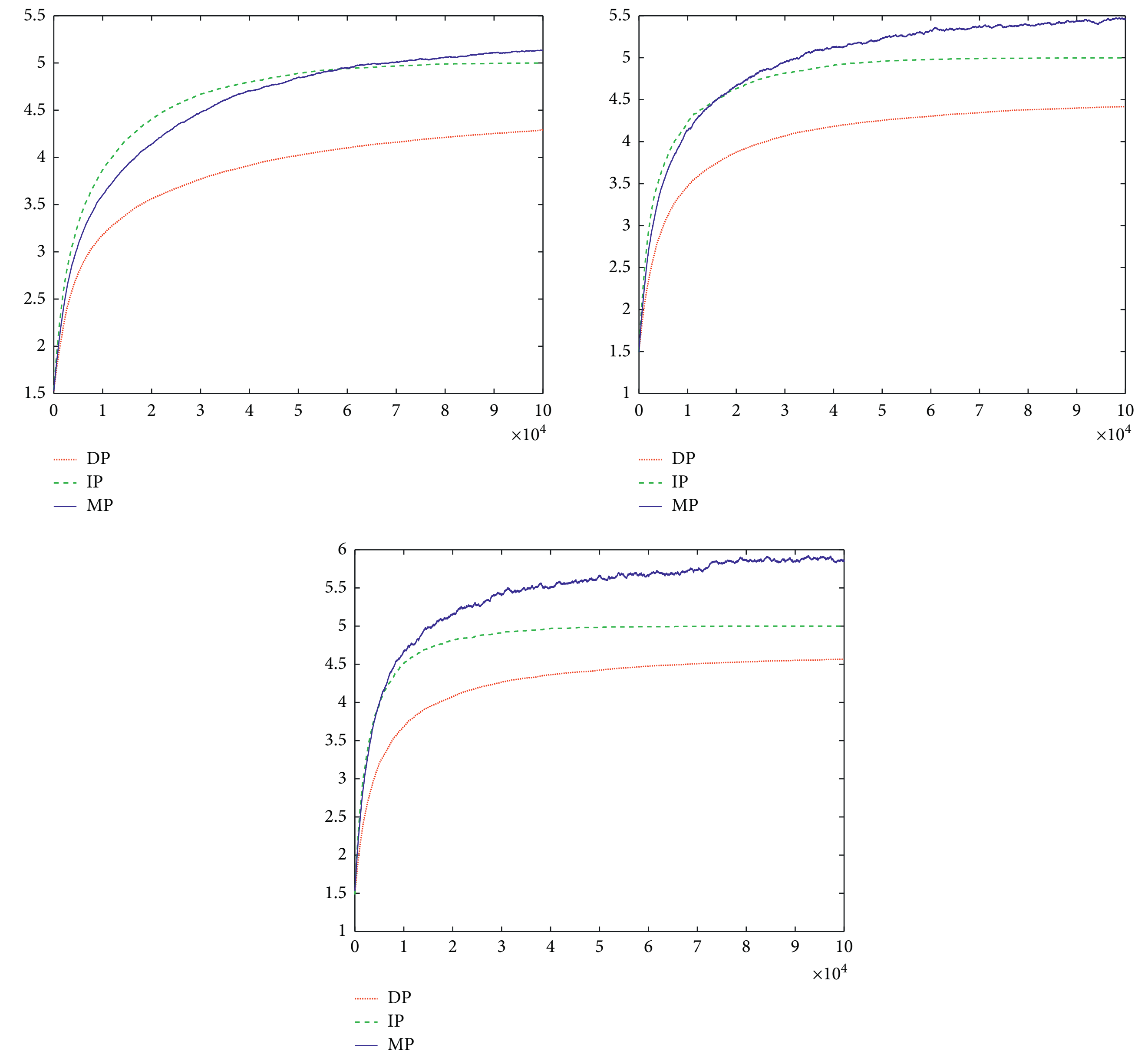

Figure 6: Average knowledge levels in a scale-free network when $L = 2$, 6, and 8.

influenced the effect of weak ties on knowledge equilibrium. This was because weak ties mainly reflect the understanding and acceptance degree of the innovation subject regarding the explicit knowledge diffused by other indirectly related subjects in the network. Therefore, with continuous increases in the number of weak ties, nodes were more likely to grasp the shared knowledge that was clearly encoded in the explicit knowledge-sharing channels, and the average knowledge level in the network reached its highest collaboration efficiency. Additionally, in a scale-free network, the network nodes often cooperated with the few nodes that had high cohesion, resulting in the relatively low aggregation of innovation nodes in the network and limited connection of the knowledge provider, which hindered the communication of implicit knowledge.

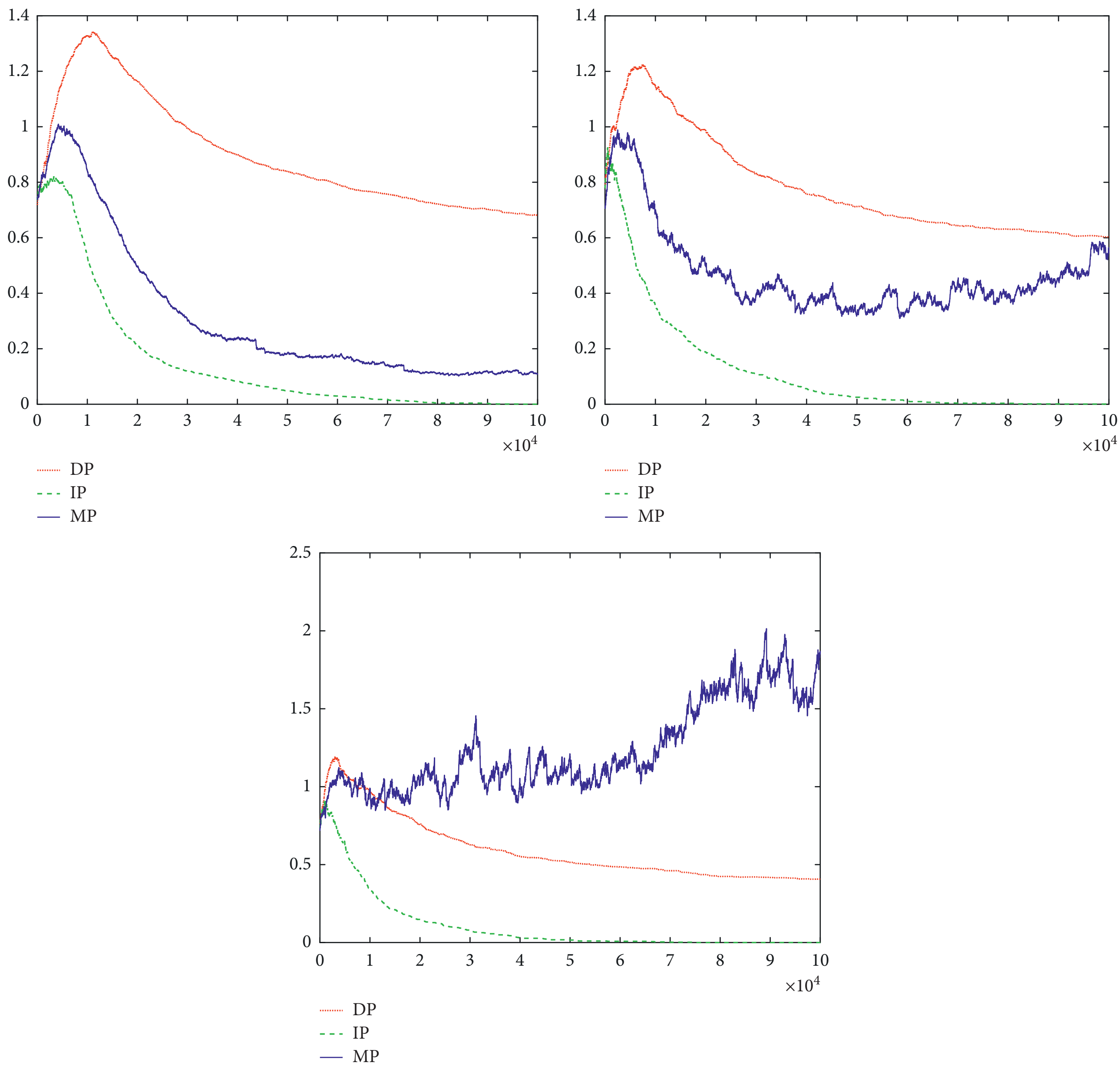

Figure 7: Knowledge equilibrium in a scale-free network when $L = 2$, 6, and 8.

As shown in Figure 7, when examining the effect of weak ties on knowledge sharing in a scale-free network, we found that the average knowledge level in the network declined after a short-term rise. When the relationships between different nodes were relatively weak, IP encountered a block in knowledge transmission and relearning, and the knowledge sender and receiver did not share well, resulting in a decline in the equilibrium of network knowledge. After weak ties increased, knowledge equilibrium in MP gradually increased.

4.3. Knowledge Sharing in a Small-World Network. Figures 8–11 depict the effects of cohesion and the number of weak ties on knowledge sharing under DP, IP, and MP in the innovation network under a small-world topology.

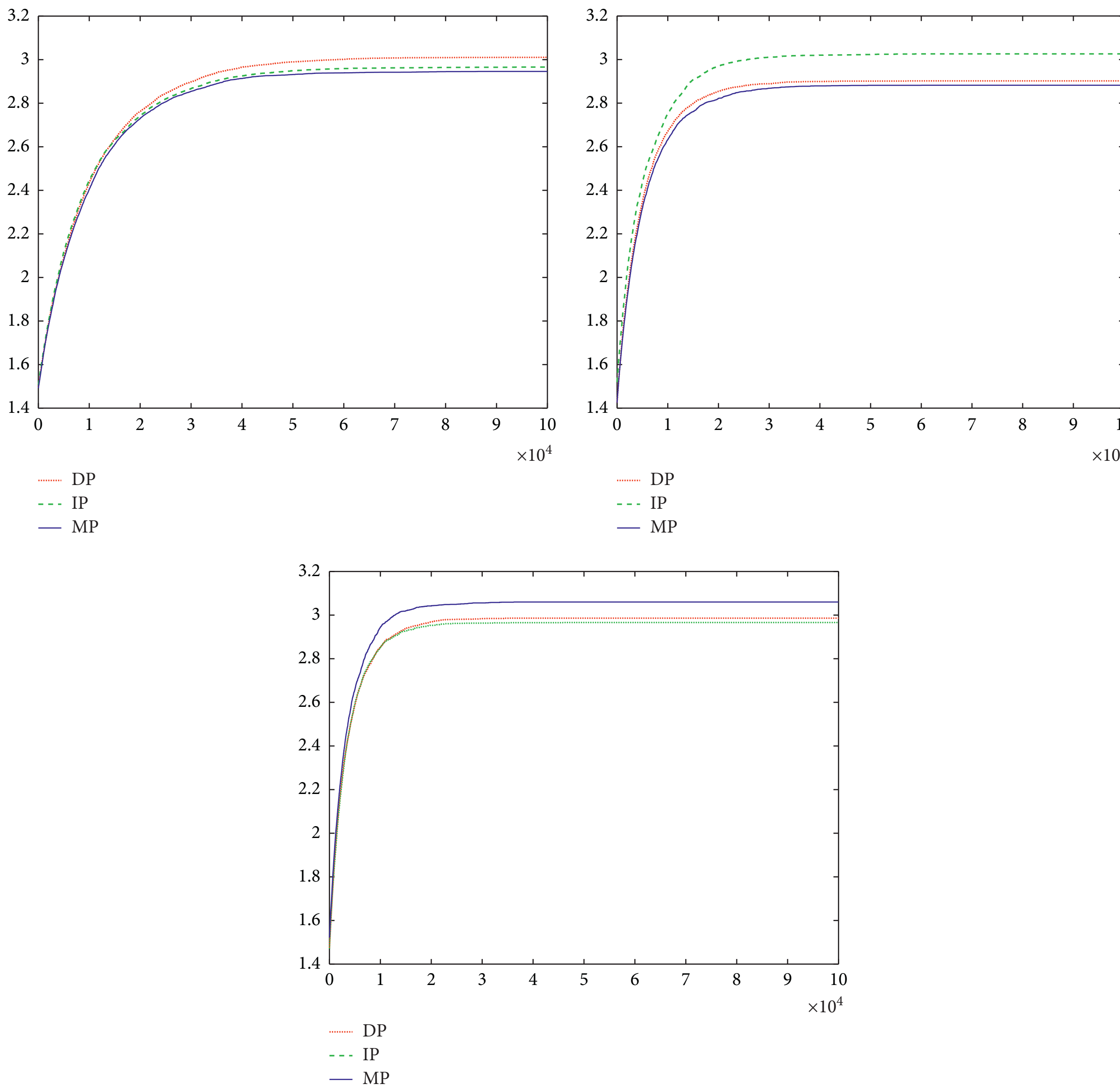

Figure 8: Average knowledge levels in a small-world network when $k = 2$, 4, and 8.

When node cohesion k is 2, 4, and 8, the average knowledge level and knowledge equilibrium in the innovation network under the small-world topology are shown in Figures 8 and 9.

Under the small-world topology, the average knowledge level in the innovation network reached the maximum under MP. The small-world network was more balanced, and the connections among partners in the network were distributed normally. The nodes in the innovation network were more evenly connected in the process of collaborative innovation, and they acquired implicit and explicit knowledge through balanced and comprehensive channels, causing innovation network knowledge to reach a higher level. The network nodes were

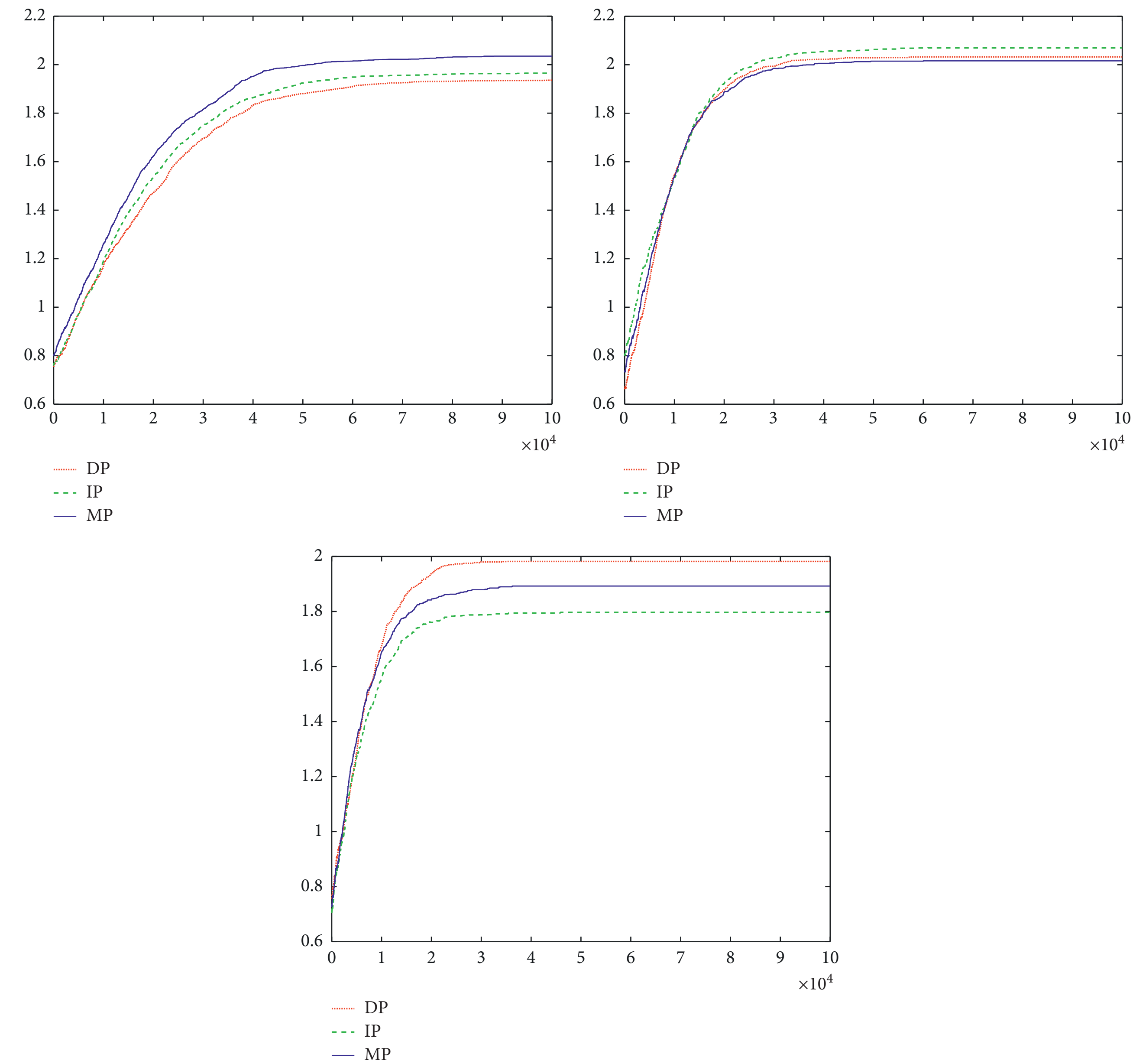

Figure 9: Knowledge equilibrium in a small-world network when $k = 2$, 4, and 8.

less sensitive to node cohesion. In terms of knowledge equilibrium, DP had the greatest effect on knowledge variance. The small-world network exhibited close cooperation, and the nodes directly communicated with and trusted one another to obtain implicit knowledge. Therefore, the innovation network had the highest knowledge equilibrium under DP.

When the weak ties of node L are 2, 6, and 8, the average knowledge level and knowledge equilibrium in the innovation network are shown in Figures 10 and 11 under the small-world topology.

As shown in Figures 10 and 11, in an innovation network with small-world characteristics, MP played a significant role in promoting the average knowledge level

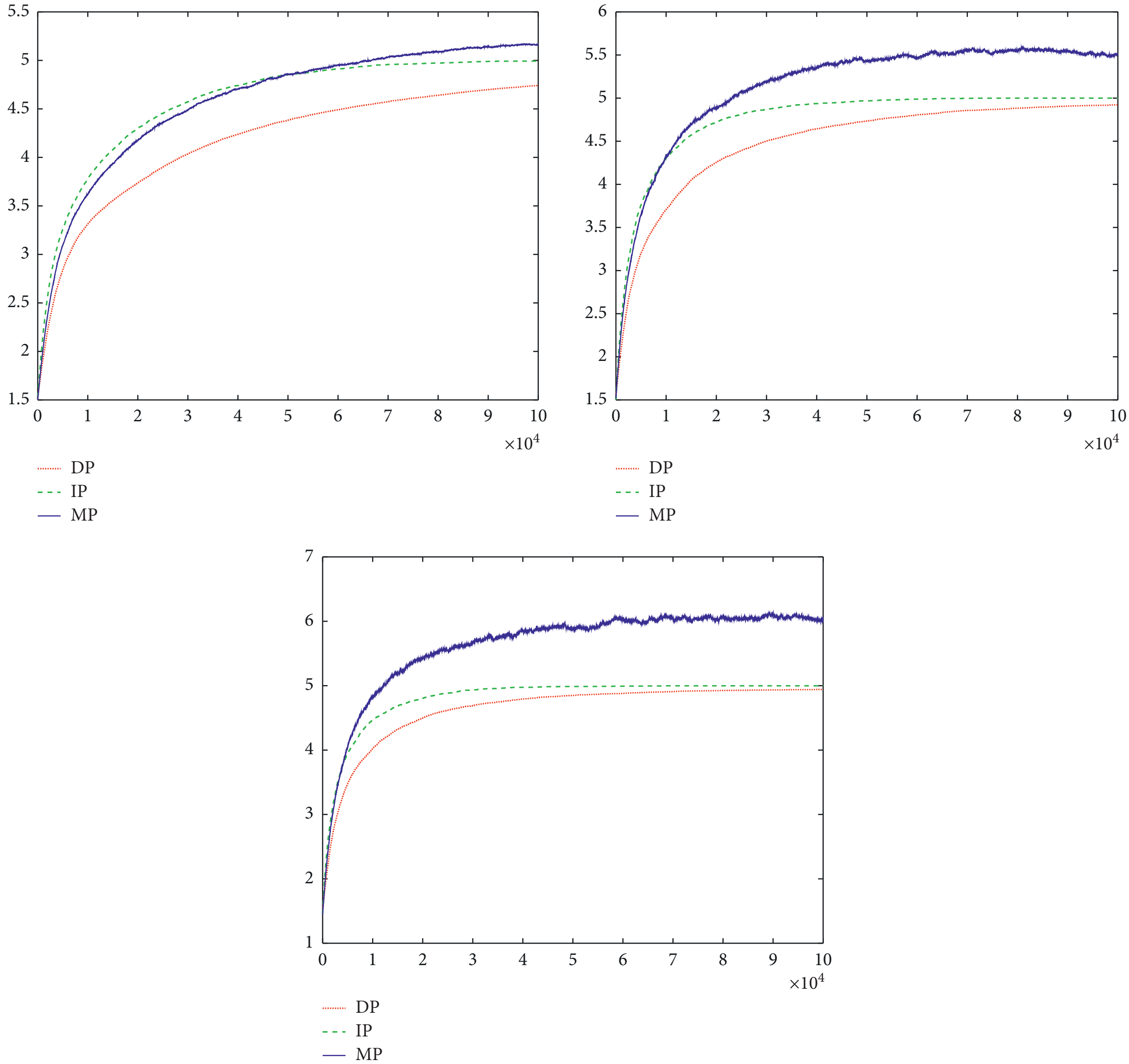

FIGURE 10: Average knowledge levels in a small-world network when $L = 2$, 6, and 8.

and knowledge equilibrium in the network. In the small-world network, the information dissemination path was short, the connection relationship between the innovation nodes was relatively close, and IP and DP both promoted the overall knowledge-sharing efficiency and level of the network. In addition, the efficiency and level of knowledge sharing were maximized when the two patterns coexisted. Moreover, under MP, with an improvement in the learning level of the innovation subjects, knowledge variance fluctuated significantly. The small-world network was highly cohesive, and the network connection was relatively close. The richer the number of weak ties among the nodes, the more subjects they shared, causing knowledge equilibrium in the network to fluctuate.

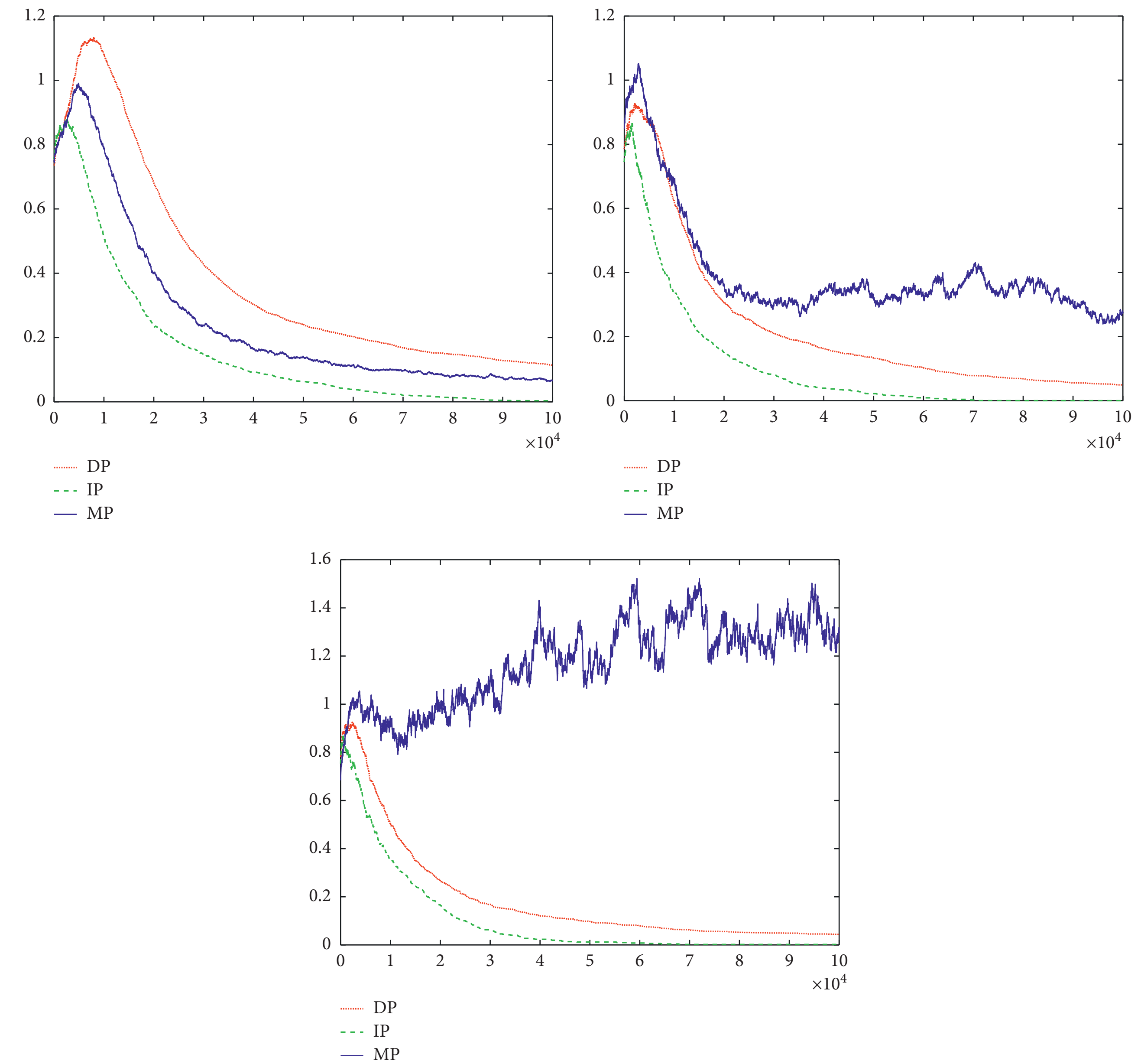

Figure 11: Knowledge equilibrium in a small-world network when $L = 2$, 6, and 8.

5. Conclusion

Based on the model setting and simulation analysis, the following conclusions can be drawn.

First, innovation network structures had different effects on knowledge sharing with different paths. Furthermore, node cohesion and the number of weak ties for making knowledge more explicitly affected the network's level of knowledge sharing.

Second, in the innovation network with a scale-free topology, node cohesion and the number of weak ties for making knowledge more explicitly significantly influenced the average knowledge level and knowledge equilibrium of the network. Overall, the direct path and mixed path had stronger effects on promoting knowledge sharing in the innovation network.

Third, in the innovation network with a small-world topology, the mixed path had the best effect on promoting the network's overall knowledge level.

Based on these findings, this study can provide a reference for improving knowledge sharing in the context of innovation networks.

Most importantly, we need to build harmonious and innovative networks. Since an innovation network includes many innovation subjects, and different subjects have different corporate concepts and cultures, innovation subjects express different opinions during collaboration and cooperation. Most enterprises lack a culture of cooperation for achieving win-win situations, which results in excessive competition in the innovation network, wasted innovation resources, and reduced efficiency. Therefore, at this stage of collaborative innovation, a corporate concept is needed to cultivate an appropriate concept of collaborative innovation and achieve the goal of mutual benefit under the joint efforts of both parties. In addition, the simulation analysis showed that a small-world topology was more conducive to knowledge collaboration and innovation in an innovation network. The most prominent feature of the small-world network was that the average network path length was short, and cohesion was strong. Therefore, trust among various innovation subjects should be cultivated to create a sound atmosphere for cooperation. Subjects who demonstrate opportunistic behavior and bring invisible losses to innovation activities should be sanctioned. Only by maintaining the trust relationship between organizations can we communicate and learn better.

This study does have some limitations. Specifically, simulation was used to estimate the trends of knowledge diffusion in multinetworks. Though the parameter settings were based on consultation with experts in the field, future research could perhaps use real numerical values. In addition, this study only considers the influence of some network characteristics on knowledge sharing, other characteristics (such as clustering coefficient) may research in the future.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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Research Article

Reverse Knowledge Transfer in Cross-Border Mergers and Acquisitions in the Chinese High-Tech Industry under Government Intervention

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The high-tech industry is the main force promoting the development of China's national economy. As its industrial economic strength grows, China's high-tech industry is increasingly using cross-border mergers and acquisitions (CBM&A) as an important way to "go out." To explore the rules governing the process and operation mechanism of reverse knowledge transfer (RKT) through the CBM&A of China's high-tech industry under government intervention, a tripartite evolutionary game model of the government, the parent company, and the subsidiary as the main subjects is constructed in this paper. The strategies adopted by the three subjects in the RKT game process are analysed, and the factors influencing RKT through CBM&A under government intervention are simulated and analysed using Python 3.7 software. The results show that, under government intervention, the parent company and subsidiary have different degrees of influence on each other. Subsidiaries are highly sensitive to the compensation rate of RKT. Positive intervention by the government tends to foster stable cooperation between the parent company and the subsidiary. However, over time, the government gradually relaxes its intervention in the RKT and innovation of multinational companies.

1. Introduction

Characterized by knowledge-intensive and technology-intensive enterprises, the high-tech industry has adapted to the needs of the fourth industrial revolution and exemplifies the future trend of industrial development. In the wave of R&D globalization, the field of cross-border M&A of Chinese enterprises has gradually entered the deep-water area and gradually emerged from the traditional resource and financial industry to the knowledge-intensive industry with high technology and high added value. Therefore, establishing subsidiaries overseas through cross-border M&A has gradually become an open innovation strategy used by Chinese high-tech enterprises to expand overseas and catch up with technology. Through the "springboard" of CBM&A, China's high-tech enterprises use their competitive advantages to leverage overseas resources and realize the two-way spillover of knowledge and technology to quickly realize the "overtaking on the curve" in terms of science, technology, and international experience and then complete the transformation from traceability to leader [1, 2]. As the main factor of production to promote economic growth, knowledge has become a key resource for the adjustment and upgrading the high-tech industrial structure and improvement in its core competitiveness [3–6]. Therefore, Chinese high-tech enterprises have obvious knowledge searching tendency in the M&A of enterprises in developed countries, and the purpose is to acquire new knowledge resources and transfer knowledge to the parent company. In recent years, China's high-tech enterprises have continued to increase FDI with the goal of technology seeking and can obtain advanced knowledge resources ahead of their competitors from the host country through M&A integration [7, 8], such as Sinopec's acquisition of Addax petroleum and

Lenovo's acquisition of IBM. Such acquisition of knowledge from subsidiaries through CBM&A is called "reverse knowledge transfer" [9]. Unlike the traditional phenomenon of knowledge flowing from the parent company to the foreign subsidiary, RKT is an international strategy that explores new knowledge in the host country and transfers such knowledge to the parent company [10–13]. "Going out" is the only way for developing countries to step forward to developed countries. As support for the "going out" national strategy, CBM&A and the successful integration of knowledge after M&A can improve the innovation performance of the high-tech industry and effectively promote China's economic development. However, owing to the complex and changeable international environment and situation, it has become an urgent task for the Chinese government to give full play to the government's function of guidance and service and create a good external environment for MNCs' overseas M&A and RKT [14]. Although it has been proven by practice that government intervention in MNCs is essential, theoretical guidance regarding practical issues, such as how to improve the efficiency of RKT, how to realize management and control over the RKT process, and the size of the control scale under government intervention, is still lacking. As the successful solution to these problems is related to improvements in the innovation ability and core competitiveness of China's high-tech industry, it is of great practical significance to explore RKT in China's high-tech industry from the perspective of government intervention.

2. Literature Review

A review of previous studies reveals that the key factors affecting RKT have been the focus of scholars' attention and research in recent years [15–17]. The existing literature concerning RKT has made some achievements. Scholars have noticed that the absorptive capacity of the parent company, organizational mechanism, role of the subsidiary company, relationship between the parent company and subsidiary, and knowledge characteristics has an influence on RKT:

(1) The aspect of M&A subjects: the subjects of RKT in CBM&A include the acquirer and the acquired [18]. During the process of RKT, the characteristics, communication ability, transfer frequency, absorptive capacity, and motivation of both subjects of the merger and acquisition affect RKT [19, 20]. Among these factors, regarding M&A, the internal motivation, absorptive capacity, language communication ability, and perception level of the subsidiaries' knowledge resources of the MNCs' parent companies have an important impact on the absorption and utilization of overseas knowledge resources. The lack of internal motivation of the parent company to acquire knowledge resources forms cognitive barriers to RKT [21]. Moreover, the decrease in the parent company's language communication ability and parent company's perception level of the subsidiary's knowledge are also key factors hindering the smooth progress of RKT [22, 23]. In addition, whether the parent company can maintain a good relationship with overseas subsidiaries determines the degree to which the parent company can benefit from RKT [24]. Regarding the acquired party, the age, language communication ability, knowledge or technology dissemination ability, and initiative of the overseas subsidiary can influence the innovation performance of the parent company to a certain extent [25–28]. The subsidiary's location is also a key factor determining the degree of knowledge and resources acquired by the outward investing enterprise. A greater geographical extension for the transnational enterprise is more conducive to feeding the innovation environment of different host countries (regions) back to the parent company to improve its innovation performance [29–31].

(2) The aspect of the transfer environment: the environmental factors of RKT in CBM&A mainly refer to established macrofactors that cannot be controlled by the two sides involved in the CBM&A but could have a certain influence on the process and results of RKT. The factors that influence RKT are focused mainly on the organizational culture, institutional distance, and geographical location [32–34]. Among these factors, although cultural differences lead to conflicts in values, management ideas, and innovation practices between the two sides, if properly addressed, such differences can improve the RKT performance of MNCs [35]. As an important artefact that affects the performance of reverse learning in CBM&A, the institutional differences between the two sides are divided into an institutional surplus and an institutional deficit. An institutional surplus is not conducive to RKT from legalized production-oriented subsidiaries to parent companies, while institutional deficits are conducive to RKT from efficiency-oriented subsidiaries to parent companies [36, 37]. In addition, a combination of organizational factors (such as history, experience, culture, values, and management skills) and/or environments (such as volatility and competition) can affect the ability and willingness of decision makers to take advantage of the unique knowledge and capabilities of different external sources and their market focus. For instance, some subsidiaries operate in highly complex and dynamic industries and national environments, requiring secondary learning by the enterprise to develop dynamic capabilities allowing the enterprise to respond to or shape market disequilibrium [38]. In fast-changing environments with discontinuous changes, the subsidiaries of MNCs that successfully implement ambidextrous activities can best adapt to the changes, thereby contributing to the overall competitiveness of the MNCs [39, 40].

(3) The aspect of transferred knowledge: constituting the basis for MNCs to develop relevant capabilities, knowledge resources are important resources that

MNCs urgently seek by adopting “springboard” behaviour. The attributes of the knowledge resources transferred from subsidiaries to parent companies, such as stickiness, complexity, and obscurity, may affect the transfer of knowledge resources from overseas subsidiaries to their parent companies [41, 42]. Simultaneously, regarding both the parent company and the subsidiary, the knowledge correlation or complementary advantages between the two may also affect the effect and efficiency of the reverse transfer of knowledge resources from the subsidiary to the parent company; that is, the difficulty in transferring knowledge resources with different categories and attributes is different. Some scholars believe that the complementary advantages of knowledge resources are a prerequisite for the success of creative asset seeking CBM&A and that only knowledge resources with complementary advantages can provide impetus for the “springboard” behaviour of domestic MNCs [43]. In addition, some scholars have confirmed the positive correlation between knowledge complexity or knowledge relevance and RKT between parent companies and subsidiaries through enterprise survey data analyses and case analyses and the moderating role of knowledge in the correlation between the parent company’s absorptive capacity and RKT [44].

Reviewing and summarizing the research literature concerning RKT in recent years shows that although these studies have made beneficial explorations of RKT in CBM&A, two gaps remain. First, the existing research methods applied to study RKT in MNCs are mainly based on panel data [45], theoretical analyses, or questionnaire surveys [46–48]. Few studies consider the dynamics and regularity of the RKT process of MNCs. Owing to the lack of quantitative research, there are some limitations in specific applications [49–51]. Second, most scholars’ research concerning the factors influencing RKT in MNCs remains limited to the internal factors of MNCs. However, as a financial supporter and supervisor of MNCs, the role of the government in the RKT process of MNCs needs to be further discussed. The value of knowledge lies in its flow. The more efficient the RKT in MNCs is, the greater the utility and value of the acquired knowledge is. Compared with other research methods, the evolutionary game model emphasizes the dynamic process of RKT over time. When analysed from a dynamic perspective, the evolutionary process of the participants’ group behaviour can be conducive to understanding the nature and contradictions of RKT in MNCs and the changing rules determining how government intervention influences the RKT process.

To compensate for the shortcomings of the above studies and on the basis of relevant research, the government is included in the game as a supporter and regulator of RKT in MNCs in the high-tech industry, and the strategic RKT adoption behaviour of MNCs under government intervention is studied. The main contributions are as follows. First, the evolutionary game model is applied to study RKT in CBM&A. Although the existing literature focuses on the factors influencing RKT, to date, RKT in CBM&A has been discussed by most scholars from a static perspective [52, 53]. In this study, evolutionary game theory is combined with RKT, and the evolutionary mechanism of RKT through CBM&A in China’s high-tech industry is revealed from a dynamic perspective, which expands and enriches the research perspective in this field. Second, most studies concerning RKT in MNCs are limited to parent companies and subsidiaries [54–59], and the role of the government has not been considered. Therefore, this study considers the influence of government intervention factors on RKT in MNCs and aims to provide guidance for the specific practice of RKT by MNCs. Overall, this study provides an integrated and holistic research perspective of RKT through CBM&A in China’s high-tech industry under government intervention and identifies new potential avenues for future research. Simultaneously, this paper highlights further research needed to promote the development of the relevant literature and provides more specific and actionable guidance for MNCs.

3. Model Assumptions

Although the subject of RKT in CBM&A is the enterprise rather than the government, the government provides necessary help to MNCs by formulating various policies to help them reduce the risk as much as possible in the process of M&A integration. However, there are different supporting policies for CBM&A between developed countries and developing countries. For example, the US gives priority to the protection of CBM&A and promotes CBM&A via domestic legislation, insurance funds, and bilateral agreements. When a bilateral agreement with the host country is signed, double taxation can be avoided, and the tax credit can be exempted while providing tax relief to domestic enterprises invested in countries with bilateral tax treaties; France has long pursued a policy of protection and support for transnational corporations’ overseas M&A (financial consolidation and deferred taxation). The central government provides government subsidies and government loans to large MNCs and nonrepayable financial support to small- and medium-sized enterprises; Japan’s CBM&A has changed from strict supervision to protection and from foreign exchange control to tax preference (tax concession system and foreign tax credit system) and information technology services. China’s State Administration of Taxation and the Ministry of Finance jointly issued a series of preferential tax policies, such as the “Notice on applicable tax rate and tax credit for overseas income of high-tech enterprises,” which reduced the tax burden of MNCs. Generally, MNCs in developed countries have stronger autonomy, and their overseas M&A behaviour can have an impact on policy-making institutions. In developing countries, the M&A integration behaviour of MNCs is affected by the policies formulated by the government. Because the autonomy of MNCs is not strong, the role of the government is more important. Compared with that of developed countries, the CBM&A and knowledge integration after M&A in China still face many problems, and the government's help is needed to create better conditions and background to realize smooth RKT in CBM&A. Thus, the government plays a very important role in RKT by providing supervision and incentives. The government can intervene in the RKT of MNCs by formulating preferential policies, providing financial support, and assessing the operational performance of RKT and the completion of tasks by MNCs. On the basis of this, the following assumptions are proposed.

Assumption 1. In the evolutionary game system of an RKT strategy through CBM&A in the high-tech industry, the main participants are the parent company (P), the subsidiary (S), and the government (G). Among the participants, the subsidiary is responsible mainly for transferring personnel with core technologies, management skills, and experience to the parent company or sharing the core technical knowledge and management experience of key personnel with the parent company [60, 61]. The main task of the parent company is to achieve breakthroughs in key technologies and ultimately achieve economies of scale by applying a new technology in a rapidly developing industry by obtaining employees or R&D teams with technical expertise for product innovation. As the motivator and supervisor of RKT in MNCs, the government is responsible mainly for supervising the RKT and innovation activities of MNCs and providing incentives for the knowledge innovation activities of MNCs by formulating preferential policies. These three types of participants are all bounded rational in the game process, and the optimal strategy can be found through repeated games.

Assumption 2. The ability to acquire the knowledge resources of the host country through RKT is a major competitive advantage of MNCs, but RKT is far from a simple internal transaction process [62] and may be affected by multiple factors, such as the disseminative capacity in RKT from subsidiaries to advanced economy headquarters [63], absorptive capacity [64], shared vision [65], subsidiary innovativeness [66], and the geographical and cultural distance between the parent company and its subsidiaries. Both the parent company and the subsidiary are bounded rational; thus, the strategies in which both subjects engage in positive transfer or positive absorption are not always adopted in the RKT game process, and the game strategies of each subject are updated according to those of the other subject. Therefore, it is assumed that, in the evolutionary game system of an RKT strategy through CBM&A in the high-tech industry, one of two strategies, i.e., positive absorption or negative absorption, is then adopted by the parent company; therefore, the strategy set is (positive absorption, negative absorption). Afterwards, one of two strategies, i.e., positive transfer or negative transfer, is then adopted by the subsidiary; therefore, the strategy set is (positive transfer, negative transfer). One of two strategies, i.e., intervention or nonintervention, is then adopted by the government; therefore, the strategy set is (intervention, nonintervention). In addition, the probability that the positive absorption strategy is adopted by the parent company is x; thus, the probability that the negative absorption strategy is adopted by the parent company is $1 - x$. The probability that a positive transfer strategy is adopted by the subsidiary is y; thus, the probability that a negative transfer strategy is adopted by the subsidiary is $1 - y$. Similarly, the probability that the intervention strategy is adopted by the government is z; thus, the probability that the nonintervention strategy is adopted by the government is $1 - z$ and $x, y, z \in [0, 1]$.

Assumption 3. On the basis of transaction cost theory, joint effort is required by the parent company and the subsidiary for an MNC to successfully achieve RKT; for example, the management of RKT by the subsidiary and construction of a reverse transfer mechanism and channels by the parent company are needed. Therefore, c is used to represent the effort cost invested by the parent company and the subsidiary to ensure the smooth progress of RKT. The input of the effort cost is unrelated to the amount of transferred knowledge but represents the price paid by the parent company and the subsidiary jointly to promote RKT, which is a comprehensive reflection of transfer willingness, ability, cognitive impairment, absorption ability, the institutional environment, geographical distance, and other influencing factors. In this paper, a is used to represent the ratio for allocating the effort cost c between the parent company and the subsidiary; thus, the effort cost invested by the parent company is ac, while the effort cost invested by the subsidiary is $(1 - a)c$ and $a \in [0, 1]$. In addition, although the government does not directly participate in the RKT process, reasonable preferential policies are formulated by the government to promote the smooth progress of RKT and knowledge innovation. D is used to represent the reduction in the effort cost of the parent company and the subsidiary due to preferential policies formulated by the government; thus, the effort cost invested by the parent company is $a(c - D)$, and the effort cost invested by the subsidiary is $(1 - a)(c - D)$.

Assumption 4. Successful CBM&A can increase the revenue of MNCs through mechanisms such as cost savings, increased profits, upscaling, and abundant resources as has been demonstrated in different economic sectors [67–69]. Therefore, in the process of RKT, the parent company can obtain not only independent innovation revenue but also additional revenue generated by absorbing the knowledge resources of the subsidiary. R and ΔR are used in this paper to represent the innovation revenue and additional revenue of the parent company, respectively. Knowledge transfer is based on cooperation towards common goals and dialogue encompassing different perspectives [70]; thus, knowledge transfer is affected by the trust level between the parent company and subsidiary; θ is used to represent the level of trust between the subjects. Therefore, the revenue obtained by the parent company is $\Delta R = \lambda\theta k$, where λ represents a discount of the expected additional revenue obtained by the parent company and k represents the value of the knowledge gained through RKT. In the game process, the balance among the value of the knowledge gained by RKT from the subsidiary, the cost required to absorb the knowledge resources, and the compensation to the subsidiary for the RKT needs to be considered by the parent company. In this paper, $w = ek$ is used to represent the compensation of the parent company for the RKT of the subsidiary, where e is the compensation rate. In addition, government intervention in the parent company is mainly reflected in the incentives provided to the parent company through the formulation of tax policies and the assessment of innovation performance. In this paper, r and r' are used to represent the tax rate when the parent company adopts a positive strategy and a negative strategy, respectively $(r < r')$, and the tax base is R. H is used to represent the government's assessment of the parent company, β is used to represent the assessment intensity, and the revenue obtained by the parent company due to the government assessment is $\pm\eta_1\beta H$, where η_1 represents the impact intensity of government assessment on the revenue obtained by the parent company.

Assumption 5. The revenue from the subsidiary's independent innovation before RKT is R_e, and the compensation obtained from the parent company during the RKT process is $w = ek$. To fully mobilize enthusiasm for RKT from the subsidiary, a subsidiary that positively engages in RKT will obtain certain financial support from the government, and G is used to represent such support. In addition, N_1 is used to represent the revenue obtained by the parent company when it adopts the negative strategy and the subsidiary adopts the positive strategy. N_2 is used to represent the revenue of the subsidiary when it adopts the negative strategy and the parent company adopts the positive strategy. The subject who adopts the negative strategy should pay a certain penalty, which is represented by T, to the subject who adopts the positive strategy to avoid opportunistic behaviour in the process of RKT.

Assumption 6. The government not only supports institutional innovation in the RKT of MNCs but also provides external regulation to ensure the smooth progress of RKT. The corresponding governance mechanism will be formulated by the government according to the behaviour of the parent company and the subsidiary in the RKT process but includes mainly formulating preferential policies and implementing supervision strategies. In this paper, c_g is used to represent the cost of the government for formulating relevant preferential policies, and $\eta_2\beta H$ is used to represent the cost of government assessment, where η_2 is the cost coefficient of the government assessment. Simultaneously, an increase in government revenue can be realized by successful RKT and knowledge innovation activities. In this paper, R_g is used to represent the revenue received when the government adopts the intervention strategy and bR_g is used to represent the revenue received when the government adopts the nonintervention strategy. b is used to represent the proportion of the revenue from the government's adoption of a nonintervention strategy to that from the adoption of an intervention strategy and $b \in [0, 1]$.

4. Decision Mechanism of RKT

4.1. Construction of the Payment Function. According to the above assumptions and the principle of profit maximization, the revenue of the parent company, the subsidiary, and the government is analysed, and the payment matrix of the tripartite evolutionary game is constructed, as shown in Table 1.

In the process of a tripartite evolutionary game, when the expectation of a particular strategy adopted by one subject is higher than the average expectation of the mixed strategy, the strategy will be adopted with a higher probability. The replication dynamic equation is the dynamic differential equation used to describe the frequency of the specific strategy adopted by the group [71]. On the basis of the payment matrix of the evolutionary game, the expected revenue when the parent company adopts the positive strategy, the expected revenue when the parent company adopts the negative strategy, and the average expected revenue will be obtained as follows:

$$\begin{aligned} E_p^Y &= yz[R + \lambda\theta k + \eta_1\beta H - a(c-D) - e\lambda\theta k - rR] \\ &\quad + (1-y)z[R + \eta_1\beta H + T - a(c-D) - rR] \\ &\quad + y(1-z)(R + \lambda\theta k - ac - e\lambda\theta k - rR) \\ &\quad + (1-y)(1-z)(R + T - ac - rR), \\ E_p^N &= yz(R + N_1 - \eta_1\beta H - T - r'R) \\ &\quad + (1-y)z(R - \eta_1\beta H - r'R) \\ &\quad + y(1-z)(R + N_1 - r'R - T) \\ &\quad + (1-y)(1-z)(R - r'R), \end{aligned} \tag{1}$$

$$\overline{E_P} = xE_p^Y + (1-x)E_p^N. \tag{2}$$

Similarly, the expected revenue when the subsidiary adopts the positive strategy, the expected revenue when the subsidiary adopts the negative strategy, and the average expected revenue are as follows:

$$\begin{aligned} E_e^Y &= xz[R_e + e\lambda\theta k + G - (1-a)(c-D)] \\ &\quad + (1-x)z[R_e + G + T - (1-a)(c-D)] \\ &\quad + x(1-z)[R_e + e\lambda\theta k - (1-a)c] \\ &\quad + (1-x)(1-z)[R_e + T - (1-a)c], \\ E_e^N &= xz(R_e + N_2 - T) \\ &\quad + (1-x)zR_e + x(1-z)(R_e + N_2 - T) \\ &\quad + (1-x)(1-z)R_e, \\ \overline{E_e} &= yE_e^Y + (1-y)E_e^N. \end{aligned} \tag{3}$$

The expected revenue when the government adopts the intervention strategy, the expected revenue when the

Table 1: Payment matrix of the evolutionary game of RKT.

S		PT	NT	PT	NT
P	PA	$R+\lambda\theta k+\eta_1\beta H-a(c-D)-e\lambda\theta k-rR$; $R_e+e\lambda\theta k+G-(1-a)(c-D)$; $R_g+rR-G-\eta_2\beta H-c_g$	$R+\eta_1\beta H+T-a(c-D)-rR$; R_e+N_2-T; $R_g+rR-\eta_2\beta H-c_g$	$R+\lambda\theta k-ac-e\lambda\theta k-rR$; $R_e+e\lambda\theta k-(1-a)c$; bR_g+rR	$R+T-ac-rR$; R_e+N_2-T; bR_g+rR
	NA	$R+N_1-\eta_1\beta H-T-r'R$; $R_e+G+T-(1-a)(c-D)$; $R_g+r'R-G-\eta_2\beta H-c_g$	$R-\eta_1\beta H-r'R$; R_e; $R_g+r'R-\eta_2\beta H-c_g$	$R+N_1-r'R-T$; $R_e+T-(1-a)c$; $bR_g+r'R$	$R-r'R$; R_e; $bR_g+r'R$
Gov		YI		NI	

Note: P represents the parent company; S represents the subsidiary; Gov represents the government; PT and NT represent positive transfer and negative transfer, respectively; PA and NA represent positive absorption and negative absorption, respectively; and YI and NI represent intervention and nonintervention, respectively.

government adopts the nonintervention strategy, and the average expected revenue are as follows:

$$\begin{aligned}E_g^Y &= xy\left(R_g+rR-G-\eta_2\beta H-c_g\right)\\&\quad+x(1-y)\left(R_g+rR-\eta_2\beta H-c_g\right)\\&\quad+(1-x)y\left(R_g+r'R-G-\eta_2\beta H-c_g\right)\\&\quad+(1-x)(1-y)\left(R_g+r'R-\eta_2\beta H-c_g\right),\\E_g^N &= xy\left(bR_g+rR\right)+x(1-y)\left(bR_g+rR\right)\\&\quad+(1-x)y\left(bR_g+r'R\right)+(1-x)(1-y)\left(bR_g+r'R\right),\\\overline{E_g} &= zE_g^Y+(1-z)E_g^N.\end{aligned}\tag{4}$$

4.2. Solution for the Stability Strategy in the Evolutionary Game. On the basis of the above analysis, the replication dynamic equation of the proportion of the positive strategy adopted by the parent company can be obtained as follows:

$$\begin{aligned}F(x)&=\frac{\mathrm{d}x}{\mathrm{d}t}=x\left(E_p^Y-\overline{E_p}\right)\\&=x(1-x)\left[(2\eta_1\beta H+aD)z+(\lambda\theta k-e\lambda\theta k-N_1)y\right.\\&\quad\left.+T+r'R-rR-ac\right].\end{aligned}\tag{5}$$

The replication dynamic equation of the proportion of the positive strategy adopted by the subsidiary is as follows:

$$\begin{aligned}F(y)&=\frac{\mathrm{d}y}{\mathrm{d}t}=y\left(E_e^Y-\overline{E_e}\right)\\&=y(1-y)\left[(G+(1-a)D)z+(e\lambda\theta k-N_2)x\right.\\&\quad\left.+T-(1-a)c\right].\end{aligned}\tag{6}$$

The replication dynamic equation of the proportion of the intervention strategy adopted by the government is as follows:

$$\begin{aligned}F(z)&=\frac{\mathrm{d}z}{\mathrm{d}t}=z\left(E_g^Y-\overline{E_g}\right)\\&=z(1-z)\left(-yG+R_g-bR_g-\eta_2\beta H-c_g\right).\end{aligned}\tag{7}$$

In the dynamic evolutionary game system, the change in probabilities x, y, and z of strategic adoption by the parent company, subsidiary, and government involved in the game is related to time t, respectively; thus, $x(t), y(t), z(t)\in[0,1]$. Equations (5)–(7) are combined to obtain the replication power system of the parent company, subsidiary, and government, respectively.

According to the requirements of the replication dynamic equation, let $F(x)=0$, $F(y)=0$, and $F(z)=0$, and the local equilibrium points in the game system will be obtained. For P_1 (0, 0, 0), P_2 (0, 0, 1), P_3 (0, 1, 0), P_4 (1, 0, 0), P_5 (0, 1, 1), P_6 (1, 0, 1), P_7 (1, 1, 0), and P_8 (1, 1, 1), the boundary of the evolutionary game solution domain of the RKT comprises the following eight equilibrium points:

$$\{(x,y,z)|0\le x\le 1, |0\le y\le 1, |0\le z\le 1\}.\tag{8}$$

The dynamic evolution process of the strategy adoption by the tripartite game subjects in the evolutionary game system is described by the differential equation system; thus, the stability of the equilibrium points mentioned above can be judged by a local stability analysis of the Jacobian matrix [72, 73]. According to equation (9), the Jacobian matrix of the system can be obtained as follows:

$$\begin{cases} F(x) = \dfrac{\mathrm{d}x}{\mathrm{d}t} = x\left(E_p^Y - \overline{E_p}\right) = x(1-x)\left[(2\eta_1\beta H + aD)z + (\lambda\theta k - e\lambda\theta k - N_1)y + T + r'R - rR - ac\right], \\ F(y) = \dfrac{\mathrm{d}y}{\mathrm{d}t} = y\left(E_e^Y - \overline{E_e}\right) = y(1-y)\left[(G + (1-a)D)z + (e\lambda\theta k - N_2)x + T - (1-a)c\right], \\ F(z) = \dfrac{\mathrm{d}z}{\mathrm{d}t} = z\left(E_g^Y - \overline{E_g}\right) = z(1-z)\left(-yG + R_g - bR_g - \eta_2\beta H - c_g\right), \end{cases} \tag{9}$$

$$J = \begin{bmatrix} (1-2x)\left[(2\eta_1\beta H + aD)z + (\lambda\theta k - e\lambda\theta k - N_1)y + T + r'R - rR - ac\right], & x(1-x)(\lambda\theta k - e\lambda\theta k - N_1), & x(1-x)(2\eta_1\beta H + aD), \\ y(1-y)(e\lambda\theta k - N_2), & (1-2y)\left[(G + (1-a)D)z + (e\lambda\theta k - N_2)x + T - (1-a)c\right], & y(1-y)\left[G + (1-a)D\right], \\ 0, & z(1-z)(-G), & (1-2z)\left(-yG + R_g - bR_g - \eta_2\beta H - c_g\right) \end{bmatrix}. \tag{10}$$

4.3. Stability Analysis of the Equilibrium Point. According to evolutionary game theory, when a certain equilibrium point satisfies the requirement that all eigenvalues of the Jacobian matrix are nonpositive, that equilibrium point is the evolutionary stable point of the game system. The strategy corresponding to the evolutionary stable point is the evolutionary stable strategy (ESS) [74, 75]. Next, the eight equilibrium points mentioned above are included in the Jacobian matrix one-by-one, and the eigenvalues of the Jacobian matrix corresponding to each equilibrium point can be obtained, as shown in Table 2.

To ensure that the model analysis is consistent with the actual situation, it is assumed that when all subjects in the game system adopt positive or intervention strategies, the revenue is always greater than that when they adopt negative or nonintervention strategies. $T + (1-e)\lambda\theta k + (r' - r)R - N_1 - ac > 0$, $e\lambda\theta k + T - N_2 - (1-a)c > 0$, and $(1-b)R_g - \eta_2\beta H - c_g - G > 0$. Owing to the large number of parameters in the model and its complexity, which lead to uncertainty in the eigenvalue symbols in the Jacobian matrix, different cases need to be discussed (Table 3).

(1) When the subsidiary adopts a negative strategy, the sum of the punishment paid by the subsidiary to the parent company and the tax preference obtained by the parent company due to the incentive policies of the government is greater than the allocated cost paid by the parent company in the case of government intervention. Alternatively, when the parent company adopts a negative strategy, the punishment paid by the parent company to the subsidiary is greater than the allocated cost paid by the subsidiary in the case of government intervention. Thus, when $T + (r' - r)R - ac > 0$ or $T - (1-a)c > 0$, the local stability of each equilibrium point is shown in Table 3. In this case, only the three eigenvalues of the Jacobian matrix corresponding to equilibrium point P_8 (1, 1, 1) are all nonpositive. Therefore, the game system has only one evolutionary stable point, i.e., P_8 (1, 1, 1), and its corresponding ESS is (positive, positive, intervention).

(2) When the subsidiary adopts the positive strategy, the sum of the punishment paid by the parent company to the subsidiary and the financial support the subsidiary obtains is greater than the allocated cost paid by the subsidiary in the case of government intervention. When the parent company adopts the negative strategy, the punishment paid by the parent company to the subsidiary is less than the allocated cost paid by the subsidiary. Alternatively, when the subsidiary adopts a negative strategy, the punishment paid by the subsidiary to the parent company, the tax preference obtained by the parent company due to the incentive policies of the government and the increased revenue due to the assessment of the government are each greater than the allocated cost paid by the parent company in the case of government intervention. When the subsidiary adopts the negative strategy, the sum of the punishment paid by the subsidiary to the parent company and the tax preference obtained by the parent company due to the government's incentive policies is less than the allocated cost paid by the parent company in the case of government intervention. Thus, when $G + T - (1-a)(c-D) > 0$ and $T - (1-a)c < 0$ or when $2\eta_1\beta H + T + (r' - r)R - a(c-D) > 0$ and

Table 2: Eigenvalues of the Jacobian matrix.

Equilibrium point	Eigenvalues of Jacobian matrix J		
	λ_1	λ_2	λ_3
P_1 (0, 0, 0)	$T+(r'-r)R-ac$	$T-(1-a)c$	$(1-b)R_g-\eta_2\beta H-c_g$
P_2 (0, 0, 1)	$2\eta_1\beta H+T+(r'-r)R-a(c-D)$	$G+T-(1-a)(c-D)$	$-[(1-b)R_g-\eta_2\beta H-c_g]$
P_3 (0, 1, 0)	$(1-e)\lambda\theta k+T+(r'-r)R-N_1-ac$	$-[T-(1-a)c]$	$(1-b)R_g-\eta_2\beta H-c_g-G$
P_4 (1, 0, 0)	$-[T+(r'-r)R-ac]$	$e\lambda\theta k+T-N_2-(1-a)c$	$(1-b)R_g-\eta_2\beta H-c_g$
P_5 (0, 1, 1)	$2\eta_1\beta H+T+(1-e)\lambda\theta k+(r'-r)R-N_1-a(c-D)$	$-[G+T-(1-a)(c-D)]$	$-[(1-b)R_g-\eta_2\beta H-c_g-G]$
P_6 (1, 0, 1)	$-[2\eta_1\beta H+T+(r'-r)R-a(c-D)]$	$e\lambda\theta k+G+T-N_2-(1-a)(c-D)$	$-[(1-b)R_g-\eta_2\beta H-c_g]$
P_7 (1, 1, 0)	$-[(1-e)\lambda\theta k+T+(r'-r)R-N_1-ac]$	$-[e\lambda\theta k+T-N_2-(1-a)c]$	$(1-b)R_g-\eta_2\beta H-c_g-G$
P_8 (1, 1, 1)	$-[2\eta_1\beta H+T+(1-e)\lambda\theta k+(r'-r)R-N_1-a(c-D)]$	$-[e\lambda\theta k+G+T-N_2-(1-a)(c-D)]$	$-[(1-b)R_g-\eta_2\beta H-c_g-G]$

Table 3: Local stability of each equilibrium point based on case (1).

Equilibrium point	Eigenvalues of Jacobian matrix J λ_1	λ_2	λ_3	Stability
P_1 (0, 0, 0)	+	+	+	Unstable point
P_2 (0, 0, 1)	+	+	−	Unstable point
P_3 (0, 1, 0)	+	−	+	Unstable point
P_4 (1, 0, 0)	−	+	+	Unstable point
P_5 (0, 1, 1)	+	−	−	Unstable point
P_6 (1, 0, 1)	−	+	−	Unstable point
P_7 (1, 1, 0)	−	−	+	Unstable point
P_8 (1, 1, 1)	−	−	−	ESS

$T + (r' - r)R - ac < 0$, as shown in Table 4, the eigenvalues of the Jacobian matrix corresponding to the equilibrium point P_8 (1, 1, 1) are all nonpositive. Therefore, in this case, the game system has only one evolutionary stable point, i.e., P_8 (1, 1, 1), and its corresponding ESS is (positive, positive, intervention) (Table 4).

(3) When the subsidiary adopts the positive strategy, the sum of the financial support received by the subsidiary and the punishment paid by the parent company to the subsidiary is less than the allocated cost paid by the subsidiary in the case of government intervention. When the subsidiary adopts the negative strategy, the punishment paid by the subsidiary to the parent company, the tax preference obtained by the parent company due to the incentive policies of the government, and the increased revenue due to government assessment are less than the allocated cost paid by the parent company in the case of government intervention. Thus, when $G + T - (1 - a)(c - D) < 0$ and $2\eta_1\beta H + T + (r' - r)R - a(c - D) < 0$, as shown in Table 5, there are two equilibrium points in the game system, and the three eigenvalues of the Jacobian matrix corresponding to each equilibrium point are nonpositive. The two equilibrium points are P_2 (0, 0, 1) and P_8 (1, 1, 1), and the corresponding evolutionary stability strategies are (negative, negative, intervention) and (positive, positive, intervention), respectively.

5. Numerical Simulation

To intuitively observe the dynamic evolution behaviour of the parent company, the subsidiary, and the government in the process of RKT, a numerical simulation is carried out. When the initial value of each parameter in the model is set, the dynamic evolution process of the strategy adoption by the game subjects in different initial states is simulated by using Python 3.7 software. On the basis of the simulation results, the initial willingness of the game subjects, the supervision, and assessment of the government, the preferential policies of the government, and other parameters are discussed.

Table 4: Local stability of each equilibrium point based on case (2).

Equilibrium point	Eigenvalues of Jacobian matrix J λ_1	λ_2	λ_3	Stability
P_1 (0, 0, 0)	−	−	+	Unstable point
P_2 (0, 0, 1)	+	+	−	Unstable point
P_3 (0, 1, 0)	+	+	+	Unstable point
P_4 (1, 0, 0)	+	+	+	Unstable point
P_5 (0, 1, 1)	+	−	−	Unstable point
P_6 (1, 0, 1)	−	+	−	Unstable point
P_7 (1, 1, 0)	−	−	+	Unstable point
P_8 (1, 1, 1)	−	−	−	ESS

Table 5: Local stability of each equilibrium point based on case (3).

Equilibrium point	Eigenvalues of Jacobian matrix J λ_1	λ_2	λ_3	Stability
P_1 (0, 0, 0)	−	−	+	Unstable point
P_2 (0, 0, 1)	−	−	−	ESS
P_3 (0, 1, 0)	+	+	+	Unstable point
P_4 (1, 0, 0)	+	+	+	Unstable point
P_5 (0, 1, 1)	+	+	−	Unstable point
P_6 (1, 0, 1)	+	+	−	Unstable point
P_7 (1, 1, 0)	−	−	+	Unstable point
P_8 (1, 1, 1)	−	−	−	ESS

5.1. Influence of the Initial Willingness of the Game Subjects on Their Strategy Evolution in the Tripartite Game. Assuming that the initial values of the other parameters remain unchanged, the initial willingness of the parent company, subsidiary, and government to choose a positive strategy or intervention strategy is the same; that is, $x = y = z$.

Figure 1 shows the evolution process of the strategies when the tripartite game subjects simultaneously change their initial willingness. As shown in the figure, the critical value of the initial willingness of the tripartite game subjects is between 0.4 and 0.5. When the initial willingness of the tripartite game subjects is less than the critical value, only z gradually converges to 1, while x and y gradually converge to 0. Finally, the equilibrium point of the evolutionary game system tends to P_2 (0, 0, 1), i.e., the stability strategy (negative, negative, intervention). Simultaneously, the willingness of the parent company and the subsidiary to choose the positive strategy converges to 0 at a similar rate. When the initial willingness of the three subjects is greater than the critical value, x, y, and z will converge to 1. Finally, the equilibrium point of the evolutionary game system tends to P_8 (1, 1, 1), that is, the stability strategy (positive, positive, intervention). When the initial willingness of the tripartite game subjects is in the middle level, as the initial willingness of the government to adopt the intervention strategy gradually increases, the rate at which the parent company's and the subsidiary's willingness to adopt the positive strategy converges to 1 gradually accelerates, while the rate at which the government's willingness to adopt the intervention strategy converges to 1 decelerates. According to the above simulation results, as the initial willingness of the tripartite

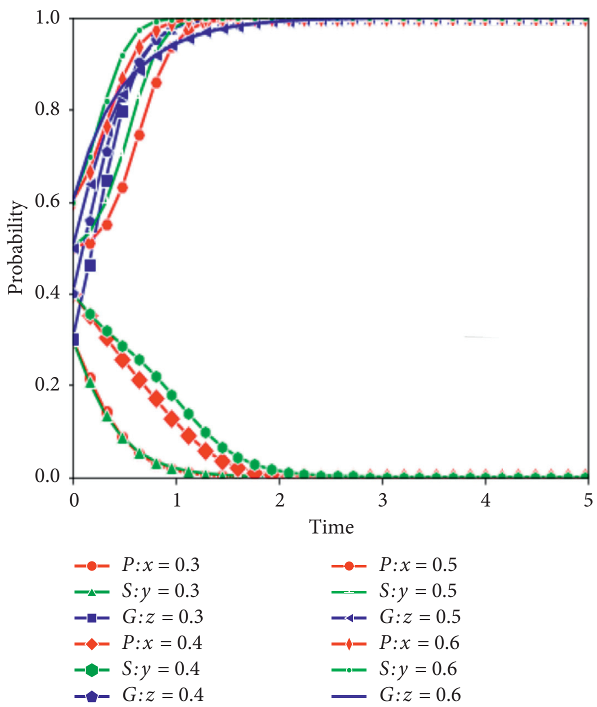

FIGURE 1: Dynamic evolution process of the tripartite game subjects when x, y, and z change simultaneously.

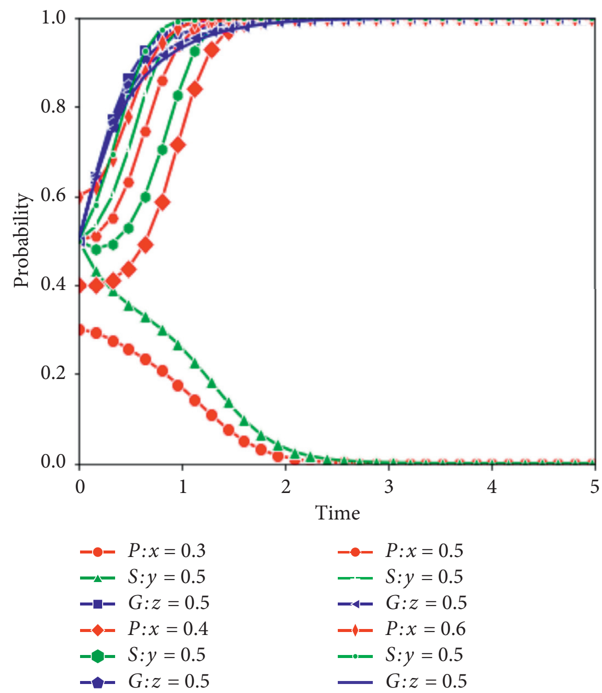

FIGURE 2: Dynamic evolution process of the tripartite game subjects when x changes.

game subjects gradually increases, the rate at which the parent company's and subsidiary's willingness to adopt positive strategies converges to 1 gradually accelerates. However, the rate at which the government's willingness to adopt the intervention strategy converges to 1 gradually decreases, but ultimately, the three subjects tend to adopt a positive or intervention strategy. In the actual process of RKT, when the willingness of the parent company and subsidiary to engage in RKT is at a low level, the government quickly plays a leading role. Through the formulation of reasonable preferential policies and supervision strategies, the government's guidance of RKT in MNCs will be realized, and the operation mechanism of RKT will be improved [76]. Finally, the efficiency of RKT by MNCs is improved.

Figure 2 shows the evolution process of strategy adoption by the tripartite game subjects in the system when the initial willingness of the parent company to adopt a positive strategy changes under the assumption that the initial values of the other parameters remain unchanged. As shown in the figure, the initial willingness of the subsidiary is the same as that of the government and at a medium level, while the critical value of the initial willingness of the parent company is between 0.3 and 0.4. When the initial willingness of the parent company is less than this critical value, the willingness of the parent company and the subsidiary to adopt the positive strategy gradually converges to 0. However, the convergence rate of the subsidiary is higher than that of the parent company, and the equilibrium point of the evolutionary game system eventually tends to P_2 (0, 0, 1). When the initial willingness of the parent company is greater than its critical value, the willingness of the tripartite game subjects to adopt positive strategies or intervention strategies gradually converges to 1. As the initial willingness of the parent company increases, the willingness of the subsidiary to adopt the positive strategy converges to 1 at a faster rate, while the willingness of the government to adopt the intervention strategy converges to 1 at a slower rate, but the equilibrium point of the evolutionary game system eventually tends to P_8 (1, 1, 1).

Figure 3 shows the evolution process of the strategy adoption by the tripartite game subjects when the initial intention of the subsidiary to adopt a positive strategy changes under the assumption that the initial values of the other parameters remain unchanged. As shown in the figure, the initial willingness of the parent company is the same as that of the government and at a medium level, while the critical value of the initial willingness of the subsidiary is between 0.3 and 0.5. When the initial intention of the subsidiary is less than this critical value, the willingness of the parent company and the subsidiary to adopt the positive strategy gradually converges to 0, and the equilibrium point of the evolutionary game system eventually tends to P_2 (0, 0, 1). At this point, the convergence rate of the parent company is higher than that of the subsidiary, and as the initial willingness of the subsidiary increases, the rate at which the parent company's willingness converges to 0 slows. When the initial willingness of the subsidiary is greater than its critical value, the willingness of the tripartite game subjects to adopt the positive strategy or intervention strategy gradually converges to 1. As the initial willingness of the subsidiary increases, the willingness of the parent company to adopt the positive strategy converges to 1 at a faster rate. The willingness of the government to adopt the intervention strategy converges to 1 at a slower rate, but the equilibrium

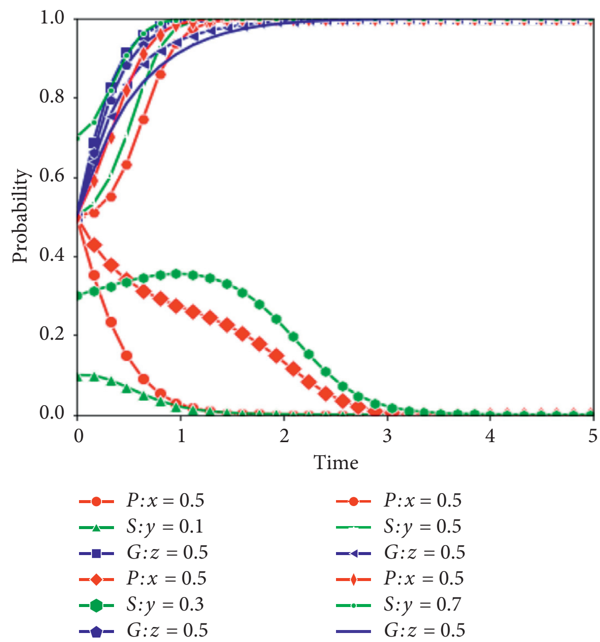

Figure 3: Dynamic evolution process of the tripartite game subjects when y changes.

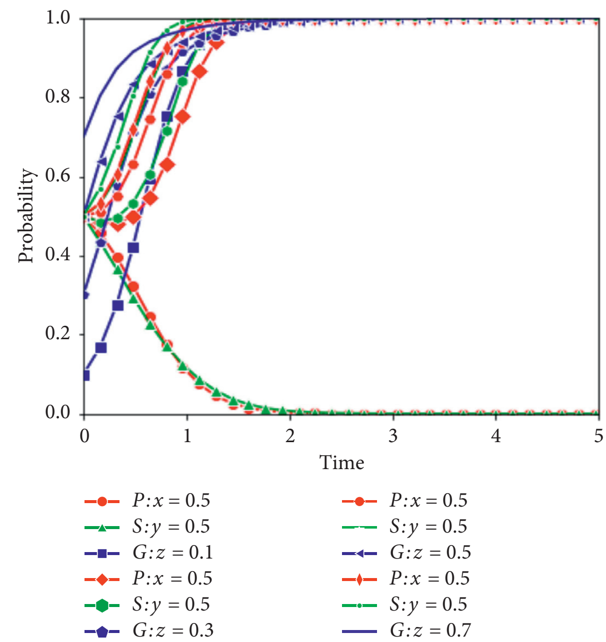

Figure 4: Dynamic evolution process of the tripartite game subjects when z changes.

point of the evolutionary game system eventually tends to P_8 (1, 1, 1). The simulation results show that the parent company is greatly influenced by the strategy selection behaviour of the subsidiary. During the actual RKT process, the main task of the subsidiary is to gather and transfer new innovation resources from the host country to the parent company [77–79]. When the subsidiary has a strong desire to engage in this transfer, the parent company's willingness to adopt a positive strategy naturally increases rapidly.

Figure 4 shows the evolution process of the strategy adoption by the tripartite game subjects in the system when the initial willingness of the government to adopt the intervention strategy changes under the assumption that the initial values of the other parameters remain unchanged. As shown in the figure, the initial willingness of the parent company is the same as that of the subsidiary and at a medium level, while the critical value of the initial willingness of the government is between 0.1 and 0.3. When the initial willingness of the government is less than the critical value, the willingness of the parent company and the subsidiary to adopt a positive strategy gradually converges to 0, and the convergence rate of the parent company and the subsidiary is similar; thus, the equilibrium point of the evolutionary game system eventually tends to P_2 (0, 0, 1). At this point, the increase in the willingness of the government to choose an intervention strategy means that the convergence rate of the parent company and its subsidiaries gradually slows. When the initial willingness of the government is greater than the critical value, the willingness of the tripartite game subjects to adopt a positive strategy or intervention strategy gradually converges to 1. As the initial willingness of the government continuously improves, the willingness of the parent company and subsidiary to adopt a positive strategy converges to 1 at a faster rate. The government's willingness to adopt the intervention strategy converges to 1 at a slower rate, but the equilibrium point of the evolutionary game system eventually tends to P_8 (1, 1, 1).

Figure 5 shows the evolution process of the strategy adoption of the tripartite game subjects in the system when the parent company and the subsidiary simultaneously change their initial intention to adopt a positive strategy under the assumption that the initial value of the other parameters remains unchanged. As shown in the figure, the initial willingness of the government is always at a medium level, while the critical value of the initial willingness of the parent company and its subsidiary is between 0.4 and 0.5. When the initial willingness of the parent company and the subsidiary is less than this critical value, their willingness to adopt a positive strategy gradually converges to 0, and the equilibrium point of the evolutionary game system eventually tends to P_2 (0, 0, 1). Simultaneously, as the initial willingness of the parent company and the subsidiary increases, the willingness of both subjects to adopt the positive strategy converges to 0 at a slower rate. The convergence rate of the subsidiary gradually becomes slower than that of the parent company. When the initial willingness of the parent company and the subsidiary is greater than the critical value, the willingness of the tripartite game subjects to adopt the positive strategy or the intervention strategy gradually converges to 1, and the equilibrium point of the evolutionary game system eventually tends to P_8 (1, 1, 1). Simultaneously, as the initial willingness of the parent company and the subsidiary increases, the willingness of the parent company and the subsidiary to adopt the positive strategy converges to 1. The government's willingness to adopt the intervention strategy also converges to 1, albeit at a slower rate.

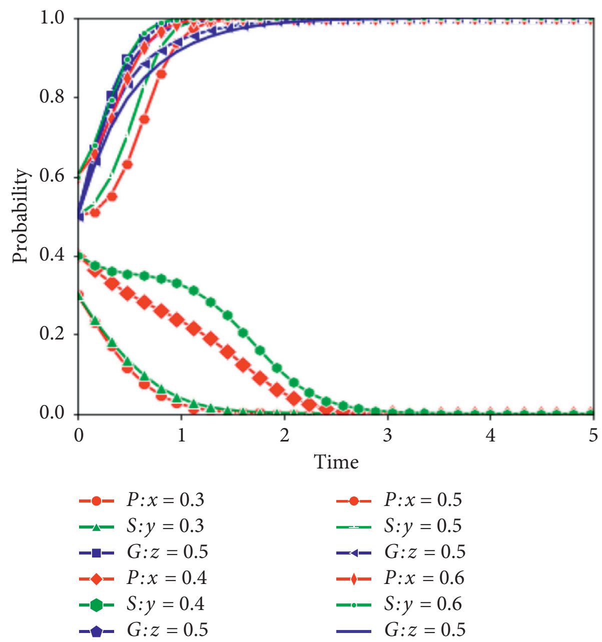

FIGURE 5: Dynamic evolution process of the tripartite game subjects when x and y change simultaneously.

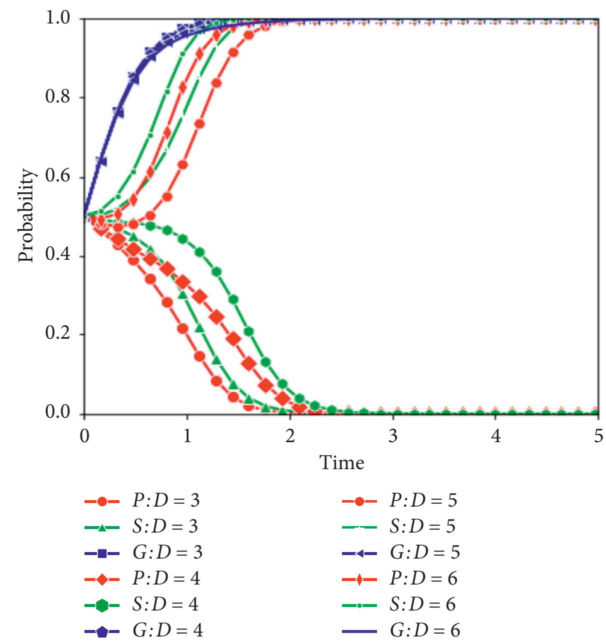

FIGURE 6: Dynamic evolution process of the tripartite game subjects when D changes.

5.2. Influence of Government Intervention Policy on the Strategy Evolution of the Tripartite Game Subjects. The government plays an important role as the supervisor, motivator, and guide of RKT in MNCs in the high-tech industry. Through financial support, guidance management, and policy incentives, the conflicts and barriers between the parent company and the subsidiary can be effectively reduced by the government, and the anticipated and actual cost of RKT for MNCs in the high-tech industry is reduced, encouraging RKT to develop in a healthier direction. The government's intervention policy is reflected mainly in preferential policies conducive to RKT in MNCs and the supervision and assessment of the process and performance of RKT by MNCs. Among them, the role of preferential policies is reflected mainly in the following: ① the formulation of preferential policies reduces the cost of the effort invested in the RKT process by MNCs; ② the government formulates preferential tax policies to provide tax relief to parent companies that adopt a positive strategy; and ③ the government offers financial incentives to subsidiaries that adopt a positive strategy. The government's supervision and assessment are embodied mainly in the supervision and assessment of the performance of the parent company in the RKT process and is considered an important indicator for evaluating the comprehensive strength, social reputation, and social status of MNCs. On the basis of the above discussion, a numerical simulation is carried out to examine relevant parameters, such as reductions in the effort cost, a reduced tax rate for MNCs, financial incentives for subsidiaries that adopt a positive strategy, and the intensity of the government's assessment of the parent company.

Figure 6 shows the evolution process of the strategy adoption of the tripartite game subjects in the system when the preferential policies of the government change due to a reduction in the effort cost under the assumption that the initial values of the other parameters remain unchanged. As shown in the figure, as D (D is the reduction in effort cost) changes, the government always adopts the intervention strategy, while the critical value of D is between 4 and 5. When D is less than the critical value, the willingness of the parent company and the subsidiary to adopt a positive strategy gradually converges to 0, and the equilibrium point of the evolutionary game system eventually tends to P_2 (0, 0, 1). Simultaneously, as D increases, the willingness of the two subjects to adopt a positive strategy converges to 0 at a slower rate. When D is greater than this critical value, the willingness of the parent company and the subsidiary to adopt a positive strategy gradually converges to 1, and the equilibrium point of the evolutionary game system eventually tends to P_8 (1, 1, 1). Simultaneously, as D increases, the willingness of the two subjects to adopt a positive strategy converges to 1 at a faster rate, and the convergence rate of the subsidiary is higher than that of the parent company. Thus, when the government adopts an intervention strategy and the parent company adopts a positive strategy, the subsidiary is more sensitive to the reduction in effort costs during the RKT process. In fact, during the process of RKT by MNCs in high-tech industries, the effort cost can be reduced through preferential policies formulated by the government, such as certain economic subsidies for MNCs. According to the simulation results, the greater the government's economic subsidy for the cost of RKT is, the faster the MNCs will evolve towards the stability strategy. Therefore, economic subsidies can be used as an effective adjustment mechanism to increase the revenue of participants in RKT.

Figure 7 shows the evolution process of the strategy adoption of the tripartite game subjects in the system given that the initial values of the other parameters remain unchanged, while the financial incentives obtained by the

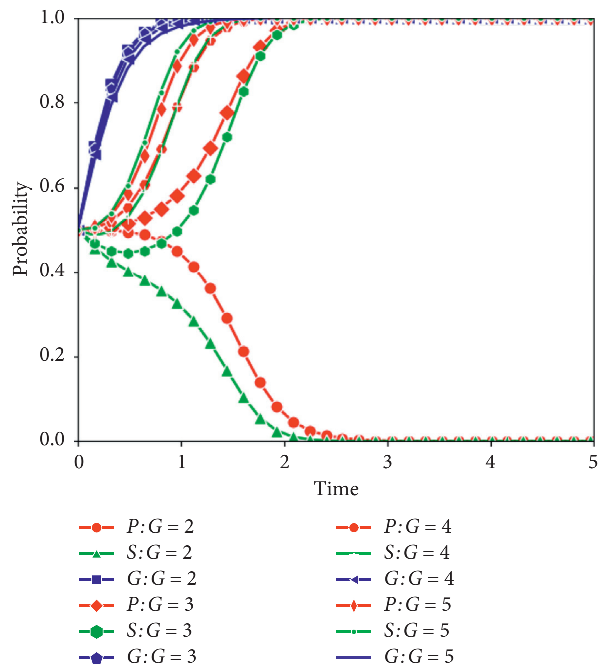

Figure 7: Dynamic evolution process of the tripartite game subjects when G changes.

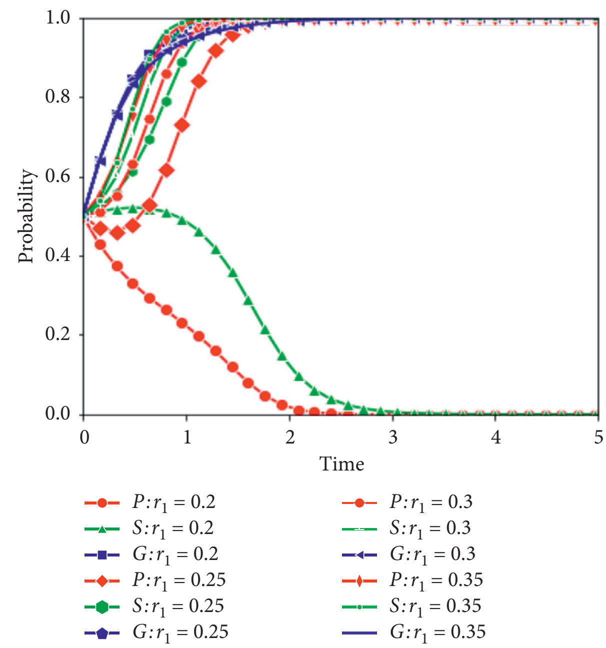

Figure 8: Dynamic evolution process of the tripartite game subjects when r' (r' is replaced by r_1 in the figure) changes.

subsidiary when it adopts the positive strategy change. As shown in the figure, as G (G is the financial revenue obtained by the subsidiary when it adopts an active strategy) changes, the government always adopts the intervention strategy, while the critical value of G is between 2 and 3. When G is less than this critical value, the willingness of the parent company and the subsidiary to adopt a positive strategy gradually converges to 0, and the equilibrium point of the evolutionary game system eventually tends to P_2 (0, 0, 1). When G is greater than this critical value, the willingness of the parent company and the subsidiary to adopt a positive strategy gradually converges to 1, and the equilibrium point of the evolutionary game system eventually tends to P_8 (1, 1, 1). In addition, as shown in Figure 7, the willingness of the parent company and the subsidiary to adopt a positive strategy converges to 0 or 1 at a similar rate regardless of whether G is above or below the critical value. Thus, a change in G has a small impact on the parent company and the subsidiary.

Figure 8 shows the evolution process of the strategy selection of the tripartite game subjects in the system given that the initial values of the other parameters remain unchanged, but the tax rate changes when the parent company adopts the negative strategy. As shown in Figure 8, as r' (r' is the tax rate when the parent company adopts the negative strategy) changes, the government always adopts the intervention strategy, and the critical value of r' is between 0.2 and 0.25. When r' is less than this critical value, the parent company's willingness to adopt a positive strategy gradually converges to 0, while the subsidiary's willingness gradually converges to 0 as the parent company's willingness to adopt a positive strategy decreases, and the equilibrium point of the evolutionary game system eventually tends to P_2 (0, 0, 1). The parent company converges to 0 faster than the subsidiary does, which means that when r' is less than the critical value, the parent company is more sensitive to the tax policies of the government. When r' is greater than the critical value, the willingness of the parent company and the subsidiary to adopt a positive strategy gradually converges to 1, and the equilibrium point of the evolutionary game system eventually tends to P_8 (1, 1, 1). At this point, as r' increases, the willingness of the parent company and the subsidiary to adopt a positive strategy converges to 1 at a faster rate. The simulation results show that the initiative of MNCs to engage in RKT can be encouraged by appropriately increasing taxes. For example, in some developed countries, such as the United States and Japan, the indirect tax incentives and financial science and technology appropriation subsidies implemented by the government are used to ensure the smooth progress of RKT by MNCs according to the actual situation.

Figure 9 shows the evolution process of the strategy adoption of the tripartite game subjects in the system given that the initial values of the other parameters remain unchanged, but the intensity of the government's assessment of the innovation performance of MNCs changes. As shown in the figure, the parent company is encouraged to gradually adopt a positive strategy under the supervision and assessment of the government. Simultaneously, the compensation rate for RKT will be improved by the parent company according to the actual situation, and then, the strategy adoption of the subsidiary is affected, which means that the strategy adoption by the subsidiary evolves in a positive direction. However, over time, the evolution rate does not greatly differ.

5.3. Influence of the Compensation Rate for RKT on the Strategy Evolution of the Tripartite Game Subjects. Figure 10 shows the evolution process of the strategy adoption of the

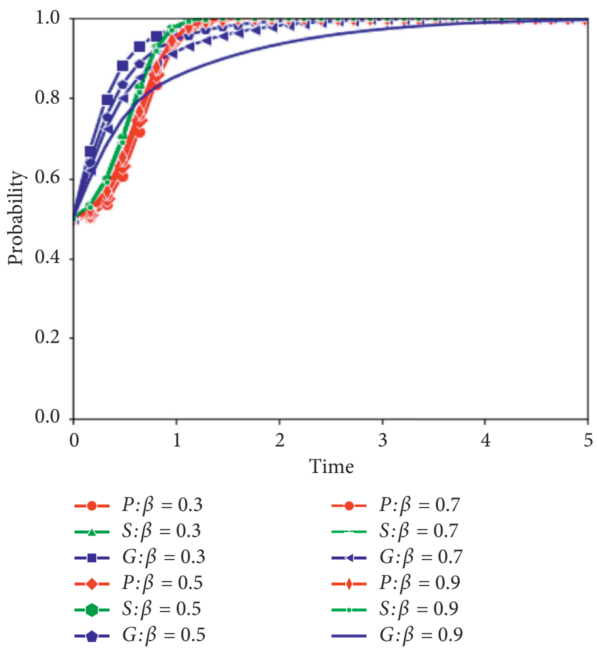

Figure 9: Dynamic evolution process of the tripartite game subjects when β changes.

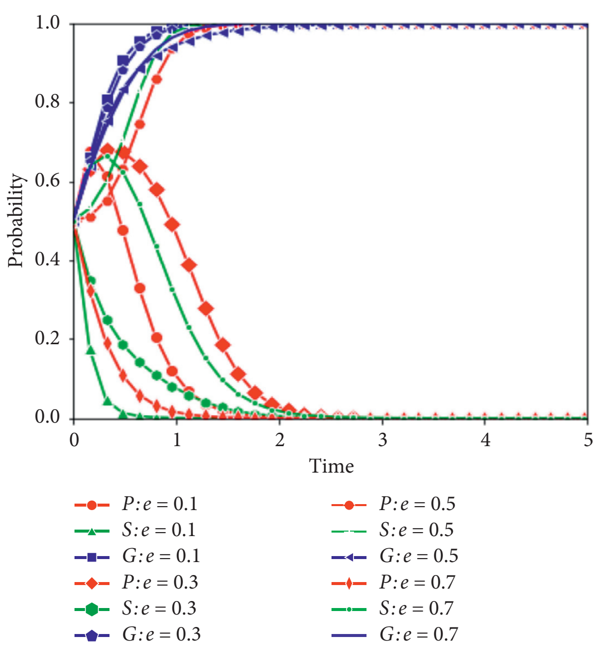

Figure 10: Dynamic evolution process of the tripartite game subjects when e changes.

tripartite game subjects in the system when the compensation rate of the parent company for the RKT of its subsidiary changes under the assumption that the initial values of the other parameters remain unchanged. As shown in the figure, as e (e is the compensation rate of the parent company for the RKT of its subsidiary) changes, the government always adopts the intervention strategy. e has two critical values, i.e., between 0.3 and 0.5 and between 0.5 and 0.7, which are denoted as the first critical value and the second critical value, respectively. When e is less than the first critical value, although the parent company's willingness to adopt a positive strategy has a temporary rising trend, as the willingness of the subsidiary rapidly declines, the willingness of the parent company also rapidly declines and gradually converges to 0, and the equilibrium point of the evolutionary game system eventually tends to P_2 (0, 0, 1). At this point, as e increases, the willingness of the parent company and the subsidiary to adopt the positive strategy converges to 0 at a slower rate, and the convergence rate of the subsidiary is higher than that of the parent company. Thus, the subsidiary is more sensitive to the compensation rate. When e is greater than the first critical value but less than the second critical value, the willingness of the parent company and the subsidiary to adopt the positive strategy gradually converges to 1, and the equilibrium point of the evolutionary game system eventually tends to P_8 (1, 1, 1). When e is greater than the second critical value, although the willingness of the subsidiary to adopt the positive strategy has a temporary rising trend, as the willingness of the parent company to adopt the positive strategy rapidly declines, the willingness of the subsidiary also rapidly declines and gradually converges to 0, and the equilibrium point of the evolutionary game system will tend to P_2 (0, 0, 1). At this point, as e increases, the willingness of the parent company and the subsidiary to adopt the positive strategy converges to 0 at a faster rate. The convergence rate of the parent company is higher than that of the subsidiary, which means that the parent company is more sensitive to the compensation rate.

6. Conclusions and Countermeasures

From the perspective of government intervention, a tripartite evolutionary game model of RKT by MNCs under government intervention is established, and the evolution of the decision-making processes of the government, parent company, and subsidiary related to RKT is systematically analysed. Finally, Python 3.7 software is used to analyse the evolution behaviour in the tripartite game among the government, parent company, and subsidiary. The following conclusions can be drawn:

(1) The degree of influence held by the government, the parent company, and the subsidiary over the other subjects varies. ① Under government intervention, the parent company and the subsidiary have similar sensitivities to government intervention policies, and the parent company is more sensitive to the strategic adoption behaviour of its subsidiary. ② Overtime, the cooperation between parent companies and subsidiaries tends to become stable under the positive intervention of the government. At this point, on the basis that the RKT activities of MNCs can proceed smoothly, the intervention of the government in the RKT and innovation of MNCs will be gradually relaxed to guarantee the sustainable and stable development of the knowledge innovation activities of MNCs at a lower cost. ③ Subsidiaries are highly sensitive to the compensation rate for RKT.

The subsidiary's enthusiasm for RKT can be improved through an appropriate compensation rate although a higher or lower compensation rate is not conducive to a smooth RKT process.

(2) As the guides and supervisors of RKT in MNCs, the evolution of parent companies and subsidiaries can be quickly and effectively promoted in the direction of positive cooperation through government intervention, and the RKT strategy of MNCs will be gradually guided to the right track. ① During the process of RKT by MNCs in the high-tech industry, the cost of MNCs' efforts will be reduced by an economic subsidy from the government. The greater the economic subsidy for the effort cost of RKT is, the greater the willingness of the MNCs to actively engage in RKT is. ② The enthusiasm of subsidiaries for RKT will be stimulated if the government provides financial support. ③ The enthusiasm of MNCs for RKT is improved by appropriately increasing the tax from the government. ④ The negative attitude of MNCs regarding RKT is reduced through the supervision and assessment of the government, which will stimulate the enthusiasm of MNCs engaged in continuous RKT.

The conclusions of this study offer certain insights and reference value for the formulation of RKT strategies for CBM&A in China's high-tech industry. RKT in MNCs in the high-tech industry should be guided in a more healthy and efficient direction. First, during the process of RKT through CBM&A in the high-tech industry, the cost of RKT for MNCs will be reduced because of economic subsidies from the government based on financial allocations to support science and technology, and the parent company and subsidiary will become motivated to participate in RKT activities. Simultaneously, the government should increase financial support to subsidiaries to fully mobilize their enthusiasm to transfer knowledge to the parent company. Second, according to the actual situation of RKT, corresponding preferential tax policies can be formulated by the government, and the enthusiasm of MNCs for RKT can be encouraged by appropriately adjusting the tax rate. In fact, the enthusiasm of the parent company for RKT cannot be mobilized by either higher or lower tax rates. Therefore, reasonable tax policies should be formulated by the government according to the innovation performance of the parent company during the RKT process to maximize performance in RKT and innovation. Third, an effective supervision and assessment mechanism should be established by the government. On the basis of the actual situation of RKT in CBM&A, the government needs to form a flexible performance evaluation mechanism to purposefully and logically evaluate MNCs. This mechanism will be used as an "incentive stone" to mobilize enthusiasm for RKT among MNCs. Fourth, the compensation rate for the subsidiary should be flexibly adjusted according to the extent of the subsidiary's participation in RKT to achieve a balance of revenues between the parent company and the subsidiary.

This study provides important contributions to the current scholarly literature. First, the existing literature proposed some new ideas regarding RKT in CBM&A [28, 80, 81], but a formal discussion of the rules through which it evolves under the influence of government intervention and other related factors is lacking. In this study, evolutionary game theory is applied, and the evolution of RKT through CBM&A over time under the influence of government intervention and the changes in its evolution direction are discussed from a dynamic perspective, constituting a new research method for the field of CBM&A and RKT and a reference for high-tech enterprises undertaking or considering CBM&A. Second, in this research field, RKT subjects attracting most scholars' concern are limited to the parent company and the subsidiary [82–85], and the role of the government as the regulator and guide of CBM&A in the process of RKT is neglected. Therefore, the influence of government intervention policies and other related factors on the evolution of RKT strategies based on CBM&A in the high-tech industry is analysed from a new perspective that includes government intervention; this approach not only expands the research perspective of RKT but also enriches the research content concerning government intervention in RKT through CBM&A. Overall, this study helps compensate for the shortage of literature concerning RKT and introduces a new research path to further speculate regarding RKT games in which multiple subsidiaries participate under government intervention.

Several limitations of this study should be noted. Although this study discusses the strategic adoption of RKT in China's high-tech industry under government intervention and some important conclusions are drawn, there are still several deficiencies. First, during the actual process of RKT through CBM&A, when a subsidiary makes a game decision, the game should consider not only the costs incurred by the subsidiary during the RKT process and the compensation of the parent company for the subsidiary's RKT but also the influence of the game strategy of the other subsidiaries supported by the RKT network of MNCs on the subsidiary's game revenue needs. Therefore, the rule of strategy evolution of RKT involving multiple subsidiaries under government intervention can be studied in the future. Second, the simulation parameters in this study are set according to expert opinions rather than actual parameters; thus, the simulation diagram can only reflect the general trend in the strategy adoption behaviour of each subject in the RKT, which also 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 there are no conflicts of interest regarding the publication of this paper.

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Research Article

Evolution of a Technology Standard Alliance Based on an Echo Model Developed through Complex Adaptive System Theory

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The evolution of the technology standard alliance (TSA) is examined using complex adaptive system (CAS) theory. Taking TSA as a dynamic CAS, an echo model is constructed to depict the mechanism of its evolution, and a model is simulated on the NetLogo platform. The echo model includes a basic model, an extended model, and a three-layer echo model. The adhesive aggregation of agents is explained, and the three evolutionary stages of agents' entry, migration, and exit are analyzed. Moreover, the adaptability of agents in TSA is quantified. The results of simulation show the evolution of the TSA in relation to the two aspects of agent adhesion aggregation and agent resource interaction, and they demonstrate the dynamic and complex hierarchical structure of the TSA system. It is proposed that greater matching ability, moderate behavior income, and lower behavior cost are more conducive to the evolution and development of TSA. Additionally, the echo model is reconstructed to expand the range of application of CAS theory.

1. Introduction

As science and technology have developed, technology standards have become a strategic command point for enterprise competition, and they affect enterprise behavior. Many enterprises actively participate in and even dominate the formulation of certain international technology standards to take the initiative in the formulation of standards and, through a novel approach to competition regarding them, to establish and maintain their core competitive advantages [1, 2]. A technology standard is a set of specifications that all elements of a product, process, format, or procedure within its jurisdiction must conform to [3]. Standards are of great strategic significance and can promote future development of enterprises, industries, and countries [4]. The present high degree of complexity of technology, the high risk and high cost of technological development, and the rapid shortening of the product life cycle restrict any single enterprise from providing all of the resources and technologies needed for R&D and the promotion of technology standards [5]. Therefore, the development of technology standards must be carried out together with other enterprises or organizations [6] to enhance their core competitiveness and help maintain long-term competitive advantages [7].

A technology standard alliance (TSA) is a kind of strategic alliance that arises to support enterprises as they formulate technology standards for a technology. The concept was first put forward formally in the 1990s [8]. A TSA is a typical alliance portfolio [9] or alliance network form [10], which takes a core of enterprises with strong R&D strengths and key technology intellectual property rights and unites others to it to jointly launch and spread a technology standard in a market [11]. TSAs are widely adopted because they can avoid reusing of resources, distribute enterprise risks, reduce costs, eliminate user concerns, and create a first-mover advantage [12]. Research on TSAs mostly focuses on the concept characteristics [13, 14], influencing factors [15, 16], mechanisms of operation [17], and performance evaluation [18]. At present, there have been few studies of the evolution of the TSA, and most of have focused on knowledge ecology [19] and innovation level [20]. Few have studied the TSA from a system perspective. The TSA phenomenon is complex, because any evolution of standards involves both macro (environmental) and micro (firm) forces and because standards both drive and are driven by the actions of firms and/or industry associations [21, 22].

In fact, the evolution of the TSA is a complex process and is the result of multilevel co-evolution among alliance agents on the one hand and between alliance agents and the external environment on the other. The interactions among agents and between agents and the environment are complex, and their specific mechanisms are not clear. The theory of complex adaptive system (CAS) focuses on the interaction of major factors within the system, and it highlights overall global behavior through interaction and feedback between the local model and the global model [23]. Using the CAS theory to build a model can provide solutions for dealing with the problems of complex systems. Kauffman [24] introduced CAS theory into organizational research. Warfield [25] studied complex aspects of organizational management and proposed a method of interactive management to solve complex problems in organizational management. Babaoglu et al. [26] found that adaptive agents in society travel through peer-to-peer networks and solve complex problems through node interaction and cooperation with other nodes. The application of CAS theory focuses on industrial clusters, ecosystems, or specific organizational structures. However, the TSA is a new type of strategic alliance, and there has been little application of CAS theory to study of TSAs. In addition, insufficient attention has been paid to the number of agents in a TSA setup, and previous models do not reflect interaction between agents and the environment. Therefore, it is necessary to apply CAS theory to create a global model to comprehensively and systematically investigate the evolution of the TSA.

The entire performance of TSA is a comprehensive embodiment of the behavior of the agents within the alliance. This paper takes the TSA as the research object, constructs a local model of internal agents, and then constructs a global model of the TSA, including the environmental factors. To accomplish our objective, we first analyze the complex adaptive characteristics of the TSA system and demonstrate that it is a typical CAS. Next, we build local models of agent interaction and a three-layer echo model that is suitable for the whole alliance, based on the idea of echo. Then, through simulation analysis of the evolutionary process of the TSA, we obtain the key factors that are conducive to the evolution and development of the alliance. Finally, we discuss and summarize the major managerial implications of our findings.

2. Summary of the Theory

CAS theory was put forward by Professor Holland [27] on the 10th anniversary of the founding of the Santa Fe Institute. Its core idea is that adaptation builds complexity. It is the foundation for an important branch of complexity science [28], which introduces the concept of agent with the adaptive ability to recognize and describe the behavior of a complex system in relation to the interaction between the agents and environment [29]. A CAS is invariably composed of a large number of active agents, called adaptive agents. As they accumulate experience, they adapt to change by constantly changing their rules [30]. In a CAS, all agents appear in a common environment, but each one conducts adaptive learning and evolution in parallel and independently, according to the local small environment around it [31]. The main part of the environment of any particular adaptive agent is composed of other adaptive agents. Therefore, each agent becomes adapted to the other adaptive agents.

The CAS operates on both the macroscopic and microscopic levels. At the macro level, it focuses on the hierarchy, diversity, and aggregation of agents [32] and emphasizes the interaction between them and the environment, so that a system that is composed of the agents is constantly evolving, exhibiting a range of complex evolutionary processes, such as emergence [33]. At the microlevel, the initiative and adaptability of the agent are emphasized. The agent actively learns or accumulates experience and changes its behavioral mode to adapt to changes. The evolution of the whole system is gradually derived from the agent [34]. In CAS theory as constructed by Holland, seven basic points are seen [27]. These are the common points extracted from all CASs, and other common points can be derived from a combination of these. They refer to the four characteristics and three mechanisms found in all CASs, namely, aggregation, nonlinearity, flows, diversity, tagging, internal model, and building blocks. The first four are some attributes of the agents, which play a role in adaptation and evolution, and the later three are the mechanism of interaction between the agents and environment. At the same time, these seven basic points also define the idea of a CAS from another angle. That is, a system with these characteristics can be understood as a CAS.

In relation to the behavior and interaction of adaptive agents, Holland proposed a macromodel of CAS, namely Echo. The Echo model is based on resources and location, and it ranges from simple to complex. Resources refer to any environmental material which affects the survival and development of the agents. The foundation of the echo model is laid by a series of renewable resources, and some resources will be consumed or used in the system, which maintains the activities of the agents with active adaptability. Location is the space place of the agent activity in a CAS. Each agent is located in different geographical positions or different development space, where the abundance of resources is also distinct. Because of the interaction between the agents, the geographical environment of the echo model is constituted by a group of interconnected locations. In the basic model, the agent is composed features attack tag, defense tag, and resource database [35]. In this model, the future of a given agent depends entirely on the tagging pairs that it carries. The resources obtained by an agent are directly proportional to the degree to which its attack tag matches other agents' defense tags. However, the basic model cannot fully describe other emergent phenomena of CASs, so the five mechanisms of conditional exchange, resource transformation, adhesion, selective mating, and conditional replication are gradually extended [36]. Through the gradual expansion, the expressive and descriptive ability of echo model is enhanced, which enables it to describe and study various complex systems. Holland's echo model draws on multidisciplinary knowledge theory to depict the ways in which CASs evolve, adapt, condense, compete, and cooperate. Thus, the echo model is an extremely beautiful model, constructed from very few principles, that provides a roadmap for how complexity emerges and adapts [37]. Nevertheless, in social science, it is difficult to perform a quantitative analysis of system complexity with objective data, especially for finding or designing feasible methods of calculation in the echo model. Therefore, this paper applies CAS theory to the TSA context and draws lessons from the basic idea of the echo model to design the quantitative method of agents' adaptability and the mechanism of alliance evolution.

3. Complex Adaptive Characteristics of the TSA System

The enterprise itself is a complex system, but the TSA, which has the enterprise as the main agent, shows even more complexity. As an adaptive agent, enterprises in an alliance interact with other agents and the environment of the alliance, leading to the performance of a series of complex behaviors, which will lead to the evolution and development of TSA. This paper takes the TSA as its research object, with an approach based on CAS theory. In other words, the TSA is seen to have seven basic points. According to CAS theory, the complex system of the TSA can be simplified by abstracting the key points out from the system. Therefore, we analyze the complex characteristics of the TSA system to simplify it, and we verify the hypothesis that the TSA is a CAS. This provides an occasion to analyze the adaptive behavior of the alliance agents and provides ideas for further research on the evolution and development of the TSA.

3.1. Aggregation. In CAS analysis, aggregation has two meanings. First, it is a means of simplifying complex systems. It refers to the aggregation of similar things into classes, which is the basis of model construction. The second meaning is more relevant to the content of CAS, which refers to simple agents that are gathered together to form a highly adaptive aggregate, also known as a higher level of meta-agent. Their interaction can produce more complex emergent phenomena, and the overall benefits may exceed the sum of the benefits for each agent, respectively.

The TSA is a contractual alliance organization used to jointly carry out standardization activities, formulating, implementing, and diffusing alliance technology standards, with enterprises as the main participants [38]. To realize their own development goals, these enterprises and organizations gather and form a TSA, which produces a series of spontaneous and complex behaviors, promotes the industrialization of the development of standards, and facilitates cost saving, interconnection, module innovation, and system integration, based on a common interface of related products [39]. Moreover, the TSA is formed by enterprises with strong R&D strength and key intellectual property rights for technology as the core, combining multiple enterprises or organizations. It is a self-organized, dynamic formation, which can easily cause emergent phenomena [40]. The boundary of the alliance then expands with the addition of new agents, and it then produces aggregation on multiple levels. Other agents and the alliance system as a whole respond, and adaptability and alliance performance change.

3.2. Nonlinearity. When agents and their attributes change in the TSA system, they no longer follow a simple linear relationship, instead showing nonlinear characteristics, especially in relation to repeated interactions with the system or environment [41]. In internal and external interactions in the TSA system, various complex relationships appear, which inevitably form the nonlinear characteristics of the TSA [42]. Specifically, in relation to the overall development of the TSA, network density [43], structural wholes [44], the small world effect [45], relationship strength [46], embeddedness [47], and government intervention [48] have an impact on the TSA, and partner selection [49, 50] and network centrality [51] are the main influencing factors for enterprise development in this context. There are many uncertain and fuzzy influencing factors in the external environment of the TSA system, and each agent must strengthen its own competitiveness by learning to adapt to the environment, thus making the nonlinear characteristics of the TSA system more obvious [52]. Generally speaking, complex relationships among agents, between the agents and the system, and between the system and the external environment can lead to nonlinear behavior and results and increase the uncertainty and possibility of the system's predictions.

3.3. Flows. In the TSA system, flows of information, materials, energy, and other resources appear between the agents and the environment. These flows vary from time to time and may even disappear as agents adapt or show maladaptation, and they have multiplier and recycling effects as well. Through cooperation and the sharing and diffusion of new knowledge, alliance members can accelerate the speed of knowledge innovation, and the knowledge level of the whole alliance can be improved due to this flow [53, 54]. As resources become invested in a certain agent, the effect produced by that agent is called the initial effect; then, resources are transferred from one agent to another in various forms, resulting in a series of changes. The total effect generated by this transfer flow multiplies the initial effect; that is, the TSA system produces a multiplier effect. Moreover, after resources from a certain agent complete their flow, they flow back to the agent, and this recycling flow produces additional resources for each agent that is connected to resources, causing a recycling effect. In addition to knowledge flow, resource flows such as information flow, capital flow, energy flow, and technology flow also exist. Each agent in the TSA system must exchange resources with the environment or other agents to survive and develop. An agent is connected with others to enable resource flow, which is an important motivation for the formation of TSA

[55]. The reason that the TSA continuously evolves, functions, and creates value is inseparable from the continuous flow of various resources between the agents of the alliance and the external environment.

3.4. Diversity. The diversity of CASs is the result of continuous adaptation. Each agent is located in a niche that is defined by an interaction centered on that agent. When an agent changes, it moves to another niche and a vacancy is generated. The system makes a series of adaptive responses, generates a new agent to fill the empty niche, and provides most of the lost interactions. Obviously, a TSA also has diversity as a characteristic, which makes the research of TSA more complex. The following discusses the diversity of a TSA in relation to agent diversity, technological diversity, and geographical diversity [56].

3.4.1. Agent Diversity. In addition to technology enterprises that have R&D functions and production functions, the members of a TSA may also be governments, universities, scientific research institutions, and industry associations [57], and these include organizations in the upper, middle, and lower reaches [58, 59].

3.4.2. Technological Diversity. In a TSA system, resource diversity can be considered in relation to technology. Technological diversity intuitively reflects the degree of focus and dispersion of different technological categories [60]. The technology owned by each agent in the alliance is diversified, so the TSA system also features technological diversity. Moreover, as new agents are added and the alliance evolves and develops, technological diversity increases accordingly [61].

3.4.3. Geographical Diversity. This means the degree of cultural, economic, and institutional differences [62]. The geographical location of each agent in the TSA system differs, and they may be located in different cities or countries [63]. For this reason, the management theories and cultural systems of different agents are also different. Some scholars use indexes of cultural or institutional distance to measure the level of difference level in the alliance combination [64].

In addition, different functions, such as market positioning [65], governance mode, and exploration/utilization [66], also bring diversity to the TSA. In essence, these diversities are caused by different configurations of the TSA. In a word, the configuration, alliance structure, management mode, standardization capability, and environment of a TSA system [67] are affected by many factors and they have an impact on the system in turn. Therefore, the TSA system presents the characteristics of diversity.

3.5. Tagging. Tagging is a mechanism that guides common hierarchical organizational structures in a CAS. In brief, it distinguishes and selects an agent or target by using the tagging. The interaction and aggregation of the agents based on tagging forms the TSA system, and from it, meta-agents and organizational structures emerge.

For agents in a TSA, organizational scale, market position, product advantage, resource capability, and geographical environment are the main tags for the choice of cooperation. Tagging has a particularly important role to play in selecting alliance partners and building and managing alliance networks [68]. The agent can choose alliance partners based on market orientation, with certain information or resources as the tag, and it can choose alliance partners that have scarce resources that are difficult to imitate and vital for improving their own ability to promote innovation and economic performance through effective integration with the internal resources of the agents [69]. At the same time, sales volume, operating cost, technology exchange and learning, developmental risk, and other aspects [70] can also be used as tags for the TSA system. The existence of these tags is conducive to the selection and cooperation of the agents in a TSA, the smooth development and realization of agents' own goals and tasks in the alliance, and the promotion of the evolution of the TSA system.

3.6. Internal Models. A valid internal model can infer the future state and environment of agents to generate behavior and predict future results. The internal model is essentially a mechanism for the realization of predictions, and to some extent, it is equivalent to the schema proposed by Gell-Mann [71].

In a TSA system, when a large amount of information is input to an agent, that agent chooses and executes a certain mode to improve its adaptability. These modes are transformed into changes in internal structure in the process of implementation; that is to say, they form the ability to foresee and have a deep understanding of the future consequences of encountering similar modes. Specifically, in the governance process of a TSA, the alliance chooses different governance modes due to the influence of the degree of trust between partners [72]. Moreover, the organizational conventions within the system have some predictive power, but this is based on the accumulated experience of past events. Experience and convention are part of this internal model, but internal models of the TSA system require further exploration and research.

3.7. Building Blocks. Building blocks are the components of a CAS and its elements that have been reused in practice. They are constituted by basic agents in various ways, and they present their own characteristics [73]. Building blocks can be used to generate internal models. When a model is implicit, the process of discovering and combining building blocks develops through the evolution of the system. Different combinations of building blocks determine the adaptability of the system, and the mode of combination and the level of building blocks determine the complexity of the system.

A TSA is often composed of a range of building blocks, including enterprises, governments, universities, research institutions, and industry associations, each of which plays a different role. Enterprises have a dominant position in the TSA. They not only participate in technological development and are the owners of technology standards, but they are also the users of patents. The government provides funds and policy support to develop technology standards. Universities and research institutions are often the main participants in and providers of technological R&D. Industry associations are intermediary organizations that provide service consultations and supervises TSAs. In a TSA system, agents at this level make up the next layer of building blocks. Taking enterprises as an example, the building blocks of enterprise hierarchy are core enterprises, participating enterprises, and peripheral enterprises [74], and their functions are different. Both core enterprises and participating enterprises are within the alliance and are distinguished according to the number of their patents and the status of their technology. Peripheral enterprises are users of standards. The next level of building blocks consists of different departments within each enterprise, and the next level after that involves individual employees. When a situation changes, the relevant building blocks are reassembled to adapt to it. For example, the deployment of employees is the arrangement of a combination of building blocks. In different combinations, the layered system produced in this way presents complexity.

4. Echo Model for the TSA System

As noted, a TSA can be seen as a CAS. The agent in a system has agentive initiatives and interacts with other agents to generate resources and make changes and adjustments to the environment. The echo model is a core model for CAS theory. It can explain the changes in the level and evolution of the TSA system as a result of interaction between agents and environment, which is especially suitable for the study of multiagent system evolution. We construct an echo model suitable for the TSA system to deeply analyze the phenomenon of emergence and the process of evolution of the system. We argue that a TSA is a contractual organization, with enterprises that set standards and pursue implementation, universities and scientific research institutions that provide auxiliary technology support, and government and industry associations that provide policy assistance. Because a TSA is enterprise-led, this paper focuses on characterizing the behavior of the enterprise agent on the basis of the echo model proposed by Holland and constructs an echo model suitable for a TSA system, including a basic echo model (model 1), an extended echo model (models 2–5), and a three-layer echo model.

4.1. Basic Echo Model

4.1.1. Model 1: Attack Defense Mechanism. In the basic version of the echo model, attack and defense describe the mechanism of acquiring resources. The agent has two parts: a repository for resources and a chromosome string that represents behavioral competence. Each agent has only one chromosome, and the attack tag and defense tag are carved on it. The interactive activities of the agents in the model are regulated by these tags. Both the attack tag and the defense tag represent resources; specifically, the former represents the resources needed by the agent and the latter represents the resources owned by the agent. In relation to enterprise development technology standards, resources can be divided into five categories: R_1, human resources; R_2, financial resources; R_3, knowledge resources; R_4, information resources; and R_5 equipment resources. R_{ij} represents specific resources, in the form R_{11}, R_{12}, etc.. When two agents meet, one attacks the other, matching its own attack tag to the other's defense tag. If the two tags have a high degree of match, they the agent can acquire most or all of the other's resources. Otherwise, it can only take the other's excess resources or nothing at all. In the model, we assume that the resources on the attack tag and defense tags either match each other plus 2 points, do not match, or exceed minus 1 point (based on the resources of the attack tag). The attack tag of each agent is marked with N resource items, which are matched with the defense resources of other agents. If n items of required resources can be provided to the agent, its matching score is $2n-(N-n)=3n-N$. For example,

The attack tag of agent 1 is $\{R_{11}, R_{12}, R_{21}, R_{22}, R_{23}, R_{41}\}$

The defense tag of agent 2 is $\{R_{11}, R_{22}, R_{23}, R_{41}, R_{51}\}$

The attack tag of agent 2 is $\{R_{12}, R_{13}, R_{21}, R_{33}\}$

The defense tag of agent 1 is $\{R_{13}, R_{14}, R_{31}, R_{32}, R_{33}, R_{42}\}$

When agent 1 and agent 2 meet, the attack tag of agent 1 is matched with the resources on the defense tag of agent 2. Agent 1 needs six kinds of resources, and agent 2 has five kinds of resources. Agent 2 can meet four of the kinds of resources needed by agent 1. The matching score is $3\times 4-6=6$ points. Similarly, the attack tag of agent 2 is matched to the defense tag of agent 1, and the score is $3\times 2-4=2$ points. Obviously, the degree of matching between agents is not equal. This degree determines the result of the resource, whether transfer, preservation, or surplus. Each agent is matched with agents that can be contacted, and then the agent with the highest matching score is selected for resource exchange. This basic model in the TSA system cannot fully present how agents decide whether to exchange resources or produce other complex phenomena in the evolution of this system. Thus, the echo model must be further expanded.

4.2. Extended Echo Model

4.2.1. Model 2: Resource Exchange Mechanism. In the resource exchange model, exchange conditions are added for the determination of whether to exchange resources, based on the matching degree of the agents. This model still follows the functions of chromosomes mentioned before, and it further refines the basic model, dividing chromosomes into tag and control segments. A tag segment matches the description above, including attack tag and defense tag. The new exchange conditions are found in the control segment. The formulation of technology standards is not done independently by one agent, and it requires constant interaction with other agents to achieve its output of technology standards. In the TSA system, agents do not unconditionally provide resources for other agents, and each exchanges its own surplus resources. When two agents in the model meet, the exchange conditions of each agent are checked in addition to consider the match with the attack tag of the other agent. Only when both conditions are met do the agents begin interactive activities for resource exchange. If one party's conditions are not met, it has the opportunity to escape interactive activities, which involves the probability of suspending them. That is, the agent is not always able to exchange resources with the most highly matched agent. In addition to the matching the attack and defense tags and the exchange conditions, resource exchange activities are also affected by the market environment.

4.2.2. Model 3: Resource Conversion Mechanism. Resource transformation mechanisms add a transformation subsegment to the control segment of the chromosome. This segment has an enzyme-like function, which converts a certain amount of resources into another specific resource. Essentially, companies adopt a series of actions to enhance their competitiveness and obtain more benefits. To share technological achievements and reduce the cost and risk of standardization [75], enterprises connect with partners such as enterprises, governments, universities and scientific research institutions, industry associations, and others to form a TSA. All enterprises in a TSA share the motivation of resource transformation, the purpose of which is to transform knowledge, information, talents, and other resources into technology standards and products and promote marketization and industrialization.

4.2.3. Model 4: Conditional Adhesion Mechanism. The cohesion model effectively explains the aggregation and evolution of the TSA system. To allow the echo model to achieve conditional adhesion, a new adhesion tag is added to the chromosome. When two agents meet, the adhesion tag of the one agent is matched to the attack tag of the other. If the matching score of the two agents is close to 0, no adhesion occurs. However, so long as there is an agent matching score that is not 0, adhesion will occur. Put simply, an agent conditionally chooses other agents to realize its connection, and it forms an aggregate with boundaries. Once this aggregate is formed, interactive activities become more complicated. In essence, business entities do not choose to connect with other companies with the same resources and technology capabilities, to better achieve adhesion. Agents tend to choose complementary agents to conduct connection cooperation, and they are, respectively, responsible for the development of different technology standards, to share risks and benefits. Within the TSA system, each agent achieves connection and adhesion with at least one agent, and they cooperate with each other to jointly develop and formulate technology standards. In adhesion, the level of the system is also spontaneously generated. When the agents stick to each other over a long period, a hierarchy emerges, that is to say, agents adopt full-time activity, and the agents in different hierarchies have special responsibilities to improve the efficiency of the development of standards.

4.2.4. Model 5: Agent Evolution Mechanism. The evolution of the TSA system is a dynamic process, and its internal agents are also undergoing constant evolution. The agent not only interacts with individual or multiple agents but also reacts to the external environment. Within the TSA system, each agent is located in an appropriate niche, defined by interactions centered on the agent. However, agents are evolving, and the role provided to other agents and alliance system is not fixed. After they enter the alliance, the agent gains the technology and other support needed for development. Through continuous learning, the agent changes its position in the alliance, and its role in technology standard setting activities changes with improvements or declines in capability and technology. The agent may move from one niche to another or from one system level to another, and it may even withdraw from the system.

The evolution of the agent in a TSA can be divided into three stages, as follows. First one is the agent entry. Suppose the probability of the agent entering the TSA during t is P_{at} and the critical probability that the system allows it to enter at this time is P_1. Then, when $P_{\mathrm{at}} \geq P_1$, new agents enter the alliance. Second is the agent migration or the change of an agent from one level in the system to another. In the TSA system, all activities support formulating and spreading technological standards. The agent's role in the formulation of these standards or changes in the ability of these standards can cause the agent's position to shift. For example, for an agent of a government or industry association, when a standard changes or there is a major change in the external environment, its role changes, and so does its ecological niche within the alliance system. Third is the agent exit. The main purpose of joining the TSA is to enhance the agent's own technological capabilities, launch more products, and achieve marketization. If the agent fails to achieve its goals or fails to obtain benefits, it withdraws from the TSA.

4.3. Three-Layer Echo Model. The basic and extended models incorporate a detailed explanation of the interaction between the agent and the mechanisms of the aggregation of multiple agents to form the TSA. The agent forms a TSA by adhering to other agents. After forming the alliance system, the interaction between agents and the environment continues. This is an integrated effect of the different mechanisms within the system that promotes the evolution of the TSA. However, models 1 to 5 are largely restricted to explaining the local mechanisms of agent interaction within a TSA system. To better describe the overall evolution of this system, a three-layer echo model is constructed, by combining the matching degree mentioned several times in the previous model mechanism. The matching of tags is key to the echo model, and it is the prerequisite for interaction and cooperation in formulating technology standards. The relevant literature indicates that the degree of matching is affected by matching time, matching speed, and matching ability [76]. Based on these three dimensions, a three-layer echo model of the evolution of the TSA system is constructed, as shown in Figure 1.

4.3.1. Upper Layer: Matching Ability. In the interaction between agents, matching ability relates to both the acquisition and exchange of resources and to the transformation of resources and to agent cooperation. The stronger the agent's resource-matching ability is, the more cooperative agents can be selected and the wider the scope is of available resources, producing greater benefit to the development of standard setting. This entails that the upper-layer model of the evolution of the TSA, matching capability, is established here.

4.3.2. Middle Layer: Matching Speed. A middle-layer model is established that corresponds to the ability-matching speed. The main motivation for joining the TSA to carry out R&D activities for a technology standard is ultimately to create greater benefit. In addition, the products are quickly updated, and it is only by developing new products more quickly that can they develop better returns. Therefore, the agent's resource-matching speed is very important. The quicker the matching speed of the agent's resources; the quicker its response ability; the faster its speed of resource acquisition, exchange, and transformation, the quicker its output of technology standards and products by the TSA.

4.3.3. Lower Layer: Matching Time. Obviously, a TSA system constantly evolves over time. An enterprise gradually evolves from a single agent at the beginning to form a TSA. The environment, agent, and alliance system are all dynamic, and their impacts at different points in time are not consistent. The agent's matching ability and matching speed also change over time, so matching time should be taken into account to establish the lower-layer model of the evolution of the TSA system.

In the three-layer echo model, the matching ability and matching speed of the agents may change with change in time, and change in matching speed may also cause a change in matching ability. Therefore, the upper-layer model is the result of the combined action of the middle-layer model and the lower-layer model.

In addition, we add the indicator alliance competency to describe the adaptability of the agent after its participation in the TSA. After joining the alliance, the agent gains a certain alliance competency, that is, an initial competency. For resource exchange, the connection and matching of the agent with other agents and the development of resource exchanges all have behavioral costs, that is, the agent loses a certain degree of competency in these transactions, namely, competency metabolism.

For the resource conversion mechanism, the agent converts the resources into technology standards and products and gains the benefits. The prerequisite for resource transformation is obtaining necessary resources for the development of technology standards. We use resource competency to express benefits. If the agent's resource competency is X, then its revenue increases by X for each unit of resource added to the resource conversion.

In the conditional adhesion mechanism, the agent achieves adhesion with other agents when certain conditions are met, while the agent remains in continuous evolution. After joining the alliance, the agent may rapidly develop and realize an expansion of scale by constantly connecting and cooperating with other agents and frequently interacting with resources. We use promotion cost to represent the cost (competency) to the agent for each promotion:

$$\begin{aligned}\text{alliance competency} = {} & \text{initial competency} \\ & + \text{resource increment} \\ & \times \text{resource competency value} \\ & - \text{competency metabolism} \\ & - \text{promotion cost.}\end{aligned} \quad (1)$$

The agent's alliance competence indicates the evolutionary state of the agent. If alliance competence > initial competence, the agent is well developed and can use the advantages of the TSA to continuously expand its own scale; if alliance competence < initial competence, the agent can cope with the competitive pressure of the market and maintain its own survival. However, when the agent's alliance competence decreases to 0, this means that the agent has withdrawn from the TSA. In other words, alliance competence reflects the agent's ability to adapt to other agents in the TSA and the external environment. The core of this model is the expression of the agent's resource acquisition, exchange, transformation, conditional adhesion, and evolution as its adaptability to provide a solution for studying how the agent's adaptive behavior evolves into a complex TSA system.

5. Simulation Analysis

The above echo model describes the evolutionary mechanism of a TSA system from the perspective of the interaction behavior of agents. This paper uses agent-based modeling and simulation [77] to study the complex system and simulates the evolution of the TSA system through NetLogo programming. NetLogo [78, 79] is a programming language and modeling platform used to simulate natural and social phenomena, proposed by Uri Wilensky in 1999 and developed by the Center for Connected Learning and Computer-Based Modeling of Northwestern University. It is especially suitable for simulating complex systems that develop over time. The introduction of random factors into the simulation gives its results improved ability to describe and express what it is simulating [80].

In this paper, the echo model of TSA system evolution is programmed and simulated in NetLogo 6.1.1, the latest version of NetLogo. The agents in the simulation model are cows, patches, and observers. Cows are operators (agents), which can be used to simulate humans, enterprises, or anything else, and they move within patches. Patches, for their part, make up a grid environment and are an activity space for the agents and can be used to signify grassland,

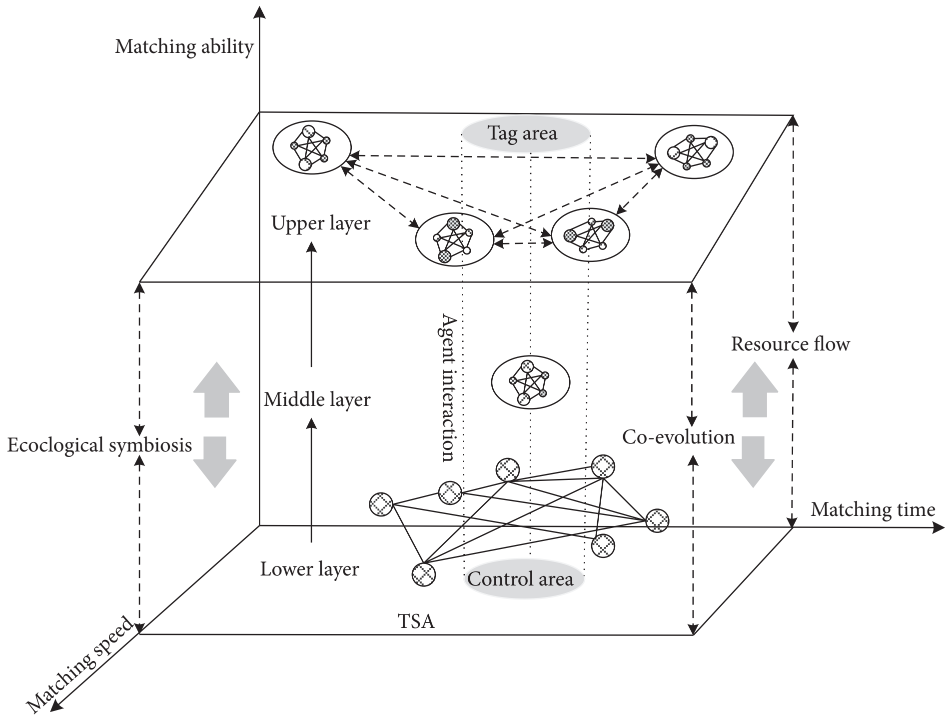

Figure 1: Three-layer echo model.

resources, or anything else. Observers are the issuers and coordinators of the main commands and the observers of the state of the simulation. In the simulation model of TSA, enterprises are the cows, and universities, scientific research institutions, government, and industry associations are part of the environment. In the TSA system, interactions and influences between agents and the environment are the main driving force of the system's evolution. Therefore, to achieve a simulation that can model the evolution process of TSA system, using NetLogo software, we set rules for behavior between one agent and another, between an agent and its environment, and among environmental variables, to make the agents evolve complex behavioral phenomena under the environment and set rules.

Based on the echo model and simulation conditions, the evolution process of the TSA system is simulated. The entire simulation experiment focuses on the angle of the agents' adhesion aggregation and resource interaction to simulate the evolution process of the TSA system.

5.1. Agent Aggregation Evolution Simulation. A prominent feature of the TSA seen as a CAS is the formation of a complex hierarchical structure among its agents. We simulate the connection hierarchy of agents in the process of forming TSA aggregation. The agents achieve long-term connections through the adhesive mechanism and thus form the TSA. The simulation model mainly incorporates the rules of the agents and simply presents an aggregate evolutionary process of the TSA system from a macroscopic view. It is assumed that all agents in the space maybe join the TSA. Due to the limitations of the simulation interface, the model only shows adhesion and aggregation of a few agents. To facilitate the simulation of adhesion, the agents are arranged randomly in a circle, and their adhesion is carried out in the middle position. Gray and red components represent agents (here, we only consider the relevant agents that may aggregate to form a TSA in the industrial environment). A gray line indicates where agents reach a short-term connection, and a red line means that a long-term connection between agents has been achieved, that is, adhesion has been achieved. Moreover, we call the number of agents directly connected to an agent the degree of that agent.

TSAs are usually initiated by enterprises with strong technological ability and a high market position. In the initial simulation state, as shown in Figure 2, the simulation interface shows the distribution of agent adhesion when the TSA is launched. We can see that 11 red agents have reached adhesion and are ready to unite with more agents to form a TSA. Two agents have a degree of 3, five agents have a degree of 2, and the degree of the remaining four is 1.

As the simulation experiment develops, more and more agents join in, and the aggregate expands. The intermediate aggregate is shown in Figure 3. At this point, the adhesion of agents in the aggregation is different, and a more complex network connection structure is formed. Moreover, in the dynamic aggregation of agents to form the TSA, it can be observed that a new aggregation may not be formed around a single agent but may be a multiagent that achieves a short-term connection. Then, the aggregation continues to evolve, and agents aggregate and form a TSA, as shown in Figure 4. We can see that other agents appear outside the TSA system. At this time, the evolution of the TSA system has not stopped, and agents continue to enter and exit.

The degree of distribution of the aggregate also indirectly indicates the aggregate connection among agents. In the

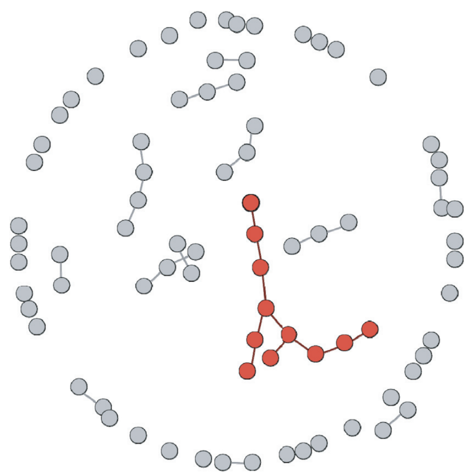

Figure 2: Initial state of alliance initiation.

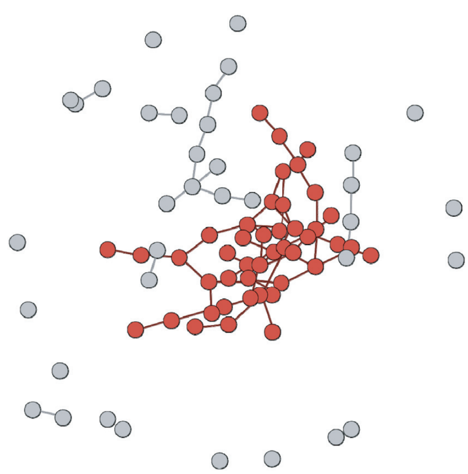

Figure 3: Intermediate state of alliance development.

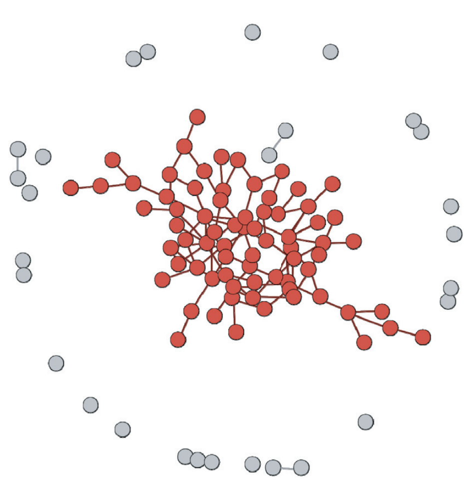

Figure 4: Stable state of alliance development.

simulation experiment, it is seen that, when the number of agents is 20, the distribution of degree of a time node aggregate is as given in Figure 5. In the aggregate network,

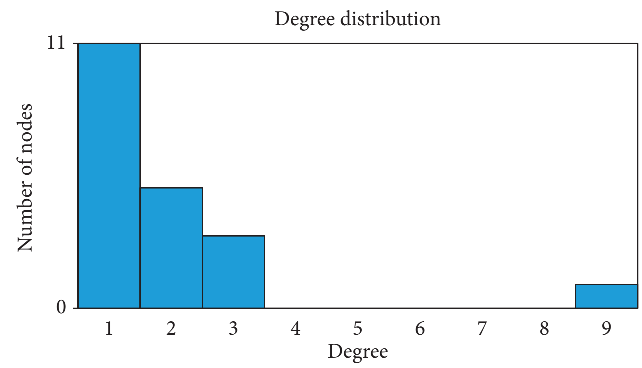

Figure 5: Degree distribution of the aggregate when the number of agents is 20.

there are 11 agents that only adhering to a single agent, and the maximum degree for an agent is 9. After the adhesion of agents, the number of agents in the aggregate continues to increase, and when a certain critical condition is reached, the TSA evolves and forms. Over the entire simulation, the number of agents with an aggregation degree of 1 is the largest and the connection between agents changes over time. These results show that the hierarchical structure of a TSA system is dynamic and changes with adhesion between the agents.

5.2. Agent Interaction Evolution Simulation. To better highlight the role of the basic model of agent interaction, namely, the attack defense mechanism, we divide enterprises in the industrial environment into two categories: cooperative and greedy agents. Cooperative agents are those that have joined a TSA and develop in coordination with the alliance as a whole. Greedy agents are those that are outside the alliance and pursue their own development, only connecting with cooperative agents for a short time. In the initial state, a small number of agents with core technologies become connected to initiate a TSA. At this time, the relationship between agents is not stable. In the simulation model, each agent is randomly assigned an initial position, and cooperative agents (in orange) and greedy agents (in blue) are distinguished by the color of the cows. Each patch represents the resources of one unit and is located in a different ecological niche. The main parameter settings and value ranges are presented in Table 1.

The evolution of a TSA system is inseparable from the interactions between the agents and the environment, that is, the flow of resources. In the simulation model, we set competency values for the agents to measure the survivability of each in the TSA system, and we took a competency value of 0 as the critical condition for the agent to exit the system. The simulation interface included the TSA system and its external environment. There were 13 cooperative agents and 7 greedy agents in the system, and the parameters of each agent were retained at the initial value. The change in the number of agents at the early stage of the simulation operation is given in Figure 6. At time steps 0–14, the number of agents in both categories is in the stage of rapid growth, and the growth rate

Table 1: Simulation parameter setting.

Parameter	Parameter description	Initial value	Value range
Cooperative agent	The agent in a TSA	13	—
Greedy agent	The agent connected with the agents in the alliance for a short time	7	—
Matching ability	Determines the flow range of the agent in a time step	0.02	0~0.3
Resource competency	Equivalent to behavior income	50	0~200
Competency metabolism	Equivalent to behavior cost	6	0~99
Promotion cost	Each agent needs to pay a certain competency cost for each promotion	60	0~99
Promotion threshold	The amount of basic resources an agent must have in order to be promoted	100	0~200
Low-high-threshold	Resource regeneration threshold	5	0~99
Low-growth-chance	Above low-high-threshold, the renewable resource is calculated with high-growth-chance	30	0~99
High-growth-chance	Below low-high-threshold, resource regeneration is calculated as low-growth-chance	70	0~99
Max-resource-height	Maximum number of resources	10	0~40
Cooperative probability	Setting an appropriate probability of cooperation between the agents	0.6	0~1.0

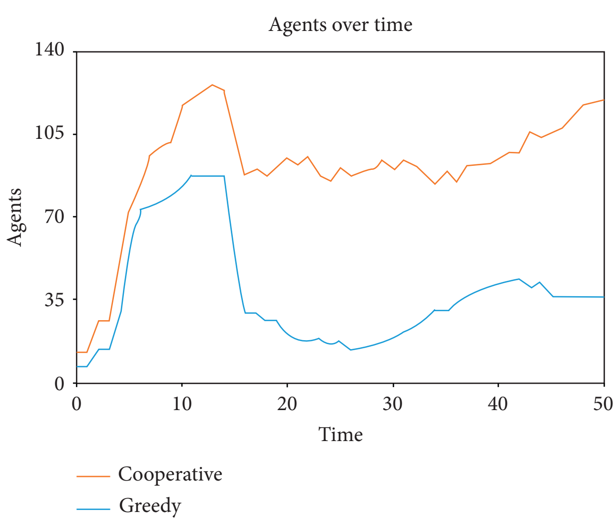

Figure 6: Early simulation interface.

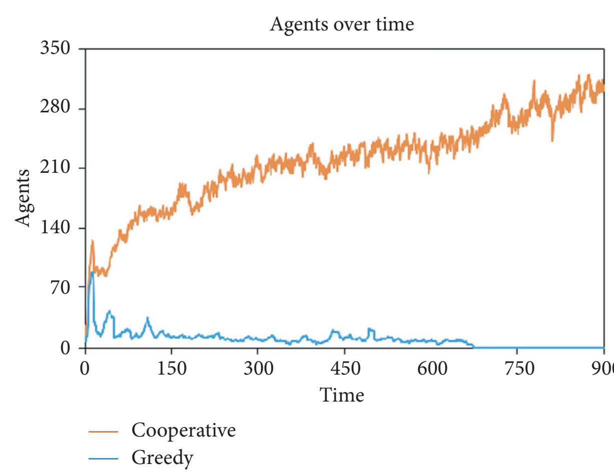

Figure 7: Later simulation interface.

is basically the same. This indicates that the number of agents is small in the initial stages of the evolution of a TSA system. On the basis of limited resources and R&D ability, it is not sufficient for a few agents to develop technology standards alone. Therefore, agents in the aggregation body need to seek partners including cooperative agents willing to join the TSA as well as greedy agents that are only seeking a short-term connection, after which the aggregation scale rapidly expands. At time step 14, the inflection point occurs for the quantity of change for both types of agents. In the early stages of the evolution of a TSA system, some agents' competency decreases to 0 after a series of interactive activities, and these withdraw from the system. As the number of entering agents falls below the number of exiting agents, the number of both types of agents decreases. After a short decrease, the number of cooperative agents stabilized at about 90 and began to rise in volatility at time step 44, indicating an overall increase in cooperative agents. After time step 14, the fluctuation of greedy agents decreases, and in the later stages of the simulation, the number of greedy agents decreases to 0, as shown in Figure 7. Finally, the agents in the TSA can meet their own resource needs in resource interactions with other agents or the system environment, and they have no further need to find short-term connections with external greedy agents to obtain resources. From this point, the agents in the TSA are committed to jointly developing, formulating, and diffusing technology standards, such that the TSA has reached a relatively stable state. In the following time step, agents interact constantly, and the TSA still accommodates the entry and exit of agents.

In many simulation experiments, the distribution of agents across the simulation interface is unequal. The setting of the matching ability of agents and the limitations of the scope of matching resources alter the simulation results. However, the following simulation phenomena are not affected.

With matching ability as the independent variable, other variables can be controlled to remain unchanged in the initial state. We observe the evolution state of TSA by adjusting the value of the matching ability. Figure 8 clearly shows that, when the matching ability is 0.01, the number of agents changes with the time step. When the time step is 50, the number of cooperative agents in the TSA is 103 and the

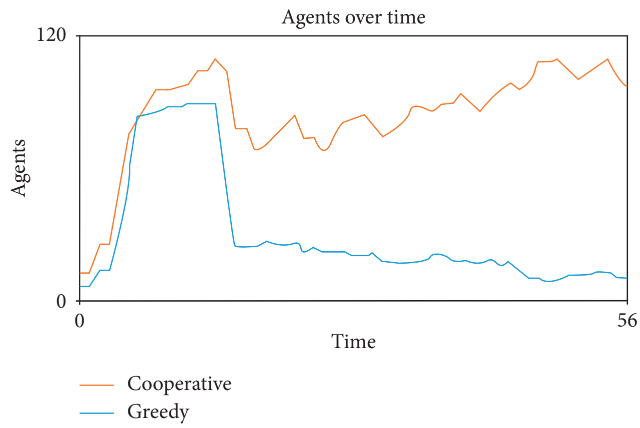

Figure 8: Matching ability = 0.01.

number of greedy agents is 11. In Figure 9, the evolution of the entry and exit of agents of the TSA is shown when the matching ability is 0.03. At time step 50, the number of cooperative agents is 178 and the number of greedy agents is 31. It is clear that the evolution scale of the TSA is also larger, due to the increased resource-matching ability among the agents. We believe that the stronger an agent's resource-matching ability is, the faster is its rate of resource acquisition, exchange, and transformation. To maintain stronger resource-matching capability, at each time step, an agent requires additional resources and needs to adhere to more other agents to meet the needs of its own technology development. Therefore, the stronger the resource-matching ability of the internal agents and the larger the number of cooperative agents adhering to the aggregation, the larger the development scale of the TSA. However, the larger the scale of the alliance, the more the agent needs to improve its adaptability to be able to match resources with more agents.

Resource competency is taken as the independent variable, and the other variables are controlled in the initial state and remain unchanged. For a single agent, the higher the resource competency, the better the promotion. Higher competency of the agent's resources entails that the agent produces more results for a unit of resources, that is, having a higher conversion rate of resources, which is more conducive to the development of the agent. However, this is not the case for the TSA system as a whole. In the simulation experiment, when resource competency is 50, the change trend of the number of agents is smaller, and the number of agents at the same time is greater than at other levels of resource competency. At time step 50, the number of cooperative agents is 130 when the resource competence is 50. When the resource competency is 40 or 60, the number of cooperative agents is 95 or 106, respectively. We believe that when resource competency is low, the development of the agents and alliance system is limited and evolution is slower. However, when resource competence is too high, the agent conflict is more obvious and the change trend of the number of agents is steeper. This indicates that agents enter and exit more frequently over the same period of time, and the agents in the alliance always seek to change their own adaptability to adapt to new agents, which is not conducive to the stable development of the TSA. However, if the resource competence of the agents is moderate, the scale of the alliance is larger, and it becomes more stable, which is beneficial to its overall development.

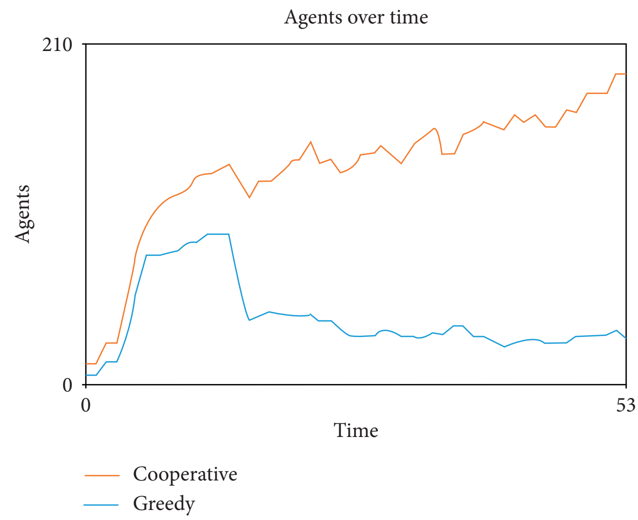

Figure 9: Matching ability = 0.03.

Competency metabolism is taken as the independent variable, and other variables are controlled in the initial state and remain unchanged. The lower the competency metabolism is, the lower the flow cost of the agent in the simulation model, that is to say, the competency cost paid by the agent to obtain the same amount of resources is less. We set the competency metabolism to different values, that is, to 4, 5, 6, 7, and 8, and through simulation it is observed that when the system reaches step 50, the number of cooperative agents is 189, 123, 110, 101, and 85, respectively. It can be concluded that when competency metabolism is lower, with the growth in time, the more agents in the TSA system, the larger the alliance scale is after development stabilizes.

6. Conclusion

6.1. Research Conclusions. In this paper, CAS theory is used to study the evolution of the TSA system. Essentially, a TSA can be understood as a kind of CAS by analyzing its complex adaptive characteristics. An echo model is reconstructed according to the evolution of a TSA, and the interaction mechanisms of the agents and the emergence of the system hierarchy are explained. The evolution process is reproduced in a NetLogo programming simulation, and the characteristics of the CAS are verified and explained. The key factors affecting the evolution of TSA are extracted. The conclusions of this study are as follows:

First, a TSA is a dynamic, complex, and multiagent CAS, which includes enterprises, governments, universities, and scientific research institutions. Whether it is in the early stages of a TSA or in its later stages of stable development, agents are always entering and exiting. The interaction between the agents within the system and the environment makes the study of a TSA complex. However, each agent has subjective initiative. In response to the uncertainty of its external environment, an agent takes corresponding actions in standardization cooperation to adapt to changes in the environment.

Second, the simulation results of the echo model demonstrate that a complex hierarchical structure is formed among the agents in an alliance, which changes with changes in adhesion between the agents. With the evolution of a TSA, this is inseparable from the flow of resources between agents and the environment, and the change of the number of agents presents a nonlinear pattern of growth. In addition, under certain environmental conditions, the TSA evolves to a certain scale, with are full-link agents responsible for its development, formulation, and diffusion within the alliance, making it unnecessary to obtain resources from enterprises outside an alliance to complete the formation of technology standards.

Third, the resource-matching ability of each agent is a key factor in the evolution of a TSA. Matching capability means the ability to acquire, exchange, and transform resources. Low matching ability means that an enterprise agent has limited access to resources, making the resource transformation activities limited, and the development of technology standards will progress slowly. This affects the evolution of the TSA. With high matching ability, moderate behavior income and low behavior cost, an agent can carry out resource interaction with more agents and adhere to more agents, thus promoting the evolution process of its TSA.

6.2. Discussions and Prospects. The above conclusions have certain significance for guiding the development and evolution of TSA. Essentially, our findings indicate that a TSA is a typical CAS, with a complex hierarchical structure. Moreover, enterprise agents continuously interact with other agents and the environment (through resource matching), which promotes the dynamic evolution and development of the TSA. Our findings support certain conclusions from previous studies. Consistent with the views of Narayanan and Chen [81], we argue that facilitating standards in complex technological systems requires the collective effort of various agents. Likewise, standardization alliances evolve through collaboration among firms to develop and implement industry technical standards [82]. In line with the conclusion of Rodon et al. [83], we further propose that it is only when the resources of enterprises in the TSA are dynamically matched with the resources required at different stages of the process can any standardization be smoothly implemented. Moreover, this paper develops the description of the evolution mechanism of the whole system on the basis of previous studies [84–86]. Additionally, changes in the external environment are also taken into account among the influencing factors of the TSA system.

Applying CAS theory, this paper not only describes the interaction between agents but also clearly presents the interaction between agents and the environment, studying the influence of internal and external factors on the evolution of TSA. It also untangles the reason why resource integration is the main influencing factor in alliance evolution and development [87]. The interaction between the alliance and the environment is accomplished through the interaction between the agents and the environment. The continuous acquisition, exchange, and integration of the main resources are the driving force of the evolution and development of the TSA. Further, our results indicate that the interaction between agents and the environment is very important. Enterprises should optimize their resource structure and improve their adaptability to the environment to reach better development in a TSA.

Besides, we admit that this paper also has some limitations. First, it focuses on the macro level, with less consideration being given to the subjective factors in the relationship between alliance agents. In the future, we intend to divide the evolutionary stages of the alliance agent more carefully in combination with relationship quality and agreement mode between alliance partners to improve study of the evolution and development of the TSA. Second, in the part of echo model construction, we present a measurement method for alliance competency (that is, the adaptability of an agent to the alliance), rather than providing the mathematical model of a multiagent. The TSA system, which can be regarded as an ecosystem, includes not only the internal adaptive agents but also the external environment. Combined with the simulation method, this can clearly indicate the specific impacts of resource interaction between agents and environment in a TSA system. This paper aims to provide a reference direction for the study of strategic alliances from a system perspective. In the future, we intend to use mathematical models to test our understanding of the evolution of the agents and the alliance system and to verify the reliability of our conclusions with empirical methods. In addition, in the simulation of the TSA system evolution, we only studied the evolution of adaptive agent aggregation and interactive evolution processes. A parameter index setting may be lacking. In the future, we may review other simulation platform software to present the entire process of TSA evolution more comprehensively.

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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