

Research Article

The Intertemporal Evolution Model of Enterprise R&D Cooperative Network

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Cooperation plays an irreplaceable role in knowledge creation and innovation. Innovation cooperation among enterprises forms a complex network of enterprise R&D. Given the intertemporal R&D network evolution and the complex influence between stock knowledge, this study constructs a discrete indefinitely intertemporal evolution model of an enterprise R&D cooperation network. The model consists of two main parts, that is, first is how technological innovation depends on the structure of enterprise R&D cooperation network and the second is how the enterprise R&D cooperation network evolves according to the level of technological innovation. This work uses calculation experiment and simulation method to study the evolution characteristics of enterprise R&D network in different initial R&D network topology structures, such as Erdos–Renyi random graph, WS small-world network, and BA scale-free network, and determine how previous history, attractiveness, and reputation for enterprise influence the steady-state characteristics of R&D network evolution. Results show that (1) when the R&D network evolution reaches a stable state, the joint distribution of stock knowledge and the number of cooperative enterprises do not affect the initial R&D network topology. However, the evolution path of the enterprise R&D network is complicated by the initial R&D network topology. (2) Among the three factors through which enterprises make decisions, if the enterprise values previous history highly, then the stock knowledge in a steady state will dissipate; if the enterprise values reputation highly, then the stock knowledge in a steady state will decrease but always above a threshold; if the enterprise values attractiveness highly, then the stock knowledge in a steady state can rise to a high level. These conclusions have important theoretical values and practical significance for the promotion of enterprise scientific and technological innovation and cooperative research.

1. Introduction

Technological progress is one of the main drivers of economic growth in developing and developed countries [1, 2]. An enterprise can achieve technological progress at the company level through internal R&D activities or external R&D means, and the enterprise's choice depends on the competitive relationship with other enterprises, the level of technological complexity involved, and innovation endowment. Since the 1980s, the technologies used for production and innovation have become increasingly complex, and the development of these new technologies by a single enterprise through its own internal R&D activities is difficult. Therefore, an increasing number of enterprises gradually realize the importance of establishing partnerships

with other companies. As a form of cooperation in which several independent economic entities agree to share certain R&D activities and results, R&D partnership has become a cooperative innovation mode among enterprises [3]. Partnerships in R&D are common in most industries, especially those with rapid technological development, and have led to a marked increase in interenterprise technological cooperation across a wide range of industries [4–10]. This type of R&D partnership among enterprises operating in the same or related industries forms an enterprise R&D network [11], which promotes the significant growth of enterprises' innovation ability and level [12–14].

In recent years, with the continuous active R&D activities among enterprises and the emergence of their value, the relevant research on the formation and evolution of R&D

network in academic circles presents a rapid growth trend [15–19]. Goyal and Moraga-Gonzalez [20] considered the bilateral and nonexclusive nature of cooperation agreements, constructed a strategic cooperation model among enterprises, analyzed the influence relationship among market competition, motivation of enterprise innovation, and R&D cooperative network structure, and concluded the relationship between R&D network structure and the intensity of market competition in equilibrium. Goyal and Joshi [21] studied the motivation of enterprises to form cooperative relationship in the oligopoly market, and the architecture of the enterprise R&D network thus formed. Westbrook [22] claimed that only a few enterprises participate in most cooperative relationships and studied the relationship between efficiency and welfare distribution based on such an enterprise R&D network structure. König et al. [23] constructed an R&D partnership exchange of enterprise knowledge network model, in which two companies set up new partnerships or termination of the existing partnership decision-making structure based on marginal revenue and cost. Marginal revenue and cost depend on the enterprise position in the network, and the results indicate that this type of partner selection mechanism can lead to the existence of a multiple equilibrium structure. Dawid and Hellmann [16] studied the evolution of the R&D cooperation network in a Cournot competition model and found that enterprises can reduce marginal cost through bilateral R&D cooperation. Zhang et al. [24] construct a two-stage oligopoly game of semicollusion in production. Not only the local stability of equilibriums but also the existence, stability, and direction of flip bifurcation of the discrete nonlinear model are investigated by using the normal form method and the center manifold theory. Tur and Azagra-Caro [19] conducted in-depth analysis and modeling of the feedback mechanism between knowledge creation and network evolution and studied the relationship between knowledge creation and the number of collaborators. The results show that the relationship between knowledge creation and the number of collaborators may be positive, negative, or independent by adjusting the costs and benefits of R&D cooperation. Zhou et al. [25] establish a dynamical two-stage Cournot duopoly game with R&D spillover effect and product differentiation. The stability of all the equilibrium points is studied using Jury criterion, and then the stability condition is given. The direction of flip bifurcation is given by using central manifold theorem and norm form theory.

Certain studies have indicated that the R&D performance of an enterprise is largely affected by its location in the R&D cooperation network; that is, enterprises are affected by the R&D network topology. Essentially, the innovation and research performance of enterprises are determined by internal and external R&D strategies [20, 26, 27]. R&D cooperation can benefit both parties involved in cooperation in numerous ways [28, 29]. For example, cooperation may lead to the sharing of information regarding new technologies or market conditions; sharing of specific facilities, such as distribution channels; or the formation of an alliance with partners to jointly develop market

standards for products. However, R&D cooperation comes at a price. Excessive R&D cooperation may lead the parties involved in the cooperation to reduce their subjective intention of innovation and choose to profit by free riding, which leads to the problem of insufficient impetus for macroinnovation.

The dynamic process of the formation of R&D network is an important and complex problem. It reflects how enterprises, as agents, choose R&D partners among numerous other enterprises. Generally, enterprises that cooperate in R&D are competitors in the market. The establishment of R&D cooperation can expand information access channels, improve product quality or reduce costs, and enhance an enterprise's competitiveness in the market. However, the establishment of R&D cooperation improves the competitiveness of competitors in the market and relatively reduces the enterprise's market competitiveness. In addition, the cost of establishing cooperation is expensive, and the marginal cost of establishing cooperation is increasing. In view of various factors, enterprises need to consider complex strategic issues when selecting R&D partners. Hagedoorn [3] indicated that numerous companies adjust their R&D partners over time, which leads to the evolution of R&D cooperation networks in their industries.

Therefore, on the basis of existing research and complex network theory, this study conducts a theoretical analysis of the complex relationship between the interaction of enterprise innovation R&D performance and R&D network and constructs a discrete time intertemporal evolution model of the R&D network. In our model, the enterprise that will set up new R&D cooperation or remove existing R&D cooperation decision-making is different from the study of König et al. [23]. Here, we establish R&D cooperation by comparing the costs and benefits of decision-making under certainty on the basis of the probability that certain enterprises have been confirmed by empirical research on R&D cooperative relationship of factors that affect the adjustment. Overall, in our model, the probability that two companies establish (or maintain) the R&D cooperative relationship is related to three factors, namely, the two companies' attractiveness, previous history, and reputation. The attractiveness of an enterprise refers to the achievements related to R&D activities in the past. The greater the attractiveness of an enterprise is, the more willing the other enterprise is in establishing R&D cooperation with it. This condition is caused by the establishment of R&D cooperation, which leads to a great probability to obtain further resources and improves the enterprise's competitiveness in the market. The previous history of two enterprises refers to the history of cooperation in the past. If two enterprises have had a cooperative relationship, then they will have a higher probability of cooperation in the following period given the trust in each other's innovation and research strength. Lastly, the reputation of an enterprise refers to the number of R&D cooperation established by an enterprise in the past. Generally, enterprises that establish an R&D relationship with numerous enterprises are the leaders with low marginal production cost in the industry and have increased influence. Given the widespread information asymmetry in the

market, enterprises cannot often completely be clear to other enterprises' innovation R&D, which cannot evaluate the attractiveness of another enterprise; hence, when the decision is made to establish cooperative relationship, the reference reputation index of the enterprise is irrational but effective. That is, we actually consider the information asymmetry in the market by including reputation in the consideration of enterprises in establishing R&D cooperation; nevertheless, the enterprise's decision continues to be rational. If relevant information cannot be obtained, then the optimal decision of the enterprise is the hybrid decision described in the preceding probability.

At present, certain theoretical models can be used to study the relationship between cooperative networks and knowledge creation. Cowan et al. [30] and Cowan and Jonard [31] emphasized the complex relationship between cooperation and knowledge generation. On this basis, a model is constructed in the present work. We explore the relationship between the amount of knowledge generated and the R&D network structure. Guimera et al. [32] constructed a mathematical model of knowledge evolution networks and investigated the empirical correlation of knowledge generation. Chen et al. [33] explained how the evolution of network structure promotes the progress of knowledge but not how the amount of knowledge generated depends on the network structure. Brummitt et al. [34] studied the relationship between knowledge cooperation network and creation and modeled knowledge creation as the probability of matching compatible knowledge between two partners. Tur and Azagra-Caro [19] mainly considered the relationship between the amount of knowledge and the number of partners when the R&D network evolves to a stable state.

On the basis of the aforementioned research, this study constructs an intertemporal evolution model of R&D cooperative networks with indefinite time. In each phase of the model, the innovation produced by the enterprise is related to its location in the network. In addition, the enterprise decides the R&D cooperation object of the next stage according to the innovation R&D results of other enterprises observed in this period and the R&D network structure of this period. On the basis of the analysis of the above model, we study how the R&D cooperative network structure at the beginning of evolution affects the evolution of the R&D cooperative network. We take the average stock knowledge of all enterprises in each period as the performance evaluation index of the total social innovation R&D in that period and explore the change of the initial R&D network structure in the dynamic process of innovation. In addition, we study the influence of model parameters on evolution and the results of the evolution to the stable state.

The remainder of this paper is organized as follows. Section 2 describes the generation mechanism of innovation R&D results, that is, how innovation R&D results are dependent on the topology of enterprise R&D cooperation networks; mathematical modeling is also performed in this section. In Section 3, we construct an intertemporal evolution model of enterprise R&D cooperation network with discrete and indefinite time on the basis of the decision-

making mechanism of enterprises that choose R&D partners. The model simulation is performed in Section 4. Section 5 presents the main conclusions and policy implications of this study.

2. R&D Network and Diffusion Mechanism of Innovation

2.1. Construction of R&D Network. We denote R&D network in period $t \in \mathbb{N}_+$ by $G(t) = (N, E(t))$ and the set of enterprises in R&D network by $N = \{1, 2, \dots, n\}$, where $n \in \mathbb{N}_+$ represents the number of enterprises in the R&D network. Given that the R&D cooperation agreement is jointly established by both parties, no difference is considered between the cooperative relationship between enterprises i and j and between enterprises j and i . Therefore, we consider R&D cooperation network $G(t)$ as an undirected graph and use adjacency matrix $X(t) = (x_{ij}(t))_{n \times n}$ to capture the topology of R&D network G_t in period t , as shown as follows:

$$x_{ij}(t) = \begin{cases} 1, & \text{if } i \text{ and } j \text{ have R\&D collaboration link at time } t, \\ 0, & \text{otherwise.} \end{cases} \quad (1)$$

We denote the set of enterprises that have a cooperative relationship with enterprise i by $N_i(G(t))$.

We study the intertemporal evolution of enterprise R&D cooperative network under various types of initial R&D cooperative network structures. The network topology used in the study is as follows:

- (1) Random graph: random graph plays a fundamental role in complex network theory. The network generated by the random graph algorithm is usually uniform and can represent the network evolution well under the condition of homogeneous nodes. In the network with N enterprises as nodes, let the cooperation probability between any two enterprises be $p_1 \in (0, 1)$, and the total number of edges generated is not fixed. The resulting network is regarded as the initial R&D network, which is called the initial R&D network on the basis of the random graph. Then, the expected average degree of the initial R&D network based on random graph is

$$E(\bar{k}) = \frac{n(n-1)p_1}{n} = (n-1)p_1. \quad (2)$$

- (2) WS small-world network: a small-world network is a type of network with a short average path length and a high clustering coefficient, which can be generated by the WS small-world network construction algorithm. In WS small-world algorithm, a small-world network is obtained via random reconnection in a circular regular network. Randomized reconnection refers to randomly reconnecting each edge of the network with probability p_2 , that is, keeping one endpoint of the edge unchanged and taking the other

endpoint as a randomly selected node in the network.

- (3) BA scale-free network: a scale-free network is a complex network with a class of characteristics. The typical characteristic of this network is that the majority of nodes in the network are only connected with a few nodes, whereas a few nodes are connected with a large number of nodes. In reality, numerous networks have scale-free characteristics, such as the Internet, financial system networks, and social networks. A scale-free network can be generated by the construction algorithm of BA scale-free network model. Specifically, the generation step is as follows.
- (a) Growth: start with a smaller network G_0 (n_0 nodes, E_0 edges) and gradually add new nodes, one at a time.
 - (b) Attachment: suppose n nodes exist. Each time a new node is added, $m < m_0$ connections are connected from this new node to the original n nodes.
 - (c) Preferential attachment: if an original node i has its degree denoted in the original network by k_i , then the probability that the new node is connected to it is as follows:

$$P_i = \frac{k_i}{\sum_{j=1}^N k_j}. \quad (3)$$

After t times of the above steps, the new network has $n_0 + t$ nodes and $E_0 + mt$ edges.

2.2. R&D Results and Innovation Diffusion Effect. R&D is a creative activity that requires high investment. The output of innovation R&D results is influenced by the innovation input of enterprises and restricted by objective historical innovation.

This study assumes that firms agree on the importance of innovation and research. Thus, given the importance of innovation and research to the survival of enterprises, any enterprise can invest sufficient innovation and research costs, regardless of the business situation, to ensure the output of future innovation and research results. Therefore, we ignore the restrictive effect of innovation R&D input on the output of innovation R&D results and believe that the output of innovation R&D results is only affected by the objective and realistic innovation. The study assumes that the output of innovation R&D results is affected by two factors to further clarify the restricting effect of the objective historical innovation on innovation R&D results. The enterprise's innovation and research ability, which is mainly determined by the stock of innovative human capital, has a certain correlation with the amount of innovation achievements generated in the past. This ability is the innovation diffusion effect of R&D network. Innovation diffusion effect refers to when an enterprise's innovation and research achievements can be partially utilized by other enterprises to gradually improve the innovation and

research strength of the entire industry in the following period. If a patent protection mechanism exists, then the understanding of new information and ideas of other enterprises can promote the innovation and research of an enterprise or an industry.

To describe the generation mechanism of the aforementioned innovation R&D achievements, we construct the total innovation R&D achievements as the sum of the influence of our own innovation R&D achievements and innovation diffusion effect subtracted by the R&D cooperation cost $C_i(t)$, shown as follows:

$$\kappa(i, t) = \kappa_s(i, t) + \kappa_d(i, t) - C_i(t), \quad (4)$$

where $\kappa_s(i, t)$ refers to the innovation research result generated by enterprise i in period t and $\kappa_d(i, t)$ represents the additional innovation R&D results brought by the positive spillover effect of innovation diffusion in period t . We assume that the innovative human capital stock is given externally; thus, the growth amount of our own innovative R&D achievements can be measured by the previous innovative R&D achievements, shown as follows:

$$\kappa_s(i, t) = \alpha \frac{1}{\tau} \sum_{s=t-\tau}^{t-1} \rho^{t-s} \kappa(i, s), \quad (5)$$

where $\rho \in (0, 1)$ describes the time depreciation coefficient of stock knowledge, $\alpha \in [0, 1)$ describes the generation rate of innovative R&D results, and τ represents the time window for stock knowledge to take effect. The formula describes the fact that innovation and research are based on a certain amount of knowledge. A positive correlation exists between the achievements of innovation and stock knowledge. In addition, the earlier the stock knowledge generated, the less the influence on the output of innovative R&D results and the more considerable the promotion effect of recently generated stock knowledge on the output of innovative R&D results will be.

As for the influence of the innovation diffusion effect, we refer to the method adopted by König et al. [23] and believe that the improvement of achievements brought by innovation diffusion is positively correlated with the degree of an enterprise. The innovation R&D achievements brought by innovation diffusion effect can be described as follows:

$$\kappa_d(i, t) = \theta \frac{1}{\tau} \sum_{s=t-\tau}^{t-1} d_s(i), \quad (6)$$

where $\theta \geq 0$ is the coefficient of the positive innovation diffusion effect, which measures the impact of the innovation diffusion effect on the output of innovative R&D results, and τ is the time window that can produce the innovation diffusion effect.

We consider the cost of R&D cooperation among enterprises, although we ignore the innovative R&D cost. If we do not consider the cooperation cost, then the optimal R&D cooperation strategy for each enterprise is to cooperate with any other enterprise; thus, we can obtain a trivial conclusion, that is, all enterprises in the second period begin when all other enterprises establish R&D cooperation. To avoid this

situation, we assume that $C_i(t): \mathbb{N}_+ \rightarrow \mathbb{R}_+$, the cost of establishing R&D cooperative relationship with other enterprises in the period t of enterprise i is the marginal increasing function of the total number of R&D cooperative relationships d established by enterprise i in period t , shown as follows:

$$C_i(t) = \gamma d_i(t)^2, \quad (7)$$

where $\gamma \geq 0$ represents the R&D cooperation cost coefficient. These costs are directly reflected in the reduction of the stock knowledge, not in the profits after innovation and research. Therefore, the hypothesis of this study is implied, that is, sharing one's stock knowledge with other companies is not free. Although cooperation can bring new information and ideas, such sharing can make one's key technologies be mastered by competitors, which can bring negative effect. Moreover, this negative effect increases with the number of innovation and research cooperation.

From the aforementioned discussion, when the structure of R&D network $G(t)$ is determined, the innovation R&D achievements of enterprise i ($\kappa(i, t)$) in period t is endogenously determined as follows:

$$\begin{aligned} \kappa(i, t) &= \kappa_s(i, t) + \kappa_d(i, t) - C_i(t) \\ &= \alpha \frac{1}{\tau} \sum_{s=t-\tau}^{t-1} \rho^{t-s} \kappa(i, s) + \theta \frac{1}{\tau} \sum_{s=t-\tau}^{t-1} d_s(i) - \gamma d_i(t)^2. \end{aligned} \quad (8)$$

3. Enterprise R&D Cooperation Decision and the Intertemporal Evolution Mechanism of R&D Network

In the evolution of each phase of the R&D network, the agent can choose to establish an R&D cooperative relationship with other enterprises or remove the R&D cooperative relationship. Therefore, the topology of the R&D cooperative network can change within each phase.

We assume that the R&D cooperation strategy is influenced by three factors, namely, previous history, attractiveness, and reputation. Specifically, the previous history of two firms renders them as each other's information control and enhances the trust in each other. The history of the cooperation promotes their cooperation in the follow-up period. Therefore, the more instances of historical cooperation between two enterprises, the more inclined they are to continue to cooperate. The previous history of enterprises i and j in the previous period τ_1 is defined as

$$H(i, j, t, \tau_1) = \frac{1}{\tau_1} \sum_{s=t-\tau_1}^{t-1} x_{ij}(s). \quad (9)$$

The attractiveness of an enterprise can be measured by its past relative innovation achievements. On the basis of (8), the innovation and development achievements $\kappa(i, t)$ of enterprise i in period t is an incremental function of $\kappa_s(k, t)$ ($k \neq i$), the independent innovation and development achievements of other enterprises. Therefore, enterprise i is inclined to establish R&D cooperative relationship

with enterprises with a relatively large number of innovative R&D achievements in the past to maximize its own innovative R&D achievements under the same cooperation cost. We define the attractiveness of enterprise j in period t as follows:

$$A(j, t) = \frac{\kappa(j, t)}{\max_{1 \leq k \leq n} \kappa(k, t)}. \quad (10)$$

Moreover, we define the total attractiveness of enterprise j in the past period τ_2 , shown as follows:

$$A(j, t, \tau_2) = \frac{1}{\tau_2} \sum_{s=t-\tau_2}^{t-1} A(j, s). \quad (11)$$

The reputation of an enterprise can be described in terms of the number of R&D partnerships in the past. The more R&D partnerships an enterprise has, the more recognized by its peers and the more influence the enterprise has in the industry. Therefore, in the case of asymmetric market information, other enterprises are likely to choose R&D partners in the future. We define the company reputation of enterprise i as follows:

$$R(j, t, \tau_3) = \frac{1}{\tau_3} \frac{1}{n} \sum_{s=t-\tau_3}^{t-1} d_j(s). \quad (12)$$

On the basis of the preceding analysis, we set the probability that enterprise i desires to establish an R&D cooperation with enterprise j to be a linear combination of the previous history of enterprises i and j , the attractiveness of enterprise j , and the reputation of enterprise j , shown as follows:

$$P(i \rightarrow j, t) = \lambda H(i, j, t, \tau_1) + \mu A(j, t, \tau_2) + \nu R(j, t, \tau_3), \quad (13)$$

where $\lambda + \mu + \nu = 1$ and $\lambda, \mu, \nu \in (0, 1)$; these parameters measure the importance of previous history, attractiveness, and reputation when enterprises choose the R&D cooperation partner.

We avoid several extreme cases, such as $\lambda = 1$ by setting parameters $\lambda, \mu, \nu \in (0, 1)$ rather than $\lambda, \mu, \nu \in [0, 1]$; an enterprise that has an R&D partnership continues to do so for any extended period of time. The meanings and values of the above parameters are shown in Table 1.

We define that enterprise i is in R&D cooperation with enterprise j if and only if enterprise i desires to establish an R&D relationship with enterprise j and enterprise j hopes to establish R&D relationship with enterprise i . Thus, we have

$$P(i \leftrightarrow j, t) = P(i \rightarrow j \cap j \rightarrow i, t). \quad (14)$$

We have constructed the relationship between innovation research achievement and R&D network structure and described how companies create an R&D network in the next period on the basis of the attractiveness of other enterprises, previous history, reputation, and other factors for R&D cooperation decision-making. That is, we have described the intertemporal evolution mechanism of R&D cooperative network.

TABLE 1: Parameters used in the model.

Parameter	Interpretation	Constraints
α	Production rate of innovation R&D results	$\alpha \in [0, 1]$
ρ	Stock knowledge depreciation rate	$\rho \in (0, 1)$
θ	Positive effect of innovation diffusion	$\theta \in [0, \infty)$
γ	Cost of R&D collaboration	$\gamma \in [0, \infty)$
τ	Length of innovation diffusion and stock knowledge time window	$\tau \in \mathbb{N}$
τ_1	Length of previous history time window	$\tau_1 \in \mathbb{N}$
τ_2	Length of attractiveness time window	$\tau_2 \in \mathbb{N}$
τ_3	Length of reputation time window	$\tau_3 \in \mathbb{N}$
λ	Weight of previous collaboration in the probability to collaborate	$\lambda \in (0, 1)$
μ	Weight of attractiveness in the probability to collaborate	$\mu \in (0, 1)$
ν	Weight of reputation in the probability to collaborate	$\nu \in (0, 1)$

4. Computational Experiment

We set the number of agents N at 200 and the total evolutionary period T at 500. The time window of innovation diffusion and stock knowledge τ , previous history τ_1 , attractiveness τ_2 , and reputation τ_3 is set to 1. The initial stock knowledge of each agent is standardized and set to 1. Therefore, at the beginning of the evolution of enterprise R&D cooperative network, the agent's stock knowledge is homogeneous, whereas each agent's egocentric network is heterogeneous. However, with the intertemporal evolution of the R&D network, agents gradually evolve into heterogeneity in terms of stock knowledge and egocentric network.

4.1. Influence of Initial R&D Network Structure on R&D Innovation Evolution. We control other constant parameters and consider the evolution results under different initial R&D network structure to study the influence of initial R&D network structure on the intertemporal evolution of R&D network.

We choose the average degree as the control parameter for different initial R&D network structures. That is, we keep the average degree of various R&D networks at the same level and study the influence of initial R&D network structure on the evolution results. Concretely, the number of edges does not change after the random reconnection. Thus, we only need to control that the number of edges of the ring-rule network before the random reconnection is equal to the total number of edges in the corresponding random graph to control that the average degree of WS small-world network is the same as the random graph. Moreover, we only need to make $E_0 + mt$ equal to the number of edges generated in the corresponding random graph to control the average degree of BA scale-free network.

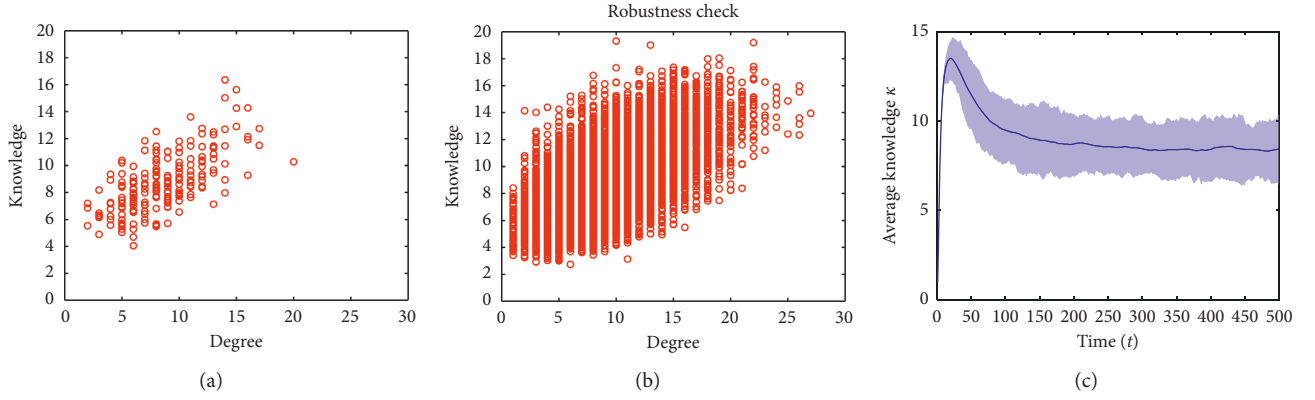
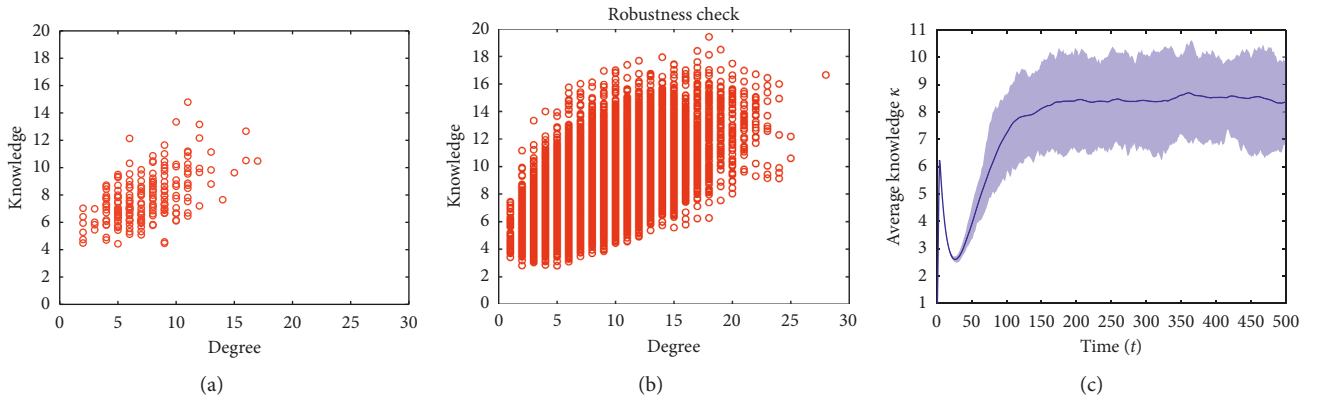
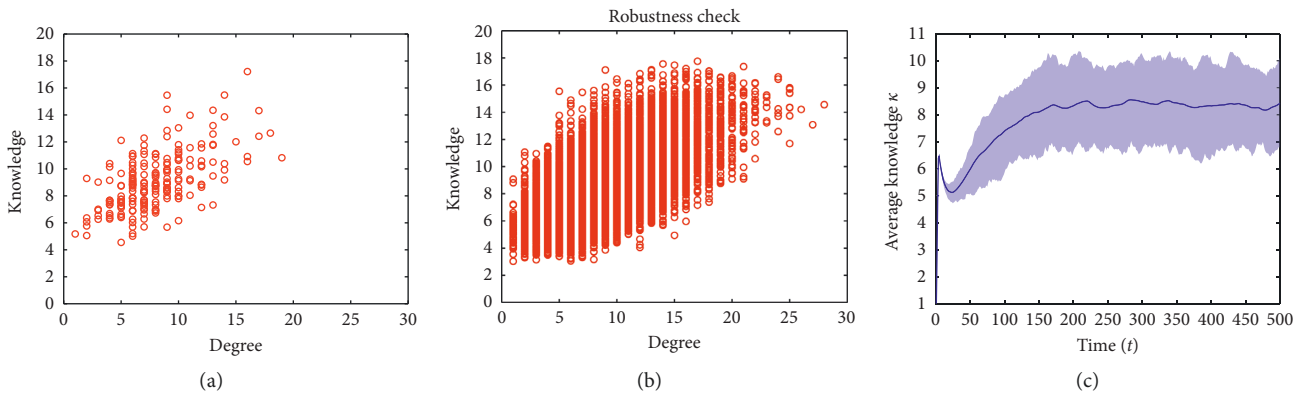
In each simulation, we use the algorithm as Section 2.1 explained, and we repeat the R&D network evolution 100 times to test the robustness of R&D network evolution results. Then, we draw the relationship between degree and stock knowledge of enterprise nodes at the end of each evolution period in the same graph and compare it with the standard results.

Figure 1 shows the R&D network intertemporal evolution results when the initial R&D network is a Erdos-Renyi random graph (connection probability $p = 0.1$). Figures 2 and 3 show the R&D network intertemporal evolution results when the initial R&D network is WS small-world network and BA scale-free network, respectively, with the same average degree as random graph. Figures 1(a), 2(a), and 3(a) show the relationship between the number of cooperation (measured by the degree of nodes) and stock knowledge of each enterprise when the R&D network evolution reaches the 500th phase. Each point represents an enterprise. In the figure above, other relevant parameters are set as follows, except for the general parameter setting described at the beginning of this section: $\lambda = 0.2$, $\mu = 0.3$, and $\nu = 0.5$.

Figures 1(b), 2(b), and 3(b) are the robustness check of Figures 1(a), 2(a), and 3(a), respectively, from which we can derive that the results of the cross-period evolution of repeated R&D network are relatively consistent with the specific evolution results in the corresponding (a). Therefore, the single evolution results are not the results of extreme cases but of generality; thus, they have the value of analysis.

Figures 1(c), 2(c), and 3(c) denote the average stock knowledge evolution characteristic of N enterprises when the initial network structures are Erdos-Renyi random graph, WS small-world network, and BA scale-free network, respectively, where the dark blue lines represent the average of 100 replicates and the light-colored areas represent the range of 95% of the observations. A comparison of Figures 1(c), 2(c), and 3(c) indicates that when the evolution period is considered sufficiently long, the evolution results of R&D network are the same regardless of the initial network structure. Figures 1(a), 2(a), and 3(a) show the relationship between enterprise degree and stock knowledge at the end of R&D network evolution under the three initial network structures. This result indicates that the stable state of R&D network evolution is not connected with the initial network structure.

However, although the final results of interperiod evolution of R&D network are independent of the initial R&D network structure, the average stock knowledge in the R&D network evolution shows great heterogeneity under different

FIGURE 1: Evolution result when the initial R&D network structure is a random graph ($p = 0.1$).FIGURE 2: Evolution result when the initial R&D network structure is a WS small-world network ($p = 0.1$).FIGURE 3: Evolution result when the initial R&D network structure is a BA scale-free network ($p = 0.1$).

initial network structures (Figures 1(c), 2(c), and 3(c)). Under the initial network structure of Erdos–Rényi random graph, the average stock knowledge of the enterprise initially increases to a maximum and then slowly declines to a stable state. In the situation wherein the initial network structure is WS small-world networks, the enterprise's average stock knowledge evolution is relatively complex, frequently changes, and increases or decreases at the early stage of the

evolution. We find that in the early evolution, the certainty of R&D network evolution is relatively high on the basis of the observation value range diagram. Therefore, under the initial R&D WS small-world network structure, the complexity of the network evolution characteristics is not caused by accidental factors but the nature of the WS small-world networks. Under the initial network structure of BA scale-free network, the intertemporal evolution of the average

stock knowledge of enterprises is similar to that of WS small-world network; however, the fluctuation range of the average stock knowledge at the early stage of evolution is small. Similarly, the 95% observation range graph can guarantee the robustness of this conclusion.

Figure 4 shows the R&D intertemporal evolution results in the initial R&D network for Erdos–Renyi random graph (connection probability $p = 0.2$). Figures 5 and 6 show the R&D intertemporal evolution results by controlling the average degree, in the situation wherein initial network structures are WS small-world network and BA scale-free network, respectively. Figures 4(a), 5(a), and 6(a) show the relationship between the amount of cooperation (measured by the degree of nodes) and the stock knowledge of each enterprise when the R&D network evolution reaches the 500th phase. Each point represents an enterprise. In the figure above, other relevant parameters are set as follows, except for the general parameter setting described at the beginning of this section: $\lambda = 0.2$, $\mu = 0.3$, and $\nu = 0.5$.

The combination of Figures 1(a)–6(a) and Figures 1(c)–6(c) indicate that the final result of intertemporal R&D network evolution is not connected with the initial R&D network structure. After a sufficiently long period of evolution, the joint distribution of degrees of enterprises and the stock knowledge will tend to be the same, which is same as the conclusion above (Figures 1–3).

A comparison of Figures 1 and 4, 2 and 5, and 3 and 6 indicates the relationship between the intertemporal evolution of the average stock knowledge of enterprises and the average degree of the network. In the Erdos–Renyi random graph initial R&D network, the evolution of enterprise average stock knowledge is in high homogeneity, the average degree is high, and the average peak value of the stock knowledge evolution will be high (Figures 1(c) and 4(c)). This result can be interpreted as the positive influence of cooperation on the R&D network. When the initial R&D network is a WS small-world network, the intertemporal evolution image of average stock knowledge is similar (Figures 2(c) and 5(c)); however, the higher the average degree is, the higher the peak and trough values will be. When the initial R&D is a BA scale-free network, the relationship between average stock knowledge of the evolution of intertemporal and the average degree is relatively complex; when the average degree increases, an extremely large increase in the evolution peak is evident, whereas the natural evolution of the trough is eliminated (Figures 3(c) and 6(c)). That is, we perform a simple analysis of the influence of the initial R&D network structure on the evolution path of the average stock knowledge.

The analysis shows that although the stable-state result of R&D network evolution is unrelated to the initial R&D network structure, the initial R&D network structure influences the evolution path of R&D network. Therefore, if the government wants to see the promotion effect of R&D cooperation on the total social innovation R&D results in the short term, then it should pay the corresponding cost to identify the current R&D network topology and further analyze and intervene in the network's evolution path. However, in the long run, the authorities should not focus on

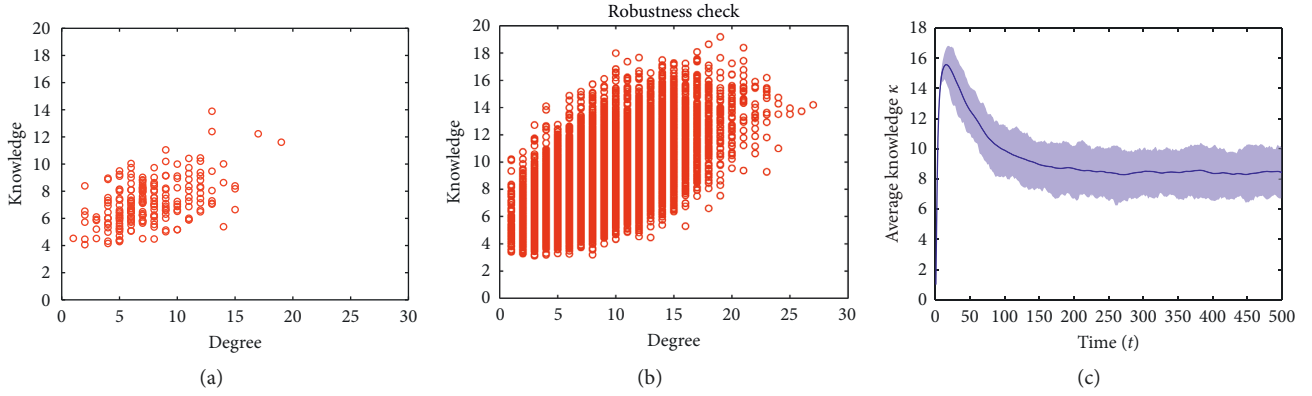
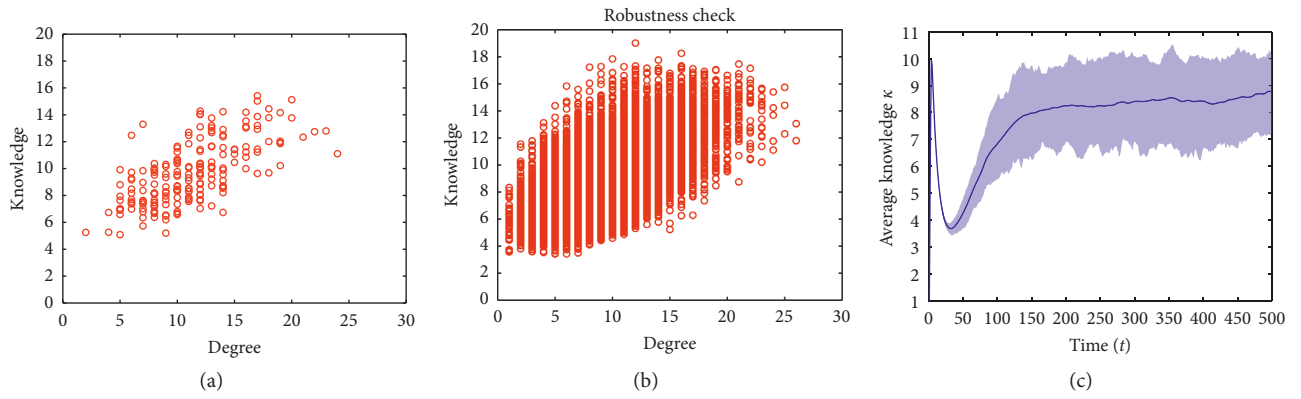
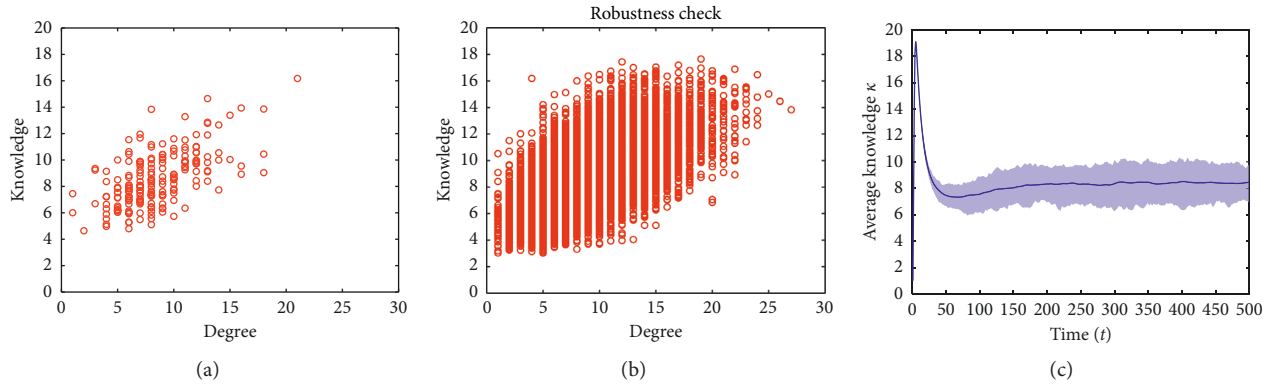
identifying the structure of the current R&D network, because the current R&D network structure will not have significant influence on the generation of innovative R&D results in the end (measured in terms of stock knowledge).

4.2. Influences of Parameters λ , μ , and ν on R&D Innovation Evolution. In this section, we focus on three parameters that set up the model, that is, the importance of previous history λ , of attractiveness μ , and of reputation ν in view of enterprises. We investigate how these parameters affect the stable state of enterprise R&D network evolution. Although the stable evolutionary state of the R&D network is independent of the topological structure of the initial R&D network, we choose the Erdos–Renyi random graph with connection probability $p = 0.1$ as the topological structure of the initial R&D network. In order to make sure the evolution has reached the steady state, according to the conclusion in Section 4.1, we assume that the evolution of innovation has reached the steady state when the step t is greater than 300, and the difference of total knowledge stock between t and $t - 1$ is small enough (for example, smaller than ε times total knowledge stock).

We make a certain evolutionary factor change under the control of the ratio of the determinants of the other two evolutionary processes to study the influence of a certain factor on the evolution result and investigate the stable state of the evolution of the R&D network. For example, we need to investigate certain characteristics of evolution results under different λ to consider the influence of enterprises' emphasis λ on previous history on intertemporal evolution results of R&D network. However, when λ changes, keeping μ and ν unchanged in the usual way of controlling variables is impossible because $\lambda + \mu + \nu = 1$. To solve this problem, we instead keep unchanged ratio μ/ν , which indicates the situation where the enterprise is deciding whether to establish R&D cooperation for attractiveness and reputation in proportion to the importance to keep the same situation before the change.

Figure 7 shows the influence of evolution parameters λ , μ , and ν on the steady-state evolution results of R&D network (mainly taking the average interenterprise stock knowledge as a measurement). When μ/ν is fixed, the average stock knowledge of the stable state of R&D network evolution decreases monotonously with the increase of λ (Figure 7(a)). With λ close to 1, the steady-state average stock knowledge is inclined to zero, which is consistent with the discussion in Section 3 regarding extreme cases. When $\lambda = 1$, the enterprise has a simple R&D cooperation decision-making mechanism. Which cooperation will continue to cooperation once, never cooperation will never cooperation. Therefore, the R&D network topology in the evolutionary process will not change. In this case, the cost coefficient, which resulted in the setting of parameters, such as each enterprise's innovation development, will gradually dissipate due to the diffusion coefficient of innovation.

When λ/ν is fixed, the average stock knowledge of the steady state of R&D network evolution increases monotonously with the increase of μ , and the increase rate of certain

FIGURE 4: Evolution result when the initial R&D network structure is a random graph ($p = 0.2$).FIGURE 5: Evolution result when the initial R&D network structure is a WS small-world network ($p = 0.2$).FIGURE 6: Evolution result when the initial R&D network structure is a BA scale-free network ($p = 0.2$).

parts rises significantly (Figure 7(b)). When μ is inclined to zero, the steady-state average stock knowledge is also inclined to zero regardless of the value of λ/ν (Figure 7(b)). This result indicates that if the enterprise's decision-making level of considering attractiveness when choosing R&D partners is gradually reduced to zero, then it is now considering the main reputation or any previous history, which will lead to the depletion of stock knowledge, thereby decreasing the innovative R&D output. This finding shows that attractiveness is a rational decision indicator in selecting R&D partners and

suggests that if the government wants to promote the development of a certain industry of the entire industry technology innovation level, then it should strengthen the information disclosure level, encourage enterprises to learn and evaluate one another with regard to the amount of R&D innovation, and promote R&D cooperation rationally. This approach will aid knowledge fusion and innovation R&D and thus promote the welfare of the entire society.

The stable-state average stock knowledge of R&D network evolution changes in a complicated manner with the

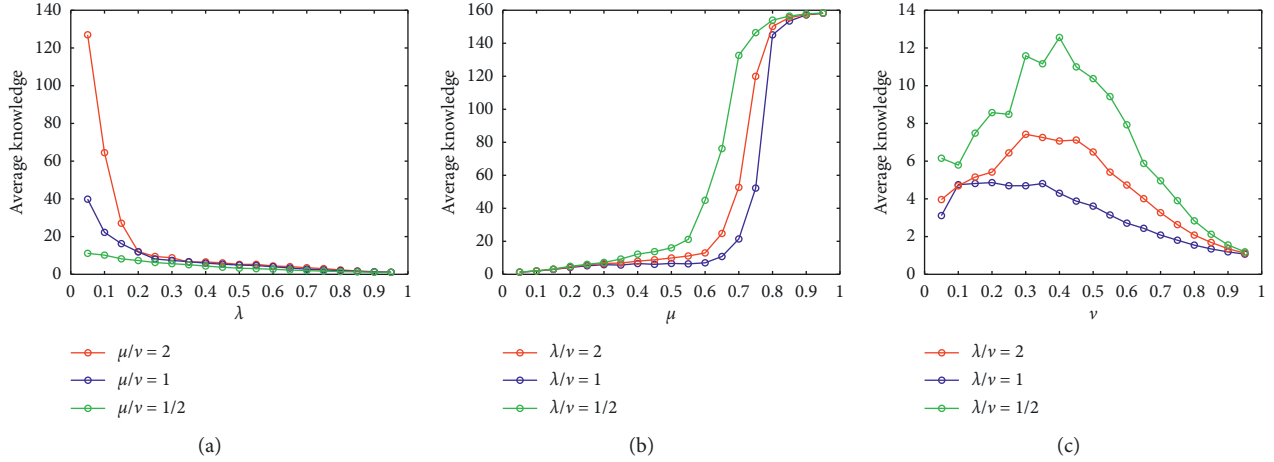


FIGURE 7: Influence of evolution process parameters λ , μ , and ν on the steady state of R&D network evolution.

increase of ν (Figure 7(c)). When λ/μ is fixed, the change mode of the average stock knowledge in stable state is not monotonous as ν increases. Meanwhile, when λ/μ changes, the average stock knowledge in a stable state presents high heterogeneity along with the change curve of ν , that is, the extreme value and the extreme point change. Moreover, when ν is inclined to 1, the steady-state average stock knowledge gradually converges to 1, which has policy implications. This result shows that if the innovative R&D-related information disclosure is completely opaque, then enterprises can only rely on reputation for an R&D partner selection decision, and the worst result will not lead to the attenuation of stock knowledge, which can ensure that innovation efficiency is higher than a certain lower limit.

5. Conclusion

Cooperation plays an irreplaceable role in knowledge creation and innovation. The cooperative relationship among enterprises forms a complicated R&D network, and the topology of the R&D network has an obvious regulatory effect on the innovation performance of enterprises. The intertemporal evolution of R&D network and the mutual influence of stock knowledge are complex. The innovation R&D achievements of enterprises are affected by the spill-over effect of innovation diffusion of other enterprises in the R&D network. Meanwhile, the complex mechanism of enterprises that choose R&D partners determines the complexity of R&D network evolution.

This study constructs an intertemporal evolution model of enterprise R&D cooperation network on the basis of complex network theory and evolutionary economics. It considers the complexity of enterprises that make R&D cooperation strategies and the complex influence of the resulting R&D network on the innovation and research performance of enterprises. The innovation rate and research achievements of an enterprise are positively correlated with the stock knowledge of the enterprise and is affected by the innovation diffusion effect of other enterprises in the R&D network that have cooperative relationship with it. In addition, the cost of R&D cooperation increases with the amount of cooperation.

Enterprises mainly consider three factors in selecting R&D partners, namely, cooperation history, corporate attractiveness, and corporate reputation. Our model is composed of the method by which enterprise innovation R&D results depend on the R&D network structure and the method wherein R&D network structure evolves according to the innovation R&D results of each enterprise.

From the simulation of the model built in this study, we draw the following main conclusions. (1) When the R&D network evolution reaches a stable state, the joint distribution of stock knowledge and cooperative number is not connected to the initial R&D network topology. However, the specific R&D network evolution path is affected by the initial R&D network topology. (2) Among the three factors considered in the enterprise's decision to establish an R&D cooperative relationship, if the cooperation history is highly valued, then the steady-state average stock knowledge will be gradually exhausted; if corporate reputation is highly valued, then the average steady-state stock knowledge is always above a certain threshold; if the attractiveness of enterprises is highly valued, then the average steady-state stock knowledge can rise to a higher level. This finding suggests that if enterprises want to promote the level of scientific and technological innovation in the entire industry, then they should promote the level of innovation-related information disclosure. In this manner, enterprises can choose R&D partners on the basis of the attractiveness of enterprises rather than cooperation history and corporate reputation.

The study of this paper shows that corporate reputation, as an irrational evaluation factor, can often play a role of correct investment guidance, especially in the case of serious information asymmetry, which becomes a supplement to this series of literatures. The possible direction in the future is to continue to consider how information asymmetry affects enterprises' R&D decisions.

Data Availability

The method in this article is computer mathematical simulation. Numerical simulation analysis is the most effective way to test real-time dynamic data without a large number of

empirical validations. The authors simulate to explore the evolution characteristics of enterprise R&D network in different initial R&D network topology structures by using Matlab 2016b software. This paper does not have the data that can be obtained because they directly use the plot function of Matlab 2016b software to make the images.

Conflicts of Interest

The authors declare that they have no competing interests.

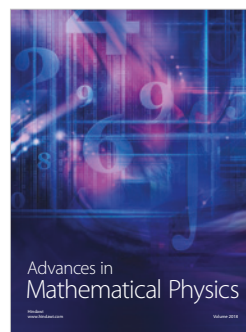
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