How Does the R&D Cooperation Path of Supply and Demand Network Enterprises Evolve?

JIANJIA HE, JUSHENG LIU, ZHIPING QIU, NGAYUA ESTHER NANZAYI, AND MIN ZHANG

1Business School, University of Shanghai for Science and Technology, Shanghai 200093, China
2Super Network Research Center (China), Shanghai 200093, China
3Shanghai Institute of Public Diplomacy, Shanghai 200093, China
4School of Information Management and Engineering, Shanghai University of Finance and Economics, Shanghai 200433, China
5School of Urban and Regional Science, Shanghai University of Finance and Economics, Shanghai 200433, China
6Laboratory Center, Shanghai University of Finance and Economics, Shanghai 200433, China
7Shanghai Financial Intelligent Engineering Technology Research Center, Shanghai University of Finance and Economics, Shanghai 200433, China

Corresponding authors: Jusheng Liu (jusheng.liu@163.sufe.edu.cn) and Ngayua Esther Nanzayi (esthernanzayi@yahoo.com)

This work was supported in part by the National Natural Science Foundation Project under Grant 71871144, in part by the Science and Technology Development Program of University of Shanghai for Science and Technology under Grant 2020KJFZ046, in part by the Project of Shanghai Financial Intelligent Engineering Technology Research Center under Grant 19DZ2254600, and in part by the Shanghai University of Finance and Economics Graduate Innovation Fund under Grant CXJJ-2019-400 and Grant CXJJ-2020-306.

ABSTRACT To explore the complexity and uncertainty of R&D cooperation in supply and demand network (SDN) enterprises, this study used the evolutionary game theory and the duplicate dynamic equation to construct the R&D cooperation strategy selection model. Based on the perspective of knowledge spillover, the model investigated the influence of knowledge spillover, government reward, government penalty, cooperative cost, and R&D cooperation risk in the cooperation of SDN enterprises. Next, this study analyzed the stability and the system evolution path of the model. Finally, it used numerical simulation to vary the rationality of the model. Based on this research, there are some conclusions can be obtained: Firstly, the evolution of R&D cooperation strategy for SDN enterprises may eventually stabilize at cooperation or selfishness strategy under different situations. Secondly, there are two stable states in the game system: cooperation and selfishness. If one party chooses cooperation and the other party chooses selfishness, the system will not be stable. Thirdly, knowledge spillover degree, government reward, government penalty, government penalty, cooperation cost, and cooperation risk are important factors that can influence the cooperation evolution of SDN enterprises. Fourth, under certain situations, if knowledge spillover degree, government reward, government penalty increase, cooperation cost and cooperation risk decrease, the R&D cooperation in SDN enterprises will be improved. Related implications and suggestions are finally proposed, which can offer some valuable guidance for the development of SDN enterprises.

INDEX TERMS Supply and demand network, knowledge spillover, R&D cooperation, evolutionary game theory, business management.
structure is a single chain structure, the whole supply chain’s risk depends on a single enterprise; if one fails, the game is lost. Based on this, the supply and demand network (SDN) management model based on global manufacturing, global production, global sales, and global win-win has gradually become the goal that is pursued by most enterprises [1]. The SDN enterprise includes the following five characters: (1) Network nature. The supply demand network is different from the supply chain. SDN is a network structure, not a chain in the network structure, and every enterprise has an equal partnership. There is no core node here, and the node has multiple meanings: it can be an enterprise or an independent economic man. (2) Multifunctionality. Excluding the logistics function in the supply chain, the SDN better considers other supply and demand flow functions, such as technology, capital, management, information, talent, facilities, and corporate culture. These supply and demand flows can also interact to realize the integration function of “1 + 1 > 2”. Among them, information flow, as the most active factor in the supply and demand flow, reflects the strong information interaction capacity of the whole supply and demand flow. At the same time, the multi-functionality of SDN is also reflected in the level of interaction between supply and demand enterprises, such as raw materials and products, system and technology, and business philosophy. (3) Openness. The SDN is an open and complex system that emphasizes global full cooperation and win-win situations, other than internal cooperation and external competition. (4) Dynamic stability. Because of the network structure, the SDN enterprises will carry out the cooperation based on multiple flows such as technology, capital, management, information, talent, facilities and corporate culture. If one flow breaks, other flows can work well. Therefore, the SDN has dynamic stability. Since the SDN concept was proposed, it has been applied to many fields such as enterprise reverse logistics, enterprise knowledge modeling, mass customization, and JIT purchase. At present, some scholars have explored topics such as role-facing modelling, workflow analysis [1], food SDN [2], and dynamic matching operation in SDN [3]. However, fewer scholars explored R&D cooperation behavior in SDN enterprise. In SDN enterprise, the cooperation between SDN enterprises always flows along with knowledge spillover. Thus, based on knowledge spillover, it is significant and valuable to explore the R&D cooperation in SDN enterprises.

Evolutionary game theory is a tool that can explore evolutionary trends and can also imitate the population’s strategy evolution and guide the next strategy. According to the behavior of both sides in the game, existing researches have divided the game-type into five types: direct reciprocity, indirect reciprocity, kin selection, group selection and network reciprocity [4]–[6]. These types can be converted mathematically into a $2 \times 2$ payoff matrix. Later, according to different benefits and game relations of both sides in the game, scholars proposed several classical dilemma games to explain different social viscosity, such as prisoner’s dilemma game, chicken game(hawk-dove game or snowdrift game) and stag-hunt game [7], [8]. In nature and human activities, direct reciprocity and indirect reciprocity are the footstone of cooperation. Kin selection, group selection and network reciprocity are the accelerators of the cooperation. When the probability of two individuals meeting again is higher than the cost-benefit ratio of selfless behavior, direct reciprocity can lead to the evolution of cooperation. Indirect reciprocity pays more attention to a reputation mechanism, although one person perhaps not obtain direct benefit from another, he/she can obtain benefit from another person’s reputation, it is also a way to improve cooperation. As for as kin selection, group selection or network reciprocity, it is a manifestation of group cooperation and the result of the nature selection. In these cooperation, people are willing to sacrifice some personal interests to maximize the interests of the group.

At present, scholars have used evolutionary game theory to explore many fields, such as Physics [9], [10], Biology [11], Economics [12], Sociology [13], and Management [10], [14]–[16]. Specifically, Zhang et al. [17] used the method of evolutionary game analysis and simulation with system to explore the manufacturer’s emissions abatement behavior under cap-and-trade regulation. Liu et al. [18] used evolutionary game theory to research the relationship between doctor and the patient. Brandt and Svendsen [19] used an evolutionary game model to explore the free riding behavior and reciprocal behavior in the welfare state. Zhang et al. [20] used game-based theory to build an evolutionary game model of technology diffusion between enterprises under background of complex network. Boris et al [21] investigated the relationship between cooperation and selfishness in human society and found that punishment can make the system more cooperative. Croll et al. [22] explored the eco-evolutionary feedback loop between populations based on the evolutionary game theory. Li et al. [23] explored prisoner’s dilemma game with two kinds of relations in the network and found that when initial network structure is heterogeneous, cooperation can be effectively promoted. In addition, some scholars have also explored factors that affect human cooperation based on evolutionary game theory, such as the reputation mechanism [24] and moral hazard [25]. Furthermore, some researchers investigated cooperation and trust in social activity based on game theory. In particularly, Matjaž et al. [26] carried out a comprehensive exposition discussion on the cooperation of human beings based on statistical physics. Kumar et al. [27] explored the evolution of trust and trustworthiness based on a game model. Fang et al. [28] discussed the cooperation and anti-corruption in public goods dilemmas with benevolent leaders and bribery. Fang et al. [29] explored evolution of cooperation in the spatial public goods game under the background of third-party rewarding and punishment. Besides, some scholars also explored three-party game model and multi-party game model.

Although scholars have carried out lots of work based on evolutionary game theory, few scholars use game theory to explore the R&D cooperation in the SDN enterprises.
Based on this, we use the evolutionary game theory to explore the R&D cooperation from knowledge spillover. We hope to provide some suggestions to improve the cooperation level between SDN enterprises. In this paper, we mainly solve the following problems: (1) What’s the relationship in the process of R&D cooperation between SDN enterprises from knowledge spillover? Cooperation or the selfishness?
(2) How does the strategy path evolve in R&D cooperation in SDN enterprises?
(3) How can the R&D cooperation be boosted in SDN enterprises?

To explore above problems, this research build an evolutionary game model from knowledge spillover, government reward, government penalty, cooperation cost and cooperation risk. It uses the duplicate dynamic equation to analyze the evolution process. Finally, this study uses the numerical simulation to analyze the related factors that can affect the model’s stability. This study is organized as follows: Section 2 is literature review. In section 3, some assumptions are made, and the evolutionary game theory model of the R&D cooperation is built. Section 4 includes numerical simulation and analysis. In section 5, we obtain some conclusions and put forward some suggestions to the related departments.

II. LITERATURE REVIEW

In this part, we comb the relevant literature around R&D cooperation in enterprises and knowledge spillover between enterprises.

A. R&D COOPERATION IN ENTERPRISES

With the rise of collaborative innovation, institutional innovation, and knowledge innovation, cooperation in Research and Development (R&D) has gradually become an important cooperation that seriously affects enterprises’ sustainable development. At present, the traditional single closed independent R&D production model has struggled to meet the needs of enterprise development. The “one big” management model can’t adapt to rapid market environment. Collaborative innovation, research, and development have become a sustainable way to achieve success. Therefore, it is necessary to build a multi-functional and open supply and demand integrated dynamic network management model based on the “supply and demand flow”. This model is called the multi-functional open enterprise supply and demand network, and it can be abbreviated as SDN. Under the background of collaborative innovation, SDN enterprises and other entities have formed a large-span innovative organizational model for major technological innovations, including specialized research institutions, various universities and some high-tech enterprises. Among them, enterprises provide technology, universities provide talent, and research institutions provide policy consultation. Under the interaction of various supply and demand flows, multiple cooperative entities have formed a multi-functional open enterprise supply and demand network. In SDN enterprises, R&D is necessary to the whole organization. At present, scholars have done some researches on R&D. David et al. [30] explored the relationship between public R&D and private R&D. Cristina et al. [31] examined gender diversity impact on radicalness of innovation in R&D teams; Ying [32] explored how to manage knowledge in the process of the R&D enterprise effectively. Michelino et al. [33] investigated the relationship between the adoption of open innovation, internal R&D, and financial performances, and they considered that internal R&D is complementary to openness. Nishimura and Okamuro [34] examined the spillover effects of government-sponsored R&D consortia, they found that only large firms can obtain the benefit from knowledge spillover in the R&D consortia. Xu et al. [35] estimated the relationship among the enterprise’s total factor productivity (TFP), R&D expenditures and financial constraints. Zhao and Song [36] hold that R&D investment can significantly promote regional economy growth when the enterprise has a high production efficiency level, technological level, and knowledge storage. Meanwhile, Schlapp et al. [37] discussed how to balance the individual and shared incentives in enterprise R&D projects. Besides, some scholars explored the university’s role in R&D cooperation, enterprise’s innovation practices [38], R&D production and knowledge commercialization [39]. The aforementioned research discussed some phenomena and patterns in the R&D, such as knowledge management, R&D expenditures, R&D investment, and individual and shared incentives as well as the university’s role in R&D. However, few researchers use dynamic methods such as evolutionary game theory to explore cooperative behavior among different subjects. In fact, dynamic cooperation behavior has an important role in R&D cooperation, and how to improve R&D cooperation in SDN enterprises is important to enterprise’s development.

B. KNOWLEDGE SPILLOVER BETWEEN ENTERPRISES

Knowledge is a structured experience, textual information, and expert insights in the corporate cooperation activities, and it bears the role of information interaction and value-added production. When R&D activities are carried out in SDN enterprises, enterprises cooperate on various supply and demand flows such as capital, technology, information, management, and experience. Cooperation is often accompanied by mutual interaction and overflow of knowledge, and knowledge overflow further promotes cooperation between two parties. In the process of cooperation, as one of the main concept, knowledge spillover plays an important role in the process of corporate R&D cooperation. In terms of knowledge spillover, some scholars have recently discussed it from different perspectives. Considering that most research focuses on the explicit knowledge spillover and fewer scholars have researched tacit knowledge spillover, Suntie [40] discussed knowledge spillover based on companies’ innovation activities. Samuli [41] found that extent of spillover and industry’s R&D efficiency can result in higher levels of effective R&D. Mastromarco et al. [42] considered that knowledge spillover was more likely to be induced by...
technological proximity. Li et al. [43] found that when enterprises’ technology gap was small, the enterprise could absorb the spillover knowledge and obtain the relevant benefits. Foster-Mcgregor and Pöschl [44] found that the technology level of the giving industry is related to the spillover effects, and it is easier to improve knowledge spillover in high-tech and medium-tech contexts. Chalioti [45] hold that no matter the internal or external spillover, knowledge spillover also has a positive role on R&D and innovation. Furthermore, scholars have also explored technology spillover [46], risk spillover [47], and spatial spillover [48]. These researches explored knowledge spillover from different perspectives, but few scholars have explored knowledge spillover between enterprises from a dynamic perspective.

III. BASIC ASSUMPTIONS AND MODEL CONSTRUCTION

A. THE THEORY OF SUPPLY AND THE DEMAND NETWORK

At the beginning of the 21st century, American scholar Bovet proposed the value net theory in his book “ValueNets” [49]. In the book, the author elaborated on the following five key elements: value positioning, business scope, profit capture, strategic control, and implementation design. From the connotative perspective of the five major elements, the value network theory has not fundamentally changed the supply chain’s structure. Based on value network theory, subsequent scholars put forward the concept of collaborative supply chain management. They believe that collaborative supply chain management can be summarized as based on a collaborative mechanism, supported by collaborative technology, based on information sharing, and starting from a holistic system view. It can promote the coordinated development of internal and external supply chain enterprises, improve the overall competitiveness of the supply chain, and maximize the entire supply chain’s value. These theories have further enriched the connotation and extension of supply chain management. In recent years, with the spread of economic globalization and risk globalization, the traditional single chain production method has become increasingly difficult to adapt to rapidly developing market demand. It is a collection of global resource acquisition, global manufacturing, and global sales based on the interaction of supply and demand flows. The role of multifunctional open supply and demand integrated dynamic network management model, namely, the multifunctional open supply and demand network (Supply and Demand Network of enterprise with multifunctional and opening characteristics, referred to as supply and demand network or SDN) came into being. As a multi-functional and open complex network system, the supply and demand network has a huge impact on business management since its proposal by Chinese scholar Xu Fuyuan in 2002. Scholars have conducted extensive research on the cooperation mechanism, evolution mechanism, and operation mechanism from different aspects. The specific structure model is shown in Figure 1.

In Figure 1, the main body of cooperation in the supply and demand network is not limited to traditional enterprises but rather extends to enterprise alliances and economic people with dual nature of supply and demand. These entities carry out cooperative activities on the information platform based on a variety of supply and demand qualities such as material, information quality, technical quality, capital quality, talent quality, and management quality. The scope of cooperation is wider than that of traditional supply chain cooperation. Cooperation is more complicated. The specific performance is that the main body of supply and demand can compete with each other in products but cooperate with each other technically, sometimes, it can compete with each other technically but cooperate with each other in terms of talents. “All visitors are customers” is SDN enterprises’ cooperative concept, thus, the enterprise cooperation behavior at the supply and demand network level is more complicated than traditional enterprise cooperation.

B. BASIC ASSUMPTIONS

In the process of cooperative activities between two parties, one of them may choose cooperative strategy for joint research and development to achieve integration effect of “1 + 1 > 2”, or one may be subject to bounded rationality and selfishness may choose selfish strategy to obtain more benefit. From the perspective of knowledge spillover, how do the SDN enterprises select a strategy in the R&D cooperation process between SDN enterprises, the cooperation strategy or the selfishness strategy? How does the strategy path evolve? To clarify the problem boundary, the following assumptions are made:

1) HYPOTHESIS 1

In the process of cooperation between SDN enterprises, we assume that the partners’ strategy choices of the partners are cooperation and selfishness. If the SDN enterprise i chooses the cooperation strategy, the probability is \( x \); if it
chooses the selfishness strategy, the probability is \(1 - x\). If the SDN enterprise \(j\) chooses the cooperation, the probability is \(y\); if it chooses the selfishness strategy, the probability is \(1 - y\), \(x, y \in [0, 1]\).

2) HYPOTHESIS 2
We assume that the total amount of knowledge resources invested by the SDN enterprise \(i\) and \(j\) in the cooperation process is \(\Lambda_i\) and \(\Lambda_j\) respectively. \(\Lambda_i, \Lambda_j > 0\), and the SDN enterprises \(i\) and \(j\) can obtain some profit \(M_i\) and \(M_j\) in the cooperation process. We also assume that the profit coefficients of SDN enterprises \(i\) and \(j\) are \(\alpha_i\) and \(\alpha_j\), \(\alpha_i, \alpha_j > 0\), so \(M_i = \alpha_i \Lambda_i\), \(M_j = \alpha_j \Lambda_j\). In the process of cooperation, due to the incompleteness of information and the uncertainty of people’s behavior, as well as the existence of factors such as “incomplete information market”, “animal spirit” and “herd effect”, it often causes rational expectation failure, which makes cooperation between enterprises have certain market risks. In addition, because the risk of cooperation between two enterprises is affected by the benefits of cooperation, so we can assume that the coefficients of cooperation risk between two enterprises are \(\lambda_i\) and \(\lambda_j\), and the cooperation risks are \(E_i\) and \(E_j\); then \(E_i = \lambda_i \Lambda_i = \lambda_i \alpha_i \Lambda_i\), and \(E_j = \lambda_j \Lambda_j = \lambda_j \alpha_j \Lambda_j\).

3) HYPOTHESIS 3
We assume that the cooperation costs of the two parties in the R&D cooperation process are \(C_i\) and \(C_j\) respectively, and the cost coefficients of two parties are \(\gamma_i\) and \(\gamma_j\); then \(C_i = \gamma_i \Lambda_i\), and \(C_j = \gamma_j \Lambda_j\). If two enterprises choose the selfishness strategy, we assume that the revenues obtained by the SDN enterprises \(i\) and \(j\) are \(\Pi_i\) and \(\Pi_j\) respectively.

4) HYPOTHESIS 4
In the process of cooperation, if one party chooses the cooperation strategy and the other party chooses the selfishness strategy, because the cooperation party does not retain its own knowledge input, the selfishness party will receive all of the other party’s knowledge input. However, the cooperation party has the knowledge input, but the selfishness party does not input the knowledge, so in this moment limited knowledge transfer will occur, that is, knowledge spillover will occur. Therefore, it can be assumed that \(\beta_i\) is the knowledge spillover coefficient of enterprise \(i\); it indicates the capability of knowledge spillovers from enterprise \(i\) to enterprise \(j\), whereas \(\beta_j\) is the knowledge spillover coefficient of enterprise \(j\), which indicates the capability knowledge spillovers from enterprise \(j\) to enterprise \(i\). The knowledge spillover coefficient reflects the knowledge transfer between innovation subjects.

5) HYPOTHESIS 5
To make sure that the knowledge spillover can continue sustainably, we assume that a government supervision department can punish companies and let them pay for the penalty \(D\) if they do not carry out knowledge spillovers. The government penalties are \(D_i\) and \(D_j\), and it also can give reward \(W\) to motivate enterprises to engage in knowledge spillovers, so that the government rewards for the SDN enterprises are \(W_i\) and \(W_j\).

To make the problem and parameters clearer, the related parameter settings and meaning are shown in Table 1.

C. MODEL CONSTRUCTION
In nature, the cooperation is a dynamic game process in an uncertain and bounded rational situation. Their strategies are influenced by the last game strategy’s inheritance and dynamic adjustment. In the process of a group evolution game, replicator dynamics equation can describe the dynamic competition process of population strategy selection. The basic form can be expressed as follows:

\[
F(x) = \frac{d \tilde{x}}{d t} = x [u_n(x) - \bar{u}] \quad (1)
\]

As shown in formula (1), \(x\) indicates the proportion of the strategy adopted in the population; \(u_n\) is the expected return of the strategy adopted by the player \(n\); and \(\bar{u}\) is the average return of the strategy adopted by the player \(n\). Based on the above assumptions, combined with the basic concept of duplicate dynamic equations, the payment matrix of SDN enterprises is shown in Table 2.

According to the payment matrix of Table 2, if the SDN enterprise \(i\) chooses the cooperation strategy, the expected profit is \(\tau_{i1}\):

\[
\tau_{i1} = y(\Pi_i + \alpha_i \Lambda_i - \gamma_i \Lambda_i + W_i) + (1 - y)(\Pi_i - \gamma_i \Lambda_i + W_i - \lambda_i \alpha_i \Lambda_i) \quad (2)
\]

If the SDN enterprise \(i\) chooses the selfishness strategy, the expected profit is \(\tau_{i2}\):

\[
\tau_{i2} = y(\Pi_i + \beta_i \Lambda_j - D_i) + (1 - y)\Pi_j \quad (3)
\]

If the SDN enterprise \(i\) chooses the cooperation and selfishness strategy, the expected profit is \(\tau_{1}\):

\[
\tau_1 = x \tau_{i1} + (1 - x)\tau_{i2} = x[y(\Pi_i + \alpha_i \Lambda_i - \gamma_i \Lambda_i + W_i) + (1 - y)(\Pi_i - \gamma_i \Lambda_i + W_i - \lambda_i \alpha_i \Lambda_i)] + (1 - x)[y(\Pi_i + \beta_i \Lambda_j - D_i) + (1 - y)\Pi_j] \quad (4)
\]

The duplication dynamic equation of the SDN enterprises \(i\) in the process of cooperation between the two parties is \(f(x)\):

\[
f(x) = \frac{dx}{dt} = x(1 - x)[y(\alpha_i \Lambda_i - \beta_i \Lambda_j + D_i + \lambda_i \alpha_i \Lambda_i) + W_i - \gamma_i \Lambda_i - \lambda_i \alpha_i \Lambda_i] \quad (5)
\]

If the SDN enterprise \(j\) chooses the cooperation strategy, the expected profit is \(\tau_{2}\):

\[
\tau_{21} = x(\Pi_j + \alpha_j \Lambda_j - \gamma_j \Lambda_j + W_j) + (1 - x)(\Pi_j - \gamma_j \Lambda_j + W_j - \lambda_j \alpha_j \Lambda_j) \quad (6)
\]

If the SDN enterprise \(j\) chooses the selfishness strategy, the expected profit is \(\tau_{22}\):

\[
\tau_{22} = x(\Pi_j + \beta_i \Lambda_i - D_j) + (1 - x)\Pi_j \quad (7)
\]
If the SDN enterprise \( j \) chooses the cooperation and selfishness strategy, the expected profit is \( \bar{\tau}_2 \):

\[
\bar{\tau}_2 = y\tau_{21} + (1 - y)\tau_{22} = y[x(\Pi_j + \alpha_i\Lambda_j - \gamma_j\Lambda_j + W_j) + (1 - x)(\Pi_j - \gamma_j\Lambda_j + W_j - \lambda_j\alpha_j\Lambda_j)] + (1 - y)[x(\Pi_j + \beta_i\Lambda_i - D_j) + (1 - x)\Pi_j]
\]

(8)

The duplicate dynamic equation of the SDN enterprises \( j \) is \( f(y) \):

\[
f(y) = \frac{dy}{dt} = y(1 - y)[x(\alpha_i\Lambda_j - \beta_i\Lambda_i + D_j + \lambda_j\alpha_j\Lambda_j) + W_j - \gamma_j\Lambda_j - \lambda_j\alpha_j\Lambda_j]
\]

(9)

By combining (5) and (9), two-dimensional dynamic equations can be constructed. By solving the two-dimensional dynamic equations, we can obtain 5 equilibrium solutions. They are \( S(0, 0) \), \( K(0, 1) \), \( I(1, 0) \), \( M(1, 1) \), and \( P(x, y) \),

\[
x = \frac{y\gamma_j\Lambda_j + \lambda_j\alpha_j\Lambda_j - W_j}{\alpha_i\Lambda_i + \lambda_j\alpha_j\Lambda_j - \beta_i\Lambda_i + D_j}, \quad y = \frac{y\gamma_j\Lambda_j + \lambda_j\alpha_j\Lambda_j - W_j}{\alpha_i\Lambda_i + \lambda_j\alpha_j\Lambda_j - \beta_i\Lambda_i + D_j}.
\]

Further, we calculate the Jacobian matrix of two-dimensional dynamic equations as (10), shown at the bottom of the page.

According to the Jacobian matrix, we can obtain the \( Tr J \) and \( Det J \) of Jacobian matrix at each equilibrium point, and the specific result is shown in Table 3.

According to the results of Table 3 and the value of initial parameters, the system’s evolution path can be divided into 3 situations:

(1) \( \alpha_i\Lambda_i + \lambda_j\alpha_i\Lambda_j - \beta_i\Lambda_j + D_i > 0, \gamma_j\Lambda_j + \lambda_j\alpha_j\Lambda_i - W_i < 0, \alpha_j\Lambda_j + \lambda_j\alpha_j\Lambda_j - \beta_j\Lambda_j + D_j > 0, \gamma_i\Lambda_i + \lambda_i\alpha_i\Lambda_j - W_j < 0 \), that is \( x < 0, y < 0 \). At this moment, there are 4 equilibrium points in the system. The stability of the Jacobian matrix at each equilibrium point is shown in Table 4.

In Table 4, we can see that there are 4 equilibrium points in the system: Two saddle points \( K(0, 1), I(1, 0) \), one unstable points \( S(0, 0) \) and one stable point \( M(1, 1) \). The unstable
point $S(0, 0)$ will move to $M(1, 1)$ by the path $SKM$ or $SIM$, and the system’s strategy will transform from selfishness to cooperation. 

(2) $0 < y_{ij} < y_{ij} + \lambda_{ij} - \lambda_{ij} + y_{ij} < y_{ij} + \lambda_{ij} - \lambda_{ij} + y_{ij}$, $0 < y_{ij} < y_{ij} + \lambda_{ij} - \lambda_{ij} + y_{ij} < y_{ij} + \lambda_{ij} - \lambda_{ij} + y_{ij}$, that is $0 < x < 1$. At this time, there are 5 equilibrium points in the system. The stability of the Jacobian matrix at each equilibrium point is shown in Table 5.

Table 5. Stability of Jacobian matrix at each equilibrium point under situation 2.

| Equilibrium point | Det J | Tr J | Stability  |
|-------------------|-------|------|------------|
| $S(0, 0)$         | $+$   | $+$  | Unstable   |
| $K(0, 1)$         | $-$   | $+$  | Saddle point |
| $I(1, 0)$         | $-$   | $+$  | Saddle point |
| $M(1, 1)$         | $+$   | $-$  | ESS        |
| $P(x, y)$         | $-$   | $-$  | Saddle point |

In Table 5, we can see that there are 5 equilibrium points in the system: Two unstable points $K(0, 1)$ and $I(1, 0)$, two stable points $S(0, 0)$ and $M(1, 1)$, and one saddle point $P(x, y)$. At this moment, the system’s strategy will stabilize at $K(0, 1)$ and $I(1, 0)$ will move to (0, 0) or $M(1, 1)$. As for stabilizing at which point, it depends on the initial value of $x$ and $y$. If $x < \frac{1}{2}$, $y < \frac{1}{2}$, the final strategy will move to cooperation, if $x = \frac{1}{2}$, $y = \frac{1}{2}$, the final strategy will move to cooperation or selfishness, if $x > \frac{1}{2}$, $y > \frac{1}{2}$, the final strategy will move to selfishness.

In order to show the system’s evolution path of the system more clearly, the system’s path evolution simulation results under the situation 1, situation 2, and situation 3 are shown in Figure 2.

As show in Figure 2, five figures indicate the system’s path evolution simulation result. In Figure 2(a), the system’s final evolution result will stabilize at $M(1, 1)$ under situation 1. Under situation 2, when $x < \frac{1}{2}$, $y < \frac{1}{2}$, the system’s final evolution result will stabilize at $S(0, 0)$ and the system’s final strategy will stabilize at cooperation strategy in Figure 2(b). When $x = \frac{1}{2}$, $y = \frac{1}{2}$, the system’s final evolution result will stabilize at $S(0, 0)$ or $M(1, 1)$; at this moment, the system’s strategy will stabilize at selfishness or cooperation in Figure 2(c); when $x > \frac{1}{2}$, $y > \frac{1}{2}$, the system’s final evolution result will stabilize at $S(0, 0)$, at this moment, the system’s strategy will stabilize at selfishness in Figure 2(d). In Figure 2(e), the system’s final evolution result will stabilize at $M(0, 0)$ under situation 3, and at this time, the system’s strategy will stabilize at selfishness.
Before the simulation, we select the mechanisms, based on the above analysis, we carry out the evolution path of SDN enterprises and the specific impact of R&D cooperation strategy evolution. In this part, we make a simulation about the SDN enterprises’ cooperation evolution path. To explore the evolution of the R&D cooperation strategy evolution path of SDN enterprises and the specific impact mechanisms, based on the above analysis, we carry out the simulation of SDN enterprise’s cooperation evolution path and the sensitivity analysis of the payment matrix.

IV. NUMERICAL SIMULATION AND ANALYSIS

To explore the evolution of the R&D cooperation strategy evolution path of SDN enterprises and the specific impact mechanisms, based on the above analysis, we carry out the simulation of SDN enterprise’s cooperation evolution path and the sensitivity analysis of the payment matrix.

A. ENTERPRISE COOPERATION PATH EVOLUTION SIMULATION

In this part, we make a simulation about the SDN enterprises’ cooperation evolution path. Before the simulation, we select some related parameters, set $\lambda = 0.4$, $\gamma = 0.1$, $\alpha = 0.5$, $\beta = 0.5$, $\delta = 0.5$, $W = 0.8$, $\Lambda = 2$, $\Lambda = 2$ under situation 1. According to above parameters, the values of $x$ and $y$ are -0.4 and -0.4. Under situation 2, when $x < \frac{1}{2}$, $y < \frac{1}{2}$, we set $\lambda = 0.4$, $\gamma = 0.1$, $\alpha = 0.5$, $\beta = 0.5$, $\delta = 0.1$, $D = 0.1$, $\Lambda = 2$, $\Lambda = 2$ and the values of $x$ and $y$ are 0.2727 and 0.2727. When we set $\lambda = 0.4$, $\gamma = 0.1$, $\alpha = 0.5$, $\beta = 0.5$, $\delta = 0.1$, $D = 0.1$, $\Lambda = 2$, $\Lambda = 2$, the values of $x$ and $y$ are $x = \frac{1}{2}$, $y = \frac{1}{2}$. When $x > \frac{1}{2}$, $y > \frac{1}{2}$, we set $\lambda = 0.4$, $\gamma = 0.1$, $\alpha = 0.5$, $\beta = 0.5$, $\delta = 0.1$, $D = 0.1$, $\Lambda = 2$, $\Lambda = 2$, $\Lambda = 2$, $\Lambda = 2$, $\Lambda = 2$, $\Lambda = 2$, and the values of $x$ and $y$ are $x = 1.4$, $y = 1.4$. The specific simulation results are shown in Figure 3.

As shown in Figure 3(a), when $x = -0.4$, $y = -0.4$ under situation 1, the system’s strategy path will move from the unstable point $S(0, 0)$ to the stable point $M(1, 1)$, and the strategy will transform from selfishness to the cooperation. Under situation 2, in Figure 3(b), when $x < \frac{1}{2}$, $y < \frac{1}{2}$, such as when $x = 0.2727$, $y = 0.2727$, the system’s strategy path will move to $S(0, 0)$, and the final strategy will stabilize at cooperation. In Figure 3(c), when $x = \frac{1}{2}$, $y = \frac{1}{2}$, the system’s strategy path will move to $S(0, 0)$ or $M(1, 1)$, and at this moment, the system’s final strategy will stabilize at cooperation or selfishness. In Figure 3(d), when $x > \frac{1}{2}$, $y > \frac{1}{2}$, for example, when $x = 0.6$, $y = 0.6$, the system’s strategy path will move from $S(0, 0)$ to the $M(1, 1)$ and the strategy will stabilize at selfishness. Under situation 3, when $x = 1.4$, $y = 1.4$, the system’s strategy path will move...
the evolution process, we set evolution path. We select some parameters under situation 2. Based on the selection of related parameters, we explore the stabilize at cooperation.

3) KNOWLEDGE SPILLOVER COEFFICIENT β
When \( x < \frac{1}{2}, \ y < \frac{1}{2} \), such as \( x = 0.35, \ y = 0.35 \), we set \( \lambda_i = 0.4, \lambda_j = 0.4, \gamma_i = 0.1, \gamma_j = 0.1, D_i = 0.1, D_j = 0.1, \alpha_i = 0.5, \alpha_j = 0.5, W_i = 0.3, W_j = 0.3, \Lambda_i = 2, \Lambda_j = 2 \); keep above parameters unchanged and let \( \beta_i, \beta_j \) increase from 0.2 to 0.28, and the simulation result is shown in Figure 4.

As shown in Figure 4, when the knowledge spillover coefficient \( \beta_i \) and \( \beta_j \) increase from 0.20 to 0.28 in situation 2, the system’s strategy will move to cooperation and steps of evolution will extend from 14 to 20 gradually. It indicates that when the knowledge spillover coefficient increases, the cooperation between SDN enterprises will be more difficult, at this moment, in situation 2, \( \gamma_i \Lambda_i + \lambda_i \alpha_i \Lambda_i - W_i > 0 \), \( \gamma_j \Lambda_j + \lambda_j \alpha_j \Lambda_j - W_j > 0 \). Because the government reward \( W_i \) and \( W_j \) are smaller than \( \gamma_i \Lambda_i + \lambda_i \alpha_i \Lambda_i \) and \( \gamma_j \Lambda_j + \lambda_j \alpha_j \Lambda_j \), two parties do not want to spillover knowledge and steps of the evolution will extend.

2) GOVERNMENT REWARD \( W \)
When \( x < \frac{1}{2}, x < \frac{1}{2} \), such as when \( x = 0.35, y = 0.35 \), we set \( \lambda_i = 0.4, \lambda_j = 0.4, \gamma_i = 0.1, \gamma_j = 0.1, D_i = 0.1, D_j = 0.1, \alpha_i = 0.5, \alpha_j = 0.5, W_i = 0.3, W_j = 0.3, \Lambda_i = 2, \Lambda_j = 2 \); we keep above parameters unchanged and keep \( W_i, W_j \) increasing from 0.3 to 0.38, and the simulation results are shown in Figure 5.

As shown in Figure 5, when the government rewards \( W_i \) and \( W_j \) increase from 0.30 to 0.38, the evolution steps will shorten from 15 to 10. It indicates that the larger government reward will be conducive to cooperation in SDN enterprises. If we increase the government reward, the SDN enterprises will spillover knowledge between each other and the two parties will cooperate finally.

from \( M(1, 1) \) to \( S(0, 0) \), and the system’s final strategy will stabilize at cooperation.

B. SENSITIVITY ANALYSIS OF PAYMENT MATRIX
Based on the selection of related parameters, we explore the influence of knowledge spillover coefficient \( \beta \), government reward \( W \), government penalty \( D \), cooperation cost coefficient \( y \), and cooperation risk coefficient \( \lambda \) on the system’s evolution path. We select some parameters under situation 2. Furthermore, to explore different initial value’s influence on the evolution process, we set \( x = 0.35, y = 0.35 \) and \( x = 0.7, y = 0.7 \) separately. The simulation results are as follows:

### 1) KNOWLEDGE SPILLOVER COEFFICIENT \( \beta \)
When \( x < \frac{1}{2}, x < \frac{1}{2} \), such as \( x = 0.35, y = 0.35 \), we set \( \lambda_i = 0.4, \lambda_j = 0.4, \gamma_i = 0.1, \gamma_j = 0.1, D_i = 0.1, D_j = 0.1, \alpha_i = 0.5, \alpha_j = 0.5, W_i = 0.3, W_j = 0.3, \Lambda_i = 2, \Lambda_j = 2 \); keep above parameters unchanged and let \( \beta_i, \beta_j \) increase from 0.2 to 0.28, and the simulation result is shown in Figure 4.

As shown in Figure 4, when the knowledge spillover coefficient \( \beta_i \) and \( \beta_j \) increase from 0.20 to 0.28 in situation 2, the system’s strategy can not be sure, it may stabilize at cooperation or selfishness. In situation 3, the final strategy will stabilize at selfishness.
J. He et al.: How Does R&D Cooperation Path of Supply and Demand Network Enterprises Evolve?

3) GOVERNMENT PENALTY $D$

When $x < \frac{1}{2}$, $x > \frac{1}{2}$, such as when $x = 0.35$, $y = 0.35$, we set $\lambda_i = 0.4$, $\lambda_j = 0.4$, $\gamma_i = 0.1$, $\gamma_j = 0.1$, $\alpha_i = 0.5$, $\alpha_j = 0.5$, $\beta_i = 0.2$, $\beta_j = 0.2$, $W_i = 0.3$, $W_j = 0.3$, $\Lambda_i = 2$, $\Lambda_j = 2$; we keep the above parameters unchanged and keep $D_i$, $D_j$ increasing from 0.1 to 0.18, and the simulation results are shown in Figure 6.

As shown in Figure 6, when the government penalties $D_i$ and $D_j$ increase from 0.10 to 0.18, the strategy will move to the cooperation. If $D_i$ and $D_j$ continue to increase, the steps of system evolution will shorten gradually. It indicates that when government penalty increases, the cooperation between two parties will accelerate. Under the government penalty, the two parties will spillover knowledge and the cooperation will be achieved quickly.

4) COOPERATION COST COEFFICIENT $\gamma$

When $x > \frac{1}{2}$, $x > \frac{1}{2}$, such as when $x = 0.7$, $y = 0.7$, we set $\lambda_i = 0.4$, $\lambda_j = 0.4$, $\alpha_i = 0.5$, $\alpha_j = 0.5$, $\beta_i = 0.5$, $\beta_j = 0.5$, $W_i = 0.3$, $W_j = 0.3$, $D_i = 0.1$, $D_j = 0.1$, $\Lambda_i = 2$, $\Lambda_j = 2$; we keep the above parameters unchanged and keep $\gamma_i$, $\gamma_j$ increasing from 0.1 to 0.18. The simulation results are shown in Figure 7.

As shown in Figure 7, when $x = 0.7$, $y = 0.7$, the system’s strategy will shift from cooperation to selfishness. Furthermore, when cooperation cost coefficients $\gamma_i$ and $\gamma_j$ increase from 0.10 to 0.18, the steps of the system’s evolution will shorten, it indicated that the larger cooperation cost will prevent the cooperation easily. At this moment, if two parties have larger cooperation costs, they do not want to cooperate with each other.
5) COOPERATION RISK COEFFICIENT $\lambda$
When $x > \frac{1}{2}$, $x > \frac{1}{2}$, such as when $x = 0.7$, $y = 0.7$, we set $\gamma_i = 0.1$, $\gamma_j = 0.1$, $\alpha_i = 0.5$, $\alpha_j = 0.5$, $\beta_i = 0.5$, $\beta_j = 0.5$, $W_i = 0.3$, $W_j = 0.3$, $D_i = 0.1$, $D_j = 0.1$, $\Lambda_i = 2$, $\Lambda_j = 2$; we keep above parameters unchanged and keep $\lambda_i$, $\lambda_j$ increasing from 0.6 to 1.0. The simulation results are shown in Figure 8.

![Figure 8: Strategy selection process of the SDN enterprises when cooperation cost risk coefficient $\lambda_i$ and $\lambda_j$ increase from 0.60 to 1.00.](image)

As shown in Figure 8, when the cooperation cost coefficients $\lambda_i$ and $\lambda_j$ increase from 0.60 to 1.00, the system’s evolution path will move to the selfishness. Furthermore, with the increase in the cooperation risk, the steps of system evolution will shorten gradually, it indicated that cooperation risk will have a negative effect on the cooperation between two parties. At this moment, because of the cooperation risk, the SDN enterprises will evaluate the possibility of cooperation and make the best choice between cooperation and selfishness.

V. CONCLUSION
With the development of economic globalization, supply and demand network enterprises have become a trend. In the process of the R&D cooperation between SDN enterprises, cooperative activities were always accompanied by knowledge spillover. Therefore, it is of certain practical significance to explore the R&D cooperation between the SDN enterprises from knowledge spillover. Under the aforementioned background, we use evolutionary game theory and the duplicate dynamic equation to explore the cooperation behavior between SDN enterprises from knowledge spillover. We made some assumptions and built a game model on the cooperation between SDN enterprises, and then, we analyzed the process of the evolution and used the numerical simulation to vary the model’s rationality. Based on this research, we obtained some conclusions: (1) The evolution of R&D cooperation strategy for SDN enterprises may eventually stabilize at cooperation or selfishness strategy under different situations. As for which strategy is ultimately stable, it is closely related to the construction of the initial payment matrix and the selection of initial parameters. (2) Under certain situations, increasing the knowledge spillover degree, government reward, and government penalty and decreasing the cooperation cost and cooperation risk can improve the R&D cooperation level.

In the process of R&D cooperation, it is important to build a stable cooperative relationship between two parties, but how to promote the selfishness strategy transform to the cooperation strategy and how to construct a good cooperation atmosphere to promote cooperation between SDN enterprises? Based on the above conclusions, we put forward some relevant proposals to enterprises and government to promote R&D cooperation between SDN enterprises. Our specific suggestions are as follows:

(1) Strengthen knowledge spillover and build a knowledge sharing platform. In the process of R&D cooperation, the two partners should carry out knowledge spillover activities, optimize the knowledge structure of both parties continuously, adjust the knowledge stock, and promote collaborative research and development in order to finally achieve the goal of win-win situation.

(2) Strengthen supervision and establish a good salary incentive mechanism. By strengthening the construction of the supervision system, increase the economic penalties for enterprises that do not cooperate and carry out knowledge spillover. Similarly, the government should establish a good salary incentive mechanism and give larger rewards if the enterprise wants to spillover knowledge. In addition, enterprises should build a good salary incentive mechanism and give different levels of salary incentives and job promotion to employees if they carry out knowledge spillovers. Enterprises also need to encourage staff to promote the values of mutual benefit behavior, to enhance employees’ willingness to share knowledge, and to build a good cooperative atmosphere to respect knowledge, create knowledge and share knowledge.

(3) Reduce cooperation costs and prevent cooperation risks. When R&D cooperation activities are carried out by SDN enterprises, it is necessary to lower the cooperation threshold, reduce cooperation costs, and establish a cooperation foundation continuously. Two parties should design a cooperation mechanism that can lower the cooperation threshold and ensure the quality of cooperation. In addition, by establishing a cooperative risk-sharing mechanism, the spread of unilateral opportunism and the expansion of cooperation risks will be suppressed, and the partners can carry out knowledge sharing activities in a safe and secure environment.

Generally speaking, we use evolutionary game theory to explore the R&D cooperation between SDN enterprises from the perspective of knowledge spillover and obtain some conclusions. We hope that our research will provide some valuable guidance for SDN enterprise cooperation. In the future, our model also can apply to the cooperation between universities and enterprises, the cooperation between top management teams in an enterprise, and the cooperation among
employees within an enterprise. Besides, in examining the cooperation between SDN enterprises, future research also can take knowledge flow, knowledge sharing, and knowledge absorption into account the cooperation model.

DATA AVAILABILITY
The open data used to support the finding of this study are available from the corresponding author upon request.

DECLARATION OF COMPETING INTEREST
The authors declared that there is no interest of their manuscript. We also declare that there is no commercial or associative interest about the manuscript submitted.

ACKNOWLEDGMENT
The authors would like to thanks the valuable review comments of every expert and editor.

REFERENCES
[1] J. He, F. Xu, and Z. Gii, “Role-facing modelling and analysis of workflow based on supply and demand network with multi-function and opening characteristics,” Int. J. Electron. Finance, vol. 6, pp. 199–218, Jan. 2012.
[2] Q. Ma, J. He, and F. Xu, “The impact of building FSDN traceability system on corporate profits,” in Proc. 4th Int. Conf. Logistics, Inf. Service Sci., 2015, pp. 1369–1373.
[3] C. Liu and F. Xu, “Dynamic matching operation in SDN,” in Proc. 2nd Int. Conf. Innov. Comput., Inf. Control (ICICIC), Sep. 2007, p. 486.
[4] H. Ito and J. Tanimoto, “Scaling the phase-planes of social dilemma strengths shows game-class changes in the five rules governing the evolution of cooperation,” Roy. Soc. Open Sci., vol. 5, no. 10, Oct. 2018, Art. no. 181085.
[5] Z. Wang, S. Kokubo, M. Jusup, and J. Tanimoto, “Universal scaling for the dilemma strength in evolutionary games,” Phys. Life Rev., vol. 14, pp. 1–30, Sep. 2015.
[6] J. Tanimoto and H. Sagara, “Relationship between dilemma occurrence and the existence of a weakly dominant strategy in a two-player symmetric game,” Biosystems, vol. 90, no. 1, pp. 105–114, Jul. 2007.
[7] J. Tanimoto, Evolutionary Games with Sociophysics Analysis of Traffic Flow and Epidemics. Tokyo, Japan: Springer, 2019.
[8] J. Tanimoto, Fundamentals of Evolutionary Game Theory and its Applications. Tokyo, Japan: Springer, 2015.
[9] J. Knebel, M. F. Weber, T. Kräger, and E. Frey, “Evolutionary games of condensates in coupled birth–death processes,” Nature Commun., vol. 6, no. 1, p. 6977, Nov. 2015.
[10] T. Wang, C. Li, Y. Yuan, J. Liu, and I. B. Adeleke, “An evolutionary game approach for manufacturing service allocation management in cloud manufacturing,” Comput. Ind. Eng., vol. 133, pp. 231–240, Jul. 2019.
[11] M. A. O’Malley, “Endosymbiosis and its implications for evolutionary theory,” Proc. Nat. Acad. Sci. USA, vol. 112, no. 33, pp. 10270–10277, 2015.
[12] J. Mielke and G. A. Steudle, “Green investment and coordination failure: An Investors’ perspective,” Ecol. Econ., vol. 150, pp. 88–95, Aug. 2018.
[13] D. Cowdren, K. Eriksson, and P. Strimling, “A popular misapplication of evolutionary modeling to the study of human cooperation,” Evol. Hum. Behav., vol. 38, no. 3, pp. 421–427, May 2017.
[14] L. Y. Zhao, S. S. Yuan, and C. L. Yu, “Analysis of intellectual property cooperation behavior and its simulation under two types of scenarios using evolutionary game theory,” Comput. Ind. Eng., vol. 125, pp. 739–750, Nov. 2018.
[15] Y. Cheng, Y. Xue, and M. Chang, “Career choice as an extended spatial evolutionary public goods game,” Chaos, Solitons Fractals, vol. 137, Aug. 2020, Art. no. 109856.
[16] Y. Xie, S. Zhang, Z. Zhang, and H. Bu, “Impact of binary social status with hierarchical punishment on the evolution of cooperation in the spatial prisoner’s dilemma game,” Chaos, Solitons Fractals, vol. 130, Jan. 2020, Art. no. 109422.
[17] S. Zhang, C. Wang, and C. Yu, “The evolutionary game analysis and simulation with system dynamics of manufacturer’s emissions abatement behavior under cap-and-trade regulation,” Appl. Math. Comput., vol. 355, pp. 343–355, Aug. 2019.
[18] J. Liu, C. Yu, C. Li, and J. Han, “Cooperation or conflict in doctor-patient relationship? An analysis from the perspective of evolutionary game,” IEEE Access, vol. 8, pp. 42898–42908, 2020.
[19] U. S. Brandt and G. T. Svendsen, “How robust is the welfare state when facing open borders? An evolutionary-game-theoretic model,” Public Choice, vol. 178, nos. 1–2, pp. 179–195, Jan. 2019.
[20] L. Zhang, L. Xue, and Y. Zhou, “How do low-carbon policies promote green diffusion among alliance-based firms in China? An evolutionary-game model of complex networks,” J. Cleaner Prod., vol. 210, pp. 518–529, Feb. 2019.
[21] B. Podobnik, A. M. Gabor, and I. S. Kirbis, “Scale-free growth of human society based on cooperation and altruistic punishment,” Phys. A. Stat. Mech. Appl., vol. 513, pp. 613–619, Jan. 2019.
[22] J. C. Croll, M. Egas, and I. M. Smallegange, “An eco-evolutionary feedback loop between population dynamics and fighter expression affects the evolution of alternative reproductive tactics,” J. Animal Ecol., vol. 88, no. 1, pp. 11–23, Jan. 2019.
[23] D. Li, Z. Ma, J. Du, and D. Han, “The evolutionary game with asymmetry and variable interaction relations,” Europhys. Lett., vol. 125, no. 1, p. 10009, 2019.
[24] E. Gallo and C. Yan, “The effects of reputational and social knowledge on cooperation,” Proc. Nat. Acad. Sci. USA, vol. 112, no. 12, pp. 3647–3652, Mar. 2015.
[25] H. Fu, J. Yang, and Y. An, “Contracts for venture capital financing with double-sided moral hazard,” Small Bus. Econ., vol. 53, no. 1, pp. 129–144, Jun. 2019.
[26] M. Perc, J. J. Jordan, D. G. Rand, Z. Wang, S. Boccaletti, and A. Szolnoki, “Statistical physics of human cooperation,” Phys. Rep., vol. 687, pp. 1–51, May 2017.
[27] A. Kumar, V. Caprarro, and M. Perc, “The evolution of trust and trustworthiness,” J. Roy. Soc. Interface, vol. 17, Oct. 2020, Art. no. 20200491.
[28] Y. Fang, M. Perc, and H. Xu, “The Singaporean model in public goods dilemmas with benevolent leaders and bribery,” J. Theor. Biol., vol. 501, Sep. 2020, Art. no. 110345.
[29] Y. Fang, T. P. Benko, M. Perc, H. Xu, and Q. Tan, “Synergistic third-party rewarding and punishment in the public goods game,” Proc. Roy. Soc. A, Math., Phys. Eng. Sci., vol. 475, no. 2227, Jul. 2019, Art. no. 20190349.
[30] P. A. David, B. H. Hall, and A. Toolo, “Is public R&D a complement or substitute for private R&D? A review of the econometric evidence,” Res. Policy, vol. 29, no. 4, pp. 497–529, Apr. 2000.
[31] C. Díaz-García, A. González-Moreno, and F. J. Sáez-Martínez, “Gender diversity within R&D teams: Its impact on radicalness of innovation,” Innovation, vol. 15, no. 2, pp. 149–160, 2013.
[32] J. Ying, “The study on R&D enterprise management based on knowledge management,” J. Conveng. Inf Technol., vol. 7, no. 16, pp. 289–297, 2012.
[33] F. Micheline, E. Lamberti, A. Cammarano, and M. Caputo, “Open innovation in the pharmaceutical industry: An empirical analysis on context features, internal R&D, and financial performances,” IEEE Trans. Eng. Manag., vol. 62, no. 3, pp. 1–15, 2015.
[34] J. Nishimura and H. Okamuro, “Knowledge and rent spillovers through government-sponsored R&D consortia,” Sci. Public Policy, vol. 43, no. 2, pp. 207–225, Apr. 2016.
[35] M. Xu, W. Yang, L. Pang, and D. Kong, “R&D, financial constraints and productivity: Evidence from the Chinese industrial enterprises,” Singap. Econ. Rev., vol. 65, no. 4, pp. 947–967, Jun. 2017.
[36] Y. Zhao and X. Song, “How should the Chinese government invest R&D funds: Enterprises or institutions?” Comput. Econ., vol. 52, no. 4, pp. 1089–1112, Dec. 2018.
[37] J. Schlapp, N. Oraiopoulos, and V. Mak, “Resource allocation decisions under imperfect evaluation and organizational dynamics,” Manage. Sci., vol. 61, pp. 1–37, Dec. 2015.
[38] M. Guerrero, D. Urbano, and F. Herrera, “Innovation practices in emerging economies: Do university partnerships matter?” J. Technol. Transf., vol. 44, no. 2, pp. 615–646, Apr. 2019.
[39] D. Minguillo and M. Thelwall, “Which are the best innovation support infrastructures for universities? Evidence from R&D output and commercial activities,” Scientometrics, vol. 102, no. 1, pp. 1057–1081, Jan. 2015.
[40] S. Schmidt, “Balancing the spatial localisation ‘Tilt’: Knowledge spillovers in processes of knowledge-intensive services,” Geoforum, vol. 65, pp. 374–386, Oct. 2015.
[41] S. Leppälä, “Theoretical perspectives on localized knowledge spillovers and agglomeration,” Papers Regional Sci., vol. 97, no. 3, pp. 467–484, Aug. 2018.

[42] C. Mastromarco, L. Serlenga, and Y. Shin, “Modelling technical efficiency in cross sectionally dependent stochastic frontier panels,” J. Appl. Econometrics, vol. 31, no. 1, pp. 281–297, Jan. 2016.

[43] M. Li, D. Li, M. Lyles, and S. Liu, “Chinese MNEs’ outward FDI and home country productivity: The moderating effect of technology gap: Chinese MNEs’ outward FDI and home country productivity,” Global Strategy J., vol. 6, no. 4, pp. 289–308, Nov. 2016.

[44] N. Foster-McGregor and J. Pöschl, “Productivity effects of knowledge transfers through labour mobility,” J. Productiv. Anal., vol. 46, nos. 2–3, pp. 169–184, Dec. 2016.

[45] E. Chalioti, “Spillover feedback loops and strategic complements in R&D,” J. Public Econ. Theory, vol. 21, no. 6, pp. 1126–1142, Dec. 2019.

[46] J. Huang, X. Chen, B. Huang, and X. Yang, “Economic and environmental impacts of foreign direct investment in China: A spatial spillover analysis,” China Econ. Rev., vol. 45, pp. 289–309, Sep. 2017.

[47] B. David, M. Joseph, and K. R. Kirk, ValueNets. Hoboken, NJ, USA: Wiley, 2001.

**JIANJIA HE** received the Ph.D. degree in management from the University of Shanghai Science and Technology, Shanghai, China, in 2009. He is currently an Associate Professor and a Doctoral Adviser at the Business School, University of Shanghai for Science and Technology. He is also a Researcher at the Super Network Research Center, China and the Shanghai Institute of Public Diplomacy. He has published some papers in Computers and Industrial Engineering, Scientometrics, Technological Forecasting and Social Change, and Frontiers in Public Health. His research interests include management science, supply and demand networks, and artificial intelligence.

**JUSHENG LIU** received the M.S. degree in industrial engineering from the University of Shanghai for Science and Technology, Shanghai, China, in 2018. He is currently a Researcher at the Shanghai Financial Intelligent Engineering Technology Research Center, Shanghai University of Finance and Economics, Shanghai. His research interests include supply and demand networks, game theory, big data, and online healthcare.

**ZHIPING QIU** received the M.S. degree in regional economics from the Jiangxi University of Finance and Economics, Nanchang, China, in 2018. He is currently pursuing the Ph.D. degree with the School of Urban and Regional Science, Shanghai University of Finance and Economics, Shanghai, China. His research interests include regional economic cooperation, regional innovation, and social network analysis.

**NGAYUA ESTHER NANZAYI** was born in Nairobi, Kenya. She received the bachelor’s degree in pharmaceutical engineering from the University of Shanghai for Science and Technology, Shanghai, China, in 2018, where she is currently pursuing the master’s degree in enterprise management. Her research interests include new computer related research in enterprises and disruptive technology in healthcare industry.

**MIN ZHANG** received the M.S. degree in engineering management from the Shanghai University of Finance and Economics, Shanghai, China, in 2021. He is currently an Engineer at the Laboratory Center and the Shanghai Financial Intelligent Engineering Technology Research Center, Shanghai University of Finance and Economics. His research interests include financial engineering and big data.