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*Research Article*

# A Dynamic Evolutionary Game Model of Modular Production Network

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As a new organization mode of production in the 21st century, modular production network is deemed extensively to be a source of competitiveness for lead firms in manufacturing industries. However, despite the abundant studies on the modular production network, there are very few studies from a dynamic perspective to discuss the conditions on which a modular production network develops. Based on the dynamic evolutionary game theory, this paper constructs a model, which incorporates several main factors influencing the development of modular production network. By calculating the replicator dynamics equations and analyzing the evolutionary stable strategies, this paper discusses the evolution process of cooperation strategies of member enterprises in a modular production network. Furthermore, by using NetLogo software to simulate the model, this paper verifies the effectiveness of the model. From the model, we can find that the final stable equilibrium strategy is related to such factors as the initial cost, the extra payoff, the cooperation willingness of both parties, the cooperation efforts, and the proportion each party can get from the extra payoff. To encourage the cooperation of production integrator and modular supplier, some suggestions are also provided.

## 1. Introduction

Since the 1980s, a new organization mode of production has been gradually emerging in the manufacturing industries in many developed countries. Namely, the lead firms in the industries focus on their core businesses such as design and creation of products or provision of services while outsourcing the manufacturing activities to the contract manufacturers. Scholars called this particular production pattern modular production network [1]. The popularity of modular production network is mainly drawn from the rapid development of modern information technology and modularity technology. In general, the structure of the modular production network has the following features [2]: firstly, its structure is flat. Within a modular production network, the relationship between the production integrator and modular supplier is built on a relatively equal basis. The power is symmetrically distributed. And knowledge flows more horizontally. Secondly, it is flexible. Flexibility here refers to the ability of a modular production network to respond to the fast changing environment. Because the modular production network is built on modular production and flexible modular organization, it can give a quick response to the external environment. Thirdly, it is quite open. In a modular structure, under the premise of the same standards, the modular suppliers with the same function are highly substitutive and they have to compete with each other. The mechanism of selecting the superior and eliminating the inferior endows the modular production network with high openness. Fourthly, it is a self-organization system. Coordination arises out of the interactions between members of modular production network and it can be spontaneous, which is not necessarily controlled by an auxiliary agent outside of the system. As such, the system is typically robust and able to develop.

Nowadays, the modular production network is widely recognized as a source of competitiveness for lead firms in the industries [3–6]. According to scholars and practitioners, the modular production network has a lot of advantages. Some scholars emphasized product innovation function of modular production network. They noticed that in modular production environment the product innovation ways are diversified, the products are differentiated, and the production cycles are shortened [3, 7, 8]. Furthermore, some scholars pointed out that the modular production network can help enterprises to obtain strategic flexibility [9], facilitate outsourcing and the development of industries [10], and optimize resource allocation [11]. What is more, modular production network can contribute to reducing transactional cost and business risks of member enterprises as well as bringing external scale effect [1, 12]. Therefore, under the background of the global value chain, it is not difficult to conclude that modular production network of complicated products is a powerful weapon for lead enterprises to compete in the industries [13].

Originally, the modular production network is derived from the concept "modularity." In 1962, Simon put forward the concept "modularity." Then, modularity technology was first introduced in the computer design field. Langlois and Robertson (1992) pointed out that modularity is a set of rules to manage the complicated objects [2]. A complex system is divided into several independent parts and each party exchanges information through the interface. After studying the data of the computer industry between 1950 and 1996, Baldwin and Clark (2000) proposed that the modularity of computer stimulated the industry to transform from the initial highly concentrated and integrated production to the present highly scattered structure [7]. What is more, they pointed out that the modularity phenomenon was very popular in industries like information and automotive industries and it has important significance for the evolution of industrial organization. Majority studies on product modularity are carried out on the technical level and the product modularity is thought to be leading to modularity of industry. On the basis of that, the abroad scholars mainly focused on the influence on the evolution of industrial organization, the organizational strategy, and organizational capability by case studies while the domestic scholars focused more on the influence on enterprise value networks, innovation networks, and industrial clusters. In other words, at that time, scholars were more enthusiastic about studying the influence of modularity on industrial organizations. Afterwards, scholars gradually shifted the study focus to the organization mode of production itself. By studying different cases, they have explored the reasons behind the formation of modular production network, the characteristics of modular production network, the different forms of modular production network, and the influencing factors of modular production network and its influence on a single production organization.

However, we find that previous studies mainly focused on qualitative and static analysis with case studies being used extensively. There are rarely quantitative and dynamic studies on the formation and evolution of a single modular production network. The modular production network consists of two types of enterprises: the production integrators and the modular suppliers. By nature, the formation and evolution of a modular production network are an interactive and game process of the two organizations. Usually, a classical game theory deals with a rational player, who is involved in a given game with other players and has to decide between different strategies in order to maximize the payoff which depends on the strategies of the coplayers. In contrast, evolutionary game theory deals with entire populations of players. By learning, copying, and inheriting strategies, or even by infection, strategies with high payoff will spread within the population. The payoffs depend on the actions of the coplayers and hence the frequencies of the strategies within the population [14]. The most distinctive difference between evolutionary game theory and classical game theory is that evolutionary game theory assumes the subjects have bounded rationality which is much closer to reality. Evolutionary game theory deems that participants have limited abilities to find the optimal behaviors. By learning and copying the best strategies, finally each party can reach the equilibrium point. Therefore, due to these advantages, this paper adopts evolutionary game dynamics to analyze the interaction between production integrators and modular suppliers. By creating a dynamic evolutionary game model, this paper examines the evolutionary game process and the stable equilibrium of modular outsourcing. In addition, by simulation analysis based on multiagent modeling method and NetLogo platform, this paper further tests the effectiveness of the game model.

This paper proceeds as follows: Section 2 is literature review; Section 3 is the construction of an evolutionary game model and discussion of the equilibrium of the model; Section 4 is the simulation analysis of the game model by using NetLogo software; Section 5 is the conclusions.

## 2. Literature Review

By analyzing transactional activities between the lead firms and the "turn-key" firms in the American electronic information industry, Sturgeon (2002) made detailed analysis on modular production networks and called it "the new form of American industrial organization" [4]. In general, the modular production network can be characterized by functional partitioning into discrete scalable, reusable modules, rigorous use of well-defined modular interfaces, and making use of industry standards for interfaces. Based on modularity, the modular production network is a topology structure, connected by interface rules and guaranteed by allocation rules [15]. The overall orderliness of this structure and the active nodes in the structure can facilitate the evolution of the complicated product system. As a global production system, production integrators and modular suppliers within a modular production network have formed a new type of cooperative relationship [16].

Currently, the major studies on the modular production network mainly examined the historical evolution process of modular production networks and discussed the nature and causes of modular production networks [17–21]. Other scholars combined modularity with different network forms such as enterprise value networks, industrial value chains, industrial clusters, and innovation networks to study the formation mechanism of modular production network [22–26]. However, despite these abundant researches, there is a lack of studies which explore the specific formation and evolution process of a single modular production network and there is no study from member enterprise perspective to examine the operation of modular production network. The related researches are quite limited. Next, we make a literature review on evolution of modular production network. As a new form of network organization, we extend the scope to network organization.

According to Zhu and Zhou (2007), network organization can be divided into two types: one with core enterprise and one without core enterprise [27]. Furthermore, they discussed in detail the different evolutionary patterns of these two modes. Taking a cue from the complex system theory, Pan and Yao (2011) studied the evolutionary process of network organizations and indicated that the formation of network organizations was a self-organization process [16]. It is the interaction of the market mechanism and hierarchy mechanism that facilitate the formation of network organizations. And the interaction between the two governance mechanisms decides the development path and direction of network organizations. Learning from CAS theory, Ruan and Gao (2009) pointed out that the network organization was a complex adaptive system [28]. Its evolutionary process can be seen as a nonlinear interactive process between subjects of the network. By active adaptation of subjects and their interactions with the system, the evolution of the whole system is promoted. Plowman et al. (2007) applied complex adaptive system theory to explain the problem of mutual cooperation and decision participation in a network organization [22]. They deemed that by mutual cooperation a network organization could accomplish the synergy effect, that is, the creation of benefits that are greater than the simple sum of all parts. Furthermore, they revealed that it was the synergy effect that stimulated the formation of a network organization. Anderson noted that to understand the networking process of organizations we needed to initiate the studies from the perspectives of their form and the cooperative relationship separately. Johanson and Mattsson developed Anderson's study and for the first time proposed a mutual aid model, which well connected the networking relationship between nodes with the interactive behaviors of them [1].

Wu et al. (2009) established an evolutionary game model for information sharing in a network organization [29]. They found that the excess profits from information sharing, initial cost of cooperation, differences in service abilities of member enterprises, and discount factor are the key factors that affect the evolution of the network organization. Zhang and He (2010) combined the views of different theory perspectives and analyzed in detail the characteristics and influencing factors of the four spiral upward stages in the evolution process of network organizations [30]. Koka et al. (2006) pointed out that when the environment was uncertain and the resource supply capacity changed, interfirm networks generally experienced four patterns of network change (network expansion, network churning, network strengthening, and network shrinking) [14]. Furthermore, based on environmental context and strategic action, they further expounded the evolutionary path of network organizations. Hakansson and Snehota (1995) reckoned that the formation of network organizations needed to experience the resource searching, coordination, and integration stage [10]. Salancik (1995) pointed out that it was the division of labor that drove the formation of a network [31]. Networking can not only produce synergy effect but also develop diversified contracts to govern the long-term interdependent relationship between enterprises.

Evolutionary game theory is the application of game theory to evolving populations of life forms in biology [32]. A key difference between evolutionary game theory and classical game theory is that evolutionary game theory focuses more on the dynamics of strategy change as influenced not solely by the quality of the various competing strategies, but by the effect of the frequency with which those various competing strategies are found in the population [33, 34]. Originally, evolutionary game theoretical framework stems from biology. Maynard Smith and Price's (1973) seminal article in Nature ignited further development of evolutionary game theory [35]. Since the 1990s, evolutionary game theory has been enriched with phenomena such as pattern formation, equilibrium selection, and self-organization and has gained great development [36]. For instance, Tanimoto (2007) discussed the coevolution mechanisms of both networks and strategy and proved that this mechanism can solve dilemmas in several game classes [37]. Wang et al. (2015) proposed new universal scaling parameters for the dilemma strength [36]. Moreover, some textbooks and papers have appeared, describing the theory of evolutionary games in relation to economics or, more broadly, the social sciences. For example, Ritzberger and Weibull (1995) investigated stability properties of evolutionary selection dynamics in normal-form games [38]. Samuelson (1997) described the usefulness of evolutionary game theory as a tool for equilibrium selection [39]. By building an evolutionary model, Guttman (2000) showed that preferences for reciprocity could survive in a population partly consisting of "opportunists" [40]. Levine and Pesendorfer (2007) discussed evolutionarily stable outcomes for a class of games that admit cooperation and conflict as possible Nash equilibria [41]. Recently, what needs to be noticed is a shift of the research interest to the discussions on the cooperation problems in network organizations and enterprise alliances [42, 43]. For example, Qin et al. (2011) analyzed the influence of absorptive capacity on the behavior of partners in R&D alliances based on evolutionary game theory [44]. Wang and Jiang (2013) constructed a Hawk-Dove game model on the interorganizational resource sharing of the technological innovation network and analyzed the dynamic evolutionary process of resource sharing game strategies of both parties [45]. Han and Peng (2015) analyzed the factors which affect the stability of network organization by building a single group evolutionary model [46].

Based on the literature review, we can find that, in terms of the evolution of network, studies were mainly drawn from economics, organizational ecology theory, evolutionary game theory, and complex system theory. However, in general, these studies are relatively autonomous from each other. Studies which synthesize these diverse theories are still rare. What is more, network organizations have various forms and modular production networks are quite different from others. It develops with the maturation of modularity technology and the development of information technology. It is not restricted to regions and is closely related to the decomposable and integrated features of complicated product or complicated technology. Therefore, there is a necessity to discuss the evolutionary law of modular production network by focusing on its unique characteristics. Besides, in terms of the evolutionary game theory, currently, there were affluent studies discussing the cooperation problems in network organizations. However, until now, there is no specific study focusing on the formation of modular production network which is a unique type of network organization and discussing the influencing factors. Moreover, most studies centered on building an evolutionary model to discuss the equilibrium conditions. The validity of the evolutionary model is seldom tested. So by focusing on the particularity of modular production network and combining the dynamic evolutionary game theory and multiagent simulation method, this paper constructs a model to explore the cooperation between production integrators and modular suppliers in a modular production network and discuss the evolution of the modular production network. Furthermore, it also tests the effectiveness of the model.

## 3. Replicator Dynamic Evolutionary Game Model of Modular Production Network

*3.1. Model Assumptions.* We suppose that within the modular production network there are two types of individual enterprises: the production integrator (enterprise $A$) and the modular supplier (enterprise $B$). They game with each other in the network. The two types of enterprises are enterprises with different production scales. The set of their cooperative strategies is {cooperation, noncooperation}. Under the cooperation strategy, both sides cooperate with each other to produce. Under the noncooperation strategy, each party may produce independently or one party refuses to continue to cooperate because of the other party's contract breach behaviors. During the evolutionary game process, both sides select and adjust their cooperative strategies according to the other party's strategies. In this model, we simplify the interaction and cooperation between production integrators and modular suppliers and do not consider the social networks or network reciprocity that may exist in the population mainly for the following two reasons: firstly, although with large population there may be spatial structures and networks, for production integrators and modular suppliers in a modular production network, it is hard to obtain some key information such as the cost of opponent from a network. Thus, the asymmetry of information still remains, which may affect cooperation choice. Secondly, even if the key information of opponent can be obtained from a network, due to the bounded rationality, the agent's next action will not totally depend on the economic calculation of the outcome of its former action. It is influenced by many factors such as its cognition, risk preference, and environmental factors. In other words, it is still hard to predict an agent's cooperation action. So, considering the two reasons, we decide to mainly focus on the economic interaction between production integrators and modular suppliers and have not taken network reciprocity into account.

The normal payoffs of enterprise $A$ and enterprise $B$ are $\pi_A$ and $\pi_B$. If the two enterprises cooperate with each other to form the modular production network, they can obtain the extra payoffs $\pi$ and the proportion each party can get is $a$, $b$. And $a + b = 1$. To cooperate with each other, each party needs to pay a certain amount of initial cost ($C_A$ and $C_B$, resp.) and effort cost which is decided by both sides' cooperation willingness ($\delta_a$ and $\delta_b$, resp.) and their level of effort ($\alpha$ and $\beta$, resp.). So, the payoffs both sides can obtain when networking and cooperating with each other are

$$U_A = \pi_A + a\pi - C_A - \delta_a\alpha,$$
$$U_B = \pi_B + b\pi - C_B - \delta_b\beta. \quad (1)$$

Table 1: The general payoff matrix for enterprise $A$ and enterprise $B$.

| Enterprise $A$ | Enterprise $B$ | |
|---|---|---|
| | Cooperation ($y$) | Noncooperation ($1 - y$) |
| Cooperation ($x$) | $U_A, U_B$ | $\pi_A - C_A, \pi_B$ |
| Noncooperation ($1 - x$) | $\pi_A, \pi_B - C_B$ | $\pi_A, \pi_B$ |

*3.2. Model Construction*

*3.2.1. Game Payoff Matrix.* For enterprise $A$, the probability of enterprise $A$ to choose to join the modular production network to cooperate and to produce is $x$. Then, the probability for enterprise $A$ not to join the modular production network is $1 - x$. Suppose the probability of enterprise $B$ to choose to join the modular production network is $y$ and the probability for enterprise $B$ not to join the modular production network is $1 - y$. Based on the above assumptions, the strategy sets of both sides are {cooperation, noncooperation}. The two enterprises game with the proceeding of negotiation. The negotiation space is an uncertain and bounded rationality space. The two enterprises continuously select and adjust their own strategies with the consideration of their own payoff and the other party's strategy. Therefore, the payoff matrix of the two enterprises in the modular production network is shown in Table 1.

Then, the expected payoff of enterprise $A$ choosing "cooperation" strategy is

$$E_{C_A} = yU_A + (1 - y)(\pi_A - C_A). \quad (2)$$

The expected payoff of enterprise $A$ choosing "noncooperation" strategy is

$$E_{U_A} = y\pi_A + (1 - y)\pi_A = \pi_A. \quad (3)$$

According to the above expected payoff of enterprise $A$, we can calculate the average payoff:

$$\overline{E}_A = xE_{C_A} + (1 - x)E_{U_A}. \quad (4)$$

Similarly, the expected payoff of enterprise $B$ choosing "cooperation" strategy is

$$E_{C_B} = xU_B + (1 - x)(\pi_B - C_B). \quad (5)$$

The expected payoff of enterprise $B$ choosing "noncooperation" strategy is

$$E_{U_B} = x\pi_B + (1 - x)\pi_B = \pi_B. \quad (6)$$

The average payoff of enterprise $B$ is

$$\overline{E}_B = yE_{C_B} + (1 - y)E_{U_B}. \quad (7)$$

*3.2.2. Replicator Dynamics Game Model.* The replicator dynamic evolutionary game model describes the progressive process of the transformation of both sides' favorable strategy. Both sides are not adjusting their strategies at the same time. One side needs to decide its strategy by considering the other side's strategy and the payoff the strategy brings. Hence, it is a learning process. The specific calculation process is as follows.

Suppose there are two types of individuals who are playing a game in competition with one another. Both of them adopt pure strategies. Let $Q$ denote the set of pure strategies; let $N_t(q)$ denote the set of individuals who adopt the pure strategy $q \in Q$ at the $t$ moment. The state variable $n_t(q)$ denotes the proportion of individuals who adopt the pure strategy $q$ at the $t$ moment. So we have

$$n_t(q) = \frac{N_t(q)}{\sum_{h\in Q} N_t(h)}. \quad (8)$$

The expected payoff of individuals who adopt the pure strategy $q$ at the $t$ moment is

$$u_t(q) = \sum_{h\in Q} n_t(h)\, u_t(q,h), \quad (9)$$

where $u_t(q)$ denotes the expected payoff one group gets when taking the pure strategy $q$ while the other group is taking the pure strategy $h$.

The average expected utility of the group is

$$\overline{u}_t = \sum_{q\in Q} n_t(q)\, u_t(q). \quad (10)$$

According to the above assumptions, the individuals who have fewer payoffs will find the differences sooner or later and will start to imitate other individuals. Therefore, the proportion of individuals who take the same strategy will change with time and is the function of time. The speed changes with time and depends on the learning speed of individuals.

Taylor and Jonker proposed a continuous replicator dynamics model:

$$N_t'(q) = N_t(q)\, u_t(q). \quad (11)$$

The derivative of (8) with respect to time is

$$\frac{dn_t(q)}{dt} = \frac{N_t'(q)\sum_{h\in Q} N_t(h) - N_t(q)\sum_{h\in Q} N_t'(h)}{\left[\sum_{h\in Q} N_t(h)\right]^2}. \quad (12)$$

Combining with (11), we can simplify (12) into

$$\frac{dn_t(q)}{dt} = n_t(q)\left[u_t(q) - \overline{u}_t\right]. \quad (13)$$

According to the above deduction, we can get the replicator dynamics model of the production integrator:

$$\begin{aligned} F(x) = \frac{dx}{dt} &= x\left(E_{C_A} - \overline{E}_A\right) = x(1-x)\left(E_{C_A} - E_{U_A}\right) \\ &= x(1-x)\left(yU_A - C_A - y\pi_A + yC_A\right). \end{aligned} \quad (14)$$

Similarly, the replicator dynamics model of the modular supplier is

$$\begin{aligned} G(y) = \frac{dy}{dt} &= y\left(E_{C_B} - \overline{E}_B\right) = y(1-y)\left(E_{C_B} - E_{U_B}\right) \\ &= y(1-y)\left(xU_B - C_B - x\pi_B + xC_B\right). \end{aligned} \quad (15)$$

*3.3. Analysis of Game Process.* In the bounded rationality repeated game, if the optimal equilibrium strategy can return as before when there is small amount of interference, we call the equilibrium evolutionary stable strategy (ESS). Let the replicator dynamics equation be equal to 0. Then, we can get all the replicator dynamic stable states. According to the "stability theory" of the differential equations, we can discuss the stability of these states and therefore decide the evolutionary stable strategies of production integrator and modular supplier in the modular production network.

*3.3.1. Analysis of Game Process of the Production Integrator.* From the replicator dynamic differential equation of the production integrator $F(x)$, we can know when $y^* = C_A/(U_A - \pi_A + C_A)$ and $F(x)$ is always equal to 0. This indicates that within $[0,1]$ $x$ is always in stable state.

Let $F(x) = 0$; we can get $x = 0$ and $x = 1$ and they are two stable points of the dynamic differential equation.

(1) When $0 < y_0 < y^*$, $(dF(x)/dx)|_{x=0} < 0$, and $(dF(x)/dx)|_{x=1} > 0$, therefore $x = 0$ is the evolutionary stable strategy. Namely, the production integrator intends to choose "noncooperation" strategy.

(2) When $y^* < y_0 < 1$, $(dF(x)/dx)|_{x=0} > 0$, and $(dF(x)/dx)|_{x=1} < 0$, therefore $x = 1$ is the evolutionary stable strategy. Namely, the production integrator intends to choose "cooperation" strategy.

*3.3.2. Analysis of Game Process of the Modular Supplier.* Similarly, from the replicator dynamic differential equation of the modular supplier $G(y)$, we can know when $x^* = C_B/(U_B - \pi_B + C_B)$ and $G(y)$ is always equal to 0. This indicates that within $[0,1]$ $y$ is always in stable state.

Make $G(y) = 0$; we can get $y = 0$ and $y = 1$ and they are two stable points of the dynamic differential equation.

(1) When $0 < x_0 < x^*$, $(dG(y)/dy)|_{y=0} < 0$, and $(dG(y)/dy)|_{y=1} > 0$, therefore $y = 0$ is the evolutionary stable strategy. Namely, the modular supplier intends to choose "noncooperation" strategy.

(2) When $x^* < x_0 < 1$, $(dG(y)/dy)|_{y=0} > 0$, and $(dG(y)/dy)|_{y=1} < 0$, therefore $y = 1$ is the evolutionary stable strategy. Namely, the modular supplier intends to choose "cooperation" strategy.

*3.3.3. Discussion.* From the replicator dynamics models, we can find that there are five local equilibrium points: $(0,0)$, $(0,1)$, $(1,0)$, $(1,1)$, and $(C_B/(U_B - \pi_B + C_B), C_A/(U_A - \pi_A + C_A))$. According to the method proposed by Friedman, we can analyze the stability of the equilibrium points by analyzing the local stability of the Jacobian matrix of the whole system.

From the partial derivatives of (12) and (13) with respect to $x$ and $y$, we can get the Jacobian matrix:

Table 2: Analysis of equilibrium points.

| The equilibrium point | The determinant of matrix $J$ | Sign | The trace of matrix $J$ | Sign | Result |
|---|---|---|---|---|---|
| $x = 0, y = 0$ | $C_A C_B$ | + | $-(C_A + C_B)$ | − | ESS |
| $x = 0, y = 1$ | $(U_A - \pi_A)(U_B - \pi_B)$ | + | $(U_A - \pi_A) + (U_B - \pi_B)$ | + | Not stable |
| $x = 1, y = 0$ | $C_A C_B$ | + | $C_A + C_B$ | + | Not stable |
| $x = 1, y = 1$ | $(U_A - \pi_A)(U_B - \pi_B)$ | + | $(\pi_A - U_A) + (\pi_B - U_B)$ | − | ESS |
| $x = \frac{C_B}{U_B - \pi_B + C_B} = \frac{C_B}{b\pi - \delta_b \beta}$, $y = \frac{C_A}{U_A - \pi_A + C_A} = \frac{C_A}{a\pi - \delta_a \alpha}$ | $\frac{C_A C_B (U_A - \pi_A)(U_B - \pi_B)}{(U_A - \pi_A + C_A)(U_B - \pi_B + C_B)}$ | + | 0 | | Saddle point |

$$\begin{bmatrix} (1-2x)(yU_A - C_A - y\pi_A + yC_A), x(1-x)(U_A - \pi_A + C_A) \\ y(1-y)(U_B - \pi_B + C_B), (1-2y)(xU_B - C_B - x\pi_B + xC_B) \end{bmatrix}. \tag{16}$$

At each equilibrium point, the determinant and trace of the above Jacobian matrix are shown in Table 2.

There are two stable strategies: "cooperation, cooperation" and "noncooperation, noncooperation." How the production integrator and the modular supplier game and evolve depend on the payoff matrix and initial states?

Firstly, the analysis of the saddle point is important because the saddle point is the threshold point of the system. If an initial state of the system is closer to an equilibrium state, then it is more likely to converge to this point. From the above analysis, we can know that the saddle point of this problem is $x = C_B/(b\pi - \delta_b\beta)$, and $y = C_A/(a\pi - \delta_a\alpha)$. For enterprise $A$, when $x = x^* = C_B/(b\pi - \delta_b\beta)$, we have $dy/dt = 0$ all the time. This indicates that all are in stable states under this condition while $y = 0$ and $y = 1$ are the two stable states when $x \neq C_B/(b\pi - \delta_b\beta)$. It is the same for enterprise $B$.

Secondly, when $x > C_B/(b\pi - \delta_b\beta)$, the expected payoff of enterprise $B$ to "cooperate" minus the expected payoff of enterprise $B$ to "noncooperate" is $E_{C_B} - E_{U_B} = x(U_B - \pi_B + C_B) - C_B > 0$. Therefore, enterprise $B$ will choose to cooperate. And the equilibrium strategy is "cooperation, cooperation."

Thirdly, when $x < C_B/(b\pi - \delta_b\beta)$, the expected payoff of enterprise $B$ to "cooperate" minus the expected payoff of enterprise $B$ to "noncooperate" is $E_{C_B} - E_{U_B} = x(U_B - \pi_B + C_B) - C_B < 0$. Therefore, enterprise $B$ will choose not to cooperate. And the equilibrium strategy is "noncooperation, noncooperation."

According to the symmetry of the game, this analysis can also be applied to enterprise $B$. That means when $y > C_A/(a\pi - \delta_a\alpha)$, the equilibrium strategy is "cooperation, cooperation"; when $y < C_A/(a\pi - \delta_a\alpha)$, the equilibrium strategy is "noncooperation, noncooperation."

## 4. Simulation Analysis

In this section, we use NetLogo software to simulate the dynamic evolutionary model. In a modular production network, there are two types of agents: the production integrator and the modular supplier. The payoff matrix for enterprise $A$ and enterprise $B$ shown in Table 3. By setting the values of parameters in the payoff matrix and simulating the game process of the two agents, we can obtain different evolutionary equilibrium states. In Figures 1, 2, 3, and 4, the two curves, respectively, denote the cooperation fractions of production integrators and modular suppliers. We name these curves $x$ and $y$. They show the replicator dynamics game process and the final evolutionary stable strategies. The population of each agent is 100 and the patches are $100 * 100$.

We suppose in a modular production network the extra payoff $\pi$ both parties can get is 1. Because the production integrator usually works as lead organization in the modular production network, it takes bigger pieces of the extra payoffs. Hence, we suppose the proportion the production integrator and the modular supplier can get is 0.6 and 0.4, respectively. As for the production integrator, we suppose the normal payoff $\pi_A$ it can get is 4. Its initial cost $C_A$ is 0.2. Comparing with the production integrator, the modular supplier is usually smaller in size and production scale. Therefore, the normal payoffs and initial cost of the modular supplier are relatively smaller and we suppose $\pi_B$ is 3 and $C_B$ is 0.1. In addition, we suppose the cooperation willingness of each party is the same and $\delta_a = \delta_b = 0.5$. But the level of effort they put in the cooperation is different due to the different roles they play in the network. Accordingly, we suppose $\alpha$ is 0.6 and $\beta$ is 0.4.

Table 3: The specific payoff matrix for enterprise $A$ and enterprise $B$.

| Enterprise $A$ | Enterprise $B$ | |
|---|---|---|
| | Cooperation ($y$) | Noncooperation ($1 - y$) |
| Cooperation ($x$) | 2.9, 2.3 | 3.8, 3 |
| Noncooperation ($1 - x$) | 4, 2.9 | 4, 3 |

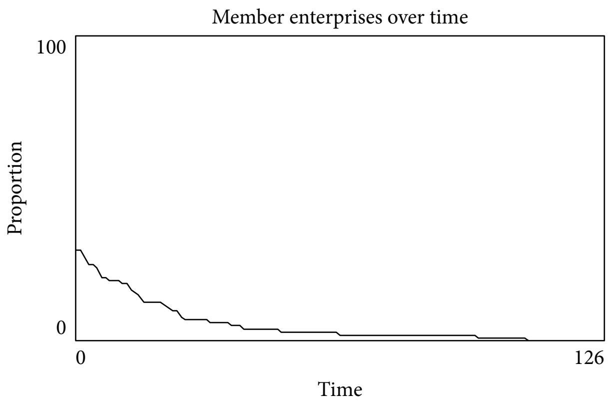


Figure 1: Simulation result for $x_0 = 0.3$ and $y_0 = 0.4$.

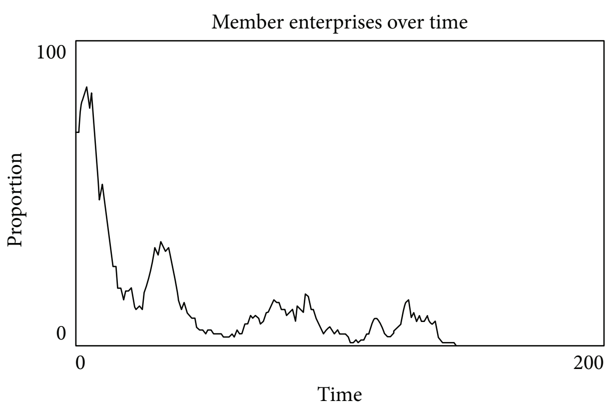


Figure 2: Simulation result for $x_0 = 0.7$ and $y_0 = 0.4$.

By calculation, we can get the payoff matrix, $x^* = 0.5$ and $y^* = 0.67$.

Based on four groups of initial values of $x$ and $y$, we simulate the game process of the modular production network. The horizontal axis is time and the vertical axis is the values of $x$ and $y$. The results are as follows.

(1) We give $x_0 = 0.3$ and $y_0 = 0.4$. That is, $0 < x_0 < x^*$ and $0 < y_0 < y^*$. We can get Figure 1 and the final game result is $x = 0$, $y = 0$. Namely, the evolutionary game strategy of the game subjects is "noncooperation."

(2) We give $x_0 = 0.7$ and $y_0 = 0.4$. That is, $x^* < x_0 < 1$ and $0 < y_0 < y^*$. We can get Figure 2 and the final game result is $x = 0$ and $y = 0$. Namely, the evolutionary game strategy of the game subjects is "noncooperation."

(3) We give $x_0 = 0.7$ and $y_0 = 0.9$. That is, $x^* < x_0 < 1$ and $y^* < y_0 < 1$. We can get Figure 3 and the final game result is $x = 1$ and $y = 1$. Namely, the evolutionary game strategy of the game subjects is "cooperation."

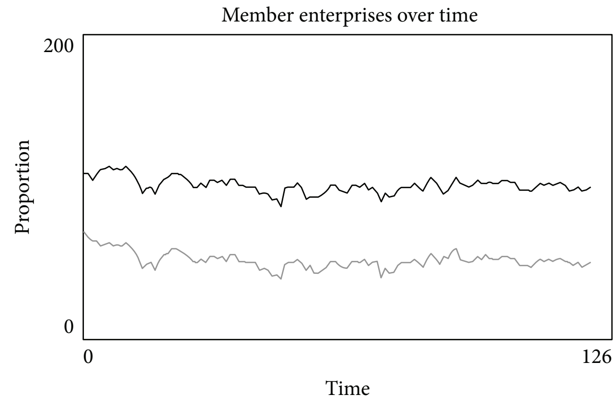


Figure 3: Simulation result for $x_0 = 0.7$ and $y_0 = 0.9$.

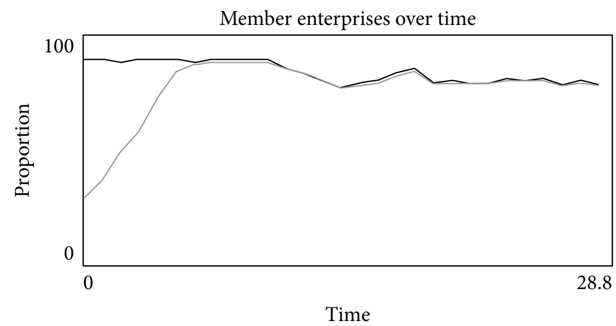


Figure 4: Simulation result for $x_0 = 0.3$ and $y_0 = 0.9$.

(4) We give $x_0 = 0.3$ and $y_0 = 0.9$. That is, $0 < x_0 < x^*$ and $y^* < y_0 < 1$. We can get Figure 4 and the final game result is $x = 1$ and $y = 1$. Namely, the evolutionary game strategy of the game subjects is "cooperation."

## 5. Conclusions

In today's cooperation society, the competition featured as alliances and cooperative network impels major manufacturing enterprises to join global production network to acquire competitive advantages. It is a necessity for these enterprises to take proper cooperative strategies and safeguard the healthy development of the modular production network so that utmost benefits can be obtained. Based on the evolutionary game theory, by analyzing the game process between the bounded rational suppliers and integrators in a modular production network, this paper establishes a dynamic evolutionary game model. By simulating the game model, this paper further verifies the validity of the model. From the results, we can see that, through the evolutionary game between subjects in the modular production network, the final stable equilibrium strategy is related to the cooperative strategies of the subjects and the saddle point. From the expression of the saddle point, we can further know that the saddle point is influenced by the initial cost, the extra payoff, the cooperation willingness of both parties, the cooperation efforts, and the proportion each party can get from the extra payoff. For these variables, what we can be sure of is that the bigger the initial cost, the higher the probability that both sides will choose the initial strategy and not cooperate with each other. The bigger the extra payoff, the more the willingness of both sides to cooperate with each other. Moreover, we can know that an effective incentive and punishment mechanism is useful for coordination in a modular production network. From the model, we can see that the levels of effort $\alpha$, $\beta$ and the proportions each party can get from the extra payoffs $a$, $b$ can decide the initial state and the evolutionary path of the whole system. The motivator, no matter whether it is a positive motivator or a negative motivator, in the premise of fairness, can improve the level of effort of member enterprises in a modular production network. By the increase of information disclosure level, the opportunistic behaviors of member enterprises can greatly be reduced and a sound cooperative atmosphere can be formed. More importantly, proper payoff distribution and cost sharing schemes are critical to guarantee the fairness of decisions in a modular production network. They can not only well motivate member enterprises to take concerted actions and form a good cooperative relationship but also reduce transactional cost and realize the optimization of overall benefits of the modular production network.

## Competing Interests

The author declares no competing interests. The author has no financial and personal relationships with other people or organizations that can inappropriately influence the work.

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