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Research Article

Evolutionary Game Dynamics for Financial Risk Decision-Making in Global Supply Chain

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This paper focuses on the game evolution process and its influencing factors of financial risk cooperation behavior between suppliers and manufacturers in global supply chain system. Using two-population evolutionary game theory, the performance of supply chain members under financial risk environment is modeled. Further, the proposed financial risk game model is applied to simulation cases of global supply chain. Based on the theory analysis and simulation results, it is shown that the cooperation strategy is the optimal evolutionarily stable strategy (ESS) for all supply chain members, when facing the high financial risk. The financial risk-sharing coefficient can be regarded as an adjuster that affects risk ESS of both suppliers and manufacturers under the low financial risk setting. By reducing the financial risk-sharing ratio of one supply chain player, his intention of adopting cooperation strategy would be enhanced. Finally, it is observed that financial risk sharing approach may lead to the alignment among supply chain members. Therefore, setting up an effective financial risk-sharing mechanism is beneficial to realize sustainable development of global supply chain.

1. Introduction

In the wake of the global financial crisis, the world's trend of trade protectionism is rising, which brings lingering weakness to the economic recovery. In order to advance the development of economic globalization, the global supply chains are gradually formed to promote regional economic integration. However, in the complex and ever-changing economic environment, supply chains globalization is vulnerable to various risks because of products variety, market uncertainty, and cooperative relationship vulnerability [1, 2]. Among supply chains risks, financial risk has become increasingly prominent and critical in today's economic world. According to "McKinsey Global Survey Results" [3], the financial volatility is one of top three factors that could influence supply chain strategies. Hence, it is necessary for managers to evaluate the supply chain partnerships when making decisions, under the consideration of financial and economic uncertainty.

Recent researches of supply chains emphasize on the role of collaboration among supply chain members and proposes solutions to reduce financial risks. As Huff and Rogers (2015) pointed out, financial partnerships are important for all members to solve financing dilemma, reduce capital cost, and mitigate risks in supply chain system [4]. The financial partnerships of global supply chain originate from traditional enterprise relations, which is a kind of internal transaction relationship based on the ownership relationship on the premise of "vertical integration" mode [5, 6]. Likewise, Nooraie and Parast (2016) studied the relationship among supply chain risk, supply chain visibility, and supply chain cost [7]. He (2017) analyzed the different supply risk sharing contracts in a closed-loop supply chain system and studied the influence of demand risk reduction on supply chain finance [8].

Many studies have focused on the risk measurement methods. Such as, Liu and Cruz (2012) used the net present value method (NPV) to investigate the effects of

financial risk and economic uncertainty on the optimal supply chain prices, profits, and values [9]. Soni and Kodali (2013) implemented the risk assessment decision of global supply chain by establishing the Pomethee-II model and using target programming tools [10]. Bandaly et al. (2014) developed an integrated risk management model to examine the performance of supply chain at the levels of risk aversion, demand variability, and price volatility [11]. The results showed that low level of risk averse better improves supply chain performance. Zeng and Yen (2017) applied topology theory and Markov chain technology to measure the resilience of supply chain financial risk from the perspective of partnership [12]. Cardoso et al. (2016) proposed a mixed integer linear programming model to measure the financial risk in the design and planning of closed-loop supply chains [13]. Using empirical methodology—analytic hierarchy process AHP, Caniato et al. (2016) analyzed the applications of 14 programs of global supply chain finance, and proposed 9 financial risk evaluation indexes, including economic risk, operational risk, external risk, etc. [14].

The above literature shows that multicriteria risk measurement methods, such as NPV, AHP, and linear programming, the traditional ones, still belong to static analysis methods. However, the response strategy of supply chain members to financial risks is a gradual learning process, which is dynamically changing with time and strategies of the others. In order to gain deeper insight on dynamic change trend of financial risk strategy, this paper applies Evolutionary Game Theory (EGT) to investigate strategy selecting issue. EGT is a good method to study players' interaction behaviors [15, 16], to reflect the relationship between strategy change and payoff fluctuation [17]. Thus, EGT has been applied in many research fields, such as economics, management, military and biology [18–22]. Since EGT has the advantage of dealing with strategy selection which can be naturally used in the field of financial risk decision-making. Based on EGT, the paper focuses on strategic interaction of financial risk: the cooperation strategy and non-cooperation strategy, between suppliers and manufacturers in a global supply chain system. The strategy game of financial risk repeats over a finite time horizon. This problem can be formulated as an evolutionary game model, where each player (supplier or manufacturer) tries to maximize his payoff—the profit.

To the best of our knowledge, there were no works considering the responses of suppliers and manufacturers to financial risk in global supply chain using EGT. The main contributions of the research are twofold. Firstly, the two-population evolutionary game model is proposed for the first time to investigate the cooperation and noncooperation strategies of financial risk problems in global supply chain environment. Secondly, simulation cases under different financial risk scenarios in real application are studied. The results have been analyzed. By identifying the influencing factors, the optimal evolutionarily stable strategies of financial risk have been suggested to enterprises in global supply chain.

2. An Evolutionary Game Model for Financial Risk Relationship

2.1. Model Description. In the global supply chain, due to uncertainty of financial risk, supply chain members have to constantly adjust risk-response strategies; thus the relationships among them play an important role during the decision process. The strategy adjustment can be regarded as a learning process of financial risk. Since evolutionary game theory has the advantage of reflecting the changing process of population's strategies, it can be applied in modeling the likely behaviors of supply chain members in response to financial risk within global supply chain system. Unlike the static game models, evolutionary game theory provides a dynamic framework for players' behaviors. That is, in an evolutionary game, supported by different strategies, players' payoffs are directly influenced by their interaction behaviors. Therefore, the payoffs are fluctuated during the evolutionary game process. The relationship between strategy change and payoff fluctuation can be formulated as an EGT model.

Define the financial risk in terms of the equilibrium of global supply chain over a finite time horizon. As existing studies do not focus on financial risk of global supply chain in this way, we model the problem with EGT. It involves supply chain players coming from two populations: the suppliers and manufacturers, who interact with each other over a period of time and receive rewards. As the objective of each population is to maximize the reward, the players may adjust their strategies accordingly in games. Based on EGT, the paper specifically analyzes how financial risk strategic choices of game players might change over time given different parameters such as financial risk factor, financial risk-sharing coefficient, and cooperation cost. To this end, it needs to describe the behaviors of cooperation or noncooperation between suppliers and manufacturers in global supply chain. The details of the evolutionary game model are described in the following sections.

2.2. Notations. Throughout this study, the subscript "c" denotes cooperation strategy and "n" denotes noncooperation strategy; "s" is for the supplier and "m" is for the manufacturer. Moreover, symbols and notations used in the paper are shown below:

α financial risk factor in global supply chain $\alpha > 0$

$F(\alpha)$ financial risk function of global supply chain

γ financial risk-sharing coefficient $0 < \gamma < 1$

V_s revenue of supplier without considering the financial risk

V_m revenue of manufacturer without considering the financial risk

C_s cooperation cost of supplier who takes the cooperation strategy $0 < C_s < V_s$

C_m cooperation cost of manufacturer who takes the cooperation strategy $0 < C_m < V_m$

Π_{sc} profit of supplier who takes the cooperation strategy

Π_{sn} profit of supplier who takes the noncooperation strategy

Π_{mc} profit of manufacturer who takes the cooperation strategy

Π_{mn} profit of manufacturer who takes the noncooperation strategy

2.3. The Model. Based on its transnational characteristic, global supply chain expends financial risk among members in a greater scale. Thus, the cooperation strategies for sharing financial risk is significant in global supply chain system. However, coordinated development initiatives often complicate supply chain members' decisions and require them to make trade-offs between financial risk impact and business profit. To reflect the process of decision making in practical supply chain system, the factors such as financial risk level, risk-sharing coefficient, cooperation cost, and revenue, which might directly influence risk response strategies have been considered in our model. As the selling of products is not the main focus of this paper, price factor is not taken into account.

In order to describe the influence of financial risk on the performance of global supply chain, define $F(\alpha) = 1 - e^{-\alpha}$ is the financial risk function of global supply chain. This financial risk function is similar to those in Chern et al. (2014) [23] and Wu et al. (2017) [24]. In the model, if both suppliers and manufacturers are willing to cooperate together to defense the financial risk, there exists a financial risk-sharing proportion γ representing the financial risk allocation in supply chain, namely γ is for suppliers and $1 - \gamma$ is for manufacturers. Besides, the cooperation strategy may result in cooperation cost. In another scenario, if one of the participants does not want the cooperation, he has to accept the consequence of financial risk. So, considering the financial risk in the global supply chain, suppliers and manufacturers should face the trade-offs between the cooperation decision and noncooperation decision. In the game model, considering the pure strategies cooperation or noncooperation of each player, different strategy leads to different payoffs. The suppliers and manufacturers are playing the game under bounded rationality. Among the suppliers, some accept the cooperation strategy and some accept the noncooperation strategy. Let x represents the probability of suppliers who accept the cooperation strategy among all suppliers, then 1-x is the probability of suppliers who accept the noncooperation strategy. Similarly, y represents the probability of manufacturers who accept the cooperation strategy among all manufacturers, and 1-y represents the probability of manufacturers who are using the non-cooperation strategy. Because of bounded rationality, players' (suppliers and manufacturers) perception of financial risk is an evolutionary learning process. That is, both suppliers and manufacturers adjust their strategies during the game process. Therefore,$(x, y) \in [0, 1] \times [0, 1]$, which means x and y are changing with players' strategies. Based on the above assumption, the payoff matrix of the game between suppliers and manufacturers is determined in Table 1.

Table 1: The payoff matrix of game between suppliers and manufacturers.

Suppliers	**Manufacturers**	
	Cooperation y	Non-Cooperation 1-y
Cooperation x	Π_{sc1}, Π_{mc1}	Π_{sc2}, Π_{mn2}
Non-Cooperation 1-x	Π_{sn3}, Π_{mc3}	Π_{sn4}, Π_{mn4}

Let $U_{s,coo}$ and $U_{s,non}$ denote the expected payoffs of the suppliers who take different strategies (cooperation or noncooperation, respectively):

$$U_{s,coo} = y\Pi_{sc1} + (1 - y)\Pi_{sc2}, \tag{1}$$

$$U_{s,non} = y\Pi_{sn3} + (1 - y)\Pi_{sn4}, \tag{2}$$

where

$$\Pi_{sc1} = V_s\left[1 - \gamma\left(1 - e^{-\alpha}\right)\right] - C_s, \tag{3}$$

$$\Pi_{sc2} = V_s e^{-\alpha} - C_s, \tag{4}$$

$$\Pi_{sn3} = \Pi_{sn4} = V_s e^{-\alpha}. \tag{5}$$

Equations (3)-(5) are payoff functions, showing the profits of a supplier who takes different strategies. If a supplier adopts the cooperation strategy, his profits can be described as Π_{sc1} or Π_{sc2}, which depends on the strategies of manufacturers. Under the noncooperation strategy, the profits could be $\Pi_{sn3} = \Pi_{sn4}$. Similarly, the mixed strategy expectations of the manufacturers who adopt cooperation or noncooperation strategies can be defined as $U_{m,coo}$ and $U_{m,non}$, respectively.

$$U_{m,coo} = x\Pi_{mc1} + (1 - x)\Pi_{mc3}, \tag{6}$$

$$U_{m,non} = x\Pi_{mn2} + (1 - x)\Pi_{mn4}, \tag{7}$$

where

$$\Pi_{mc1} = V_m\left[1 - (1 - \gamma)\left(1 - e^{-\alpha}\right)\right] - C_m \tag{8}$$

$$\Pi_{mc3} = V_m e^{-\alpha} - C_m \tag{9}$$

$$\Pi_{mn2} = \Pi_{mn4} = V_m e^{-\alpha} \tag{10}$$

Equations (8)-(10) are the payoff functions of a manufacturer who adopts different strategies. Among them, Π_{mc1} and Π_{mc3} depict the profits generated under the cooperation strategy, while Π_{mn2} and Π_{mn4} represent the profits gained under the noncooperation strategy.

Based on the above payoff analysis, the average payoffs of the suppliers ($\overline{U}_s$) and of manufacturers ($\overline{U}_m$) can be determined as follows:

$$\overline{U}_s = xU_{s,coo} + (1 - x)U_{s,non}, \tag{11}$$

$$\overline{U}_m = yU_{m,coo} + (1 - y)U_{m,non}, \tag{12}$$

The replicator dynamic equations of cooperation strategies selected by the suppliers (dx/dt) and by manufacturers (dy/dt) are determined as

$$\begin{aligned}\frac{dx}{dt} &= x\left(U_{s,coo} - \overline{U}_s\right) \\ &= x(1-x)\left[yV_s(1-\gamma)\left(1-e^{-\alpha}\right) - C_s\right],\end{aligned} \tag{13}$$

$$\begin{aligned}\frac{dy}{dt} &= y\left(U_{m,coo} - \overline{U}_m\right) \\ &= y(1-y)\left[xV_m\gamma\left(1-e^{-\alpha}\right) - C_m\right].\end{aligned} \tag{14}$$

Let $dx/dt = 0$ and $dy/dt = 0$, a solution that does not change over time will be a steady-state, equilibrium, or stationary solution.

Any solution pair $(x, y) \in [0,1] \times [0,1]$ for ($dx/dt = 0, dy/dt = 0$) belongs to the evolutionarily stable strategy (ESS), meaning that $x(t)$ and $y(t)$ are not varying over time. Thus, the following solutions can be an ESS:(0,0), (1,0), (0,1), (1,1), and $(x^*, y^*) = (C_m/\gamma V_m(1-e^{-\alpha}), C_s/(1-\gamma)V_s(1-e^{-\alpha}))$, where $0 < C_m/\gamma V_m(1-e^{-\alpha}) < 1$ and $0 < C_s/(1-\gamma)V_s(1-e^{-\alpha}) < 1$.

Using Jacobian matrix (Hofbauer and Sigmund, 1998) [25], ESS values of replicator dynamic system can be obtained:

$$J = \begin{pmatrix} \dfrac{\partial(dx/dt)}{\partial x} & \dfrac{\partial(dx/dt)}{\partial y} \\ \dfrac{\partial(dy/dt)}{\partial x} & \dfrac{\partial(dy/dt)}{\partial y} \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix}, \tag{15}$$

where

$$\begin{aligned} a_{11} &= (1-2x)\left[yV_s(1-\gamma)\left(1-e^{-\alpha}\right) - C_s\right], \\ a_{12} &= (1-2x)V_s(1-\gamma)\left(1-e^{-\alpha}\right), \\ a_{21} &= y(1-y)V_m\gamma\left(1-e^{-\alpha}\right), \\ a_{22} &= (1-2y)\left[xV_m\gamma\left(1-e^{-\alpha}\right) - C_m\right]. \end{aligned} \tag{16}$$

A solution pair from (15) is an ESS, if $\det(J) > 0$ and $\mathrm{tr}(J) < 0$, where

$$\begin{aligned} \det(J) &= a_{11}a_{22} - a_{12}a_{21} \\ &= (1-2x)\left[yV_s(1-\gamma)\left(1-e^{-\alpha}\right) - C_s\right] \\ &\quad \times (1-2y)\left[xV_m\gamma\left(1-e^{-\alpha}\right) - C_m\right] \\ &\quad - (1-2x)V_s(1-\gamma)\left(1-e^{-\alpha}\right) \\ &\quad \times y(1-y)V_m\gamma\left(1-e^{-\alpha}\right) > 0, \\ \mathrm{tr}(J) &= a_{11} + a_{22} \\ &= (1-2x)\left[yV_s(1-\gamma)\left(1-e^{-\alpha}\right) - C_s\right] \\ &\quad + (1-2y)\left[xV_m\gamma\left(1-e^{-\alpha}\right) - C_m\right] < 0. \end{aligned} \tag{17}$$

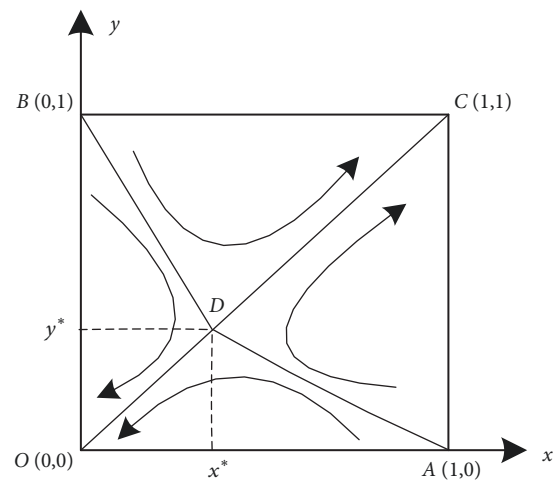

Figure 1: Phase diagram for evolutionary suppliers & manufacturers game.

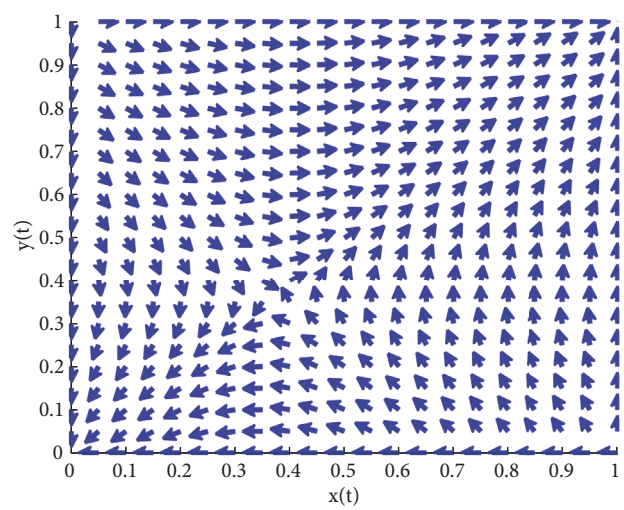

Figure 2: Convergence to ESS for dx/dt and dy/dt.

By calculating, the solutions (0,0), (1,1) are the ESS for both suppliers and manufacturers, corresponding to the strategies (noncooperation, noncooperation) and (cooperation, cooperation), respectively. The equilibrium point (x^*, y^*) is a saddle point.

The two-dimensional phase diagram of the relationship between the replication dynamics and evolution path of suppliers and manufacturers is as shown in Figure 1. Point O and point C represent the game evolutionary stability strategies between suppliers and manufacturers. Point O shows that both of them are not willing to cooperate with each other, while point C indicates the (cooperation, cooperation) strategies are taken by players. In the region OACB of Figure 1, the replicator dynamic system will converge to the Pareto optimal equilibrium points O (0,0) and C (1,1). Based on that, Figure 2 illustrates the evolutionary tendency of strategies between suppliers and manufacturers, and how these strategies converge to ESS in global supply chain system.

2.4. Model Discussion. According to Figure 1, define the area of ADBO as S_{ADBO} and the area of ADBC as S_{ADBC}:

$$S_{ADBO} = \frac{1}{2}\left(\frac{C_m}{\gamma V_m (1-e^{-\alpha})} + \frac{C_s}{(1-\gamma) V_s (1-e^{-\alpha})}\right), \quad (18)$$

$$S_{ADBC} = 1 - S_{ADBO}, \quad (19)$$

where S_{ADBO} represents the evolutionary proportion of (noncooperation, noncooperation) strategy and $S_{ADBC} = 1 - S_{ADBO}$ represents the evolutionary proportion of (cooperation, cooperation) strategy.

Proposition 1. *Among game players (suppliers and manufacturers), the evolutionary probability of selecting strategy pair (cooperation, cooperation) is the same as that of selecting (nocooperation, noncooperation), when $C_m/C_s = \gamma V_m/(1-\gamma)V_s$.*

Proof. When $C_m/\gamma V_m(1-e^{-\alpha}) = C_s/(1-\gamma)V_s(1-e^{-\alpha}) = 1/2$ and $S_{ADBC} = S_{ADBO}$, then $C_m/C_s = \gamma V_m/(1-\gamma)V_s$ is obtained, indicating that the number of cooperative groups is equivalent to that of noncooperative group. Under this condition, the global supply chain system reaches an equilibrium state. □

Proposition 2. *The number of game players (suppliers and manufacturers) who select the strategy pair (cooperation, cooperation) increases with increasing of financial risk factor α.*

Proof. Given the values of C_m, C_s, γ, the influence of financial risk factor α on S_{ADBO} is determined by the following: $\partial S_{ADBO}/\partial\alpha = (1/2)[-\gamma V_m C_m e^{-\alpha}/[\gamma V_m(1-e^{-\alpha})]^2 - (1-\gamma)V_s C_s e^{-\alpha}/[(1-\gamma)V_s(1-e^{-\alpha})]^2] < 0$; thus S_{ADBO} is decreasing with the increase of α. That is, the point D evolves into point O, and (noncooperation, noncooperation) strategy area S_{ADBO} goes to 0, meaning the replicator dynamic system will converge to the evolutionary strategy pair (cooperation, cooperation).

Proposition 2 implies that, through the evolutionary game process, supply chain members grow in the awareness of how detrimental risk can be to a business. As financial risk increases, both suppliers and manufacturers tend to adopt cooperation strategies, which means they can share financial risk with others. For supply chain members, it is an efficient method to reduce their own risk costs. Clearly, the coordination mechanism of global supply chain can largely protect the benefits of its members to a large extent. Therefore, cooperation strategy is the optimal strategy in facing the high level of financial risk. □

Proposition 3. *Financial risk-sharing coefficient γ has the influence on ESS. That is when $\gamma < \gamma^*$, game players (suppliers and manufacturers) tend to select strategy pair (cooperation, cooperation), while $\gamma \geq \gamma^*$ selecting strategy pair (noncooperation, noncooperation).*

Proof. Given the values of C_m, C_s, α, the influence of financial risk-sharing coefficient γ on S_{ADBO} is identified as follows:

$$\begin{aligned}\frac{\partial S_{ADBO}}{\partial\gamma} &= \frac{1}{2}\left[\frac{-C_m}{\gamma^2 V_m (1-e^{-\alpha})} + \frac{C_s}{(1-\gamma)^2 V_s (1-e^{-\alpha})}\right] \quad (20)\\ &= \frac{\gamma^2 (C_s V_m - C_m V_s) + 2\gamma C_m V_s - C_m V_s}{2\gamma^2 (1-\gamma)^2 V_m V_s (1-e^{-\alpha})}.\end{aligned}$$

Because of $\partial^2 S_{ADBO}/\partial\gamma^2 = C_m/V_m(1-e^{-\alpha})\gamma^3 + C_s/V_s(1-e^{-\alpha})(1-\gamma)^3 > 0$, S_{ADBO} reaches the minimum value. Furthermore, from $\partial S_{ADBO}/\partial\gamma = 0$ and based on the fact that $0 < \gamma < 1$, we have a solution $\gamma^* = (C_r V_s - \sqrt{C_r C_s V_r V_s})/(C_r V_s - C_s V_r)$, where $C_s V_r < \sqrt{C_r C_s V_r V_s} < C_r V_s$. When considering that $\gamma < \gamma^*$, $\partial S_{ADBO}/\partial\gamma > 0$ can be obtained, which means that S_{ADBO} is increasing with the increase of γ. Both suppliers and manufacturers have no intention to cooperate with others, thus the optimal strategy pair is (noncooperation, noncooperation). Additionally, in an evolutionary game, the higher financial risk-sharing coefficient means that the fewer participants are willing to undertake the risk. In this situation, the real financial risk often gets overlooked. □

Proposition 4. *Risk-sharing coefficient could adjust the effect of cooperation costs on ESS. That is, when cooperation cost of one player (supplier or manufacturer) is higher, the method of reducing his financial risk-sharing coefficient enhances the intention of adopting cooperation strategy.*

Proof. Take the first derivative of S_{ADBO} with respect to C_m and C_s, respectively. Then $\partial S_{ADBO}/\partial C_m = 1/2\gamma V_m(1-e^{-\alpha}) > 0$ and $\partial S_{ADBO}/\partial C_s = 1/2(1-\gamma)V_s(1-e^{-\alpha}) > 0$ are obtained, indicating S_{ADBO} increases with increasing the values of C_m and C_s. That means that the increased cooperation cost will reduce the cooperation intentions of both suppliers and manufacturers. In global supply chain, to deal with the negative effect of cooperation cost on financial risk cooperation strategy, the interaction effect among cooperation cost, financial risk-sharing coefficient, and financial risk factor should be considered.

Now, let us continue to take the mixed second derivative of $\partial S_{ADBO}/\partial C_m$ with respect to γ, then $\partial^2 S_{ADBO}/\partial C_m \partial\gamma = -V_m(1-e^{-\alpha})/2[\gamma V_m(1-e^{-\alpha})]^2 < 0$ is obtained, which means that the effect of cooperation cost C_m could be counteracted by financial risk-sharing coefficient γ. Hence, the cooperative motivation of one manufacturer is encouraged by decreasing the proportion of financial risk-sharing $1-\gamma$ that he could take. Similarly, take the second derivative of $\partial S_{ADBO}/\partial C_s$ with respect to γ, while $\partial^2 S_{ADBO}/\partial C_s \partial\gamma = V_s(1-e^{-\alpha})/2[(1-\gamma)V_s(1-e^{-\alpha})]^2 > 0$ is obtained. □

Proposition 4 shows that the financial risk-sharing coefficient can be regarded as a lever to adjust strategies among supply chain members. Financial risk of global supply chain represents uncertainty in business capital, inducing the potential inefficiency in supply chain. To deal with such

supply chain risk, suppliers and manufacturers may negotiate the financial risk-sharing ratio. Although the cooperation cost is important in cooperation strategy making, it is not the determining factor. Indeed, by setting different financial risk-sharing ratios, most loss of the cooperation cost could be compensated. For instance, if the supplier is not willing to cooperate with the manufacturer due to high cooperation cost, reducing supplier's financial risk-sharing ratio is an efficient way to promote him to adopt the cooperation strategy. This result is quite useful to those who are striving for potential cooperators.

Proposition 5. *Financial risk factor is the key factor in the decision making of ESS. That is, when financial risk factor is much higher than a general level, the game players (suppliers and manufacturers) tend to cooperate with each other, regardless of the cooperation costs.*

Proof. Take the mixed second derivatives of $\partial S_{ADBO}/\partial C_m$ and $\partial S_{ADBO}/\partial C_s$ with respect to α, then $\partial^2 S_{ADBO}/\partial C_m \partial\alpha = -\gamma V_m e^{-\alpha}/2[\gamma V_m(1-e^{-\alpha})]^2 < 0$ and $\partial^2 S_{ADBO}/\partial C_s \partial\alpha = -(1-\gamma)Ve^{-\alpha}/2[(1-\gamma)V_s(1-e^{-\alpha})]^2 < 0$ are obtained. □

Proposition 5 indicates that the influence of cooperation costs on cooperation strategy is affected by financial risk factor α. When the cooperation cost becomes higher, the cooperation strategy is not desired for players (suppliers or manufacturers); thus evolutionary consequence reflects the most of them select the noncooperation strategy. But when the financial risk of supply chain system is getting large, the result of evolution learning for players is to make cooperation decision defending against financial risk. These results can be explained by the prospect theory. According to the prospect theory, most supply chain members are risk-averse when facing profits. For them, a loss is more significant than the equivalent gain. That is the natural response to decision making in a risky environment. Furthermore, increasing complexity and uncertainty in global supply chains has increased the awareness of financial risk prevention. In evolutionary game process, more and more supply chain members realize that the losses incurred from high financial risk are much larger than the losses from cooperation cost. Therefore, the optimal strategy for avoiding high financial risk is to cooperate with other supply chain members while ignoring cooperation cost.

3. Application Analysis

3.1. Evolution of Cooperation Tendency. To test the performance of evolutionarily stable strategies, a series of numerical experiments are carried out for a global supply chain system with several groups of suppliers and manufacturers. Experiment results are obtained by solving the replicator dynamics equation with simulation method. The objective of the section is to observe the cooperation tendency of financial risk-avoidance between suppliers and manufacturers in global supply chain. For this purpose, we set up a simulation model with several cases. The ranges for parameter values can be determined in Section 2.2 Notations, which follow a general case. A sample of 30 cases randomly generated with parameter values drawn from uniform distributions as $\alpha \sim U(0,10)$, $\gamma \sim U(0,1)$, $V_s \sim U(500,1000)$, $C_s \sim U(100,300)$, $V_m \sim U(800,1000)$, and $C_m \sim U(100,400)$. Based on ESS points (0,0), (1,0), (0,1), and (1,1), simulation results of 30 cases can be classified into four ESS scenarios. Because of space limitation, the details of simulation result for each case will not be dealt with here. Instead, we select one typical case of data from each ESS scenario to reflect the reality in dynamic supply chain processes; see Table 2.

Table 2: The values of simulation parameters.

Group	V_s	C_s	V_m	C_m	α	γ	x_0	y_0
a	565.3700	153.2614	816.3512	172.1097	9.3	0.7	0.40	0.25
b	803.0890	293.9142	830.1306	229.5534	2.1	0.3	0.55	0.35
c	559.8886	245.0529	991.3945	111.0592	1.6	0.9	0.35	0.55
d	808.9951	195.5853	813.6293	367.8652	0.2	0.8	0.45	0.65

Considering a global supply chain game model with four groups of players, each group has one supplier and one manufacturer. The parameters, as shown in Table 2, in the following simulation experiments are mainly determined by dx/dt and dy/dt. The simulation results are displayed in Figures 3(a)-3(d). The parameters x and y are the probabilities used to describe the cooperation tendency between suppliers and manufacturers. After setting initial values of x_0 and y_0, the cooperation tendency of financial risk defense can then be simulated by using the replicator dynamic (13) and (14). The simulation experiments were realized by the computing software of MATLAB R2014b.

Figure 3 reflects the proportion trend of game players by selecting the cooperation strategy, where the solid lines represent the cooperation tendency of suppliers and the dotted lines represent manufacturers' cooperation tendency. The results of simulation experiments are showed in cases (a)-(d). Each case is conducted in 300 simulations, after that the replicator dynamic system converges to a certain ESS. For instance, in case (a), the replicator dynamic system converges to the ESS (1,1) for both suppliers and manufacturers with a high value of financial risk $\alpha = 9.3$. In case (d), both suppliers and manufacturers are not willing to cooperate with each other, and the replicator dynamic system converges to the ESS (0,0). This is because that the value of financial risk is very low ($\alpha = 0.2$), and the cooperation costs of players are relatively higher ($C_s = 195.5853, C_m = 367.8652$). The players do not want to defend against a low financial risk with a high cost, thus (noncooperation, noncooperation) is the optimal strategy. In the other two cases, however, players tend to have different strategies from each other. For instance, in case (b), the replicator dynamic system converges to the ESS (1,0), meaning the cooperation strategy is selected by suppliers and the noncooperation strategy is for manufacturers. Conversely, the ESS (0,1) is converged in case (c), representing suppliers do not desire to cooperate, while manufacturers want to do that. As we can see from Table 2, the financial risk-sharing coefficient is the key factor that could affect simulation results. In case (b), the value of financial risk-sharing coefficient is $\gamma = 0.3$

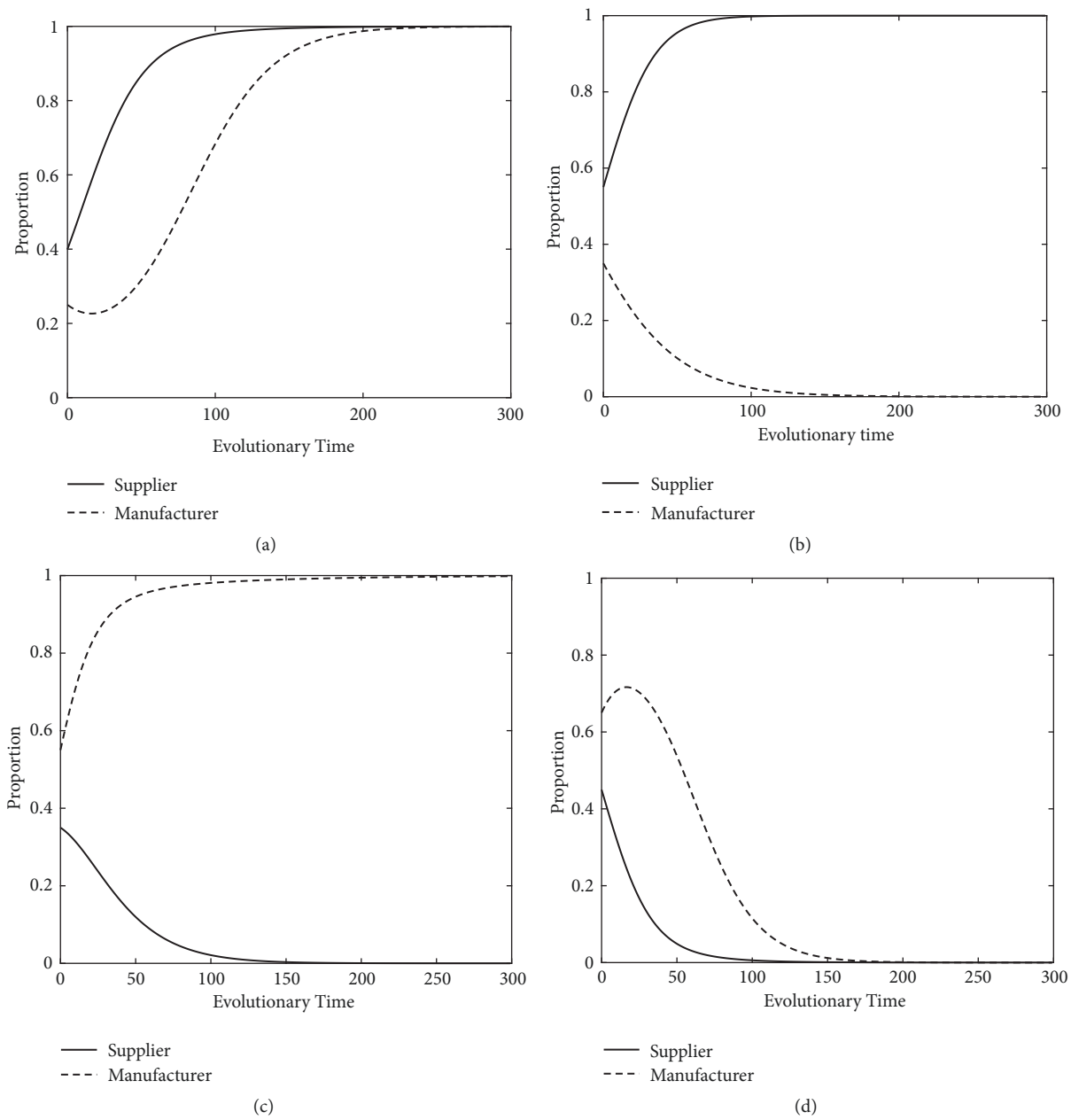

Figure 3: The evolutionary processes (a-d).

for suppliers and is $1 - \gamma = 0.7$ for manufacturers, meaning that manufacturers will undertake more financial risk than suppliers. It is less profitable to manufacturers and therefore the non-cooperation strategy is selected. In the opposite case (c), the value of financial risk-sharing coefficient is $\gamma = 0.9$ for suppliers and is $1 - \gamma = 0.1$ for manufacturers, although the system starts with 35% of the suppliers taking cooperation strategy, noncooperation strategy is the final evolutionary result to suppliers.

The experiment results above indicate that both suppliers and manufacturers could work together to resist the financial risk. As a multistakeholder, the behaviors of supply chain members interact with each other, leading to changes in the trend of evolutionary strategies. In practice, an increasing number of international enterprises have adopted cooperation strategies to deal with supply chain financial risk issues, for instance, EG and SIEMENS. Moreover, the financial risk is a key factor influencing cooperation tendency. The financial risk tolerance of the supplier (or manufacturer) is recognized by other supply chain members, which will further affect cooperation strategies.

The model developed in this paper, which is based on the EGT, was successfully implemented to describe the dynamic trend of cooperation strategies among supply chain members. The results can provide better suggestions for preventing and solving financial risk in global supply chain. In order

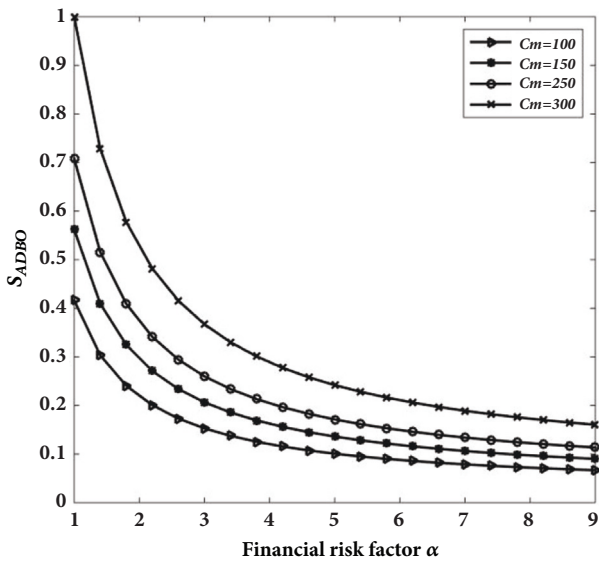

FIGURE 4: The influence of α on S_{ADBO} with different cooperation cost of manufacturer. ($V_s = 308.4436, V_m = 825.9870, C_s = 139.9783, \gamma = 0.8$).

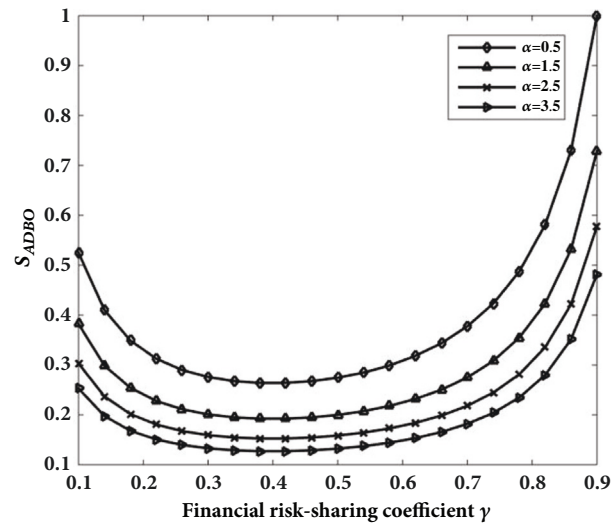

FIGURE 5: The influence of γ on S_{ADBO} with different financial risk factor. ($V_s = 615.3857, V_m = 775.5418, C_s = 285.2986, C_m = 158.0881$).

to further understand the theoretical results discussed in Section 2.4, we will investigate the influence of system parameters on cooperation strategies.

3.2. Influencing Factors of Cooperation Strategy. In this section, a numerical example of simulation study is provided to further understand the theoretical results discussed above. A simulation model based on S_{ADBO} in (18) is conducted with different values of parameters. Simulation results are obtained in the following.

As seen in Figure 4, evolutionary proportion of selecting strategy pair (cooperation, cooperation) is increasing with the increase of financial risk factor α. Given a fixed value of α, the high value of cooperation cost C_m corresponds to the low cooperation proportion (1-S_{ADBO}). However, when α is very large, like $\alpha = 9$, it is optimal for both suppliers and manufacturers to select strategy pair (cooperation, cooperation), whatever the cooperation cost is. This demonstrates Propositions 2 and 5.

Figure 5 illustrates the effects of financial risk factor α and risk-sharing coefficient γ on the evolutionary proportion of cooperation strategy. The simulation result demonstrates Proposition 3. It could be that we actually achieve a minimum of S_{ADBO} at a certain value of γ^* and with different α. Such as $\alpha = 0.5$, $\gamma^* = 0.42$, $S_{ADBO} = 0.2642$; $\alpha = 1.5$, $\gamma^* = 0.42$, $S_{ADBO} = 0.1924$; $\alpha = 2.5$, $\gamma^* = 0.42$, $S_{ADBO} = 0.1526$; and $\alpha = 3.5$, $\gamma^* = 0.42$, and $S_{ADBO} = 0.1273$. Hence, $\gamma^* = 0.42$ is the optimal financial risk-sharing coefficient, at which the proportion of cooperation strategy (1-S_{ADBO}) will reach the maximum. In addition, given a fixed value of γ, the large value of financial risk factor α corresponds to the high cooperation proportion (1-S_{ADBO}).

Figure 6 shows the effects of financial risk-sharing coefficient γ and cooperation cost C_m on the evolutionary

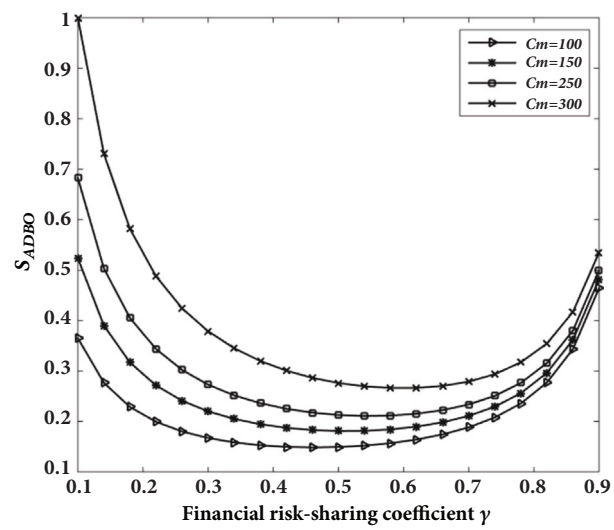

FIGURE 6: The influence of γ on S_{ADBO} with different cooperation cost of manufacturer. ($V_s = 615.3857, C_s = 258.2986, V_m = 775.5418, \alpha = 0.2$).

proportion of cooperation strategy. Risk-sharing coefficient γ can be regarded as an adjuster, which reduces the negative effect of cooperation costs on cooperation strategy. Given the fixed value of C_m, the increase of γ means the lower the financial risk-sharing coefficient $1 - \gamma$ that manufacturers could take, the higher cooperation intention they will have. For instance, see the case of C_m=300, when $\gamma = 0.1$ the proportion of cooperation strategy for players equates 1-S_{ADBO}=0, indicating that no player wants to cooperate with others. However, when the value of γ goes to 0.54, S_{ADBO}=0.2696, the proportion of cooperation strategy increases to 0.7304. Thus, Proposition 4 is demonstrated.

4. Conclusion

Facing the international environment of the global economic integration and information, the financial risk is increasingly fierce in global supply chain system. To deal with this risk, the cooperation relationship of enterprises in global supply chain becomes more significant in today's competitive world. The study proposed an evolutionary game model to effectively evaluate the relationship between suppliers and manufacturers. The payoff matrix of game players under cooperation strategy and noncooperation strategy was analyzed and the replicator dynamic system was established. By solving the replicator dynamic equations, the evolutionarily stable strategies were obtained. Furthermore, simulation experiments were conducted to verify the performance of evolutionary game model. Finally, the theoretical and simulation results indicate that, under a high financial risk scenario, the strategy pair (cooperation, cooperation) is an optimal ESS for all multi-stakeholders. While under a low financial risk scenario, the optimal ESS will vary with the change of cooperation cost of game players. In the game evolution process of ESS, the financial risk-sharing coefficient is the key factor that could adjust the strategies of multistakeholders (suppliers and manufacturers) between different ESS.

The results from both evolutionary game model and numerical analysis have some practical implications. On the one hand, in order to deal with financial risk and potential supply chain inefficiency, suppliers and manufacturers may negotiate the financial risk-sharing contracts to avoid burdening risk loss alone. The supply chain members should enhance the significance of financial risk-resisting ability and set up a long-term cooperative relationship with others in global supply chain system. On the other hand, financial risk-sharing coefficient is an important "adjustment lever" in considering cooperation strategies, especially for the members who have lack of cooperative intentions. Obviously, high level of financial risk could reduce the willingness to fulfill the planned cooperation. Hence, for the supply chain members with low cooperative desire, decreasing their financial risk-sharing ratio is an effective way to promote cooperation. In terms of business practice, it is optimal to establish financial risk-sharing mechanism to minimize the impact of financial risk and achieve a win-win situation in global supply chain.

Data Availability

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

Conflicts of Interest

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

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