Research in Economics and Management
ISSN 2470-4407 (Print) ISSN 2470-4393 (Online)
Vol. 9, No. 4, 2024
www.scholink.org/ojs/index.php/rem

Original Paper

Evolutionary Game Analysis of Knowledge Sharing among Supply Chain Enterprises Considering Incentive Strategy

Zhengtao Han[1]

[1] School of Business, Guangdong Polytechnic, Foshan, China

Received: August 3, 2024 Accepted: September 1, 2024 Online Published: September 30, 2024
doi:10.22158/rem.v9n4p1 URL: http://dx.doi.org/10.22158/rem.v9n4p1

Abstract

This paper aims to explore and enhance the influencing factors which effect the evolution of supply chain knowledge sharing under different incentive strategies. Furthermore, it also helps supply chain managers determine whether incentives are needed and if needed to what extent they are needed to deal with the dynamic changes of factors in the evolution of supply chain knowledge sharing. The evolutionary game model of knowledge sharing without considering incentives is established respectively, and the influence of relevant influencing factors on the evolutionary results of knowledge sharing is analyzed. The results show that enterprises' strategy of selecting knowledge sharing can be attributed to the change by the degree of knowledge complementarity among enterprises when the incentive is not considered. The incentive of supply chain will stimulate knowledge sharing between enterprises but then the incentive coefficient needs to meet certain conditions; can the evolutionary system converge to the state of {knowledge sharing, knowledge sharing}, and the analysis shows that the relationship capital, knowledge's unit value, knowledge sharing cost, knowledge sharing risk and other factors have significant effects on the evolution rate of knowledge sharing. Finally, based on the research conclusions, the countermeasures and suggestions for supply chain knowledge sharing are proposed.

Keywords

supply chain, knowledge sharing, evolutionary game, incentive coefficient, numerical simulation

1. Introduction

Modern enterprises are facing a fierce competition and survival pressure, which requires enterprises to form a supply chain alliance to cope with the complex competitive environment. Therefore, supply chain management has become a global research and application hotspot. Supply chain is not only a logistics, information flow and capital flow connecting suppliers, manufacturers, distributors and customers, but also a knowledge flow, which has become an indispensable part of the supply chain. Knowledge is an important strategic resource for the supply chain to enhance its competitive advantage and continuously improves the relationship between supply chain partners. For a single enterprise, it is impossible to have all the knowledge needed to update its products and services. Enterprises must be clear about the knowledge they need to play a role in the supply chain, so as to interact with the external environment constantly in order to acquire knowledge that cannot be generated internally. After gaining knowledge, apply it to production and operation to ensure enterprises' competitive advantage in the market. Being a part of twenty first century which is greatly an era of knowledge economy, cost-efficiency competition has given way to the competition of knowledge ability and significance of knowledge in supply chain management which means knowledge has increasingly become one of the key factors restricting the overall operation efficiency of supply chain (Cerchione, 2016). Knowledge sharing among supply chain enterprises, essentially knowledge sharing between organizations, can improve the collaborative innovation ability of supply chain, which is the core content of supply chain knowledge management (Craighead, 2009). Lack of knowledge sharing among member enterprises has always been the most important factor in poor performance of supply chain management. Supply chain knowledge sharing has become an important way for enterprises to acquire knowledge from outside. Through knowledge sharing activities, knowledge can flow between supply chain nodes, connect knowledge bases of member companies, re-optimize the allocation of knowledge resources and promote overall affordability of the supply chain (Wu, 2014).

Knowledge sharing among supply chain enterprises is essentially an interaction between knowledge-contributing enterprises and knowledge-receiving enterprises. Enterprises actually play the roles of both knowledge contributors and knowledge recipients. Supply chain member enterprises can not only share their experience or knowledge with other members but can also hope to learn some unknown knowledge from other enterprises. However, sharing knowledge with other enterprises requires certain amount of energy and time along with sharing cost and risk. Knowledge contributors are afraid of losing profits, reducing core competitiveness and unwilling knowledge sharing participation (Zhang, 2012). Consequently, in order to ensure smooth occurrence of knowledge sharing among supply chain enterprises certain incentive measures should be taken for enterprises' encouragement to contribute knowledge actively.

It means that incentive strategies will have an important impact on knowledge sharing among supply chain enterprises. The corresponding incentive policies should be formulated in order to promote knowledge sharing activities of independent enterprises in supply chain. Incentive policy will be affected by many factors in the process of implementation, so the strategic analysis of incentive policy is an important problem for knowledge sharing among supply chain enterprises. Although the importance of incentive strategies for knowledge sharing is being acknowledged but still less is done to reconnoiter in the respective field including the special organization model of supply chain. The research on incentive for knowledge sharing behavior is mostly qualitative analysis, which is a research method based on static perspective, in fact, the decision-making process of knowledge sharing incentives is constantly being adjusted and the static perspective cannot reflect the interactive impact of various influencing factors on the implementation of knowledge sharing incentive strategy. This is insufficient in explaining the development and evolution of knowledge sharing incentive decision-making process. In addition, the current research has ignored the fact that different knowledge sharing incentive levels will produce different incentive effects while supply chain enterprises are facing many challenges and implementation risks arising from the formulation of incentive strategies. Therefore, the evolutionary game theory is introduced in this paper and the evolutionary game models of knowledge sharing in supply chain with and without considering incentives are respectively established including the influence of different incentive levels on knowledge sharing among supply chain enterprises. Moreover, this paper also compares the effects of incentive measures and incentive levels on the results of knowledge sharing behavior in supply chain enterprises, and tries to explore the influencing factors of knowledge sharing behavior in supply chain enterprises and the evolutionary game mechanism of incentive strategies, so as to provide reference for the realization of efficient knowledge sharing in supply chain.

The rest of this paper is organized as follows: The second part is literature review, which analyses the research status of knowledge sharing in supply chain and its influencing factors, incentives for knowledge sharing, and the application of evolutionary game theory in knowledge sharing. The third part is model analysis, which establishes evolutionary game models of knowledge sharing between supply chain enterprises with and without considering incentives respectively and the model analysis of the related factors influencing knowledge sharing is carried out, focusing on how incentive strategies can play a role under the cross-influence of other factors while considering incentives. Fourth part is the numerical analysis which verifies the correctness of the research conclusions in the model analysis of third part through the simulation image. Finally, fifth part is the conclusion of this paper and proposes effective measures to promote knowledge sharing among supply chain enterprises.

2. Model Establishment

2.1 Evolutionary Game Model of Knowledge Sharing in Supply Chain Enterprises without Considering Incentives

Assuming that Enterprise A and Enterprise B are two enterprises in supply chain and both of them have bounded rationality. The knowledge sharing behavior between Enterprise A and Enterprise B is a kind of incomplete information repeated game many times. After long-term imitation, learning and self-adjustment the enterprises eventually achieve a certain state of equilibrium which fully conforms to the characteristics of evolutionary game. This part of study does not consider the existence of incentive mechanism in knowledge sharing. Before constructing the evolutionary game model, the following assumptions must be agreed:

(1) The knowledge of Enterprise A and Enterprise B can be shared, and can be expressed in the form of quantity. a_1 and a_2 respectively represents the amount of knowledge shared by Enterprise A to

Enterprise B and the amount of knowledge shared by enterprise B to Enterprise A, where $a_i(i=1,2)>0$.

(2) Knowledge has attributed value, a certain amount of knowledge corresponds to a certain value, that is, knowledge can be exchanged for corresponding benefits, let k_1 and k_2 represent the knowledge's unit value coefficient of Enterprise A and Enterprise B respectively, where $k_i(i=1,2)>0$.

(3) Before knowledge sharing between Enterprise A and Enterprise B, the enterprise already has a part of the original knowledge stock which has certain value. Let π_1 and π_2 respectively represent the value of the knowledge stock of Enterprise A and Enterprise B before knowledge sharing, where $\pi_i(i=1,2;\pi_i>0)$.

(4) The total revenue of Enterprise A and Enterprise B in the process of knowledge sharing is divided into two parts, one is direct revenue, the other is synergistic revenue.

(5) Direct revenue to the benefits obtained by the knowledge receiving enterprises from enterprises that contribute knowledge in the process of knowledge transfer. The direct revenue is proportional to the willingness of knowledge acceptance $\theta_i(i=1,2,\theta_i>0)$ and the ability of knowledge absorption $r_i(i=1,2,r_i>0)$ of knowledge receiving enterprise. Assuming that the willingness of Enterprise A and Enterprise B to accept knowledge when sharing knowledge is θ_1,θ_2, and the knowledge absorption capacity coefficient is r_1, r_2 respectively. Then, the direct revenue obtained by Enterprise A and Enterprise B in knowledge sharing can be expressed as $k_2r_1\theta_2a_2$ and $k_1r_2\theta_1a_1$ respectively.

(6) Synergy revenue refers to the innovative benefit of knowledge sharing strategy between supply chain enterprises. This is an indirect benefit in the process of knowledge sharing because of the integration of new knowledge and existing knowledge. The synergy revenue of knowledge sharing in supply chain is mainly proportional to two factors. First is the knowledge complementarity between two enterprises; the stronger the knowledge complementarity between the two enterprises is the easier it is to bring greater synergy benefits to shared enterprises both sides. Let the complementarity degree of knowledge of Enterprise B to Enterprise A be f_1, and the complementarity degree of knowledge of Enterprise A to Enterprise B is f_2, $f_i(i=1,2;\ f_i>0)$. Second is the relationship capital between Enterprise A and Enterprise B in the supply chain which is denoted by $h(h>0)$. The higher the relationship capital is, the closer the cooperation between the two enterprises will be. The higher the degree of mutual trust is, the easier the cooperative activities will be carried out. Moreover, the easier the knowledge sharing activities will occur, the greater the synergy revenue of the shared enterprises both sides will be. Therefore, the synergy revenue of knowledge sharing between Enterprise A and Enterprise B can be expressed as $k_1hf_1a_1$ and $k_2hf_2a_2$ respectively.

(7) Enterprise A and Enterprise B need to pay a certain amount of knowledge transfer cost when the knowledge is to be shared. The cost coefficient of knowledge transfer refers to the cost of transferring unit knowledge quantity from knowledge-contributing enterprises to knowledge-receiving enterprises. Let c_1 and c_2 respectively represent the knowledge transfer cost coefficient of Enterprise A and

Enterprise B, then the cost of knowledge sharing of Enterprise A and Enterprise B can be expressed as c_1a_1 and c_2a_2 respectively.

(8) Both Enterprise A and Enterprise B have certain knowledge sharing risks in knowledge sharing, such as core knowledge leakage risks. Let l_1 and l_2 respectively represent the unit knowledge sharing's risk coefficient of Enterprise A and Enterprise B when they share knowledge. The risk cost of Enterprise A and Enterprise B when they share knowledge can be expressed as l_1a_1 and l_2a_2 respectively.

Under the above assumptions, the payment matrix of A and B game of supply chain knowledge sharing enterprises without considering incentives can be obtained as shown in Table 1.

Table 1. Supply Chain Enterprise A, B knowledge Sharing Game Payment Matrix without Considering Incentives

Strategy		Enterprise B	
		Knowledge Sharing	No knowledge sharing
Enterprise A	Knowledge Sharing	$\pi_1 + k_2r_1\theta_2a_2 + k_1hf_1a_1 - l_1a_1 - c_1a_1$ $\pi_2 + k_1r_2\theta_1a_1 + k_2hf_2a_2 - l_2a_2 - c_2a_2$	$\pi_1 - l_1a_1 - c_1a_1$ $\pi_2 + k_1r_2\theta_1a_1$
	No knowledge sharing	$\pi_1 + k_2r_1\theta_2a_2$ $\pi_2 - l_2a_2 - c_2a_2$	π_1 π_2

2.1.1 Partial Equilibrium Analysis of Game Evolution in Enterprise A and Enterprise B

From the game payment matrix in Table 1, it can be calculated that the revenue of Enterprise A's choice of knowledge sharing is as U_{11}, the revenue of no knowledge sharing is as U_{12} and the average revenue is as U_1:

$$U_{11} = y(\pi_1 + k_2r_1\theta_2a_2 + k_1hf_1a_1 - l_1a_1 - c_1a_1) + (1-y)(\pi_1 - l_1a_1 - c_1a_1) \tag{1}$$

$$U_{12} = y(\pi_1 + k_2r_1\theta_2a_2) + (1-y)\pi_1 \tag{2}$$

$$U_1 = xU_{11} + (1-x)U_{12} = xyk_1hf_1a_1 - xl_1a_1 - xc_1a_1 + yk_2r_1\theta_2a_2 + \pi_1 \tag{3}$$

According to benefits from knowledge sharing , benefits from no knowledge sharing and average expectations of Enterprise A in formula (1), (2), (3), the replication dynamic equation of Enterprise A can be obtained as follows:

$$F(x) = \frac{dx}{dt} = x(U_{11} - U_1) = x(1-x)(yk_1hf_1a_1 - l_1a_1 - c_1a_1) \tag{4}$$

Similarly, the replication dynamic equation of Enterprise B can be obtained as follows:

$$G(y) = \frac{dy}{dt} = y(1-y)(xk_2hf_2a_2 - l_2a_2 - c_2a_2) \tag{5}$$

From equations (4) and (5), a replication of dynamic equations can be obtained:

$$\begin{cases} F(x)=\dfrac{dx}{dt}=x(1-x)(yk_1hf_1a_1-l_1a_1-c_1a_1) \\ G(y)=\dfrac{dy}{dt}=y(1-y)(xk_2hf_2a_2-l_2a_2-c_2a_2) \end{cases} \tag{6}$$

Take the derivative of the dynamic system of equations (6), let $\dfrac{dx}{dt}=0$, $\dfrac{dy}{dt}=0$, we can get $(x,y)=(0,0)$, $(x,y)=(1,0)$, $(x,y)=(0,1)$, $(x,y)=(1,1)$, $(x,y)=(M, N)$, where $M=\dfrac{l_2+c_2}{k_2hf_2}$, $N=\dfrac{l_1+c_1}{k_1hf_1}$, when $f_2>\dfrac{l_2+c_2}{k_2h}$, $f_1>\dfrac{l_1+c_1}{k_1h}$, it can be known that the above points are local equilibrium points of the evolutionary game of knowledge sharing between Enterprise A and Enterprise B.

2.1.2 Local Stability Analysis of the Equilibrium Point of Evolutionary Game

Although the four equilibrium points obtained above can make both sides of the game reach equilibrium decision but they can not necessarily be stable. Therefore, the combination of determinant $DetJ$ and trace trJ of Jacobian matrix J is used to further judge the local stability of equilibrium point. The Jacobian matrix J of the evolutionary game at this time is:

$$J=\begin{bmatrix} \partial F/\partial x & \partial F/\partial y \\ \partial G/\partial x & \partial G/\partial y \end{bmatrix}$$

$$=\begin{bmatrix} (1-2x)(yk_1hf_1a_1-l_1a_1-c_1a_1) & x(1-x)k_1hf_1a_1 \\ y(1-y)k_2hf_2a_2 & (1-2y)(xk_2hfa_2-l_2a_2-c_2a_2) \end{bmatrix} \tag{7}$$

The principle of judging the local stability of the equilibrium point by combining the characteristics of determinant $DetJ$ and trace trJ is as follows: when $DetJ>0$ and $trJ<0$ is satisfied, the equilibrium point becomes the local stability point; when $DetJ>0$ and $trJ<0$ is satisfied, the equilibrium point becomes the unstable point, and when $DetJ<0$ and trJ is uncertain, the equilibrium point becomes the saddle point (Young, 1993).

According to the principle of judging the local stability of the equilibrium point, the positivity and negativity of the determinant $DetJ$ and trace trJ of the Jacobian matrix J at each equilibrium point can be obtained. The local stability of the equilibrium points in four different situations can be obtained according to their combined characteristics.

Situation 1: when the degree of mutual knowledge complementarity between Enterprise A and Enterprise B in the supply chain is very low then the total benefit of knowledge sharing between the two enterprises is less than the cost of knowledge sharing and the enterprises are unwilling to share knowledge. The final evolution result of Enterprise A and Enterprise B is {no knowledge sharing, no knowledge sharing}. That is, when $0<f_1<\dfrac{l_1+c_1}{k_1h}$, $0<f_2<\dfrac{l_2+c_2}{k_2h}$ is satisfied , according to the analysis of its local stability, (0,1) and (1,0) are saddle points, (0,0) are stable points, (1,1) is unstable point.

Situation 2: When the degree of knowledge complementarity f_1 of Enterprise B to Enterprise A in supply chain increases to a certain extent, at the same time, the degree of knowledge complementarity f_2 of Enterprise A to Enterprise B is still very low. At this time, although the total benefit of Enterprise A thorough knowledge sharing is greater than the cost of knowledge sharing, it is less than the benefit of "free rider" behavior, after repeated evolutionary games, Enterprise A's willingness to knowledge sharing is obviously reduced, and eventually leads to no knowledge sharing. The final evolution result of Enterprise A and Enterprise B is {no knowledge sharing, no knowledge sharing}. That is, when $f_1 > \frac{l_1+c_1}{k_1 h}$, $0 < f_2 < \frac{l_2+c_2}{k_2 h}$ is satisfied, according to the analysis of its local stability, (1,0) and (1,1) are saddle points, (0,0) are stable points, (0,1) is unstable point.

Situation 3: When the knowledge complementarity f_2 of Enterprise A to Enterprise B increases to a certain extent in supply chain, at the same time, the knowledge complementarity f_1 of Enterprise B to Enterprise A is still very small. This situation is similar to that of situation 2, the final evolution result of Enterprise A and Enterprise B is {no knowledge sharing, no knowledge sharing}. That is, when $0 < f_1 < \frac{l_1+c_1}{k_1 h}$, $f_2 > \frac{l_2}{k_2 h}$ is satisfied, according to the analysis of its local stability, (0,1) and (1,1) are saddle points, (0,0) are stable points, (1,0) is unstable point.

Situation 4: When the degree of complementarity f_i of knowledge between Enterprise A and Enterprise B in supply chain increases to a higher level, the total benefit of knowledge sharing of both sides enterprises is greater than the cost of knowledge sharing. The final evolution result of Enterprises A and Enterprise B is {knowledge sharing, knowledge sharing} or {no knowledge sharing, no knowledge sharing}. That is, when $f_1 > \frac{l_1+c_1}{k_1 h}$, $f_2 > \frac{l_2+c_2}{k_2 h}$ is satisfied, according to the analysis of its local stability and the evolution path diagram as shown in Figure 1 can be obtained by calculation. At this time, (0,0) and (1,1) are stable points, (0,1) and (1,0) are unstable points, and (M, N) is saddle point. The polyline where the three points (0,0), (M, N) and (1,0) are located is the critical boundary of the evolutionary game convergence state in this situation.

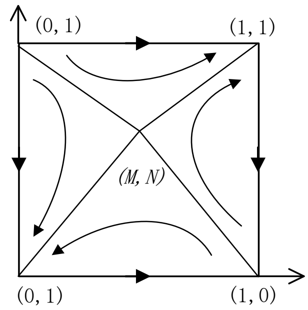

Figure 1. Evolution Path Diagram of Situation 4

The above results show that: in the process of knowledge sharing in supply chain, the degree of mutual knowledge complementarity between enterprises will affect the evolution of their knowledge sharing. When the degree of mutual knowledge complementarity is too low, knowledge sharing will not be carried out; when one enterprise has high knowledge complementarity in another and the other one has low knowledge complementarity in the other, then as a result both of them will not share knowledge. Knowledge sharing occurs when mutual knowledge complementarity is high which is also related to the initial probability value of willingness towards knowledge sharing.

2.1.3 Effect of Parameters on Evolution Results in Situation 4

When the mutual knowledge complementarity between Enterprise A and Enterprise B is high, that is, $f_1 > \frac{l_1+c_1}{k_1 h}$, $f_2 > \frac{l_2+c_2}{k_2 h}$ is satisfied. As shown in Figure 4, the final evolution result of the two enterprises can be either {knowledge sharing, knowledge sharing} or {no knowledge sharing, no knowledge sharing}. As for the specific convergence result, it is determined by the area of the corresponding quadrilateral below the critical line: when the area of the quadrilateral above the broken line equals the area of the quadrilateral below, then the probability of convergence is equal. When the area of the quadrilateral above the broken line is larger than the area of the quadrilateral below, then the probability of convergence to {knowledge sharing, knowledge sharing} is larger. When the quadrilateral area above the polyline is less than the quadrilateral area below, then the probability of convergence {no knowledge sharing, no knowledge sharing} is larger. Let the area of the quadrangle below the broken line be s and the factors affecting the size of s will be analyzed below to judge how various factors affect the evolution results in situation 4.

Easy to know:

$$s = \frac{1}{2}(M+N) = \frac{1}{2}\left(\frac{l_2+c_2}{k_2 h f_2} + \frac{l_1+c_1}{k_1 h f_1}\right) \tag{8}$$

It can be seen from the observation of (8) that the factors affecting the area are l_1, l_2, f_1, f_2, k, h. Further, the partial derivatives of s to f_1, f_2, k, h l_1, l_2 are obtained separately and $\frac{\partial s}{\partial f_i} < 0$, $\frac{\partial s}{\partial k_i} < 0$, $\frac{\partial s}{\partial h} < 0$, $\frac{\partial s}{\partial l_i} > 0$, $\frac{\partial s}{\partial c_i} > 0$ can be obtained. From the results, it is known that s is the minus function of f_i, k_i, h, and s is the increase function of l_i and c_i. It means that when the degree of knowledge complementarity f_i between Enterprise A and Enterprise B and knowledge's unit value coefficient k_i and relational capital h between Enterprise A and Enterprise B increase, s decreases, indicating that the probability of the evolution convergence of Enterprise A and Enterprise B to {no knowledge sharing, no knowledge sharing} decreases. While when the cost coefficient l_i and the risk cost coefficient c_i of knowledge sharing increase, s also increases, at this time, the probability of the convergence of Enterprise A and Enterprise B to {no knowledge sharing, no knowledge sharing} also increases.

Therefore, as the degree of mutual knowledge complementarity f_i between Enterprise A and Enterprise B, knowledge's unit value coefficient k_i and relational capital h increase, the probability that neither Enterprise A nor Enterprise B will share knowledge decreases. However, with the increase of knowledge transfer cost coefficient l_i and knowledge sharing risk cost coefficient c_i, the probability of neither Enterprise A nor Enterprise B conducting knowledge sharing increases.

2.2 Evolutionary Game Model of Knowledge Sharing in Supply Chain Enterprises with Considering Incentives

In the real process of knowledge sharing in the supply chain, enterprises are often prone to no positive phenomena and "free riders". This is due to the lack of incentives in supply chain which greatly reduces the enthusiasm and initiative of enterprises to participate in knowledge sharing. The presence of knowledge sharing in supply chain needs to be guaranteed by a sound incentive strategy. In fact, supply chain gives incentives to those enterprises which actively share knowledge, it does not only bring benefits to enterprises which actively contribute knowledge but also enable the knowledge sharing behavior to improve the overall performance of the supply chain. Therefore, in order to ensure the smooth development of knowledge sharing among enterprises in the supply chain it is necessary to formulate certain incentive measures in the supply chain knowledge sharing. The research in this part will consider introducing incentive strategies into the evolutionary game model of supply chain knowledge sharing.

Assume that the supply chain gives certain incentives to enterprises which actively contribute knowledge. The amount of incentives is determined by the product of the amount of knowledge contributed and the incentive coefficient. Let's suppose, supply chain gives the same incentive coefficient to both enterprise A and enterprise B, both of which are $e(e>0)$, then the incentives for enterprise A and enterprise B in knowledge sharing are ea_1 and ea_2 respectively. Suppose, other assumptions of the evolutionary game system of supply chain knowledge sharing with considering incentives are the same as those without considering incentives, we can get that: When both Enterprise A and Enterprise B carry out knowledge sharing then their benefits are $\pi_1 + kr_1\theta_2 a_2 + khf_1 a_1 - l_1 a_1 + ea_1$ and $\pi_2 + kr_2\theta_1 a_1 + khf_2 a_2 - l_2 a_2 + ea_2$ respectively. When both Enterprise A and Enterprise B do not share knowledge, the benefits are π_1 and π_2 respectively; When Enterprise A conducts knowledge sharing but Enterprise B does not, the benefits are $\pi_1 - l_1 a_1 + ea_1$ and $\pi_2 + kr_2\theta_1 a_1$ respectively. When Enterprise A does not carry out knowledge sharing, but Enterprise B carries out knowledge sharing, the benefits are $\pi_1 + kr_1\theta_2 a_2$ and $\pi_2 - l_2 a_2 + ea_2$ respectively. In this way, the game payment matrix of supply chain knowledge sharing between Enterprise A and Enterprise B with incentives can be obtained, as shown in Table 2.

Table 2. Game Payment Matrix of Supply Chain Knowledge Sharing Enterprise A and Enterprise B with Considering Incentives

Strategy		Enterprise B: Knowledge Sharing	Enterprise B: No knowledge sharing
Enterprise A	Knowledge Sharing	$\pi_1 + k_2 r_1 \theta_2 a_2 + k_1 h f_1 a_1 - l_1 a_1 - c_1 a_1 + e f_1 a_1$	$\pi_1 - l_1 a_1 - c_1 a_1 + e a_1$
		$\pi_2 + k_1 r_2 \theta_1 a_1 + k_2 h f_2 a_2 - l_2 a_2 - c_2 a_2 + e f_2 a_2$	$\pi_2 + k_1 r_2 \theta_1 a_1$
	No knowledge sharing	$\pi_1 + k_2 r_1 \theta_2 a_2$	π_1
		$\pi_2 - l_2 a_2 - c_2 a_2 + e a_2$	π_2

2.2.1 Evolutionary Game Model with Considering Incentives

Under the condition that Enterprise B chooses the mixed game, after n repeated games, it can be known that the profit of Enterprise A that has been carried out knowledge sharing is:

$$y(\pi_1 + k_2 r_1 \theta_2 a_2 + k_1 h f_1 a_1 - l_1 a_1 - c_1 a_1 + e f_1 a_1) + (1-y)(\pi_1 - l_1 a_1 - c_1 a_1 + e a_1) \tag{9}$$

It can be also concluded that benefits of Enterprise A has not been engaged in knowledge sharing is as follows:

$$y(\pi_1 + k_2 r_1 \theta_2 a_2) + (1-y)\pi_1 \tag{10}$$

In the same way, with incentives, the replication dynamic equation of Enterprise A is as follows:

$$F(x)' = \frac{dx}{dt} = x(1-x)(y k_1 h f_1 a_1 + e a_1 - l_1 a_1 - c_1 a_1) \tag{11}$$

Similarly, with incentives, the replication dynamic equation of Enterprise B is as follows:

$$G(y)' = \frac{dy}{dt} = y(1-y)(x k_2 h f_2 a_2 + e a_2 - l_2 a_2 - c_2 a_2) \tag{12}$$

A dynamic replication equation (13) is obtained from equations (10) and (11):

$$\begin{cases} F(x)' = \dfrac{dx}{dt} = x(1-x)(y k_1 h f_1 a_1 + e a_1 - l_1 a_1 - c_1 a_1) \\ G(y)' = \dfrac{dy}{dt} = y(1-y)(x k_2 h f_2 a_2 + e a_2 - l_2 a_2 - c_2 a_2) \end{cases} \tag{13}$$

When there are incentives, the local equilibrium points of evolutionary game of knowledge sharing between Enterprise A and Enterprise B are as follows: $(x,y)=(0,0)$, $(x,y)=(1,0)$, $(x,y)=(0,1)$, $(x,y)=(1,1)$, $(x,y)=(M', N')$, where $M' = \dfrac{l_2 + c_2 - e}{k_2 h f_2}$, $N' = \dfrac{l_1 + c_1 - e}{k_1 h f_1}$.

And the Jacobian matrix with incentives will become J':

$$J' = \begin{bmatrix} (1-2x)(yk_1hf_1a_1+ea_1-l_1a_1) & x(1-x)k_1hf_1a_1 \\ y(1-y)k_2hf_2a_2 & (1-2y)(xk_2hf_2a_2+ea_2-l_2a_2) \end{bmatrix} \tag{14}$$

2.2.2 Analysis of Evolutionary Equilibrium Conditions of Enterprise A and Enterprise B Considering Incentives

When the magnitude of the excitation coefficient e changes, the evolutionary equilibrium results of the two enterprises also change. Similarly, it is easy to calculate the symbols of determinant $DetJ$ and trace TrJ of Jacobian matrix J' in the presence of incentives considering the following three situations and then judging them according to the principle of local equilibrium of evolutionary game. The specific results are shown in Table 3. The evolutionary equilibrium results of the three situations are as follows:

Table 3. Local Stability Analysis of the Equilibrium Point of Evolutionary Game between Enterprise A and Enterprise B When Considering Incentives

Equilibrium point	$0<e<min\{l_1+c_1-k_1hf_1,l_2+c_2-k_2hf_2\}$			$max\{l_1+c_1-k_1hf_1, l_2+c_2-k_2hf_2\}<e<min\{l_1+c,l_2+c_2\}$			$e>max\{l_1+c,l_2+c_2\}$		
	DetJ	TrJ	Result	DetJ	TrJ	Result	DetJ	TrJ	Result
(0,0)	+	-	ESS	+	-	ESS	+	+	Unstable point
(0,1)	-	N	Saddle point	+	+	N	-	N	Saddle point
(1,0)	-	N	Saddle point	+	+	Unstable point	-	N	Saddle point
(1,1)	+	+	Unstable point	+	-	ESS	+	-	ESS
(M’,N’)	-	0	Saddle point	-	0	Saddle point	-	0	Saddle point

Situation 5: When the incentives given to enterprises with active knowledge contribution are set small, the incentive strategy does not play any role. That is to say, if the incentive coefficient e is small and meets $0<e<min\left\{l_1+c_1-k_1hf_1,l_2+c_2-k_2hf_2\right\}$, the final evolution result of the two enterprises is {no knowledge sharing, no knowledge sharing}. This shows that it does not work to promote the participation of enterprises in the supply chain in knowledge sharing when the incentives are too small.

Situation 6: When the incentives given to enterprises with active knowledge contribution are medium, then the incentive strategy may play a certain role. That is, if the incentive coefficient e is medium and meets $max\left\{l_1+c_1-k_1hf_1, l_2+c_2-k_2hf_2\right\}<e<min\left\{l_1+c_1, l_2+c_2\right\}$, the final evolution of the two enterprises may be {knowledge sharing, knowledge sharing}, may also be {no knowledge sharing, no knowledge sharing}, which is similar to the initial conditions, indicating that certain amount of incentives may play a role in promoting the participation of enterprises in the supply chain knowledge sharing.

Situation 7: Incentive mechanism plays an important role when there are more incentives for enterprises to give active knowledge contribution. That is, if the incentive coefficient e is larger to satisfy $e>max\left\{l_1+c_1, l_2+c_2\right\}$, the final evolution result of the two enterprises is {knowledge sharing, knowledge sharing}, which means that generous incentives play a significant role in promoting enterprises to participate in supply chain knowledge sharing.

The above research shows that in the process of knowledge sharing in supply chain, it is very effective for supply chain to give incentives to enterprises which actively contribute knowledge. Appropriate incentives will improve the enthusiasm of enterprises to participate in knowledge sharing. By comparing the local stability with incentives in Table 3 and the local stability in situations 1-4, it can be seen that when there is no incentives enterprises choose not to participate in knowledge sharing to a large extent. When the incentive coefficient is too small, it does not work. If the incentive coefficient is medium, the initial value of the probability of willingness to share knowledge is also dependent on the fact that whether the incentive coefficient is effective or not. Moreover when the incentive coefficient is larger than the sum of knowledge transfer cost coefficient and knowledge sharing risk cost coefficient only then can it be fully effective.

2.2.3 Analysis of the Influence of Parameters on Evolution Rate when Considering Incentive

To make Enterprise A so as always willing to carry out knowledge sharing it is necessary to make Enterprise B choose mixed game, and after n times of repeated game ensure that the income of Enterprise A from knowledge sharing is not less than the expected income when it does not share knowledge, so that the probability of Enterprise B choosing knowledge sharing is not less than N', in other words, $y \geq \frac{l_1+c_1-e}{k_1hf_1}=N'$ is satisfied. Similarly, the condition that B enterprise is always willing to share knowledge is $x \geq \frac{l_2+c_2-e}{k_2hf_2}=M'$. The condition for both Enterprise A and Enterprise B to be willing to share knowledge is: $x \geq M'$ and $y \geq N'$.

Further analysis shows that if one wants to increase the willingness of knowledge sharing in Enterprise A then he/she must minimize the value of N', because this will increase the range of value of y. It is easy to see from the expression of N' that N' is proportional to l_1, c_1 and inversely proportional to k, h and f_1. Therefore, to reduce N' and increase the probability of knowledge sharing it is necessary to reduce l_1, c_1 and increase k_1, h and f_1. This shows that when other conditions remain unchanged, the greater the knowledge transfer cost l_1 and the risk cost c_1 of knowledge sharing of Enterprise A is, the weaker its enthusiasm for knowledge sharing will be. However, when knowledge complementarity f_1, relationship capital h and knowledge's unit value k_1 is larger, then the enthusiasm of Enterprise A for knowledge sharing is stronger. The same conclusion can be drawn for Enterprise B.

Therefore, when there is incentive, the greater the knowledge complementarity f_i, relational capital h and knowledge's unit value k_i of Enterprise A and Enterprise B in the supply chain, the more active the enterprise will be to participate in knowledge sharing, while the higher the knowledge transfer cost coefficient l_i and knowledge sharing risk cost coefficient c_i is, the weaker the enthusiasm of enterprises to participate in knowledge sharing will be.

3. Numerical Analysis

3.1 Simulation Analysis of the Influence of the Change of Incentive Coefficient e on the Results of Evolutionary Stability

This section further verifies the influence of parameters in the above conclusions on the supply chain knowledge sharing in the presence of incentives. It is going to use Mat lab software to simulate the evolutionary game process under the variation of various parameters. The initial values of various parameters are set as flows: l_1=0.3, l_2=0.3, c_1=0.2, c_2=0.1, f_1=0.3, f_2=0.2, a_1=20, a_2=10, k_1=1, k_2=2, h=0.6, e=0.8.

(1) To verify the situation 5, take e as 0.3, that is to say, when $0<e<min\{l_1+c_1-k_1hf_1$ $l_2+c_2-k_2hf_2\}$ is satisfied, it can be seen from Figure 5: when the evolution time reaches 3, the final probability of knowledge sharing between Enterprise A and Enterprise B tends to zero, which indicates that the final evolution stability result of Enterprise A and Enterprise B is {no knowledge sharing, no knowledge sharing}.

(2) To verify the situation 6, take e as 0.5, that is, when $max\{l_1+c_1-k_1hf_1, l_2+c_2-k_1hf_1\}<e<$ $min\left\{l_1+c_1, l_2+c_2\right\}$ is satisfied, the final evolutionary stability result of the Enterprise A and Enterprise B is {knowledge sharing, knowledge sharing} or {no knowledge sharing, no knowledge sharing}, specifically related to the initial value. As can be seen from Figure 6: When the initial probability combination value of knowledge sharing selected by Enterprise A and Enterprise B is (0.4,0.6) and when the evolutionary time reaches 40, the final probability of knowledge sharing by Enterprise A and Enterprise B both tends to 1, which indicates that the final evolution of Enterprise A and Enterprise B is stable to {knowledge sharing, knowledge sharing}. When the initial combination value of knowledge sharing selected by Enterprise A and Enterprise B is (0.6,0.4), it can be seen from Figure 7 that: when the evolutionary time reaches 40, the final probability of knowledge sharing between Enterprise A and

Enterprise B tends to 0, indicating that the final evolutionary constant result of Enterprise A and Enterprise B is {no knowledge sharing, no knowledge sharing}.

(3) To verify the situation 7, take e as 0.8, that is, when $e > max\{l_1+c_1, l_2+c_2\}$ is satisfied, it can be seen from Figure 8 that when the evolution time reaches 3, the final probability of knowledge sharing between Enterprise A and Enterprise B both tends to 1, indicating that the final evolutionary stable result of Enterprise A and Enterprise B is {knowledge sharing, knowledge sharing}.

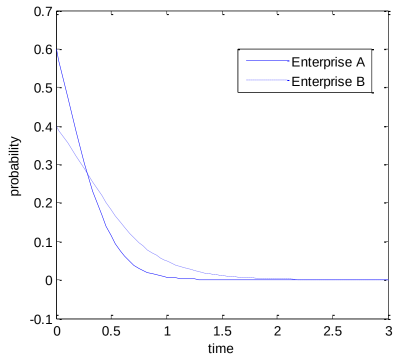

Figure 2. Evolutionary Game Diagram when e=1

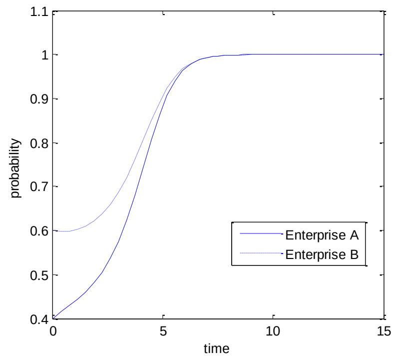

Figure 3. Evolutionary Game Diagram When e=0.28 with Initial Value Point

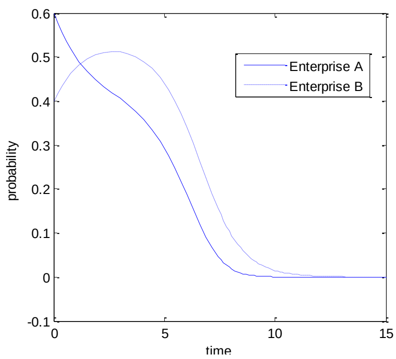

Figure 4. Evolutionary Game Diagram When e=0.28 with ***initial value point is(0.4,0.6)***

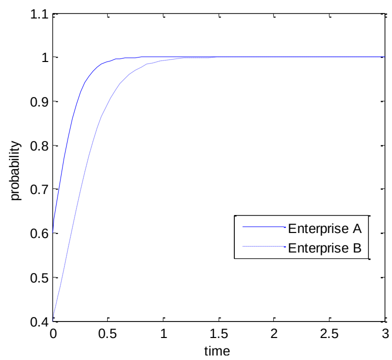

Figure 5. Evolutionary Game Diagram When e=0.7

3.2 Simulation Analysis of the Influence of Various Parameters on Evolutionary Game Rate Considering Incentives

In order to further verify the influence of various parameter value changes on the system evolutionary stability equilibrium results while considering incentives in Section 3.3, the initial value of other parameters in Section 3.1 is kept unchanged and each parameter is changed to observe the influence of its changes on the final evolutionary stability results of Enterprise A and Enterprise B. As a result specific simulation results are as follows, the blue curve represents evolution image of the two enterprises

(Enterprise A and Enterprise B) before the parameter has changed and the red curve represents evolution image of the two enterprises (Enterprise A' and Enterprise B')after the parameter has changed.

3.2.1 Simulation Analysis of the Influence of k_i on Evolutionary Game Rate

Keep the values of the parameters other than k in Section 3.1 unchanged, increase k_1 from 1 to 2, and increase k_2 from 2 to 4. As can be seen from Figure 9 that the coincidence time of two red curves tends to 1 is faster than that of two blue curves and the increase of k leads to a significant acceleration of the evolutionary game rate, indicating that the increase in knowledge's unit profit of enterprise will promote the motivation of enterprises to share knowledge. This shows that the greater knowledge's unit knowledge value of enterprise is, the greater the value knowledge sharing brings to enterprises thus making enterprises more eager to acquire knowledge and more willing to actively participate in knowledge sharing.

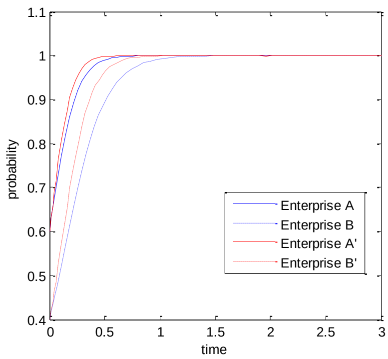

Figure 6. Simulation Results before and after k Change

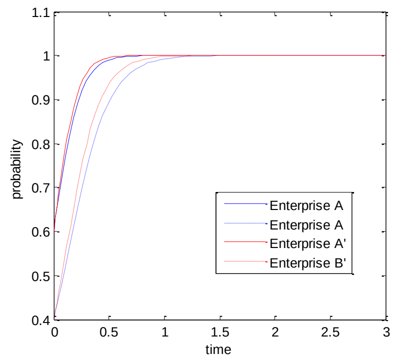

Figure 7. Simulation Results before and after h Change

3.2.2 Simulation Analysis of the Influence of h on Evolutionary Game Rate

Keeping the values of other parameters except h in Section 3.1 unchanged and increasing h from 0.6 to 0.9, as can be seen from the Figure 10: the coincidence time of two red curves tends to be a little faster than that of two blue curves, the increase of h leads to the acceleration of evolutionary game speed, which indicates that the increase of complementarity of knowledge h promotes the motivation of knowledge sharing among enterprises. This is because a high degree of relational capital can enable both sides to build efficient communication mechanism and solve conflicts in time, thus ensuring the smooth progress of knowledge sharing among supply chain members.

3.2.3 Simulation Analysis of the Influence of e on Evolutionary Game Rate

Keep the values of the parameters other than e in Section 3.1 unchanged, and increase e from 0.8 to 0.9. It can be seen from Figure 11 that : the coincidence time of two red curves tends to be 1 faster than that of two blue curves, and that the increase of e leads to an obvious acceleration of evolutionary game rate, indicating that the increase in the knowledge sharing incentive coefficient e will promote the motivation of enterprises to share knowledge. This shows that due to the pursuit of additional benefits, incentives play an active role in knowledge sharing among members of the supply chain and appropriate incentives to enterprises which actively share knowledge will make them more willing to participate in knowledge sharing.

3.2.4 Simulation Analysis of the Influence of f_i on Evolutionary Game Rate

In keeping the other parameters in Section 3.1 unchanged, f_1 is increased from 0.3 to 0.6, and f_2 is increased from 0.2 to 0.4, as can be seen from the Figure 12: the coincidence time of two red dotted line overlap tends to 1 significantly faster than the two blue lines, the increase of f_i leads to the acceleration of evolutionary game speed, indicating that the increase in the degree of mutual knowledge complementarity f_i in knowledge sharing will promote the motivation of enterprises to share knowledge. It shows that when there is a good degree of mutual knowledge complementarity between supply chain enterprises, it is extremely beneficial to promote knowledge sharing between them. Therefore, when knowledge-sharing enterprises in the supply chain have more knowledge that the others does not have, which is more conducive to the collaboration between enterprises, thereby improving the synergy revenue of knowledge sharing.

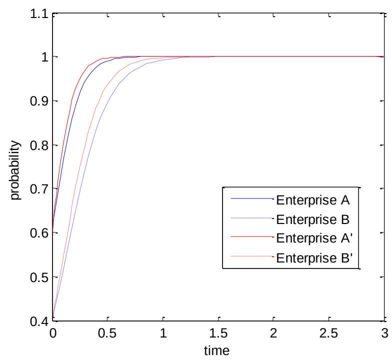

Figure 8. Simulation Results before and after e Change

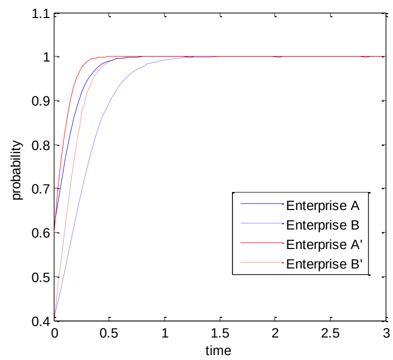

Figure 9. Simulation Results before and after f_i Change

3.2.5 Simulation Analysis of the Influence of c_i on Evolutionary Game Rate

In the situation where the other parameters in Section 3.1 are kept unchanged, when c_1 is increased from 0.2 to 0.3, and c_2 is increased from 0.3 to 0.4, as can be seen from Figure 13：the time when the two red curves coincide with 1 is significantly behind two solid blue lines, the increase of c_i leads to a significant decrease in the rate of evolutionary game, indicating that the higher knowledge sharing transfer cost c_i will seriously dampen the enthusiasm of enterprises for knowledge sharing. This shows that the pursuit of maximizing self-interest is the essence of the enterprise, as the cost of knowledge sharing transfer increases, the benefits acquired by enterprises will be reduced, and the willingness to share knowledge will be significantly reduced. It can be seen that efforts to reduce the cost of knowledge sharing play an important role in attracting more enterprises to participate in supply chain knowledge sharing.

3.2.6 Simulation Analysis of the Influence of l_i on Evolutionary Game Rate

In keeping other parameters constant in Table 8, when l_1 is increased from 0.4 to 0.6 and l_2 is increased from 0.3 to 0.5, as can be seen from the Figure 14: the coincidence time of the two red curves tends to be 1 is obviously behind the two blue curves, the increase of l_i leads to a significant decrease in the rate of evolutionary game, indicating that the higher unit risk cost coefficient of knowledge sharing l_i will seriously hamper the enthusiasm of enterprises for knowledge sharing. This indicates that the risk of knowledge sharing has a hindrance to knowledge sharing behavior. With the increase of the unit knowledge sharing's risk coefficient, knowledge sharing enterprises may face the possibility of losing more core intellectual property rights, so the enthusiasm of participating in knowledge sharing is greatly reduced. Therefore, effectively preventing the risk of knowledge sharing will be more conducive to promote knowledge sharing among supply chain enterprises.

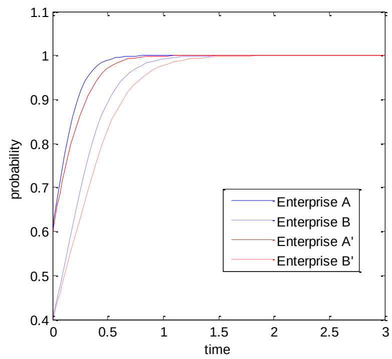

Figure 10. Simulation Results before and after c_i Change

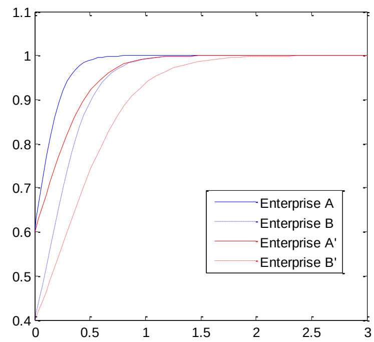

Figure 11. Simulation Results before and after l_i Change

4. Conclusion

This paper uses evolutionary game model to study the process of knowledge sharing among enterprises in supply chain. Without incentive, it showed that the change of mutual knowledge complementarity f_i among enterprises will affect the evolutionary equilibrium strategy of knowledge sharing. It also analyzed the degree of relational capital, knowledge's unit value and knowledge complementarity in Situation 4, which has positive impact on knowledge sharing, while the cost and risk of knowledge sharing has negative impact on knowledge sharing. In reality, in order to avoid the phenomenon that enterprises in the supply chain share knowledge inactively or "free ride", the supply chain needs to give knowledge sharing enterprises a certain sharing incentive. With incentives, the analysis showed that when the supply chain gave certain incentives to knowledge-sharing parties, the willingness to share knowledge among the enterprises is enhanced as compared to the lack of incentives. However, when the incentive coefficient e varied the results affected final evolutionary convergence state of knowledge sharing in supply chain enterprises. When the incentive coefficient is large enough only then enterprises will share knowledge. When the other conditions remain unchanged, the greater the knowledge's unit value, the stronger the knowledge complementarity, the higher the relational capital level among enterprises sharing, the greater the incentive coefficient, the stronger the willingness of enterprises to participate in supply chain knowledge sharing; and the greater the cost and risk of knowledge sharing, the weaker the willingness of enterprises to participate in supply chain knowledge sharing. Finally, Mat lab is used to verify the correctness of the model and numerical results.

In order to further improve the willingness of knowledge sharing between enterprises in the supply chain members, combined with the research results, this paper put forward the following countermeasures and suggestions for supply chain managers: First, be sure to give supply chain enterprise the knowledge contributing necessary incentives and this incentive level should not be too low, otherwise it will not work. When the incentive level is high enough only then it can stimulate the sharing enthusiasm of its knowledge contributors and promote the more efficient transfer and sharing of knowledge in the supply chain. Secondly, to enhance the knowledge's value of enterprise, the higher the value attribute of knowledge, the greater its exchange and sharing value will be, the higher enterprise income of knowledge is the premise to promote knowledge sharing. Third, strive to form heterogeneous knowledge with other enterprises in the supply chain so that the knowledge owned by the enterprises is complementary to others, thus attracting knowledge exchange and sharing. Fourthly, cultivate good mutual relationship among supply chain enterprises, enhance mutual understanding among supply chain enterprises, thereby increasing mutual trust and promoting knowledge sharing. Fifthly, efforts should be made to reduce the cost and risk of knowledge sharing in supply chain and improve the efficiency of knowledge sharing so as to enhance the willingness of enterprises to share knowledge.

Acknowledgements

This paper is a phased research result of Humanities and Social Sciences Youth Foundation, Department of Education of Guangdong Province “Research on the Mechanism and Evolutionary Game of Knowledge Sharing Behavior among Supply Chain Enterprises on Technological Collaborative Innovation” (Project Number: 2020WQNCX139)

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