Evolutionary Game of Supply Chain Alliance Based on Blockchain

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***Abstract*—The combination of blockchain and supply chain is conducive to building a trusted and shared alliance environment. This paper discusses the evolution direction of alliance members in a supply chain under the environment of blockchain network. Income matrix is firstly established and then dynamic equation is obtained. Based on dynamic equation, equilibrium points and Jacobian matrix are derived. Through analyzing the sign of determinant and trace of Jacobian matrix, the stability of equilibrium point is studied. Further, the simulation presents the evolution trajectories of alliance members under different situations. The experimental results show that blockchain has a positive effect on the choice of the strategy and on evolution speed of the alliance. The work will help to develop a supply chain alliance relationship that features openness, sharing, credibility and win-win cooperation.**

Keywords—blockchain, supply chain alliance, stability analysis, evolutionary game

I. INTRODUCTION

The lack of information sharing makes it difficult to obtain the relationship between supply and demand in supply chain. Taking advantage of information asymmetry, some alliance members might take completely selfish behaviors and betray the alliance, which ultimately lead to the collapse of the alliance.

Blockchain is a digital, decentralized and distributed ledger [1], [2]. It provides a tool for solving the problem of information asymmetry. From the technical perspective, blockchain is composed of distributed database, consensus mechanism and cryptography algorithm. From the perspective of economics, blockchain makes new contracts and new transactions. When some laws, regulations, fund management mechanism and other features are added, the blockchain builds a rule-based economic order. Davidson et al. [3] believed that the blockchain system enables all nodes to exchange data freely and securely in a decentralized environment, which avoids human intervention and obtains system autonomy.

Therefore, we integrate the blockchain into the supply chain. But, the overhead of consensus mechanism in blockchain will increase with the increase of transaction data volume. Because there are large amounts of data in supply chain, the service might be inefficient if a single blockchain network is adopted. We propose a supply chain system with the help of cloud platform.

In a real supply chain system, the members are usually in a changing environment and they require to adjust the strategy dynamically. So, a static game model is difficult to adapt to changing business conditions. Using evolutionary game to analyze supply chain is more suitable for market demand. Alchian [4] believed that moderate competition offers the opportunities for evolutionary game. Smith [5] provided the basic concept of evolutionary stability. Since then, evolutionary game has developed rapidly in various fields. And domestic scholars have gradually paid attention to evolutionary game. Cui et al. [6] used evolutionary game theory to discuss the process of limited rational stakeholders participating in enterprise ownership allocation and reaching Nash equilibrium. Yuan et al. [7] developed a dynamic pricing game model of multichannel supply chain, and focused on the impacts of channel competition on the complex. In [8], a general evolutionary game model composed of green sensitive governments, enterprises and consumers is built. The above works [4-8] have not studied the fusion of blockchain and supply chain.

At present, there are few works on the fusion issue. [9] proposed a framework integrating supply chain with blockchain and designed a consensus mechanism to improve system performance; but the paper has not studied economic game and evolution direction of alliance members. Sun et al. [10] aimed to reduce financing risks by analyzing the mechanism of blockchain technology in supply chain finance using the evolutionary game; there is no further discussion on the evolution path under different conditions.

The main contributions of this paper are as follows. (1) In order to solve the problems in the supply chain such as information sharing and dishonest transactions, the blockchain is introduced. In order to improve the efficiency of the blockchain network in processing large-scale data, we introduce cloud storage. (2) The evolutionary game of supply chain alliance based on blockchain is studied. Firstly, the incomes of suppliers and retailers under the cooperation and defection are modeled. Based on the average incomes of suppliers and retailers, a dynamic equation is obtained. Then, the Jacobian matrix is derived from the dynamic equation, and the signs of determinant and trace are discussed. Further, the stability of equilibrium points is obtained. (3) Through the simulation, the impact of the introduction of blockchain on the supply chain is presented. And the evolution processes at different initial values are discussed. Our work will help to understand the evolution of supply chain in the blockchain network, establish a reliable alliance, and promote the healthy development of supply chain.

The remaining of the paper is organized as follows. Section II presents supply chain framework. Section III discusses basic assumptions, model parameters and income matrix. Section IV offers stability analysis of equilibrium game for supply chain based on blockchain. Section V provides simulation experiments. Finally, Section VI concludes our work.

II. Supply Chain Framework

A. The Framework

The supply chain system consists of blockchain network, cloud platform and supply chain alliance. 1) The blockchain provides tamper-proof services. It stores the important transactions and their signature data. 2) Cloud platform provides other services such as the storage of a large number of transaction details. 3) Supply chain alliance has a two-level chain structure and it consists of suppliers and retailers. Suppliers provide raw materials, equipment, energy, labor services, and so on. Retailers buy some goods from suppliers, and then sell the goods to the customers (Fig. 1).

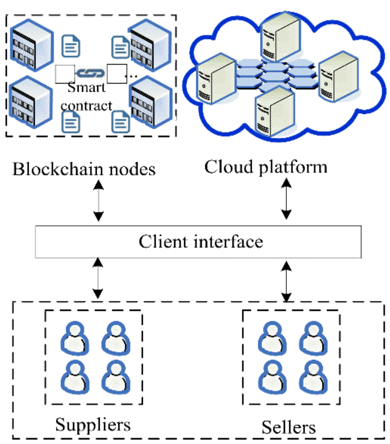

Fig. 1. System framework

When suppliers and retailers publish supply and demand information through the interface, smart contracts on the blockchain execute matching algorithm for suppliers and retailers. Once the matching is successful, the transaction is triggered. Then, the hash value and the signature of the transaction are stored on the blockchain, and the detailed data are stored on the cloud. Next, the transaction is confirmed by verifying whether the signature is correct. If the verification is passed, logistics work begins.

B. Benefits of Blockchain

The distributed storage and cryptography technology in blockchain can ensure that authenticity and integrity of data to prevent some deception activities in supply chain. On the other hand, the submitting to the cloud can reduce the load of blockchain and improve the overall performance of the system. More benefits of introducing blockchain are as follows.

1) Open and fair transaction. In the framework, the transaction is automatically completed by the smart contract. When the supplier and the retailer publish their information to the platform, smart contracts make the matches according to their demands. So, the transaction is open, fair and intelligent.

2) Secure transaction. For an attack on the blockchain, the blockchain network can reach a consensus if the malicious nodes do not exceed 50% in Ethereum or if they do not exceed 1/3 in Hyperledger. In general, there are many nodes in the supply chain system, so it is very difficult to launch the attack.

3) Tamper-proof. For an attack on cloud storage, once the data in the cloud storage is tampered with, it will not match the signature in the blockchain. And the tampering will be found.

But, the introduction of blockchain brings about some changes in the game research of traditional supply chain. So, it is the focus of our research.

III. Game Model

A. Basic Assumptions

The alliance has complex and dynamic behaviors. The assumptions of alliance members are as follows.

Assumption 1. Basic strategy of alliance member is {cooperation, defection}.

Assumption 2. Each member should undertake the construction costs of the alliance, cloud platform and blockchain network.

Assumption 3. When the relationship between supply and demand meets the conditions, the smart contract automatically executes the transaction, which eliminates human intervention.

Assumption 4. If some members betray the alliance, they will be punished. Cooperative members will obtain some rewards from the penalty of defected opponents and additional benefits such as increased goodwill.

B. Model Parameters

According to the above assumptions, we adopt evolutionary game theory to study decision-making of the members in supply chain. The parameters are as follows in Table I.

TABLE I. Model Parameters

Symbol	Description
A_s	Operating income of a supplier
A_r	Operating income of a retailer
V_s	Income of a supplier due to blockchain
V_r	Income of a retailer due to blockchain
α	Cooperation probability of a supplier
β	Cooperation probability of a retailer
R_s	Cooperation income of a supplier
R_r	Cooperation income of a retailer
B_s	Additional income of a supplier due to his increased goodwill
B_r	Additional income of a retailer due to his increased goodwill
D_s	Opportunity income of a supplier due to his defection
D_r	Opportunity income of a retailer due to his defection
F	Financial penalty due to defection
C_t	Total operating cost
θ	Proportion of operating cost undertaken by suppliers

C. Income Matrix

Under the strategies of cooperation and defection, income matrix of supplier and retailer is shown in Table II.

TABLE II. INCOME MATRIX

Members		Retailer: Cooperation (β)	Retailer: Defection (1-β)
Supplier	Cooperation (α)	$A_s + R_s + V_s - C_t * \theta$ $A_r + R_r + V_r - C_t * (1-\theta)$	$A_s + B_s + V_s + F - C_t * \theta$ $A_r + D_r - F$
	Defection (1-α)	$A_s + D_s - F$ $A_r + B_r + V_r + F - C_t * (1-\theta)$	A_s A_r

From Table II, we infer the following results.

The expected cooperation income of a supplier is $U_{s1} = \beta * (A_s + R_s + V_s - C_t * \theta) + (1-\beta) * (A_s + B_s + V_s + F - C_t * \theta)$ The expected defection income of a supplier is $U_{s2} = \beta * (A_s + D_s - F) + (1-\beta) * A_s$.

Therefore, the expected income of a supplier is $U_s = \alpha * U_{s1} + (1-\alpha) * U_{s2}$.

The expected cooperation income of a retailer is $U_{r1} = \alpha * (A_r + R_r + V_r - C_t * (1-\theta)) + (1-\alpha) * (A_r + B_r + V_r + F - C_t * (1-\theta))$ The expected defection income of a retailer is $U_{r2} = \alpha * (A_r + D_r - F) + (1-\alpha) * A_r$.

Therefore, the expected income of a retailer is $U_r = \beta * U_{r1} + (1-\beta) * U_{r2}$.

IV. STABILITY ANALYSIS

Based on the expected incomes, we obtain the dynamic equation of suppliers and retailers. By solving the dynamic equation, we obtain Nash equilibrium points. And Jacobian matrix is also calculated. After analyzing the signs of the determinant and the trace of Jacobian matrix, we obtain the stability conditions about the equilibrium of model.

A. Equilibrium Game

The dynamic equation of evolution game for a supplier is

$$F(\alpha,\beta) = \alpha * (1-\alpha) * (U_{s1} - U_{s2}) = \alpha * (1-\alpha) * [\beta * (R_s - B_s - D_s) + B_s + V_s + F - C_t * \theta].$$

The dynamic equation for a retailer is

$$G(\alpha,\beta) = \beta * (1-\beta) * (U_{r1} - U_{r2}) = \beta * (1-\beta) * [\alpha * (R_r - B_r - D_r) + B_r + V_r + F - C_t * (1-\theta)].$$

Let $F(\alpha,\beta) = 0$, $G(\alpha,\beta) = 0$.

The equilibrium points of the system are

$$X_1 = \begin{pmatrix} 0 \\ 0 \end{pmatrix}, X_2 = \begin{pmatrix} 0 \\ 1 \end{pmatrix}, X_3 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, X_4 = \begin{pmatrix} 1 \\ 1 \end{pmatrix},$$

$$X_5 = \begin{pmatrix} \alpha^* \\ \beta^* \end{pmatrix} = \left(\frac{B_r + V_r + F - C_t * (1-\theta)}{D_r + B_r - R_r}, \frac{B_s + V_s + F - C_t * \theta}{D_s + B_s - R_s}\right)^T.$$

X_1, X_2, X_3 and X_4 are the Nash equilibrium points of pure strategy, and X_5 is the equilibrium point of mixed strategy.

B. Stability analysis

We discuss the stability of the model.

Condition 1. $B_s + V_s + F - C_t * \theta < 0$. For a supplier, the sum of the incomes due to blockchain, increased goodwill and opponent's penalty is less than the alliance costs.

Condition 2. $B_r + V_r + F - C_t * (1-\theta) < 0$. Similar to condition 1, but it is for a retailer.

Condition 3. $R_s + V_s + F - C_t * \theta - D_s > 0$. For a supplier, cooperation income + blockchain income > opportunity benefit by defection - defection fine + operating cost.

Condition 4. $R_r + V_r + F - C_t * (1-\theta) - D_r > 0$. Similar to condition 3, but it is for a retailer.

The Jacobian matrix of dynamic system is $J = \begin{pmatrix} \frac{\partial F}{\partial \alpha} & \frac{\partial F}{\partial \beta} \\ \frac{\partial G}{\partial \alpha} & \frac{\partial G}{\partial \beta} \end{pmatrix} =$

$$\begin{bmatrix} (1-2\alpha) * (\beta * (R_s - B_s - D_s) + B_s + V_s + F - C_t * \theta) & \alpha * (1-\alpha) * (R_s - B_s - D_s) \\ \beta * (1-\beta) * (R_r - B_r - D_r) & (1-2\beta) * (\alpha * (R_r - B_r - D_r) + B_r + V_r + F - C_t * (1-\theta)) \end{bmatrix}$$

If $X_1 = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$,

$$J(X_1) = \begin{pmatrix} B_s + V_s + F - C_t * \theta & 0 \\ 0 & B_r + V_r + F - C_t * (1-\theta) \end{pmatrix}.$$

If $X_2 = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$,

$$J(X_2) = \begin{pmatrix} R_s + V_s + F - C_t * \theta - D_s & 0 \\ 0 & C_t * (1-\theta) - B_r - V_r - F \end{pmatrix}.$$

If $X_3 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$,

$$J(X_3) = \begin{pmatrix} C_t * \theta - B_s - V_s - F & 0 \\ 0 & R_r + V_r + F - C_t * (1-\theta) - D_r \end{pmatrix}.$$

If $X_4 = \begin{pmatrix} 1 \\ 1 \end{pmatrix}$,

$$J(X_4) = \begin{pmatrix} D_s + C_t * \theta - R_s - V_s - F & 0 \\ 0 & D_r + C_t * (1-\theta) - R_r - V_r - F \end{pmatrix}.$$

If $X_5 = \left(\frac{B_r + V_r + F - C_t * (1-\theta)}{D_r + B_r - R_r}, \frac{B_s + V_s + F - C_t * \theta}{D_s + B_s - R_s}\right)^T$

$$J(X_5) = \begin{pmatrix} 0 & \frac{[B_r + V_r + F - C_t * (1-\theta)] * [D_r - R_r - V_r - F + C_t * (1-\theta)] * (R_s - B_s - D_s)}{(D_r + B_r - R_r)^2} \\ \frac{(B_s + V_s + F - C_t * \theta) * (D_s - R_s - V_s - F + C_t * \theta) * (R_r - B_r - D_r)}{(D_s + B_s - R_s)^2} & 0 \end{pmatrix}$$

According to the evolutionary stability theory, when det(J) > 0 and tr(J) < 0, the game has the local stability. Here, det() is matrix determinant and tr() is matrix trace. The computation of det() and tr() of five equilibrium points under different conditions are shown in Table III. X_1 and X_4 are stable points, and their game strategies are {Defection, Defection}, {Cooperation, Cooperation}, respectively. X_2 and X_3 are unstable equilibrium points, and their corresponding strategies are{Cooperation, Defection}, {Defection, Cooperation}. For X_5, because its trace is 0, it is a saddle point.

TABLE III. EQUILIBRIUM POINT AND STABILITY CALCULATION

Equilibrium point	Conditions	Determinant	Trace	Stability
X_1	1, 2	+	-	ESS
X_2	2, 3	+	+	instability
X_3	1, 4	+	+	instability
X_4	3, 4	+	-	ESS
X_5			0	saddle

Note: ESS means evolutionarily stable strategy; + means positive; - means negative.

V. SIMULATION EXPERIMENTS

A. Evolution in Different Situations

The model is simulated by Vensim. The initial parameters are initial time=0, final time=30, time step=1, and the unit is month. In addition, α=0.5, β=0.5, A_s=50, and A_r=50. Different parameters may lead to different results. Therefore, we try different parameters to conduct simulation research. The parameters satisfy Situation 1 to Situation 5.

Situation 1. $B_s + V_s + F - C_t * \theta < 0$, $B_r + V_r + F - C_t *(1-\theta) < 0$, $R_s + V_s + F - D_s - C_t * \theta < 0$, $R_r + V_r + F - D_r - C_t *(1-\theta) < 0$.

TABLE IV. SIMULATION PARAMETERS OF SITUATION 1

Parameters	Initial value	Parameters	Initial value
R_s	9	D_s	6
R_r	9	D_r	6
B_s	3	V_s	4
B_r	3	V_r	4
C_t	25	θ	0.5
F	5		

The parameters are shown in Table IV, which satisfy Situation 1. The change of α value (cooperation probability) of a supplier in 30 months is shown in Fig. 2. A retailer has similar results. From the figure, we find that the cooperation probability of alliance members gradually decreases from 0.5 to 0. It means that the members tend to adopt a strategy of defection and the game enters a stable equilibrium of defection.

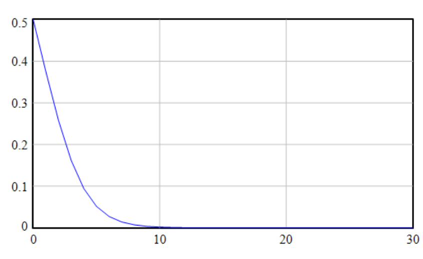

Fig. 2. α value of a supplier in Situation 1.

Situation 2. $B_s + V_s + F - C_t * \theta > 0$, $B_r + V_r + F - C_t *(1-\theta) > 0$. $R_s + V_s + F - D_s - C_t * \theta > 0$, $R_r + V_r + F - D_r - C_t *(1-\theta) > 0$.

We increase the blockchain income (V_s, V_r), financial penalty (F), and decrease opportunity income (D_s, D_r). We modify the parameters V_s=5, V_r=5, F=5.3, D_s=5, and D_r=5 and keep other parameters unchanged as Condition 1. The α value of a supplier is shown in Fig. 3. A retailer has the similar results. Cooperation probability of alliance members increases from 0.5 to 1, and the game tends to a stable balance of cooperation.

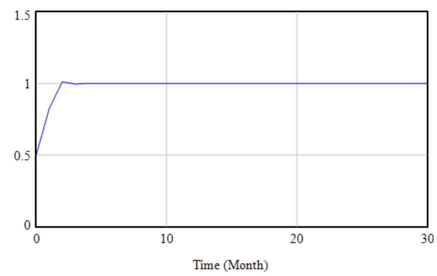

Fig. 3. α value of a supplier in Situation 2.

Situation 3. $B_s + V_s + F - C_t * \theta > 0$, $B_r + V_r + F - C_t *(1-\theta) < 0$, $R_s + V_s + F - D_s - C_t * \theta > 0$, $R_r + V_r + F - D_r - C_t *(1-\theta) < 0$.

The modified parameters are V_s=7, V_r=4, F=3, D_s=2, D_r=7, which satisfy Situation 3. For a supplier, cooperation income is always more than defection income, so he chooses cooperation. Meanwhile, for a retailer, defection income is always more than cooperation income, he chooses defection. Because their strategy choices are completely different, the simulation results overflow.

Situation 4. $B_s + V_s + F - C_t * \theta < 0$, $B_r + V_r + F - C_t *(1-\theta) > 0$, $R_s + V_s + F - D_s - C_t * \theta < 0$, $R_r + V_r + F - D_r - C_t *(1-\theta) > 0$.

The modified parameters are V_s=4, V_r=7, F=5, D_s=7, D_r=2, satisfying Situation 4. Contrary to situation 3， a supplier chooses defection and a retailer chooses cooperation. And the model is divergent.

Situation 5. $B_s + V_s + F - C_t * \theta < 0$, $B_r + V_r + F - C_t *(1-\theta) < 0$, $R_s + V_s + F - D_s - C_t * \theta > 0$, $R_r + V_r + F - D_r - C_t *(1-\theta) > 0$.

The modified parameters are V_s=4, V_r=4, F=5, D_s=3, D_r=3, satisfying Situation 5. A supplier or a retailer might change his own choice because of the other's choice, which increases the uncertainty of the system, and the model eventually fluctuates at the point of 1 (Fig. 4).

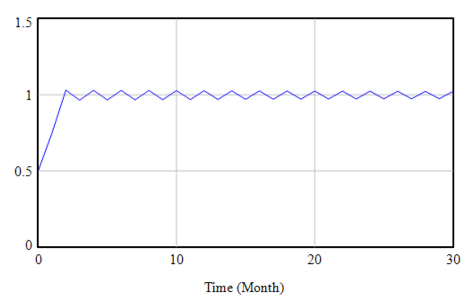

Fig. 4. α value of a supplier in Situation 5.

Summing up the above experimental results, Table V can be obtained. The related conclusions are as follows.

TABLE V. EVOLUTION RESULTS IN DIFFERENT SITUATIONS

Situation1	Situation2	Situation3	Situation4	Situation5
converge $X_1 = (0, 0)$	converge $X_4 = (1, 1)$	diverge	diverge	fluctuate $X_4 = (1, 1)$

(1) For any member, if his income when defection is less than that when cooperation, the evolution result is that both parties will adopt the strategy of defection. And the system will converge to $X_1 = (0, 0)$. In this situation, the alliance will be dismissed.

(2) For any member, if the income when cooperation is more than that when defection. And the system will converge to $X_4 = (1, 1)$. In this situation, the alliance will continue existing.

(3) For one member, cooperation income is always more than defection income. And for the other member, defection come is always more than cooperation income. The model is divergent.

(4) A supplier or a retailer will change own strategy because of the other's choice, and the model eventually fluctuates at 1.

B. *Influence of Blockchain on Supply Chain Evolution*

For a supplier and a retailer, their initial blockchain incomes are set as V_s=4, V_r=4. Then, V_s and V_r are increased or decreased by 0.5. Fig. 5 shows the influence of blockchain on the decision-making of the members in supply chain.

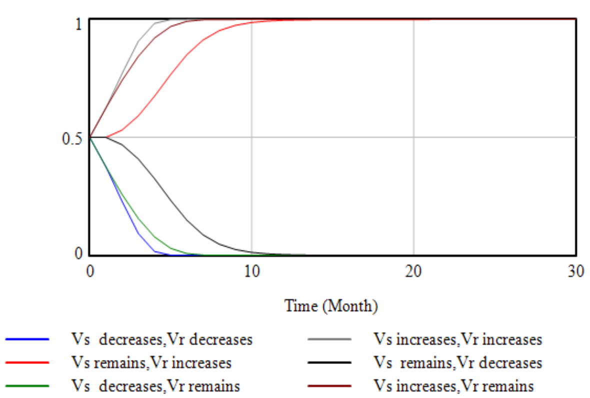

Fig. 5. Influence of blockchain on the decision-making of supply chain.

When blockchain income changes, both sides of the game can adjust their own strategies.

(1) When blockchain income of one party increases and blockchain income of the other party has not changed, the probability of cooperation gradually increases from 0.5 to 1, and finally the model tends to a stable equilibrium of cooperation.

(2) Conversely, when blockchain income of one party decreases and the other party remains unchanged, the probability of cooperation gradually decreases from 0.5 to 0. Defection is their common strategy.

(3) If blockchain income of both sides increases or decreases, their strategy is cooperation or defection, and their evolution speed will be faster than that when only one-party changes.

Blockchain not only builds a credible operation mechanism for supply chain alliance cooperation, but also it improves the intelligent processing of the supply chain. Furthermore, it helps supply chain alliance to reach the steady state faster. It has a positive effect on the choice of the strategy and on evolution speed of the alliance.

VI. CONCLUSIONS

Under the framework of open and shared blockchain, the evolution of supply chain is studied. First, a game model composed of suppliers and retailers with blockchain network is established under four basic assumptions. Then, the stability of the points is analyzed using Jacobian matrix. Through the simulation, we present the evolution path of the alliance and the impact of blockchain on the decision-making of the members. The paper provides an idea for the game research of supply chain and blockchain, which is helpful to establish a reliable and win-win alliance. In the future, we will study the evolution game with more complex alliance relationships.

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