Decision-Making Game Research on Data Sharing in Supply Chain Network Based on Blockchain Technology

Baoku Li[1] and Yuxin Zhang[1*]

[1] College of Business Administration, Liaoning Technical University, Huludao, Liaoning, 125000, China
*zyxovo04@163.com

Abstract. Existing supply chain network leads to the limitation of data sharing methods due to its own limitations, and the development and application of blockchain technology opens up a new way for data sharing in supply chain network. The article introduces blockchain technology, constructs a tripartite evolution model of suppliers, manufacturers, and retailers in the supply chain network, researches the dynamic evolution process and the equilibrium strategy of the tripartite decision-making, and conducts simulation analysis. The results show that, first, establishing appropriate data sharing incentives is an important initiative to enhance the data sharing willingness of each subject in the supply chain. Second, corresponding data sharing penalties are needed to avoid enterprises utilizing other enterprises' data without actively sharing their own data. Finally, the reduction of data sharing costs and risks can effectively promote data sharing. By analyzing the mechanism of tripartite collaboration in supply chain network, it provides theoretical support and decision-making basis for digital governance of supply chain network under the new development pattern.

Keywords: Supply Chain Network, Data Sharing, Blockchain.

1 INTRODUCTION

Along with the advancement of the digital economy, digital technology has been constantly innovated, gradually enhancing its application in production activities, promoting industrial transformation and upgrading, and playing a key role in the reshaping of the global economic structure and the competitive environment, especially for developing countries, which is a key strategy for realizing the development leap [1]. Data, as the core and power source of the digital economy, not only contributes to the formation of large-scale data markets, but also is transformed into actual productivity, which becomes the foundation for countries or regions to gain strategic advantages. The comprehensive use of data in the production, sales and service processes of the entire supply chain enables the traditional linear supply chain model to be reconstructed, forming a network structure centered on consumer demand. Data sharing enables the supply chain network to realize real-time dynamic response, accurately matching supply and demand, effectively reducing the whip effect in the supply chain [2], promoting the development of new areas of the market, creating new competitive

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advantages, thus steadily improving the production efficiency [3]. Currently, the willingness of data sharing among multiple supply chain enterprises is not strong, and there is an obvious data silo problem. Data sharing in the supply chain involves the flow of information between multiple parties, but the issues of data ownership, risk, and sharing costs are still the main obstacles to improve the efficiency of data sharing.

The application of blockchain technology opens up a new solution path for data sharing challenges in supply chain networks, which can ensure the transparency of data among members and promote the establishment of linkage and trust mechanisms between upstream and downstream enterprises [4]. Several supply chain networks have already applied blockchain technology for data sharing, such as Haier, Lenovo, Walmart, etc., but still face the challenges of sharing willingness and efficiency [5]. In addition, due to the information asymmetry between enterprises, supply chain subjects often conceal key information such as cost and production capacity during the sharing process, and the lack of regulators exacerbates this risk, destroying the trust of inter-subject cooperation and causing serious damage to the stability of the supply chain network.

The core problem of data sharing lies in the strategic game on resources between different subjects to seek a balanced strategy that can promote cooperation. From the perspective of game, Pan et al. [6] analyzed the impact of changes in data volume and data value on enterprise sharing decisions. H. Xing [7] introduced the concept of "opportunistic sharing" to construct a dynamic evolutionary game model of data sharing. J. Gu et al [8] constructed a data sharing system model based on blockchain technology that can protect the rights and interests of data sharers, and Epiphaniou et al [9] emphasized that in terms of regulation and security, the application of blockchain can prevent a single point of failure and achieve instant regulation of data. It can be seen that blockchain technology plays a crucial role in dealing with privacy protection, benefit distribution, reliability and other issues of data sharing. Current research at home and abroad mainly focuses on the ways in which blockchain technology empowers supply chain networks, and there is a relative lack of research in digital governance.

In summary, supply chain data sharing has become a hotspot of theoretical and practical attention, and existing research mainly focuses on the perspectives of sharing value, influencing factors and role mechanisms. Although some scholars have already improved and optimized the supply chain data sharing model, the analysis of the supply chain data sharing game involving multiple subjects is still to be deepened. This paper explores the role of blockchain technology in promoting supply chain data sharing, and analyzes the dynamic interactions between subjects in the supply chain using evolutionary game theory. By comparing the evolutionary trajectories of different technological solutions, this paper aims to explore the potential contribution of blockchain technology in improving the efficiency of supply chain data sharing.

2 BLOCKCHAIN AND DATA SHARING IN SUPPLY CHAIN NETWORKS

Traditional supply chain networks have accomplished the inter-temporal transfer of data resources through the Internet, but technical limitations have led to multiple challenges in data sharing. First, it is difficult to determine the ownership of data, which reduces the motivation of data sharing among supply chain subjects. Second, data sharing requires supply chain subjects to invest high costs in data system construction and maintenance. In addition, data sharing increases the risk of core data leakage. Finally, in the process of data sharing, subjects in the supply chain may adopt opportunistic behaviors that are inconsistent with the overall interests, which reduces the motivation of cooperation among subjects.

The introduction of blockchain technology helps to promote a shift in the security management of data and information from centralized authority to regulated authorization, data sharing from information barriers to information interoperability, and data security and privacy from privacy concessions to balancing elements. Blockchain allows supply chain subjects to make special agreements on data ownership, providing a more reliable and efficient solution. Blockchain first ensures the uniqueness of data by time-stamping blocks of data through a competitive mechanism. Then, through smart contracts, it realizes the automatic transfer of rights of data among different subjects. Finally, with the help of distributed ledger technology, the consistency of data ownership is ensured under the supervision of multiple parties. For example, Walmart tracks sales information in real time by establishing a blockchain distributed ledger to quickly adjust its product mix to meet the needs and trends of a certain region, and the system is used to track food products along the production chain, from farm to consumer. Using IBM's blockchain platform, Walmart is able to track the origin of a particular food product in seconds, whereas traditional tracking systems can take days or even weeks. The implementation of this technology includes the use of encryption to secure data and the use of smart contracts to automate certain steps in the supply chain process.

In the past, data often relied on centralized storage in third-party institutions, which made it extremely vulnerable to damage or theft if the institution was attacked. In contrast, blockchain reduces the likelihood of data leakage through its distributed storage structure that ensures that even if a single or a few nodes are attacked, the data remains intact and is not tampered with. In addition, the blockchain technology-enabled system can establish an effective punishment mechanism, increase the penalty for misbehaving subjects, once the subject defaults, it becomes difficult to modify the defaulted data, and once the defaulted behavior is made public, it may result in serious reputational damage, thus increasing the cost of opportunistic behavior of enterprises, and helping to promote the supply chain network to the direction of open sharing and win-win situation.

From the analysis of the conditions of action, the effective application of blockchain relies on three key factors: the subject's initial willingness to share, reasonable incentives and penalties, which together promote the behavior of data sharing, and enhance the willingness of individual subjects to share, forming a virtuous cycle of data sharing and improving efficiency. The purpose of this paper is to construct a three-party evolutionary game model to analyze the behavioral motivation of supply chain data sharing, and to explore how the introduction of blockchain technology affects the strategic choices of participants. The article also analyzes the effects of initial willingness, costs and benefits on data sharing decisions, so as to provide theoretical support for the application of blockchain in supply chain data sharing.

3 BASIC ASSUMPTIONS AND MODEL CONSTRUCTION

3.1 Model Variables and Assumptions

In order to construct an evolutionary game model of supply chain network data sharing decision-making based on blockchain technology background, and study the sharing strategy among supply chain interested subjects, the following assumptions are made in combination with the actual situation of data sharing.

H1: The three parties involved in supply chain network data sharing are: supplier S, manufacturer M, and retailer R. For the convenience of calculation, let the supply chain subject be$i(i = x, y, z)$, and set the fact that the participating subjects are all finite rationality and there is information asymmetry.The set of strategies for all three subjects is [data sharing, no data sharing], and the probability of sharing data is x, y, z and the probability of not sharing data is $1 - x$, $1 - y$, $1 - z$ respectively.

H2: When each subject enterprise in the supply chain chooses a sharing strategy, the data receiver will obtain a certain sharing benefit. There is a difference in the value that the subject can get from the data due to the influence of the absorptive capacity of the data receiver.$k_i(i = x, y, z)$ indicates the gain coefficient.

H3: The subjects in the supply chain need to increase the construction cost and marginal cost of data sharing when they share data through the blockchain platform. Since different enterprises have different degrees of data sharing and there are differences in the complexity of blockchain platform construction, the cost of blockchain platform construction varies.$c_i(i = x, y, z)$ indicates the cost required for supply chain subjects to construct blockchain platforms.s indicates the marginal cost of data sharing, which represents the ongoing expenditures required when data sharing is carried out on the blockchain platform.

H4: Subjects will face risks such as data leakage when they engage in data sharing.$r_i(i = x, y, z)$ indicates the risk coefficient of data sharing.

H5: Incentives will be given to subjects who engage in data sharing, α indicates the data sharing incentive coefficient of supply chain subjects, and the reward benefit is proportional to the amount of data sharing. Penalties will be imposed on subjects that participate negatively, with βindicating the penalty coefficient, and if supply chain subjects do not share data but use other subjects' data, they will bear consequences including reduced business cooperation and lower corporate reputation.

3.2 Model Construction

Based on the above assumptions, the payoff matrix in the game process of the three parties in the supply chain is shown in Table 1.

Table 1. Payment benefit matrix

Player				Retailers: Data sharing z	Retailers: No data sharing $1-z$
Suppliers	Data sharing x	Makers	Data sharing y	$k_x(d_y+d_z)+\alpha d_x-c_x-sd_x-rd_x$ $k_y(d_x+d_z)+\alpha d_y-c_y-sd_y-rd_y$ $k_z(d_x+d_y)+\alpha d_z-c_z-sd_z-rd_z$	$k_xd_y+\alpha d_x-c_x-sd_x-rd_x$ $k_yd_y+\alpha d_y-c_y-sd_y-rd_y$ $k_z(d_x+d_y)-\beta(d_x+d_y)$
			No data sharing $1-y$	$k_xd_z+\alpha d_x-c_x-sd_x-rd_x$ $k_y(d_x+d_z)-\beta(d_x+d_z)$ $k_zd_x+\alpha d_z-c_z-sd_z-rd_z$	$\alpha d_x-c_x-sd_x-rd_x$ $k_yd_x-\beta d_x$ $k_zd_x-\beta d_x$
	No data sharing $1-x$	Makers	Data sharing y	$k_x(d_y+d_z)-\beta(d_y+d_z)$ $k_yd_z+\alpha d_y-c_y-sd_y-rd_y$ $k_zd_y+\alpha d_z-c_z-sd_z-rd_z$	$k_xd_y-\beta d_y$ $\alpha d_y-c_y-sd_y-rd_y$ $k_zd_y-\beta d_y$
			No data sharing $1-y$	$k_xd_z-\beta d_z$ $k_yd_z-\beta d_z$ $\alpha d_z-c_z-sd_z-rd_z$	0 0 0

4 EVOLUTIONARY GAME ANALYSIS

4.1 Three-Party Subject Game Payoff Expectation Function Construction

Based on the three-party game payment matrix of supply chain network data sharing in Table 1, the benefit expectation function of the evolving subject can be constructed and the stabilization point can be obtained.

The expected gain of suppliers choosing data sharing is calculated according to equation (1), the expected gain of suppliers choosing not to share data is calculated according to equation (2), and the average gain is calculated according to equation (3), as follows:

$$U_S^x = yz[k_x(d_y+d_z)+\alpha d_x-c_x-sd_x-rd_x]+y(1-z)(k_xd_y+\alpha d_x-c_x-sd_x-rd_x)+(1-y)z(k_xd_z+\alpha d_x-c_x-sd_x-rd_x)+(1-y)(1-z)(\alpha d_x-c_x-sd_x-rd_x) \tag{1}$$

$$U_S^{1-x} = yz[k_x(d_y+d_z)-\beta(d_y+d_z)]+y(1-z)(\alpha d_x-c_x-sd_x-rd_x)+(1-y)z(k_xd_z-\beta d_z) \tag{2}$$

$$\bar{U}_S = xU_S^x+(1-x)U_S^{1-x} \tag{3}$$

The expected return for a manufacturer choosing to share data is calculated in equation (4), the expected return for a supplier choosing not to share data is calculated in equation (5), and the average return is calculated in equation (6) as follows:

$$U_M^y = xz[k_y(d_x+d_z)+\alpha d_y-c_y-sd_y-rd_y]+x(1-z)(k_yd_y+\alpha d_y-c_y-sd_y-rd_y)+(1-x)z(k_yd_z+\alpha d_y-c_y-sd_y-rd_y)+(1-x)(1-z)(\alpha d_y-c_y-sd_y-rd_y) \tag{4}$$

$$U_M^{1-y} = xz[k_y(d_x + d_z) - \beta(d_x + d_z)] + x(1-z)(k_y d_x - \beta d_x) + (1-x)z(k_y d_z - \beta d_z) \quad (5)$$

$$\bar{U}_M = yU_M^y + (1-y)U_M^{1-y} \quad (6)$$

The expected return for a retailer choosing to share data is calculated in equation (7), the expected return for a supplier choosing not to share data is calculated in equation (8), and the average return is calculated in equation (9) as follows:

$$U_R^z = xy[k_z(d_x + d_y) + \alpha d_z - c_z - sd_z - rd_z] + x(1-y)(k_z d_x + \alpha d_z - c_z - sd_z - rd_z) + (1-x)y(k_z d_y + \alpha d_z - c_z - sd_z - rd_z) + (1-x)(1-y)(\alpha d_z - c_z - sd_z - rd_z) \quad (7)$$

$$U_R^{1-z} = xy[k_z(d_x + d_y) - \beta(d_x + d_y)] + x(1-y)(k_z d_x - \beta d_x) + (1-x)y(k_z d_y - \beta d_y) \quad (8)$$

$$\bar{U}_R = zU_R^z + (1-z)U_R^{1-z} \quad (9)$$

4.2 Analysis of Tripartite Evolutionary Stabilization Strategy

According to the calculation method of replication dynamic equation, the replication dynamic equation between supplier, manufacturer and retailer can be obtained as:

$$F_{(x)} = \frac{d_x}{d_t} = x(1-x)(y\beta d_y + z\beta d_z + \alpha d_x - c_x - sd_x - rd_x) \quad (10)$$

$$F_{(y)} = \frac{d_y}{d_t} = y(1-y)(x\beta d_x + z\beta d_z + \alpha d_y - c_y - sd_y - rd_y) \quad (11)$$

$$F_{(z)} = \frac{d_z}{d_t} = z(1-z)(x\beta d_x + y\beta d_y + \alpha d_z - c_z - sd_z - rd_z) \quad (12)$$

The above three differential equations constitute a three-way evolutionary dynamic system of suppliers, manufacturers, and retailers. Equation (13) is the Jacobi matrix:

$$\begin{bmatrix} (1-2x)(y\beta d_y + z\beta d_z + \alpha d_x - c_x - sd_x - rd_x) & y(1-y)\beta d_x & z(1-z)\beta d_x \\ x(1-x)\beta d_y & (1-2y)(x\beta d_x + z\beta d_z + \alpha d_y - c_y - sd_y - rd_y) & z(1-z)\beta d_y \\ x(1-x)\beta d_z & y(1-y)\beta d_z & (1-2z)(x\beta d_x + y\beta d_y + \alpha d_z - c_z - sd_z - rd_z) \end{bmatrix} \quad (13)$$

The eigenvalue distributions and stability conditions of the eight equilibrium points are shown in Table 2.It can be seen that there are contradictions in the stability conditions of the points in Table 2, and there are only a few stable equilibrium points in this game.

Table 2. Stability analysis of equilibrium points

Balance point	Eigenvalue			Stability conditions
	λ_1	λ_2	λ_3	
$E_1(0,0,0)$	$\alpha d_x - c_x - sd_x - rd_x$	$\alpha d_y - c_y - sd_y - rd_y$	$\alpha d_z - c_z - sd_z - rd_z$	$\alpha d_x < c_x + sd_x + rd_x$ $\alpha d_y < c_y + sd_y + rd_y$ $\alpha d_z < c_z + sd_z + rd_z$
$E_2(0,0,1)$	$\beta d_z + \alpha d_x - c_x - sd_x - rd_x$	$\beta d_z + \alpha d_y - c_y - sd_y - rd_y$	$-(\alpha d_z - c_z - sd_z - rd_z)$	$\beta d_z + \alpha d_x < c_x + sd_x + rd_x$ $\beta d_z + \alpha d_y < c_y + sd_y + rd_y$ $\alpha d_z > c_z + sd_z + rd_z$
$E_3(0,1,0)$	$\beta d_y + \alpha d_x - c_x - sd_x - rd_x$	$-(\alpha d_y - c_y - sd_y - rd_y)$	$\beta d_y + \alpha d_z - c_z - sd_z - rd_z$	$\beta d_y + \alpha d_x < c_x + sd_x + rd_x$ $\alpha d_y > c_y + sd_y + rd_y$ $\beta d_y + \alpha d_z < c_z + sd_z + rd_z$
$E_4(1,0,0)$	$-(\alpha d_x - c_x -$	$\beta d_x + \alpha d_y -$	$\beta d_x + \alpha d_z -$	$\alpha d_x > c_x + sd_x + rd_x$

	$sd_x - rd_x)$	$c_y - sd_y - rd_y$	$c_z - sd_z - rd_z$	$\beta d_x + \alpha d_y < c_y + sd_y + rd_y$ $\beta d_x + \alpha d_z < c_z + sd_z + rd_z$
$E_5(1,1,0)$	$-(\beta d_y + \alpha d_x - c_x - sd_x - rd_x)$	$-(\beta d_x + \alpha d_y - c_y - sd_y - rd_y)$	$\beta d_x + \beta d_y + \alpha d_z - c_z - sd_z - rd_z$	$\beta d_y + \alpha d_x > c_x + sd_x + rd_x$ $\beta d_x + \alpha d_y > c_y + sd_y + rd_y$ $\beta d_x + \beta d_y + \alpha d_z < c_z + sd_z + rd_z$
$E_6(1,0,1)$	$-(\beta d_z + \alpha d_x - c_x - sd_x - rd_x)$	$\beta d_x + \beta d_z + \alpha d_y - c_y - sd_y - rd_y$	$-(\beta d_x + \alpha d_z - c_z - sd_z - rd_z)$	$\beta d_z + \alpha d_x > c_x + sd_x + rd_x$ $\beta d_x + \beta d_z + \alpha d_y < c_y + sd_y + rd_y$ $\beta d_x + \alpha d_z > c_z + sd_z + rd_z$
$E_7(0,1,1)$	$\beta d_y + \beta d_z + \alpha d_x - c_x - sd_x - rd_x$	$-(\beta d_z + \alpha d_y - c_y - sd_y - rd_y)$	$-(\beta d_y + \alpha d_z - c_z - sd_z - rd_z)$	$\beta d_y + \beta d_z + \alpha d_x < c_x + sd_x + rd_x$ $\beta d_z + \alpha d_y > c_y + sd_y + rd_y$ $\beta d_y + \alpha d_z > c_z + sd_z + rd_z$
$E_8(1,1,1)$	$-(\beta d_y + \beta d_z + \alpha d_x - c_x - sd_x - rd_x)$	$-(\beta d_x + \beta d_z + \alpha d_y - c_y - sd_y - rd_y)$	$-(\beta d_x + \beta d_y + \alpha d_z - c_z - sd_z - rd_z)$	$\beta d_y + \beta d_z + \alpha d_x > c_x + sd_x + rd_x$ $\beta d_x + \beta d_z + \alpha d_y > c_y + sd_y + rd_y$ $\beta d_x + \beta d_y + \alpha d_z > c_z + sd_z + rd_z$

5 SIMULATION ANALYSIS

Evolutionary simulations of the model parameters were performed using Matlab 2018 to simulate the dynamic evolution process of the strategies under different initial states and to analyze the ideal evolution path for the three parties in the supply chain to share data effectively.

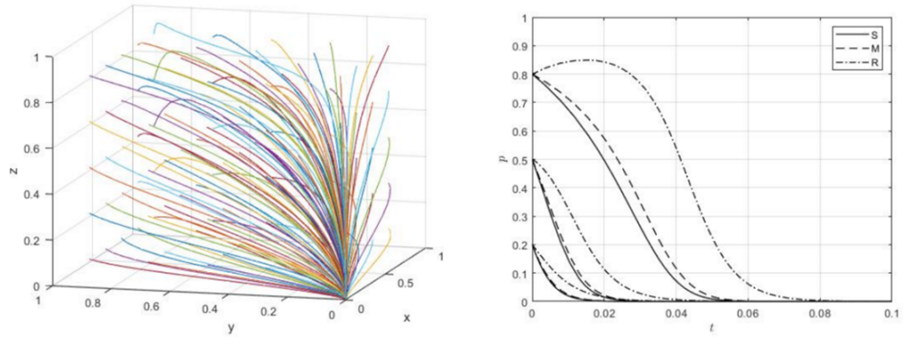
5.1 Simulation of Initial Program Parameters

Set the model parameters of the traditional digital system based on previous research. In the existing environment, retailers have more customer data compared to suppliers and manufacturers, so set the amount of subject-sharing data d_x=50,d_y=50,d_z=60; due to the high complexity of the business of manufacturers and suppliers, their data construction costs are higher, so set the cost of digital system construction c_x=200,c_y=160,c_z=50; set the marginal cost of data sharing s=1; the risk factor of data sharing r=2; data sharing incentive coefficient α=1; penalty mechanism coefficient β=3, and the values of each parameter are shown in Table 3.

Table 3. Parameter initial reference values

Parameters	d_x	d_y	d_z	c_x	c_y	c_z	s	r	α	β
Numerical value	50	50	60	200	160	50	1	2	1	3

As can be seen from Table 2, only $E_1(0,0,0)$ is a stable point among the equilibrium points under the parameters of the traditional scheme, indicating that the outcome of the game tends to be non-sharing regardless of the value of the initial sharing ratio, and the simulation is shown in Fig. 1.



(a)Initial evolutionary game result graph (b)Timing diagram of the initial evolutionary game

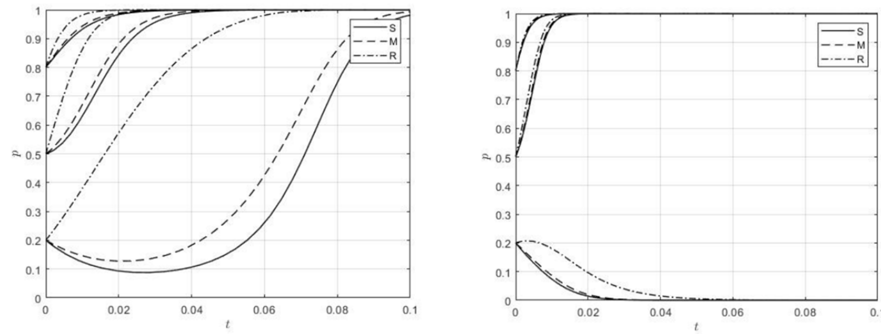
Fig. 1. Initial evolutionary game stabilization process

5.2 Parameter Simulation under the Influence of Factors

In the traditional evolutionary simulation, the equilibrium state is that none of the three parties share data, and the supply chain actors face the data silo problem. The introduction of blockchain technology significantly changes the key parameters in the model, which drives the evolutionary process to the ideal equilibrium state shared by all three parties.

Incentive and Penalty Factors. When increasing the data incentive coefficient α value of 5 is shown in Fig.2(a), where the three-party decision equilibrium reaches a stable equilibrium $E_8(1{,}1{,}1)$, indicating that different initial probabilities do not affect the equilibrium outcome of the eventual sharing, and Fig.2(b) demonstrates the results of the tendency to no sharing under low initial value settings, indicating that the that while increasing the penalty coefficient helps facilitate the achievement of the desired equilibrium, it is not sufficient to ensure that full sharing is achieved in all cases.

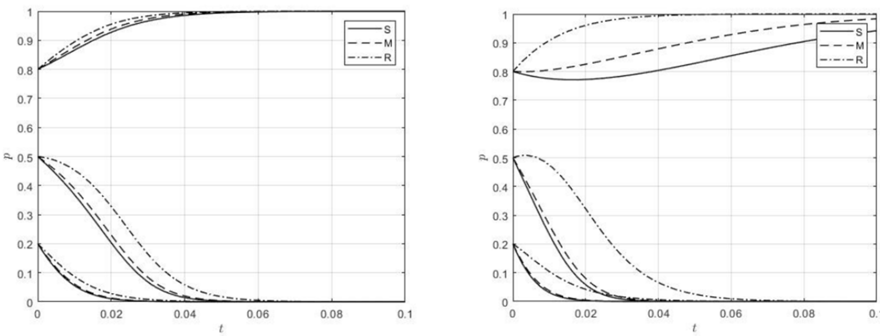
The simulation results further show that the penalty coefficient β has a significant effect on the equilibrium, and that with a low incentive coefficient α, some initial states can still be made to reach the ideal three-party sharing equilibrium, and that the higher the value of β, the larger the proportion of initial states that converge to the E_8equilibrium. However, increasing the value of β does not guarantee that the shared equilibrium is reached in all cases, as it requires a higher value of α to ensure that the E_1 point is not destabilized.



(a)Timing diagram of the incentive coefficient evolution game (b) Penalty coefficient evolution game time series diagram

Fig. 2. Evolutionary Game Timing Diagram

Construction Costs and Marginal Costs. In terms of construction cost, blockchain technology can reduce the cost of supply chain digital systems c_i.When the construction cost is reduced to c_x=100，c_y=80，c_z=25, it can realize that some of the initial states reach E_8 equilibrium while the rest of the states reach E_1 equilibrium, as shown in Fig. 3(a) below. In addition, the unified data standard of blockchain can reduce the marginal cost of data sharing, and when the marginal cost$s$is reduced to 0, a few initial states can achieve E_8 equilibrium, and most still will not share data, as shown in Fig. 3(b).



(a)Construction cost evolution game time series diagram (b)Time series diagram of the marginal cost evolution game

Fig. 3. Evolutionary Game Timing Diagram

Data Sharing Risk. The blockchain technology ensures the non-tampering of data and protects against data misuse, and reduces the data sharing risk coefficient. When the data sharing risk r is reduced to 0.5 in the model, it is similar to the result of reducing the marginal cost of data sharing, which can realize that a small number of initial states achieve the E_8 equilibrium, and most of the initial states are still moving toward the non-sharing outcome, as shown in Figure 4 below.

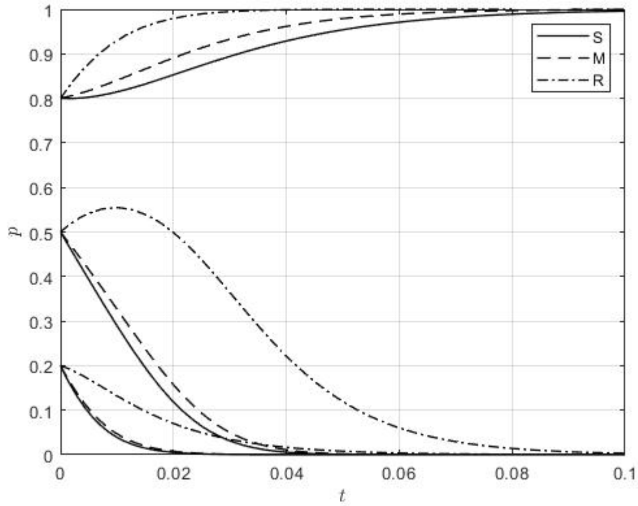


Fig. 4. Evolutionary Game Timing Diagram

6 CONCLUSION

In the context of the digital economy era, data sharing is crucial among the subjects of supply chain, which has a significant impact on exploring the potential value of data and promoting the efficient development of supply chain. The article deeply analyzes the role mechanism of blockchain technology to promote supply chain data sharing, and the attitude change of supply chain subjects towards data sharing over time. It is found that the implementation of appropriate incentives for subjects with positive data sharing behaviors can significantly increase the data sharing willingness of the subjects in the supply chain, so as to achieve the ideal state in which all subjects in the supply chain actively share data. In addition, subjects may adopt opportunistic behaviors when using shared data, and appropriate punishment mechanisms can effectively avoid such behaviors. In addition, the construction cost of data systems, the marginal cost of data sharing, and the data risk are the main obstacles affecting data sharing, and reducing these costs and risks can effectively promote data sharing.

The article summarizes the positive impact of blockchain technology on supply chain data sharing and explores the evolutionary trajectory of data sharing, and future research can consider the impact of external supply chain data and the connectivity of supply chain networks, and further explore it in depth with complex network theory.

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