Research on Industrial Collaborative Incentive Mechanism Based on Evolutionary Game in Digital Background

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Abstract: In the context of digitalization, many enterprises and industrial alliances will have some problems in the development of scientific and technological innovation, financial development and human resources to a certain extent. Through the research on the incentive mechanism of industrial alliances and enterprises in the data circulation industry, this paper discusses the key influencing factors of the incentive mechanism design results from the perspective of evolutionary game, and conducts a detailed demonstration through simulation analysis and other methods, thus deducing how to better design the incentive mechanism of industrial collaboration in the digital background.

Keywords: evolutionary game, industrial collaboration, incentive mechanism

1 Introduction

The 14th Five-Year Plan of China emphasizes the imperative to expedite digital development, promote the industrialization of digital technologies, and facilitate the digitization of industries while fostering a profound integration between the digital economy and the real economy. Currently, this integration has emerged as a pivotal long-term national development strategy. To continuously generate new drivers for high-quality development, it is essential to strategically position emerging sectors such as the digital economy and unlock novel production possibilities. The 19th National Congress of the Communist Party of China advocated for an accelerated establishment of an industrial system that ensures coordinated progress across multiple domains including the real economy, scientific innovation, modern finance, and human resources. Industries serve as vehicles for unleashing productive forces and constitute key battlegrounds in enhancing supply system quality. Constructing a harmonized industrial system stands as a fundamental endeavor in promoting high-quality development and constructing a contemporary economic framework. By mobilizing, allocating, and coordinating diverse factors within an adaptable industrial system that accommodates technological advancements, we can consistently unleash and cultivate productive forces[1].

In the context of digitalization, many enterprises and industrial alliances face challenges in scientific and technological innovation, financial development, and human resources, resulting

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in a certain degree of coordination deficiency. The primary issue lies in the inadequate support provided by scientific and technological innovation achievements for industrial development, as well as the difficulty and low rate of transforming these achievements. On one hand, numerous industries suffer from excess capacity; on the other hand, there is an insufficient effective supply to meet people's increasingly upgraded multi-level, high-quality, and diversified consumer demands[2]. Therefore, designing an industrial synergy mechanism has become an urgent problem to be addressed within the framework of industrial digitalization.

After reviewing the existing literature, it is evident that: firstly, although there have been studies on industrial collaboration in the digital context, they lack depth and research on incentive mechanisms remains scarce. Additionally, there is a dearth of research on the rationality of incentive mechanisms for industrial collaboration in this digital context. Secondly, considering industrial collaboration in the digital background, it would be more appropriate to focus on units involved in the network nodes of the industrial chain to facilitate better correlation analysis within the data circulation industry[3].

This paper primarily investigates industry collaboration in the data circulation sector. Given the diverse characteristics of this digital domain and its exclusively online data transactions, an effective incentive mechanism can be designed using emerging technologies like blockchain to expedite and streamline transactions. The focal point of this study is to demonstrate the rationale behind incentive mechanisms in the digital realm by constructing an evolutionary game model between enterprises and industry alliances within the data circulation sector, while examining their decision-making dynamics and other behaviors[4].

2 Construction of Evolutionary Game Model

Based on the theory of rational economic man, the primary objective is to ensure and pursue the maximization of individual interests. Similarly, enterprises in the industrial chain can also be considered as rational economic agents who participate in the synergy mechanism designed by industrial alliances and strive to maximize their own benefits and minimize costs[5]. However, if these enterprises perceive that they are gaining little while paying a great deal over the long term, it will inevitably undermine their positive attitude and willingness to engage in industrial synergy mechanisms, leading to stagnation or failure of synergistic development.

In today's digital era, these related enterprises have their own scale and operations within their respective domains, with some generating considerable income. For certain enterprises involved in an industrial alliance's synergy mechanism design, direct economic benefits may be limited compared to expanding their industry influence and social impact. Moreover, such participation requires significant investments in terms of time cost and opportunity cost for these enterprises. Considering various costs involved, enterprises may lack motivation or initiative to actively engage in the operational process of industrial development synergies[6].

In the process of industrial cooperation, the design and implementation of incentive mechanisms within an industrial alliance entail certain benefits and costs. The synergy-driven incentive mechanism design incurs human resource and supervision costs, while also potentially reducing the income of the industrial alliance itself due to the need for coordinating interests among all parties involved[7]. However, as more enterprises participate in synergy development, the influence of the alliance within the industry strengthens, leading to closer industry-wide synergy development and increased feedback on income for the designing industrial alliance. Both enterprises and industrial alliances consider income and cost factors in their synergy mechanisms, which establishes a game-theoretic cooperative relationship between them. To maintain the long-term stability of enterprises in the collaborative development mechanism of industrial alliance, it is necessary to analyze the game and cooperation strategy choice of industrial alliance and enterprises, as well as the economic factors including benefits and costs that have affected the decision stability of both. Finding a stable equilibrium state that maximizes income from industrial synergy development is crucial for enterprise participation in such mechanisms. Therefore, this paper employs evolutionary game theory to analyze strategic choices made by participants in order to identify stable equilibrium points[8].

2.1 Model assumptions

Evolutionary stable strategy, as a static concept, serves as a fundamental principle in evolutionary game theory to elucidate the local stability of dynamic systems. This theory emphasizes the presence of limited rationality among game participants and posits that their behavioral choices undergo continuous adjustment and change, ultimately converging towards local stability. The game subjects primarily encompass industrial alliance M and its associated enterprises N.

As bounded rational agents, participants will independently formulate sophisticated strategies throughout the process. The decision of industrial alliance M involves either "designing an incentive synergy mechanism" or "not designing an incentive synergy mechanism," while the choice for related enterprises N includes both "participating" and "not participating."

x represents the probability that related enterprises N will choose cooperation, whereas 1-x represents the probability that they will refrain from cooperating. Similarly, y denotes the probability that industrial alliance M designs an incentive synergy mechanism, while 1-y signifies the probability that it does not design such a mechanism.

R_1 symbolizes the revenue obtained by enterprise N through its own operations, and C_1 represents the cost invested by enterprise N to participate in the synergy mechanism. Likewise, R_2 stands for the revenue acquired by industrial alliance M from its own operations, with C_2 representing the cost invested in designing and maintaining this incentive synergy mechanism.

Simultaneously, collaboration between both parties generates a synergistic revenue value Q which is distributed according to a predetermined proportion. The interest distribution proportion of enterprise N is denoted as δ, resulting in a distributed revenue of δQ for them; meanwhile, industrial alliance M's distribution proportion is $(1-\delta)$, leading to a distributed revenue of $(1-\delta)Q$.

The revenue composition of R_1 encompasses the original revenue, social recognition, reputation, and other factors associated with Enterprise N. On the other hand, the cost of C_1 includes not only the time and energy invested by Enterprise N in participating in the synergy mechanism but also potential costs arising from interest redistribution. The revenue composition of δQ primarily refers to the enhancement of influence achieved by Enterprise N through participation in synergy development, as well as the acquisition and accumulation of relevant industry resources. Additionally, it encompasses improvements in corporate visibility and reputation along with reductions in daily operating costs.

R_2 represents both the original revenue generated by industrial alliance M during its operation and its overall impact on the industry. The cost of C_2 encompasses a range of operational expenses, including the expenditure on human resources and supervision for the incentive mechanism in industrial alliance design, as well as the costs incurred after interest redistribution. The benefits of $(1-\delta)\mathrm{Q}$ are manifested through the economic advantages derived from the mechanism design of an industrial alliance, wherein enterprises actively participate in the alliance's designed mechanisms, resulting in enhanced influence and resource optimization. Furthermore, this close-knit development within the entire industry fosters positive feedback across all dimensions[9].

2.2 Establishment of Interest Matrix and Evolutionary Game Model

Based on Friedman's method, the local stability of Jacobian matrix and interest matrix can be used to verify whether the strategy organization formed by both parties in the game is a stable strategy, that is, whether it is ESS, and analyze which factors will affect the strategy selection of both parties[10]. See table 1 for the specific analysis results.

Table 1: Game Benefit Matrix of Related Enterprise N and Industry Alliance M.

	Enterprise N participates	Enterprise N does not participate
Industry alliance M designs incentive mechanism	$R_2+(1-\delta)\mathrm{Q}-C_2$ $R_1+\delta\mathrm{Q}-C_1$	R_2-C_2 R_1
Industry alliance M does not design incentive mechanism	R_2 R_1-C_1	R_2 R_1

According to the model assumption in the table 1, the expected return and average return of Enterprise N when it adopts the strategy of "participating" and "not participating" are U_{11}, U_{12} and U_1 respectively, which are calculated as follows:

$$U_{11}=y(R_1+\delta\mathrm{Q}-C_1)+(1-y)(R_1-C_1)=y\delta\mathrm{Q}+R_1-C_1$$

$$U_{12}=yR_1+(1-y)R_1=R_1$$

$$U_1=xU_{11}+(1-x)U_{12}=x(y\delta\mathrm{Q}-C_1)+R_1 \tag{1}$$

The replication dynamic equation is a differential equation that captures the temporal evolution of the frequency or extent to which a group adopts a specific strategy. In the context of evolutionary game theory, the replication dynamic equation represents the dynamics governing the probability x that firm N will opt for the "Participate" strategy.

$$F_N(x)=\frac{dx}{dt}=x(U_{11}-U_1)=x(1-x)(y\delta\mathrm{Q}-C_1) \tag{2}$$

When industrial alliance M adopts the strategies of “designing incentive mechanism” and “not designing incentive mechanism”, the expected returns and average returns are U_{21}, U_{22} and U_2 respectively, which are calculated as follows:

$$U_{21}=x(R_2+(1-\delta)\mathrm{Q}-C_2)+(1-x)(R_2-C_2)=x(1-\delta)\mathrm{Q}+R_2-C_2$$

$$U_{22} = xR_2 + (1-x)R_2 = R_2$$

$$U_2 = yU_{21} + (1-y)U_{22} = y(x(1-\delta)\mathrm{Q} - C_2) + R_2 \tag{3}$$

The dynamic equation of the evolutionary game replication of the probability y of the strategy of "designing incentive mechanism" chosen by industrial alliance M is:

$$F_M(y) = \frac{dy}{dt} = y(U_{21} - U_2) = y(1-y)(x(1-\delta)\mathrm{Q} - C_2) \tag{4}$$

The replication dynamic equation set composed of Equations (2) and (4) is as follows:

$$F_N(x) = \frac{dx}{dt} = x(U_{11} - U_1) = x(1-x)(y\delta\mathrm{Q} - C_1)$$

$$F_M(y) = \frac{dy}{dt} = y(U_{21} - U_2) = y(1-y)(x(1-\delta)\mathrm{Q} - C_2) \tag{5}$$

We set the replication dynamic system (5) of equations $F_N(x) = \frac{dx}{dt} = 0$、$F_M(y) = \frac{dy}{dt} = 0$ to get five equilibrium points, respectively $A(0,1)$, $B(0,0)$, $C(1,0)$, $D(1,1)$, $E(C_2/(1-\delta)\mathrm{Q}$, $C_1/\delta\mathrm{Q})$.

From the replication dynamic system in (5) can be obtained Jacobian matrix is:

$$\begin{bmatrix} \frac{\partial F_N(x)}{\partial x} & \frac{\partial F_N(x)}{\partial y} \\ \frac{\partial F_M(y)}{\partial x} & \frac{\partial F_M(y)}{\partial y} \end{bmatrix} \tag{6}$$

According to the assumption that $C_2 < (1-\delta)\mathrm{Q}$, $C_1 < \delta\mathrm{Q}$, the determinant of the matrix is denoted as det(J), and the trace of the matrix is tr(J). The stability analysis of the five equilibrium points is shown in the following table2 and table3:

Table 2: Stability point value expression.

equilibrium points	$det(J)$	$tr(J)$
$A(0,1)$	$C_2(\delta\mathrm{Q} - C_1)$	$(\delta\mathrm{Q} - C_1) + C_2$
$B(0,0)$	C_1C_2	$-(C_1 + C_2)$
$C(1,0)$	$C_1((1-\delta)\mathrm{Q} - C_2)$	$\left((1-\delta)\mathrm{Q} - C_2\right) + C_1$
$D(1,1)$	$(C_1 - \delta\mathrm{Q})(C_2 - (1-\delta)\mathrm{Q})$	$(C_1 - \delta\mathrm{Q}) + (C_2 - (1-\delta)\mathrm{Q})$
$E(C_2/(1-\delta)\mathrm{Q},\ C_1/\delta\mathrm{Q})$	$\left[\frac{C_2}{(1-\delta)\mathrm{Q}\left(\frac{C_2}{(1-\delta)\mathrm{Q}} - 1\right)\delta\mathrm{Q}}\right][C_1/\delta\mathrm{Q}(\frac{C_1}{\delta\mathrm{Q}} - 1)(1 - \delta)\mathrm{Q}]$	0

Table 3: Evolutionary stable points of both parties in the game.

equilibrium points	The symbol of $det(J)$	The symbol of $tr(J)$	Equilibrium outcome
$A(0,1)$	+	+	point of instability
$B(0,0)$	+	−	ESS
$C(1,0)$	+	+	point of instability

$D(1,1)$	+	−	ESS
$E(C_2/(1-\delta)\text{Q},\ C_1/\delta\text{Q})$	+	/	saddle point

According to the results of evolutionary stable points, equilibrium points $B(0,0)$ and $D(1,1)$ represent two ESS equilibrium situations: either enterprise N chooses "not to participate" while industrial alliance M opts for "not designing incentive mechanism", or enterprise N chooses "to participate" while industrial alliance M decides to "design incentive mechanism". Points $A(0,1)$ and $C(1,0)$ indicate alternative strategies chosen by enterprise N and industrial alliance M respectively. Point $E(C_2/(1-\delta)\text{Q},\ C_1/\delta\text{Q})$ represents a saddle point. The Figure 1 illustrates the evolutionary process of strategy selection for both enterprise N and industrial alliance M.

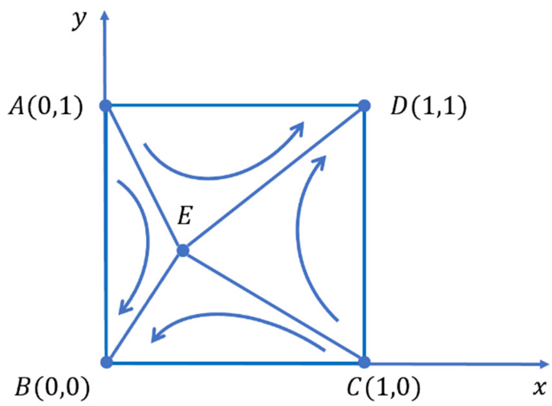

Figure 1: Evolutionary phase diagram of enterprise N and industrial alliance M.

The evolution of points $B(0,0)$ and $D(1,1)$ demonstrates two stable outcomes, indicating that the dynamic replication curves of both Enterprise N and Industrial Alliance M tend to converge towards these two points. When the dynamic replication curves converge at point $B(0,0)$, Enterprise N does not participate while Industrial Alliance M does not design an incentive mechanism, representing the normal state. Conversely, when the dynamic replication curves converge at point $D(1,1)$, Enterprise N chooses to participate and Industrial Alliance M designs an incentive mechanism as the normal state. Point $E(C_2/(1-\delta)\text{Q},\ C_1/\delta\text{Q})$ serves as a crucial determinant for assessing the likelihood of convergence towards points B and D in the two dynamic replication curves. As depicted in Figure 1, subtle changes near point E can significantly alter the evolutionary outcomes for both sides of the game. The ultimate trajectory of this game hinges on comparing region ABCE's area S_1 with region ADCE's area S_2. If $S_2 > S_1$, it indicates a tendency for Industrial Alliance M to design an incentive mechanism while Enterprise N participates as their final strategy evolves accordingly. Conversely, if $S_2 < S_1$, it suggests that both sides will evolve towards a direction where Industrial Alliance M does not design an incentive mechanism and Enterprise N does not participate.

The costs of C_1 and C_2 associated with the "participation" strategy chosen by enterprise N and the "design incentive mechanism" selected by industrial alliance M exhibit a negative correlation with S_2. An increase in both C_1 and C_2 leads to a decrease in S_2, indicating that when both parties opt for this combination of strategies, the costs incurred surpass a certain threshold, resulting in diminished benefits for both parties. Consequently, it discourages them from choosing this combination of strategies. Q represents the cooperative benefits obtained by enterprise N and industrial alliance M when they select this cooperative strategy combination. δQ and $(1-\delta)Q$ denote the distributed benefits between both parties. As Q increases, it exhibits a positive correlation with the magnitude of S_2.

3 Numerical Simulation with Matlab

This paper further demonstrates the evolutionary trajectory of each equilibrium point and different initial value points of game subjects towards the equilibrium point through numerical simulation using a Matlab program. Additionally, it analyzes the impact of changes in cost (C_1、C_2) and synergistic income (Q) on the stability of both sides in the game.

The indexes are quantized for simulation, and C_1=800, C_2=300, δ =0.75, Q =1600. The initial values (x, y) of numerical simulation are (0.1, 0.3), (0.2, 0.5), (0.3, 0.9), (0.4, 0.9), (0.5, 0.8), (0.6, 0.6), (0.7, 0.7), (0.9, 0.5), respectively. The dynamic evolution process of strategy selection of participants with time is shown in Figure 2:

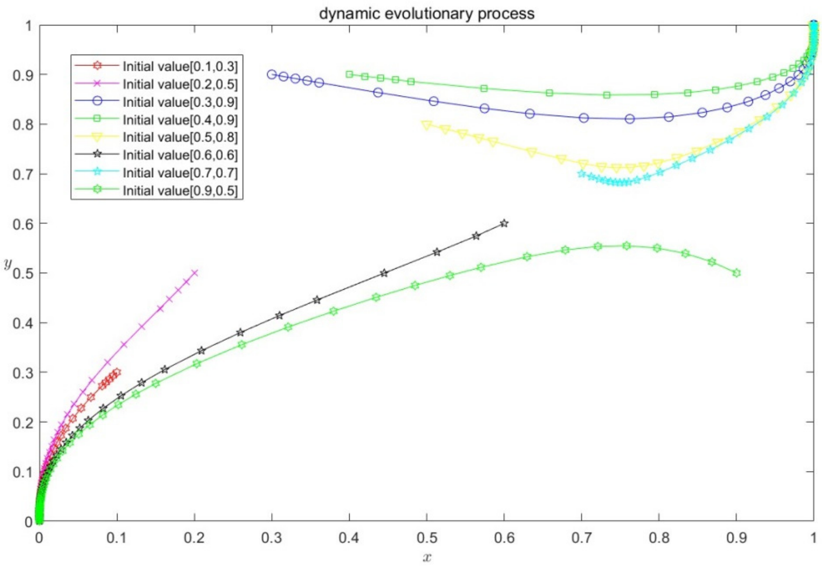

Figure 2: Dynamic evolution process of strategy selection of game participants.

The convergence of the final game evolution results to different points can be observed in Figure 2 when the initial probabilities (x, y) of both parties in the game are set to different values. In this setting, the value of saddle point E can be calculated as (0.75, 0.67). According to Figure 1, when the initial values of (x, y) fall within the ABCE region, convergence towards (0, 0) occurs and enterprise N chooses "not to participate," while industrial alliance M opts for "not designing an incentive mechanism." Conversely, when the initial values of (x, y) fall within the ADCE region, convergence towards (1, 1) takes place with enterprise N choosing to "participate" and industrial alliance M deciding to "design an incentive mechanism." These findings validate that the evolutionary outcomes of both parties' strategies are contingent upon the initial values of (x, y).

Simultaneously, as evident from the aforementioned, the influence parameters also exert a discernible impact on the ultimate evolutionary outcomes of game subjects. Initially, we consider the variable selection of synergistic benefits Q for both parties to analyze the evolutionary process of game results.

Set the initial parameter values as C_1=800, C_2=300, and δ =0.6, with an initial value of (x, y)=(0.5, 0.5). The values of Q in Figure 3 are chosen to be 2150, 2350, 2500, and 2700 to observe the trend of game subjects' evolution results with varying synergistic benefits Q. Simulation results demonstrate that as Q increases, both enterprise N's decision probability for "participation" and industrial alliance M's choice of "design incentive mechanism" accelerate significantly. This finding further confirms the positive role played by synergistic benefits Q in the dynamic evolution of both sides in this game.

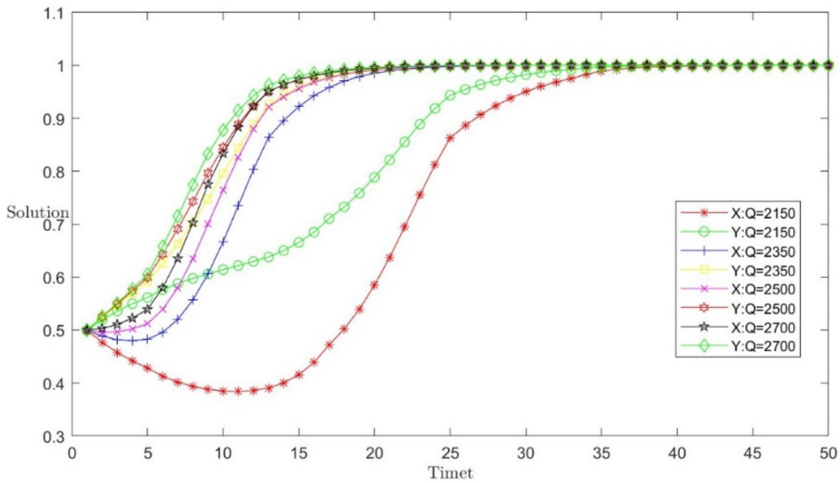

Figure 3: Influence of synergistic revenue Q on the dynamic evolution results of game participants.

The costs of both sides, C_1 and C_2, are then chosen as variables to analyze the evolutionary process of game outcomes.

By simultaneously increasing the values of C_1 and C_2 specifically setting them as 800, 900, 1000, and 1200 for C_1 and 200, 300, 400, and 600 for C_2 respectively (Figure 4), we observe the trend in the evolution results of game subjects. The simulation results demonstrate that as both cost parameters increase, not only does the speed at which players choose strategies change but also their final strategy choices alter. This confirms a negative correlation between the cost parameters C_1 and C_2 in shaping dynamic player behavior.

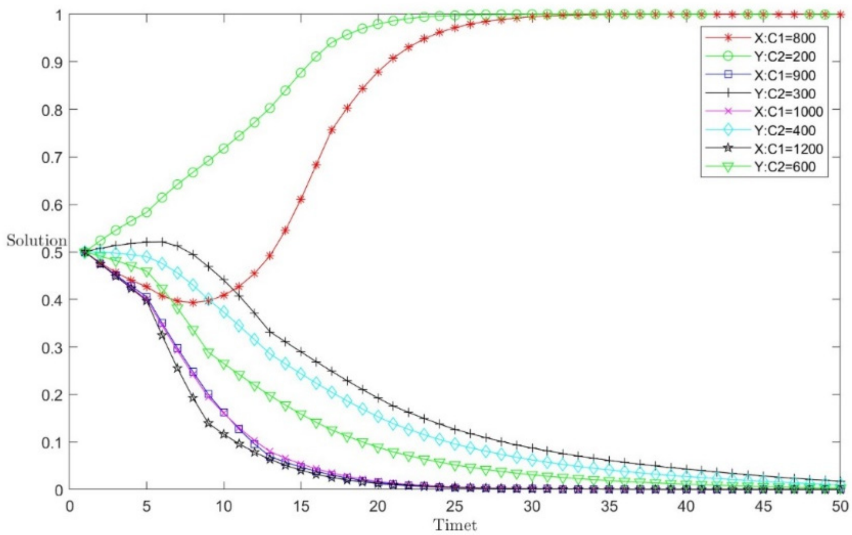

Figure 4: Influence of costs C_1 and C_2 on the dynamic evolution results of game participants.

4 Conclusions

The replication dynamic equation of both parties is derived by constructing the interest matrix for each party. Subsequently, the Jacobian matrix and its determinant and trace are obtained based on this equation. By analyzing the equilibrium point of the game model and its stability, it is found that when enterprise N chooses "participation" and industry alliance M selects "design incentive mechanism", or when enterprise N opts for "non-participation" while industry alliance M chooses "no incentive mechanism", these strategy combinations represent ESS stable points with long-term dynamic stability.

The stability of both parties' strategy selection depends on variations in parameters within the replication dynamic equation. Specifically, lower input costs (C_1 and C_2) coupled with higher synergistic income (Q) enhance the long-term stability of the strategy combination where enterprise N chooses "participation" and industry alliance M selects "design incentive mechanism". Further calculations using Matlab reveal that the dynamic evolution process of both parties' strategy selection is influenced by their initial values, ultimately leading to convergence towards two distinct ESS equilibrium points. In terms of impact on participants' dynamic evolution results, long-term stability positively correlates with synergistic revenue Q but negatively correlates with costs C_1 and C_2. Consequently, as synergistic revenue Q increases at a faster rate while costs C_1 and C_2 decrease rapidly, there is an accelerated probability speed for both parties to select the aforementioned decision combination resulting in greater overall stability.

Therefore, in the data circulation industry, the blockchain-based incentive mechanism designed by the industry alliance should play a more prominent role in fostering synergistic benefits (including enhanced enterprise influence through collaborative development participation, acquisition and accumulation of relevant resources, and improved visibility and reputation for both enterprises and industry alliances), while simultaneously reducing costs for both the industry alliance and participating enterprises (including time and energy investments in collaborative mechanisms as well as expenses associated with potential interest redistribution). This represents the primary aspect to consider when designing an incentive mechanism.

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