

The synergistic evolutionary game of multibody behavior in supply chain commercial credit financing

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Abstract: With the deepening integration of the digital economy and the supply chain system, commercial credit financing has become an important path for alleviating the financing difficulties faced by small and medium-sized enterprises. Under the assumption of finite rationality, this paper starts from the perspective of multibody behavioral evolution and clarifies the role positioning and strategic interactions among suppliers, core enterprises and clients in commercial credit financing. On the basis of evolutionary game theory, MATLAB is used to simulate the evolutionary path and is combined with system dynamics to simulate and analyze the initial strategy and external variables of the system. The results show that the suppliers' willingness to finance is significantly affected by reputation risk and time cost, the performance behavior of the core enterprise plays a decisive role in the evolution of upstream and downstream strategies, and the performance stability of the client's merchant is the foundation of the closed loop of the credit chain. The three parties internalize potential risks to a certain extent through a risk-hedging mechanism so the system maintains a stable evolutionary trend.

Keywords: commercial credit financing; supply chain; evolutionary game; system dynamics; numerical simulation

0 Introduction.

As the digital economy develops and reconstruction of the supply chain system accelerates, the role of the supply chain in China's real economy has become increasingly prominent and has gradually evolved into an important platform connecting small and medium-sized enterprises (SMEs), core enterprises and market resources. Moreover, affected by macroeconomic fluctuations and financing structure imbalances, many SMEs face the long-term problem of "difficult and expensive

financing" and are in urgent need of exploring more efficient and flexible financing methods^[1]. Commercial credit financing, as an indirect financing mode based on endogenous credit as well as upstream and downstream trading relationships, is becoming an important way to alleviate the financing pressure on SMEs because of its independence from traditional financial institutions and its high capital turnover efficiency. However, as commercial credit financing develops rapidly, problems such as credit imbalances, low default costs, and core enterprise credit abuses have gradually emerged, leading to a chain transmission of credit risk in the supply chain and exacerbating transactional instability, financing discontinuity, and the reality of SMEs' "being defaulted on"^[2]. An inadequate credit system also inhibits the benign expansion of supply chain finance to a certain extent, weakening its "credit-for-financing" system effectiveness.

To address these problems, in recent years, China has introduced a series of relevant policies. In 2020, the State Council issued the Opinions on Building a More Perfect Institutional Mechanism for Factor Market Configuration, which explicitly highlights the need to improve the credit evaluation system of enterprises and to promote the circulation of accounts receivable, warehouse receipts, and other credit tools in the supply chain. In February, 2025, the People's Bank of China and five other departments issued "Opinions on Regulating the Supply Chain Financial Business and Guiding the Supply Chain Information Service Institution". "Supply Chain Finance Business to Guide Supply Chain Information Service Institutions to Better Serve SMEs and Microenterprises" further emphasized the need to improve the supply chain credit risk management mechanism and to guard against problems such as multiple credit-granting, loss of core enterprise credibility, and supply chain information opacity. These policies not only reflect that the state attaches great importance to promoting the construction of a commercial credit system but also lay the institutional foundation for the healthy development of supply chain commercial credit financing^[3].

Driven by both policy guidance and practical demand, an increasing number of scholars have begun to pay attention to the supply chain credit mechanism and its

behavioral evolutionary law. The credit relationships among suppliers, core enterprises and clients increasingly present complex and dynamic characteristics, in which core enterprises play a key role as the central link of credit transmission. Han Minchun and Rao Yulei (2025)^[4] noted that the digitization of the supply chain can significantly improve its agility, thus effectively alleviating the credit risk problems faced by SMEs. Wang Daoping et al. (2024)^[5] further emphasized that the introduction of smart contracts and trusted interaction mechanisms in the blockchain environment can solve the real problems of delayed delivery, information opacity and default uncertainty that are commonly found in commercial credit financing, thereby enhancing credit credibility and financing efficiency. In addition, Chu et al. (2024)^[6] found that the effective design of a transaction credit mechanism and default penalty can significantly improve the credit performance of micro and small logistical enterprises by constructing an evolutionary game model, which promotes the virtuous circle of supply chain finance. Pang et al. (2022)^[7] proposed that under a platform-type supply chain structure, the default risk of micro- and small enterprises can be effectively constrained by digital trust regulation, which can improve their performance and enhance their tendency toward trustworthiness in the game. In the context of digitalization, blockchain and credit regulatory mechanism evolution, the credit relationship and behavioral game among multiple subjects in the supply chain present new features, which provide a theoretical basis and practical motivation for the subsequent in-depth analysis of three-party behavioral strategies from the perspective of game theory.

Commercial credit has an important financing function in the supply chain, especially in the establishment of a "credit chain" between core enterprises and suppliers through credit, deferred payments and other ways to realize the coupled operation of capital flow and information flow. Suppliers usually provide goods or services to the core enterprise at the early stage of production and bear the initial credit risk; core enterprises endorse the credit with their market position and performance ability; and clients further influence the stability of the credit chain through the efficiency of cash recovery at the sales end. Chao Wang and Dianfan Yu (2023)^[8] noted

that higher enterprise digitization degrees and closer credit relationship networks lead to supply chain financing conditions that are more favorable. Jing Gu et al. (2023)^[9] reported that the closeness of supply chain relationships significantly affects the availability of commercial credit financing for SMEs and that high-quality collaboration between upstream and downstream enterprises can enhance the "credit enhancement effect". Meanwhile, Zou and Zhou (2025)^[10] quantified the credit scale threshold, revealing an inverted U-shaped relationship between commercial credit and sustainable profitability for SMEs, which provides empirical evidence for dynamic adjustment of suppliers' credit terms.

In addition, the credit behaviors of the three parties in the supply chain and their evolutionary process essentially reflect the game attributes, especially under the premise of incomplete information and limited rationality, and strategy selection presents obvious dynamic evolutionary characteristics. Wan and Cui (2024)^[11] constructed an evolutionary game model in the context of the agricultural supply chain and noted that fintech tools can improve information transparency and enhance risk identification ability to improve the effectiveness and sustainability of SMEs' credit financing. Wu Chengfeng et al. (2019)^[12] analyzed the optimal decision-making behavior of suppliers under the synergy of credit period and pricing strategy on the basis of the Stackelberg game framework and revealed its impact on the overall financing efficiency of the supply chain. Wang, Daoping et al. (2023)^[13], on the other hand, extend game analysis to the capital constraint scenario and simulate the optimal strategy combinations of the three parties under different credit regimes by introducing the factors of blockchain deployment cost and market demand uncertainty. From the vertical synergy perspective, Sun, Hui & Zhang, Renshou (2021)^[14] noted that the innovative synergistic behaviors of upstream and downstream firms in the credit environment can help reduce credit risk and enhance supply chain stability. Peng, Zixian and Zhou, Peng (2023)^[15] further emphasized that the construction of digital platforms not only improves the efficiency of information transmission but also strengthens the "signal value" in the gaming strategy, which contributes to the

stabilization of credit relationships. In addition, Fang and Feng (2022)^[16] constructed an evolutionary game model to reveal the role of financial incentives in promoting trustworthy behavior and enhancing system stability by introducing government subsidy variables. Notably, studies have also conducted evolutionary analyses of different tiers of the supply chain structure. Xie and Wu (2024)^[17] expand the supply chain structure to three tiers, revealing the evolutionary trends and stability boundaries of multilayer participants under different financing mechanisms, which complements the limitations of the existing bilateral game framework.

In summary, the literature has made positive progress in revealing the commercial credit financing mechanisms among suppliers, core firms and clients, especially in the digital transformation context, and the discussion has deepened of the logic of credit supply, the behavioral strategies of the three parties and their game relationships. However, the following gaps remain: first, although evolutionary game theory has been introduced in some studies, the application is focused mostly on static strategy analyses, lacking in-depth excavations of the behavioral evolutionary mechanism, strategy adjustment rules, and system stability; second, an understanding remains imperfect of the whole-chain perspective on how commercial credit conducts, accumulates, and fails in the supply chain under the interactions of multiple actors, and a unified theoretical framework has not yet formed.

To fill these gaps, this paper constructs a business credit–financing strategy model based on evolutionary game theory from the interactions among suppliers, core enterprises and clients, and systematically analyzes the selection behavior of each subject under different credit strategies and the behavior’s dynamic evolutionary law. By introducing the assumption of finite rationality and replicating the dynamic equations, this paper not only portrays the game structure among the three parties’ strategies but also reveals the interference mechanism of external environmental factors—such as credit costs, default penalties, and potential risks—on the equilibrium path. The results of this study can provide theoretical support for understanding the stability of the credit chain as well as policy and management

suggestions for optimizing commercial credit allocation and building a high-quality supply chain financial ecology.

1 Behavioral logic and interest demand analysis of each subject

1.1 Behavioral logic and interest demand analysis of suppliers

As initiators of commercial credit financing, suppliers perform the core functions of initial capital investment and credit risk transfer in the supply chain financial system. In the coordinated commercial credit–financing structure, suppliers provide financial support to core enterprises through credit sales, etc. This credit-granting behavior is based essentially on the dynamic assessment of the credit qualifications of core enterprises, including the systematic examination of their financial statements, historical order fulfillment rate and supply chain control ability^[18]. However, in the context of incomplete information and limited rationality, this behavior puts suppliers at the forefront of risk exposure, and their strategic choices have a critical impact on the credit structure and operational efficiency of the entire supply chain.

The fundamental interest of suppliers is to protect their own capital, control their credit risk exposure, and obtain a stable return on this basis. However, in actual transactions, the uncertainty of the core enterprise's performance and possible deferred payment or delayed delivery behaviors on the part of the client may lead to a decline in credit returns and even the risk of bad debt^[19]. An important issue for suppliers has become how to continue to participate in commercial credit financing while ensuring credit security. If suppliers choose to increase the financing supply, they will face higher time costs, credit default risks and indirect losses caused by delayed downstream performance; however, doing so will help stabilize the cooperative relationship with core enterprises, resulting in more orders and long-term credit benefits^[20]. In contrast, although decreasing financing can effectively avoid risk, it may lead to the loss of cooperation opportunities and a decline in market share, thus weakening the long-term competitiveness of the enterprise.

In addition, once the core enterprise defaults, the supplier bears the corresponding economic loss directly, while the performance status of the client affects the supplier's capital recovery through the core enterprise, and the delayed behavior of the client forms a supply chain cascade that will ultimately exacerbate the credit uncertainty faced by the supplier^[21]. Therefore, a dynamically evolving and interdependent credit game system is formed among the three parties. Suppliers must construct differentiated financing strategies based on the evaluation of the credit history and performance of the counterparty in the process of continuously updated information and realize the optimal balance between credit gain and risk control by dynamically adjusting strategy weights to encourage supply chain credit cooperation in the direction of stability and sustainability.

1.2 Analysis of the behavioral logic and interests of core enterprises

Located at the center of the supply chain, the core enterprise is the key link connecting credit transmission and capital flow between suppliers and clients, and bears the responsibility of two-way credit management in commercial credit financing. For upstream suppliers, the credit rating of the core enterprise directly determines its willingness and conditions to obtain financing; for downstream clients, the core enterprise must formulate a differentiated billing period policy on the basis of the credit records of the clients. Whether they perform their obligations on time becomes an important indicator of their creditworthiness and the value of long-term cooperation^[22].

From the cost–benefit perspective, the direct cost of core firms' compliance is reflected mainly in the capital expenditure resulting from timely repayment, while the indirect benefits include stabilizing the credit relationship, enhancing bargaining power and improving the efficiency of supply chain synergy^[23]. Comparatively speaking, choosing to default can release short-term capital pressure, but doing so can also result in systemic risks such as reputation loss, upstream financing tightening, and downstream cooperation disruptions. In the supplier relationship, compliance helps maintain financing supply continuity, whereas default may trigger credit contraction

and cooperation suspension; in client interactions, default may further trigger a chain reaction of delayed deliveries, higher capital utilization costs, and even business reputation decline. Once the client doubts the creditworthiness of the core enterprise, its willingness to perform and delivery ability are weakened simultaneously, which affects the core enterprise's market delivery ability and payback efficiency^[24].

Therefore, core enterprise performance behavior not only concerns the stability of the credit chain between them and their suppliers but also determines the core enterprise's credit structure and business market sustainability. On this basis, core enterprises must make a rational choice between short-term cash flow pressure and long-term credit maintenance, adopt a performance-oriented cooperation path, and ensure the stable and efficient operation of the credit-financing system by strengthening internal financial management and credit control ability.

1.3 Behavioral Logic and Interest Analysis of Clients

As the final performance subject in the supply chain credit system, the client is at the end of the credit conduction chain, and its performance behavior is essentially constrained by the credit policy of the core enterprise, which has a direct effect on the capital return of the core enterprise and the credit return of the supplier. In the commercial credit–financing structure, the client obtains goods or services through contracts, and its performance ability is reflected mainly in whether it delivers and pays on time. This behavior not only determines the pace of core enterprise capital return but also profoundly affects the credit stability of the whole supply chain.

Client behavioral decisions show strong uncertainty, and their performance ability is easily constrained by their own financial status, market demand fluctuations, operational plans and other factors. In the case of delayed delivery or payment, the core enterprise faces greater pressure on its financial chain and may default on supplier payments, thus triggering a multilevel risk transmission^[25]. While the direct cost to the client is resource allocation and capital expenditure, the indirect benefit includes maintaining the purchasing relationship with the core enterprise, enhancing the credit image and expanding the space for future cooperation. While choosing to

postpone performance can temporarily relieve internal resource constraints, doing so results in potential penalties for breach of contract, weakened credit, and cooperative relationship deterioration, especially in the long-term game, and the negative impacts may be extended to structural losses such as loss of orders and bargaining power^[26].

In the interaction with core firms, insufficient client performance directly blocks the latter's capital flow back and affects its ability to pay upstream; in the indirect relationship with suppliers, the delayed behavior of clients is transmitted upstream through core firms, exposing suppliers to the chain risk of capital utilization, declining credit returns, and even increasing bad debts^[27]. As a result, the performance behavior of clients has become a key variable in determining the stability of the commercial credit chain. To maintain its cooperative status in the credit network, the client should establish a good credit record on the basis of the logic of risk-return balance and improve its performance ability by optimizing the internal capital operation and project execution mechanism to enhance credit stickiness and cooperative value in the multiround game.

2 Evolutionary game model construction and solution

2.1 Model variables and assumptions

This paper studies the evolutionary game model of the supply chain commercial credit–financing behaviors of multiple subjects, and the model construction is based on the following assumptions.

Assumption 1: Supply chain commercial financing involves three parties: suppliers (X), core enterprises (Y) and clients (Z). All three parties make commercial credit–financing decisions under the conditions of incomplete information and limited rationality. The key parameters governing their interactions are summarized in Table 1.

Hypothesis 2: Suppliers have two behavioral strategies. One is to increase the financing supply, which refers to the decision to increase commercial credit financing to core firms with probability $x(0 < x < 1)$; the other is to decrease the financing supply, which refers to the decrease or cessation of commercial credit financing to core

firms with probability $(1 - x)$.

Hypothesis 3: Core firms have two behavioral strategies. One is performance, which refers to loan repayment at the time agreed upon in the contract and credit obligation fulfilment to the supplier, with a probability of $y(0 < y < 1)$; the other is default, which refers to the core firm's failure to perform its repayment obligation as agreed upon in the contract, with a probability of $(1 - y)$.

Hypothesis 4: The client firm has two possible behavioral strategies. One is on-schedule delivery, which refers to completing the delivery of goods or services at or before the contracted time point, with a probability of $z(0 < z < 1)$; the other is delayed delivery, which refers to failing to complete the delivery according to the contracted time point, and the delivery time is delayed beyond the original deadline, with a probability of $1 - z$.

Table 1 Model parameters and meanings

Behavior	Parameter	Meaning
Supplier	e_1	Time costs of the core firm's capital utilization if the supplier increases financing.
	e_3	Time costs of the core company's capital utilization if the supplier decreases financing.
	s_1	Potential risks (credit default risk, market volatility, legal compliance risk and operation management risk, etc.) faced by the supplier in the process of increasing financing.
	s_3	Potential risks faced by suppliers in the process of decreasing financing.
	n_1	Indirect economic losses (delayed return of funds, lower credit returns and increased risk of potential bad debts, etc.) suffered by suppliers if they increase financing.
	n_2	Indirect economic losses suffered by suppliers if they decrease financing.
Core	e_2	Time costs incurred by the client as a result of capital tied up in the

business		core business if the supplier increases the commercial finance available to the core business.
		Time costs incurred by the client business as a result capital tied up if
	e_4	the supplier decreases the commercial finance supply to the core business.
	s_2	Potential risks faced by the core business in providing finance when the supply of commercial credit level is adequate.
	s_4	Potential risks faced by the core business in providing finance when the supply of commercial credit level is tight.
	m	Financial loss of the core business if the client delays delivery.
		Reputational loss of the core business (negative impacts such as
	α	reduced client trust, damaged brand image and decreased market share) if it defaults.
Client	w_1	Indirect economic losses suffered by client (supply chain disruption, liquidity issues and reduced trust in the market, etc.) if the core company defaults when the supplier increases financing.
	w_2	Indirect economic losses suffered by client if the core company defaults when the supplier decreases financing.
		Additional economic losses to the client (capital tie-up costs, increased supplier credit risk, disruption to production or sales
	r	programs, and possible legal fines, etc.) if the core business defaults, resulting in delayed payments.
	β	Reputational loss (loss of reputation, loss of clients and reduction of potential cooperation opportunities, etc.) if the clients defaults.

2.2 Modeling

Supplier X, core enterprise Y and client Z have different behavioral strategies in supply chain business financing, resulting in eight strategy combinations. The parameter assumptions allow the derivation of the behavioral strategy benefit matrix of the three parties in commercial credit financing, as shown in Table 2.

Table 2 Benefit matrix of the evolutionary game among suppliers, core enterprises and client merchants

Decision-making combinations	Benefit matrix		
	Supplier	Core firm	Client
{Increased Financing, Performance, On-Schedule Delivery}	$e_1 - s_1$	$-e_1 + e_2 - s_2$	$-e_2$
{Increased Financing, Performance, On-Schedule Delivery}	$e_1 - s_1 - n_1$	$-e_1 - s_2 - m$	$-\beta$
{Increased Financing, Default, On-Schedule Delivery}	$-s_1$	$e_2 - s_2 - \alpha$	$-e_2 - w_1$
{Increased Financing, Default, Delayed Delivery}	$-s_1 - n_1$	$-s_2 - \alpha$	$-\beta - w_1 - r$
{Decreased Financing, Performance, On-Schedule Delivery}	$e_3 - s_3$	$-e_3 + e_4 - s_4$	$-e_4$
{Decreased Financing, Performance, Delayed Delivery}	$e_3 - s_3 - n_2$	$-e_3 - s_4 - m$	$-\beta$
{Decreased Financing, Default, On-schedule Delivery}	$-s_3$	$e_4 - s_4 - \alpha$	$-e_4 - w_2$
{Decreased Financing, Default, Delayed Delivery}	$-s_3 - n_2$	$-s_4 - \alpha$	$-\beta - w_2 - r$

2.3 Model Analysis and Solution

According to the evolutionary game matrix, the expected and average returns of suppliers, core enterprises and clients are calculated, and then the replication dynamic equations of each subject are constructed.

2.3.1 Replicated the dynamic equations and equilibrium point of a supplier's behavior to "increase the financing supply".

On the basis of the evolution game matrix of whether suppliers increase financing supply, the expected returns corresponding to suppliers' different strategy choices are calculated, and the replicated dynamic equation of the supplier evolution game is constructed.

Expected benefits of suppliers choosing to "increase the finance supply" E_{x1} :

$$E_{x1} = y[z(e_1 - s_1) + (1 - z)(e_1 - s_1 - n_1)] \\ + (1 - y)[z(-s_1) + (1 - z)(-s_1 - n_1)]$$

Expected benefits of suppliers choosing to "decrease the financing supply" E_{x2} :

$$E_{x2} = y[z(e_3 - s_3) + (1 - z)(e_3 - s_3 - n_2)] + (1 - y)[z(-s_3) \\ + (1 - z)(-s_3 - n_2)]$$

The average expected return of the suppliers' decision-making behavior, E_x :

$$E_x = xE_{x1} + (1 - x)E_{x2}$$

According to evolutionary game theory, the replicated dynamic equation of the supplier's behavior of "increasing the financing supply," $F(x)$, is as follows:

$$F(x) = \frac{dx}{dt} = x(E_{x1} - E_x) \\ = x(x - 1)[(e_3 - e_1)y + (n_2 - n_1)z + n_1 - n_2 + s_1 - s_3]$$

Let $F(x) = \frac{dx}{dt}$; the solution is the equilibrium point of the evolutionary process:

(1) When $y = y^* = \frac{(n_2 - n_1)z + n_1 - n_2 + s_1 - s_3}{e_1 - e_3}$ 时, the points on the x axis are in a stable state; i.e., the supplier's strategy choices do not change over time.

(2) When $y \neq \frac{(n_2 - n_1)z + n_1 - n_2 + s_1 - s_3}{e_1 - e_3}$, $F(x)$ has two possible equilibrium points: $x = 0$ and $x = 1$.

According to the stability theorem of the differential equation and the nature of evolutionary stable strategy, the necessary condition the supplier must satisfy to reach the evolutionary stable strategy is $\frac{dF(x)}{dx} < 0$.

Taking the derivative of $F(x)$ yields the following:

$$\frac{dF(x)}{dx} = (1 - 2x)[(e_1 - e_3)y + (n_1 - n_2)z + n_2 - n_1 + s_3 - s_1]$$

(1) When $0 < y < \frac{(n_2 - n_1)z + n_1 - n_2 + s_1 - s_3}{e_1 - e_3}$, $\frac{dF(x)}{dx}|_{x=0} < 0$, $\frac{dF(x)}{dx}|_{x=1} > 0$, $x = 0$ is

the equilibrium point of the supplier behavioral evolution; that is, the supplier tends to choose the strategy of "decreasing the financing".

(2) When $\frac{(n_2 - n_1)z + n_1 - n_2 + s_1 - s_3}{e_1 - e_3} < y < 1$, $\frac{dF(x)}{dx}|_{x=0} > 0$, $\frac{dF(x)}{dx}|_{x=1} < 0$, $x = 1$ is

the equilibrium point of the supplier behavioral evolution; that is, the supplier tends to choose the strategy of "increasing the financing".

According to the above analysis, the above conclusions are expressed in a three-dimensional coordinate system, and the dynamic evolution of supplier behavioral trends is shown in Figure 1.

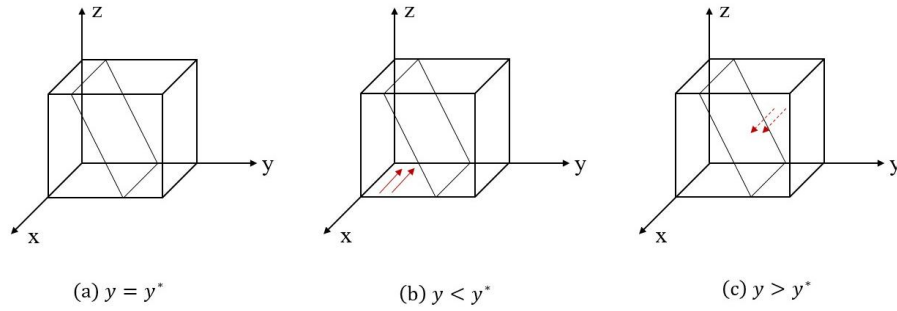


Figure 1 Dynamic evolutionary trends of supplier behavior

2.3.2 Replicating the dynamic equations of a core enterprise's "performance" behavior and its equilibrium point

On the basis of the evolution game matrix of whether the core enterprise will perform, the expected returns are calculated corresponding to the different strategy choices of the core enterprise, and the replicated dynamic equation of the core enterprise's evolution game E_{y1} is constructed:

Expected benefits of core enterprise choosing to "perform" E_{y1} :

$$E_{y1} = x[z(-e_1 + e_2 - s_2) + (1 - z)(-e_1 - s_2 - m)] \\ + (1 - x)[z(-e_3 + e_4 - s_4) + (1 - z)(-e_3 - s_4 - m)]$$

Expected benefits of core enterprise choosing to "defaults" E_{y2} :

$$E_{y2} = x[z(e_2 - s_2 - \alpha) + (1 - z)(-s_2 - \alpha)] + (1 - x)[z(e_4 - s_4 - \alpha) \\ + (1 - z)(-s_4 - \alpha)]$$

The average expected return of the core firms' decision-making behavior, E_y :

$$E_y = yE_{y1} + (1 - y)E_{y2}$$

According to evolutionary game theory, the replicated dynamic equation for the "compliance" behavior of the core firm $F(y)$ is as follows:

$$F(y) = \frac{dy}{dt} = y(E_{y1} - E_y) = y(y - 1)[(e_1 - e_3)x - mz + e_3 - \alpha + m]$$

Let $F(y) = \frac{dy}{dt}$; the solution is the equilibrium point of the evolutionary process:

(1) When $z = z^* = \frac{(e_1 - e_3)x + e_3 - \alpha + m}{m}$ 时, the points on the y axis are in a stable state; i.e., at this time, the strategic choices of the core enterprise do not change over time.

(2) When $z \neq \frac{(e_1 - e_3)x + e_3 - \alpha + m}{m}$, $F(y)$ has two possible equilibrium points: $y = 0$ and $y = 1$.

According to the stability theorem of the differential equation and the nature of the evolutionary stable strategy, the necessary condition that the core enterprise must satisfy is $\frac{dF(y)}{dy} < 0$.

Taking the derivative of $F(y)$ yields:

$$\frac{dF(y)}{dy} = (1 - 2y)[(e_3 - e_1)x + mz - e_3 + \alpha - m]$$

(1) When $0 < z < \frac{(e_1 - e_3)x + e_3 - \alpha + m}{m}$, $\frac{dF(y)}{dy}|_{y=0} < 0$, $\frac{dF(y)}{dy}|_{y=0} > 0$, $y = 0$ is the equilibrium point of the core enterprise behavioral evolution; that is, the core enterprise tends to choose the "default" strategy.

(2) When $\frac{(e_1 - e_3)x + e_3 - \alpha + m}{m} < z < 1$, $\frac{dF(y)}{dy}|_{y=0} > 0$, $\frac{dF(y)}{dy}|_{y=0} < 0$, $y = 1$ is the equilibrium point of the core enterprise behavioral evolution; that is, the core enterprise tends to choose the "performance" strategy.

According to the above analysis, the above conclusions are expressed in a three-dimensional coordinate system, and the dynamic evolutionary trends of core enterprise behavior can be obtained, as shown in Figure 2.

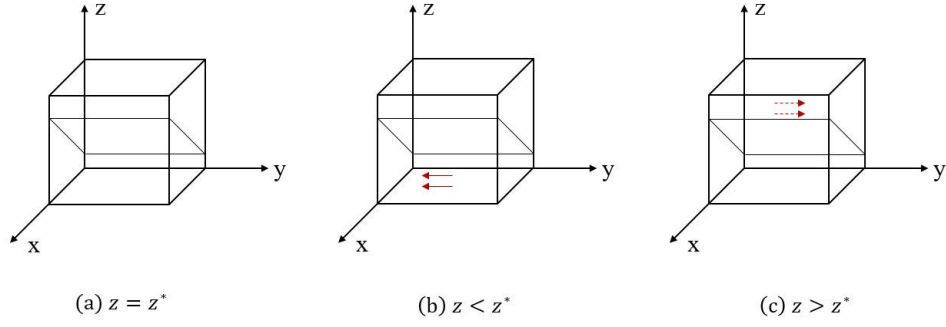


Figure 2: Dynamic evolutionary trends of core enterprise behavior

2.3.3 Replicating the dynamic equations and equilibrium points of a client's "on-time delivery" behavior

On the basis of the evolution game matrix of whether the client will deliver on time, the expected returns corresponding to the different strategy choices of the client are calculated, and then the replication dynamic equation of the client's evolution game is constructed.

Expected benefits of client's choosing to "on-time delivery" E_{z1} :

$$E_{z1} = x[y(-e_2) + (1 - y)(-e_2 - w_1)] + (1 - x)[y(-e_4) + (1 - y)(-e_4 - w_2)]$$

Expected benefits of client's choosing to "delayed delivery" E_{z2} :

$$E_{z2} = x[y(-\beta) + (1 - y)(-\beta - w_1 - r)] + (1 - x)[y(-\beta) + (1 - y)(-\beta - w_2 - r)]$$

The average expected return of the client's decision-making behavior, E_z :

$$E_z = zE_{z1} + (1 - z)E_{z2}$$

According to evolutionary game theory, the replicated dynamic equation of the client's "deliver on time" behavior, $F(y)$, is as follows:

$$F(z) = \frac{dz}{dt} = z(E_{z1} - E_z) = z(z - 1)[(e_2 - e_4)x + ry + e_4 - \beta - r]$$

Let $F(z) = \frac{dz}{dt}$; the solution is equilibrium point of the evolutionary process:

(1) When $x = x^* = \frac{-ry - e_4 + \beta + r}{e_2 - e_4}$ 时, all of the points on the z axis are in a steady

state; i.e., the strategy choices of the client do not change over time.

(2) When $x \neq \frac{-ry - e_4 + \beta + r}{e_2 - e_4}$, $F(z)$ has two possible equilibrium points: $z = 0$ and $z = 1$.

According to the stability theorem of the differential equation and the nature of evolutionary stable strategy, the necessary condition the client must satisfy to reach the evolutionary stable strategy is $\frac{dF(y)}{dy} < 0$.

Taking the derivative of $F(z)$ yields the following:

$$\frac{dF(z)}{dz} = (1 - 2z)[(e_4 - e_2)x - ry - e_4 + \beta + r]$$

(1) When $0 < x < \frac{-ry - e_4 + \beta + r}{e_2 - e_4}$, $\frac{dF(z)}{dz}|_{z=0} > 0$, $\frac{dF(z)}{dz}|_{z=1} < 0$, then $z = 0$ is the equilibrium point of the client's behavioral evolution; that is, the client tends to choose the "on-time delivery" strategy.

(2) When $\frac{-ry - e_4 + \beta + r}{e_2 - e_4} < x < 1$, $\frac{dF(z)}{dz}|_{z=0} < 0$, $\frac{dF(z)}{dz}|_{z=1} > 0$, then $z = 1$ is the equilibrium point of the client behavioral evolution, i.e., the client tends to choose the "delayed delivery" strategy.

According to the above analysis, the above conclusions are expressed in the three-dimensional coordinate system, and the dynamic evolution of the client behavioral trends can be obtained, as shown in Figure 3.

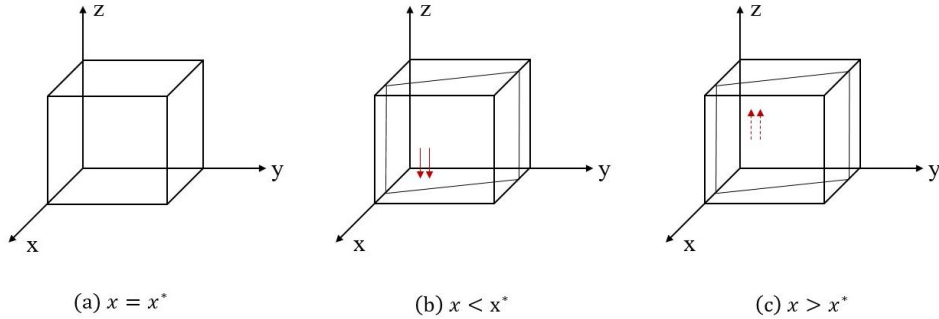


Figure 3: Dynamic evolution of client behavior

2.4 Analysis of the equilibrium strategy of the evolutionary game model

According to the above analysis, the three-dimensional dynamical system of the evolutionary game can be obtained as follows:

$$\begin{cases} F_x(x, y, z) = x(x - 1)[(e_3 - e_1)y + (n_2 - n_1)z + n_1 - n_2 + s_1 - s_3] \\ F_y(x, y, z) = y(y - 1)[(e_1 - e_3)x - mz + e_3 - \alpha + m] \\ F_z(x, y, z) = z(z - 1)[(e_2 - e_4)x + ry + e_4 - \beta - r] \end{cases}$$

From $F_x(x, y, z) = 0$, $F_y(x, y, z) = 0$ and $F_z(x, y, z) = 0$, an evolutionary system can be obtained that has 8 pure strategy equilibrium points: $D_1(0,0,0)$, $D_2(1,0,0)$, $D_3(0,1,0)$, $D_4(0,0,1)$, $D_5(1,1,0)$, $D_6(1,0,1)$, $D_7(0,1,1)$, and $D_8(1,1,1)$.

The method of Friedman^[28] is used to obtain the stability of the equilibrium points of the differential system by analyzing the eigenvalues of the Jacobi matrix of the system. The Jacobi matrix of the system is as follows:

$$J = \begin{bmatrix} \frac{\partial F_x(x,y,z)}{\partial x} & \frac{\partial F_x(x,y,z)}{\partial y} & \frac{\partial F_x(x,y,z)}{\partial z} \\ \frac{\partial F_y(x,y,z)}{\partial x} & \frac{\partial F_y(x,y,z)}{\partial y} & \frac{\partial F_y(x,y,z)}{\partial z} \\ \frac{\partial F_z(x,y,z)}{\partial x} & \frac{\partial F_z(x,y,z)}{\partial y} & \frac{\partial F_z(x,y,z)}{\partial z} \end{bmatrix}$$

$$= \begin{bmatrix} (1-2x)[(e_1-e_3)y + (n_1-n_2)z + n_2 - n_1 + s_3 - s_1] & x(x-1)(e_3-e_1) & x(x-1)(n_2-n_1) \\ y(y-1)(e_1-e_3) & (1-2y)[(e_3-e_1)x + mz - e_3 + \alpha - m] & -y(y-1)m \\ z(z-1)(e_2-e_4) & z(z-1)r & (1-2z)[(e_4-e_2)x - ry - e_4 + \beta + r] \end{bmatrix}$$

The eigenvalue analysis of the Jacobi matrix is used to analyze the stability of the eight pure strategy equilibrium points in the evolutionary system. If all of the eigenvalues of an equilibrium point are less than 0, the equilibrium point is the system evolutionary stable strategy (ESS). If at least one eigenvalue is greater than 0, the point is unstable. The stability analysis of the 8 pure strategy equilibrium points is shown in Table 3.

Table 3 Stability analysis of the pure strategy equilibrium points

Equilibrium point	λ_1	λ_2	λ_3	Stability conditions
$D_1(0,0,0)$	$\alpha - e_3$	$\beta - e_4$	$n_2 - n_1 - s_3 + s_1$	$\alpha - e_3 < m$
	$-m$	$-r$		$\beta - r < e_4$
				$n_2 - n_1 < s_3 - s_1$
$D_2(1,0,0)$	$\alpha - e_1$	$\beta - e_2$	$n_1 - n_2 + s_1 - s_3$	$\alpha - e_1 < m$
	$-m$	$-r$		$\beta + r < e_2$
				$n_1 - n_2 < s_3 - s_1$
$D_3(0,1,0)$	$\beta - e_4$	$e_3 - \alpha$	$e_1 - e_3 - n_1 + n_2 - s_1 + s_3$	$\beta < e_4$
		$+m$		$e_3 + m < \alpha$
				$e_1 - e_3 - n_1 + n_2 < s_1 - s_3$
$D_4(0,0,1)$	$\alpha - e_3$	$s_3 - s_1$	$e_4 - \beta - r$	$\alpha < e_3$
				$s_3 < s_1$
				$e_4 - \beta < r$

				$\beta < e_2$
$D_5(1,1,0)$	$\beta - e_2$	$e_1 - \alpha$ $+ m$	$e_3 - e_1 + n_1 - n_2 + s_1$ $- s_3$	$e_1 + m < \alpha$ $e_3 - e_1 + n_1 - n_2 < s_3 - s_1$
				$\alpha < e_1$
$D_6(1,0,1)$	$\alpha - e_1$	$s_1 - s_3$	$e_2 - \beta - r$	$s_1 < s_3$ $e_2 - \beta < r$
				$e_3 < \alpha$
$D_7(0,1,1)$	$e_3 - \alpha$	$e_4 - \beta$	$e_1 - e_3 - s_1 + s_3$	$e_4 < \beta$ $e_1 - e_3 < s_1 - s_3$
				$e_1 < \alpha$
$D_8(1,1,1)$	$e_1 - \alpha$	$e_2 - \beta$	$e_3 - e_1 + s_1 - s_3$	$e_2 < \beta$ $e_1 - e_3 < s_1 - s_3$

The stability conditions of the above 8 equilibrium points indicate that the dynamic relationships among the degree of risk aversion, cooperation benefits and default costs affect the behavioral choices of the three subjects. The theory of competitive cooperation^[29] is used to divide the evolutionary process of commercial credit cooperation among the supply chain subjects into 3 stages, and equilibrium point stability is analyzed at different stages.

(1) Defensive competition stage: In the early stage of supply chain cooperation, the behavioral choices of the three parties essentially embody the contradiction between short- and medium-term interests and long-term value. Under incomplete information and limited rationality, enterprises have risk-aversion motives because they cannot predict the behaviors of other parties^[30]. Suppliers decrease financing because of concerns about core enterprise default, the core enterprise defaults because it predicts delayed client delivery, and the client postpones performance to transfer cost pressure, forming the Nash equilibrium of "defensive competition", in which individual rationality leads to overall efficiency loss. Therefore, this stage corresponds to equilibrium point $D_1(0,0,0)$. The evolutionary path of the system in this stage is shown in Figure 4.

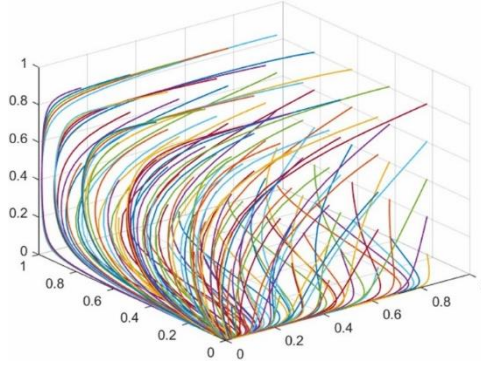


Fig. 4 System evolutionary path in the defensive competition stage

(2) Competitive equilibrium stage: In dynamic competition, supply chain subjects gradually break through the incomplete information constraint by accumulating information in repeated interactions, transforming short-term adversarial competition into limited competition on the basis of efficiency optimization. On the basis of the accurate assessment of the performance ability of the core enterprise—such as historical repayment records, cash flow transparency, etc.—the suppliers form a "moderate financing" strategy to bind the cooperative relationship with the minimum necessary financing and reduce their own risk exposure^[31]. As the long-term game involves significantly magnified risks of supply chain disruption, loss of goodwill and other default costs, the core enterprise chooses a stable performance strategy in exchange for supplier financing conditions that are more flexible or preferential client cooperation. As supply chain coordination efficiency increases, clients gradually realize that the marginal benefit of delayed delivery is lower than the long-term value of cooperation is; therefore, they tend to deliver on time. Therefore, this stage corresponds to equilibrium point $D_7(0,1,1)$. The system evolutionary path in this stage is shown in Fig. 5.

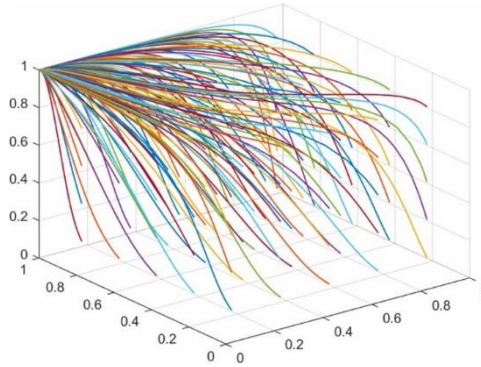


Fig. 5 System evolutionary path in the competitive equilibrium stage

(3) Symbiotic Synergy Stage: The barrier of incomplete information has been greatly dissolved because data sharing and transparency have improved, and the three subjects gradually form a symbiotic ecology dominated by cooperation and supplemented by competition. On the basis of the scale effect introduced by cooperation, the long-term zero-default record of core enterprises, real-time visualization of financial data, etc., suppliers form absolute trust in core enterprises' performance ability and finance them, converting trust into capital leverage, driving the growth of the overall value of the supply chain; core enterprises—because the long-term default cost is far greater than the short-term gains, and because their market position relies ultimately on the client's delivery capacity—adhere to the supply chain in cooperation. Core firms insist on supply chain cooperation because the long-term cost of default far exceeds the short-term benefit, and their market position depends on the ultimate delivery capability of their clients; thus, they insist on supply chain cooperation^[32]. Clients choose to deliver on time because the internal cost structures of their clients are highly matched with the supply chain rhythm as a result of their deep synergy, and the marginal benefit of delaying delivery is nearly zero. The positive-sum game forms a steady-state equilibrium, and the supply chain achieves a threefold increase in resilience, efficiency and innovation. This stage corresponds to equilibrium point $D_8(1,1,1)$. The system evolutionary path in this stage is shown in Fig. 6.

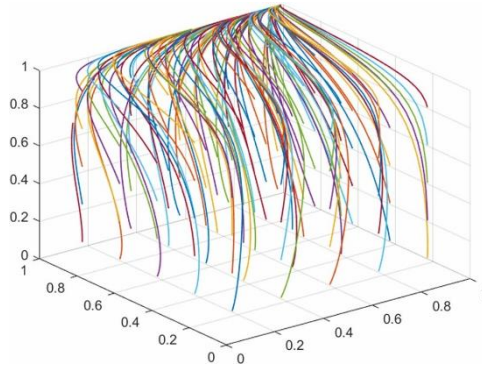


Fig. 6 System evolutionary path in the symbiotic cooperation stage

3 Numerically simulated analysis of the evolution game model

3.1 System dynamics

System dynamics is a modeling method based on system theory, information theory, cybernetics and computer technology and is used to analyze the feedback mechanism, structure and dynamic behavior relationship of a system. This method can effectively portray the decision-making behavior of the subject by establishing a simulation model and using it to study the dynamic mechanism of a complex system. In the strategy selection of supply chain business credit, suppliers, core enterprises and clients interact dynamically, and the decision-making behaviors of each party are continuously adjusted over time^[33]. On the basis of the benefit comparison and learning mechanism, the participating subjects dynamically modify their own decision-making strategies according to the benefits of other parties.

To analyze the evolutionary trends of each subject systematically, VENSIM software is used to establish the SD model of the evolution game of commercial credit decision-making suppliers, core enterprises and clients, and a simulation analysis is conducted to explore the evolutionary strategy among the subjects. The SD model of the commercial credit behavioral strategy is shown in Figure 7. The model includes three state variables, namely, suppliers increase financing supply (x), core enterprises perform their contracts, (y) and clients deliver on schedule (z); three flow rate variables, namely, financing supply change rate, contract fulfillment change rate and delivery time change rate; as well as nine auxiliary and 16 external variables. To ensure that the system reaches the ideal state—i.e., $D8(1,1,1)$, or the system ESS—three conditions must be satisfied: $e_1 < \alpha$, $e_2 < \beta$ and $e_3 - e_1 < s_3 - s_1$. Therefore, this paper refers to the literature^[34] to set the initial parameter values, as shown in Table 4. Only the simulation parameters are changed in the simulation process, and the rest of the parameters remain unchanged.

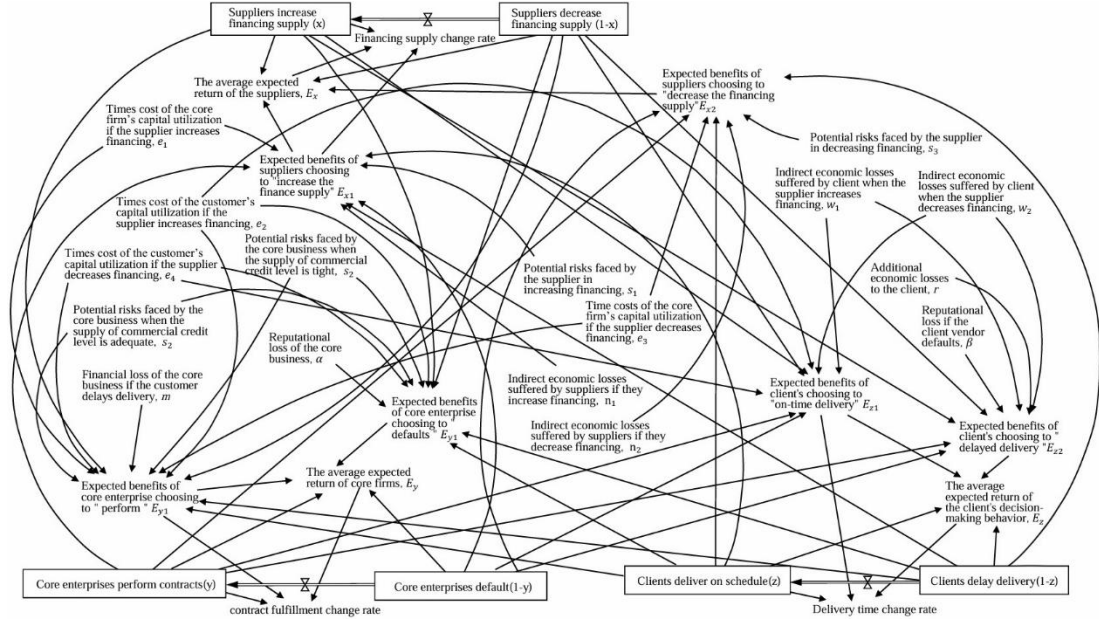


Fig. 7 SD model of the business credit behavioral strategy

Table 4 Initial parameter values

Variable	Value	Variable	Value
e_1	0.3	s_1	0.5
e_2	0.4	s_2	1.2
e_3	0.6	s_3	1
e_4	0.8	s_4	0.7
n_1	0.9	w_1	0.7
n_2	0.6	w_2	1
m	1.1	α	1.5
r	0.8	β	1

3.2 Numerically simulated analysis of the model parameters

3.2.1 Initial strategy simulation analysis

Evolutionary game simulation analyzes the influence of key elements on the equilibrium results and explores how the ideal equilibrium can be achieved. In this work, we simulate the influence of each influential factor on the evolutionary stable strategy through MATLAB simulations. According to the initial parameter values, we explore the impact of the initial strategy share on the system evolutionary results, as shown in Figure 8.

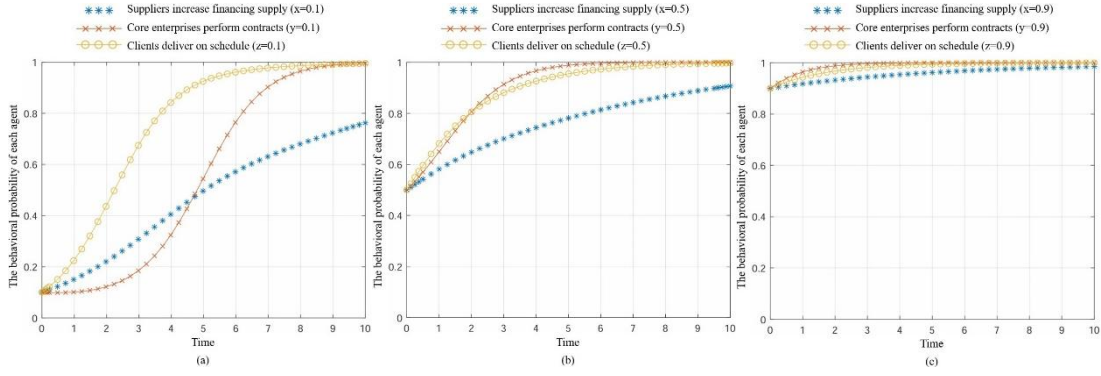


Fig. 8 Influence of the initial strategy share ratio on the system evolution result

Figure 8 shows that the convergence curve of the strategy selection of suppliers, core enterprises and clients possesses path dependence characteristics. The initial proportion of the three parties' strategy selection affects the system convergence speed such that when that proportion is closer to the equilibrium point, the system converges faster, which indicates that the proportion of the initial strategy is crucial to whether the three parties can enter a mode of increased financing, fulfillment, and on-schedule delivery. Therefore, suppliers, core enterprises and clients should be guided to optimize their initial strategy selection, and they should collaborate to promote model evolution to accelerate the system convergence speed and promote the efficient operation of the supply chain system.

3.2.2 Simulation analysis of the external variables

When the ideal points $e_1 < \alpha$, $e_2 < \beta$ and $e_3 - e_1 < s_3 - s_1$ are stable, suppliers, core enterprises and clients must individually weigh risks and benefits and choose strategy combinations that can maximize their own interests and coordinate with each other, so their behaviors can gradually evolve into a situation of increased financing, fulfillment, and on-schedule delivery. Therefore, scenarios and factors are combined to explore the effects of external variables on the system evolution results.

(1) The trends of the impact of reputation loss on the system evolution outcome are shown in Figure 9. Suppliers are subject to indirect economic impacts suffered by core firms and clients due to fluctuations in the reputation loss level, as shown in Figure 9(a). As core firms and clients suffer from increased reputational losses, the pressure on suppliers to provide more commercial credit financing increases. From a risk

management perspective, suppliers tend to adopt a more conservative strategy to decrease financing to reputation-damaged firms, thereby protecting the suppliers' financial security. In this process, suppliers must also weigh how to maintain long-term relationships with core firms and the suppliers' market position. As a result, suppliers must exercise a high degree of caution in providing financing support, even within manageable risk boundaries, to avoid excessive financial losses, which decrease the probability of suppliers' financing increases. The economic impact of a 50% fluctuation in the reputational loss degree due to defaults or delayed deliveries for core firms and clients is shown in Figures 9(b) and 9(c). As the impact of potential reputation loss increases, both core firms and clients are more inclined to perform their business credit responsibilities. To maintain their market reputation and competitive advantage, and to avoid economic and cooperation risks, core enterprises and clients are more inclined to maintain their reputation value, which leads to a significant increase in the evolutionary trend of their performance behavior.

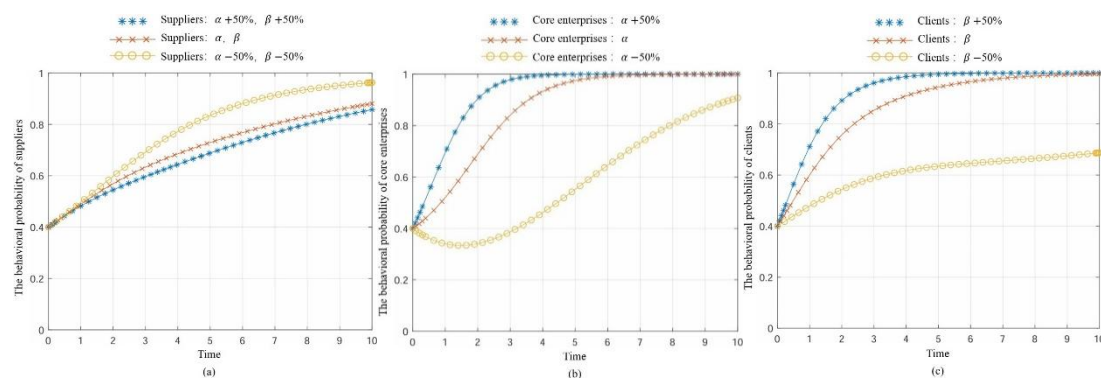


Fig. 9 Impacts of reputational loss on the system evolutionary outcome

(2) The trends of the impact of the time cost of money on the evolutionary outcome of the system is shown in Figure 10. Suppliers have less variation in the economic impact because the time cost of money fluctuates, as shown in Figure 10(a). As the time cost increases of funds from core firms and suppliers, suppliers converge to the stabilization point faster, suggesting that increasing the time cost of funds accelerates suppliers' tendency to increase financing behavior. The economic behavioral impact of core firms due to the volatility of the market interest rates to which they are exposed is shown in Figure 10(b). As the time cost of money increases, the debt leverage of core

firms intensifies, and the speed of their evolutionary trends tends to decrease significantly. The economic behavioral choices of the client-dealer as the end of the supply chain due to the time cost of money are shown in Figure 10(c). When the time cost of money suffered by the client merchant increases by 50%, the evolutionary curve of the client merchant shows a trend of first rising and then falling, and the long-term behavioral choice tends to delay delivery; when the time cost of money suffered by the client merchant decreases by 50%, the evolutionary curve of the supplier rises to a certain extent, which indicates that the release of the money pressure is conducive to promoting the client merchant's on-time delivery.

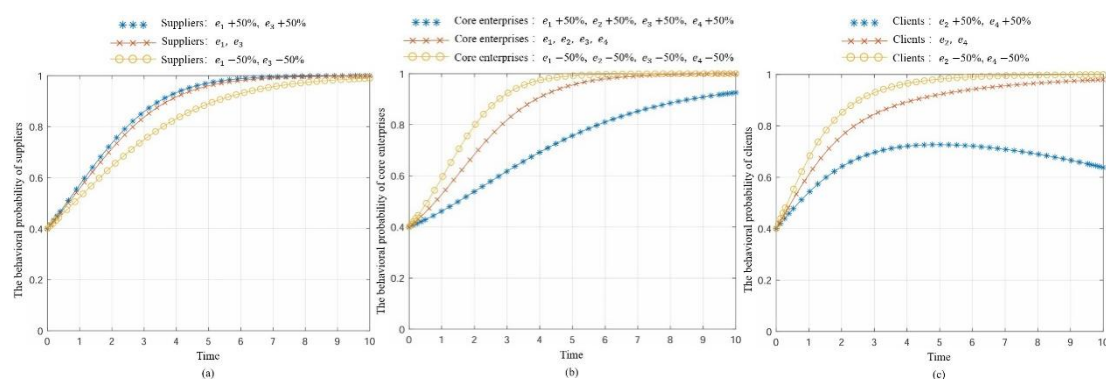


Fig. 10 Influences of the time cost of funds on the system evolutionary outcome

(3) The trends of the influence of the potential risk of the financing process on the system evolution results are shown in Figure 11. As the assigned value of the potential financing risk fluctuates by 50%, the evolutionary trends of suppliers and clients change slightly, as shown in Figs. 11(a) and 11(c). For clients, as shown in Figure 11(b), the potential financing risk does not affect their economic behaviors, and the evolutionary trends completely overlap. The behavioral decisions of suppliers, core firms and clients remain relatively stable, mainly because each of them has an effective risk-coping mechanism that can effectively mitigate the negative impact of the potential financing risks. Although the fluctuation of the potential financing risk may have a certain effect on enterprise financial decisions, each party usually adopts corresponding measures to mitigate the risk, thus maintaining the stability of their behavioral decisions and leading to a consistent evolutionary trend. Suppliers usually reduce the impact of potential risks, such as credit defaults, by optimizing risk management strategies, such

as diversifying financing channels and strengthening credit assessment; core businesses reduce the negative effects of market fluctuations and legal compliance risks by enhancing financial transparency, adjusting debt structures and working closely with suppliers; and clients rely on establishing stable capital flows and sound operational management systems to mitigate pressure due to market volatility or increasing financing costs.

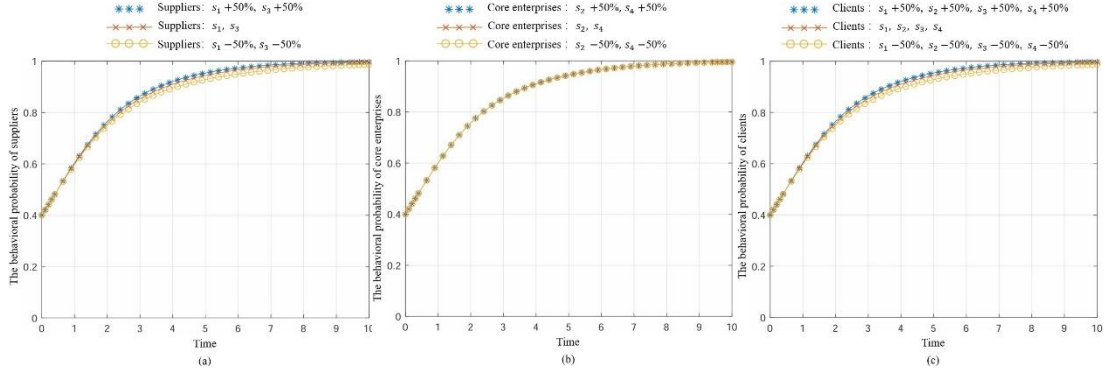


Figure 11 Impact of potential financing risk on the system evolution results

4 Conclusion

On the basis of the perspective of the interests of each subject in supply chain commercial credit financing, this paper constructs an evolutionary game model of suppliers, core enterprises and clients by using a combination of evolutionary game and system dynamics theories to analyze the interests, evolutionary behaviors, and influencing factors of each subject. The results show (1) there is a link between the amount of commercial credit financing provided by suppliers and the attendant costs. As reputational losses increase, suppliers tend to adopt financing strategies that more conservative to avoid risks and ensure financial security. Moreover, the increase in the time cost of money prompts suppliers to increase their financing efforts, thus accelerating system convergence and stabilization. (2) Defaults result in reputational damage suffered by core firms, prompting them to take active measures to avoid further damage caused by defaults or delayed deliveries. In addition, an increase in the time cost of money puts core firms under greater financial pressure, leading to an increase in their debt leverage, which makes their behavior conservative and slows their

evolution. When the time cost of money decreases, the core firm can obtain lower financing costs and higher liquidity, prompting it to be more inclined to perform on schedule. Clients can likewise obtain conclusions similar to those of the core firms described above. (3) Potential risk fluctuations in financing on the strategy of the supply chain main body have a weak influence because the three parties internalize the risk through a risk-hedging mechanism, which effectively mitigates the influence of potential risk fluctuations in financing on their strategy choices and stabilizes the evolution of the overall system.

To promote the synergy of various interested parties in commercial credit financing, this paper makes the following suggestions: (1) As the financing supply source driver, the scale of commercial credit placement and the risk appetite of suppliers directly determine supply chain liquidity. Therefore, suppliers should strengthen risk management, optimize financing channels, and enhance the credit assessment system to reduce the negative impact of reputation loss and capital cost fluctuations^[35]. Meanwhile, suppliers should actively establish long-term and stable cooperative relationships with core enterprises and clients to ensure better risk sharing in the face of uncertainty and enhance the sustainability of financing support. (2) As the key hub of the credit center, the core enterprise's performance behavior forms a chain of trust between upstream and downstream entities and has a system-level transmission effect. Core enterprises should improve their market credibility and reduce the pressure on the time cost of capital by strengthening financial transparency, optimizing debt structure, and maintaining close cooperation with suppliers and clients^[36]. In addition, core enterprises should ensure that they can maintain their performance ability when capital costs increase by establishing an effective risk management mechanism to promote the stable development of the overall supply chain. (3) The delivery behavior of clients is both the ultimate link in supply chain value and the starting point of reverse risk feedback. Therefore, clients should optimize capital flow management and adopt effective risk-hedging strategies to mitigate the impact of fluctuations in capital time costs^[37]. By improving operational efficiency and reinforcing fulfillment capabilities,

clients can ensure on-schedule delivery, which enhances their stability and cooperative trust in the supply chain.

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Competing interests

The authors declare no competing interests. The authors thank anonymous referees.

Data Availability

The datasets analyzed during the current study are available from the corresponding author on reasonable request.

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Ethical approval statement & Informed consent statement

Ethical approval statement & Informed consent statement are not required for this study