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Blockchain and Supply-Chain Financing: An Evolutionary Game Approach with Guarantee Considerations

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Abstract: Blockchain technology enables innovative financing models in supply-chain finance. This research constructs a tripartite evolutionary game model that includes core enterprises as employers, small- and medium-sized enterprises (SMEs) as contractors, and banks as financial institutions, where they have been simulated for their impact on blockchain technology, especially on the strategic choices of supply-chain financing behavior and the system's evolutionary path under core enterprises' guarantee mechanism. The findings show the application of blockchain technology can effectively reduce the regulatory and review costs for financial institutions, thereby enhancing the efficiency of supply-chain financing. Particularly, blockchain technology provides a more reliable credit endorsement platform for SMEs in reducing their tendency to default. The guarantee mechanism of core enterprises is more effective with the support of blockchain technology, which helps to build more solid supply-chain financial cooperation relationships. The research contributes to the theoretical research on the integration of blockchain technology into supply-chain finance, especially for improving the operational efficiency of financial services. It also highlights the need for blockchain-backed guarantees from core enterprises in optimizing supply-chain financial services.

Keywords: blockchain; supply chain; financing behavior; evolutionary game; evolutionary path; guarantee mechanism

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1. Introduction

Supply-chain finance (SCF) has emerged as a pivotal financial mechanism designed to alleviate the capital constraints faced by small- and medium-sized enterprises (SMEs) within the supply chain [1]. SMEs often operate with limited financial reserves and face significant challenges in sustaining liquidity throughout the supply chain, which can impede their growth and competitiveness. SCF mitigates SME funding challenges by dynamically aligning capital infusion with SME operational cycles, optimizing cash flow to enhance financial stability and promote SME growth. By leveraging the creditworthiness of core enterprises in the supply chain, SCF operates on the principles of extending short-term credit to SMEs, for example, with inventory financing [2], accounts receivable financing [3], prepayment financing [4], and credit financing [5].

Despite the transformative potential of SCF, traditional financing modes are often hindered by a myriad of challenges that detract from their effectiveness. One of the most significant challenges is information asymmetry, which can lead to adverse selection and moral hazard, thereby escalating the risk profile for financiers [6,7]. This asymmetry stems from the lack of transparency in the operational dealings and financial standings of SMEs, making it onerous for lenders to accurately assess the creditworthiness and concomitant risks associated with extending credit facilities. Additionally, high transaction costs, including those associated with due diligence, settlement, and administration, can erode the profitability of SCF arrangements and limit their scalability. The prevalence of credit risks, particularly for SMEs with less established credit histories, further complicates the SCF landscape [8,9]. These risks are exacerbated by the dynamic nature of supply chains, where market volatility and operational disruptions can disproportionately affect the financial stability of SMEs. These challenges necessitate a robust risk management framework and call for innovative solutions to ensure the sustainability and inclusivity of SCF mechanisms. The advent of blockchain technology introduces a paradigm shift in the realm of SCF, offering a decentralized, transparent, and secure platform for financial transactions without the need for intermediaries. Blockchain's inherent features, such as an immutable ledger, smart contracts, and consensus mechanisms, are expected to transform the way financial institutions evaluate credit risks and how SMEs approach financing opportunities.

Related studies have examined the integration of blockchain into SCF. The application of blockchain in SCF can enhance trust among supply-chain participants, leading to a more efficient allocation of capital and reduced financing costs for SMEs [10]. Moreover, the integration can fortify the risk management capabilities, enabling financiers to extend credit more confidently to SMEs; for example, smart contracts can automate the execution of financing agreements, ensuring that payments are released only upon the fulfillment of pre-specified conditions [11]. This automation not only streamlines the operational complexities but also introduces a layer of security in mitigating the risk of default. However, in the burgeoning landscape of blockchain–SCF, the role of core enterprises extends beyond mere intermediaries to pivotal actors whose pre-guarantee significantly influences the operational dynamics and financing behaviors within the supply chain [12]. The pre-guarantee by core enterprises serves as a catalyst for trust and risk mitigation, particularly for SMEs at the periphery of traditional financing modes. This guarantee mechanism, underpinned by the immutable and transparent ledger of blockchain technology, fortifies the credit enhancement and ensures a more secure financial environment for SMEs. This mode of core enterprises' guarantee mechanism serves as the main motivation of this research.

As a result, some areas of SCF need further investigation. First, by examining data immutability, smart contract automation, and real-time transaction transparency facilitated by blockchain technology, we can better understand how blockchain features reshape the financing behavior for SMEs and bolster their operational efficiency. Second, in the context of limited rationality, decision-makers are bound by information and cognitive constraints; therefore, an evolutionary game-theoretic approach is instrumental in modeling the strategic interactions among core enterprises, SMEs, and financial institutions. It is important to understand how to construct a tripartite evolutionary game model that encapsulates the dynamic interplay among entities in the ecosystem of SCF and the stability of the dynamic evolution of blockchain–SCF. In addition, the influence of blockchain technology's implementation costs, SME default gains, and core enterprises' guarantee benefits on evolutionary game dynamics is also important.

Therefore, in order to solve the above problems, this study aims to construct an evolutionary game model that encapsulates the strategic behaviors of financial institutions (e.g., banks), SMEs (e.g., contractors) and core enterprises (e.g., employers). The proposed framework first delineates the decision-making processes and strategic interactions among the core players in the supply-chain ecosystem. Second, it explores the stability and dynamic evolution of the equilibrium condition within the blockchain-enabled SCF. Lastly, the integration of blockchain technology with the pre-guarantee in the framework would facilitate a more efficient capital inflow for SMEs.

The rest of this study is organized as follows. Section 2 highlights the theoretical background of SCF, the blockchain-enabled SCF and the application of evolutionary game theory. Section 3 constructs the triple evolutionary game model and presents some basic assumptions. Section 4 analyzes the results of the model and Section 5 provides the evolutionary stable strategies and evolutionary path of the system. Section 6 concludes the main findings and provides managerial insights.

2. Theoretical Background

This section explains the theoretical foundation related to SCF, blockchain-enabled SCF and the application of evolutionary game theory in SCF.

2.1. SCF

SCF plays as an important role in supply-chain management, which is related to financial flows of operational activities in improving the network's performance and stability. SCF encompasses a range of practices, including accounts receivable financing, inventory financing, and prepayment solutions, which are designed to improve the financial efficiency of all participants within the supply-chain ecosystem.

With extensive application in practice, SCF has attracted the attention of scholars in academy [13–15]. They have highlighted the need to address the capital constraints faced by SMEs. SMEs often struggle to secure traditional bank financing due to their limited assets and higher perceived risk profiles. SCF provides an alternative by leveraging the creditworthiness of the entire supply chain or that of the larger, more creditworthy entities within it. SCF not only aids SMEs in obtaining necessary funds but also fosters stronger, more resilient relationships among supply-chain partners. Empirical studies have underscored the transformative impact of SCF on payment efficiency and risk management within supply chains. The integration of financial services with supply-chain operations is seen as a key strategy for optimizing cash flows, reducing costs, and enhancing the competitiveness of the supply chain as a whole. Banks and other financial institutions play a pivotal role in this context, offering tailored financial products that cater to the specific needs of different supply-chain actors.

Despite the evident benefits, SCF is not without its challenges. Information asymmetry is a prominent issue that can impede the effectiveness of SCF initiatives [16]. This asymmetry can lead to trust deficits and suboptimal decision-making, potentially undermining the collaborative nature of supply-chain relationships. To mitigate this, researchers have explored the use of advanced analytical techniques, such as machine learning and data analytics, to better assess credit risks and improve the transparency of financial transactions within the supply chain [7,17].

The principal-agent problem is another critical area of concern in SCF. It arises from the inherent conflicts of interest between different supply-chain entities and can lead to inefficiencies and increased financial risks [18]. This requires innovative contract designs and risk-sharing mechanisms to address this problem. In summary, SCF is a multifaceted field that offers significant opportunities for improving the financial dynamics of supply chains. It is a subject of ongoing research, with scholars continuously exploring new models, technologies, and strategies to enhance its effectiveness. As the field evolves, there is a growing interest in understanding how emerging technologies, such as blockchain, can be leveraged to further streamline SCF processes and create more secure, transparent, and efficient supply-chain financial ecosystems.

2.2. Blockchain-Enabled SCF

In the burgeoning field of SCF, the advent of blockchain technology has introduced a paradigm shift in how financial transactions are conducted within supply-chain networks. Blockchain-enabled SCF is a rapidly evolving area. It holds the promise of addressing some of the most persistent challenges in SCF, such as information asymmetry, transaction costs, and trust among parties [19–21].

The integration of blockchain technology into SCF has opened new avenues for research and practical application. Blockchain, with its inherent characteristics of decentralization, transparency, and immutability, offers a robust framework for enhancing the efficiency and security of financial transactions. It enables the creation of a shared, real-time ledger that can be accessed by all participants in the supply chain, thereby reducing the need for intermediaries and facilitating trust among stakeholders.

Empirical studies have begun to explore the potential benefits of blockchain technology in SCF [22]. For instance, the use of blockchain technology can lead to more effective management of accounts receivable and payable, as it allows for the tokenization of trade assets, which can be traded and settled on a blockchain platform [23]. This not only accelerates the settlement process but also reduces the risk of default, as the blockchain maintains an immutable record of transactions.

Moreover, the smart contract functionality of blockchain technology automates the execution of contract terms, which can lead to significant cost savings and efficiency gains in the administration of trade finance [24,25]. Smart contracts can be programmed to execute payments upon the confirmation of delivery or other pre-specified conditions, thereby streamlining the process and reducing the potential for disputes.

Research in the field of blockchain-enabled SCF is also examining the impact on risk management [26–28]. Blockchain technology presents a transformative opportunity for SCF by enhancing transparency, reducing transaction costs, and improving the overall efficiency of financial transactions within supply chains. Blockchain technology's traceability feature can improve allows for better tracking of goods and funds, which is particularly beneficial in mitigating counterparty risk and fraud.

Although blockchain adoption in SCF offers potential benefits, it is not without challenges [20,29]. The technology is still maturing, and concerns persist regarding scalability, interoperability with existing systems, and the need for regulatory clarity. Furthermore, the transition to blockchain-based systems requires significant investment in infrastructure and presents a steep learning curve for organizations not familiar with the technology. Integrating blockchain with SCF requires a number of necessities such as integration with IoT systems to improve data quality, and continuous improvement of regulatory as well as legal frameworks [30]. By leveraging the related data science techniques, scalability issues from network latency, throughput and capacity could be addressed in future studies [31].

2.3. The Application of Evolutionary Game Theory

Evolutionary game theory posits that participants in a game, bounded by rationality, reach equilibrium through continuous learning and adaptation. This theory has been widely applied to model the behavior of supply-chain entities, accounting for the uncertainties and adaptive strategies of firms within the supply chain.

In the context of SCF, evolutionary game models have been particularly insightful in analyzing the strategic decisions of financial institutions, core enterprises, and SMEs. Evolutionary game theory can effectively capture the essence of SCF [32,33], where the default behavior of SMEs and the credit endorsement from CEs are critical factors influencing financing outcomes. Studies such as [34,35] have utilized evolutionary game theory to explore financing strategies within supply chains, highlighting the impact of capital constraints and loss avoidance on operational decisions. The application of evolutionary game theory in the context of blockchain-enabled SCF provides a robust framework for analyzing the complex interactions among supply-chain stakeholders. It offers insights into how blockchain technology can be leveraged to achieve more efficient, transparent, and trustworthy supply-chain financing mechanisms.

From the above analysis of the literature, most related work focuses on the dynamic game analysis between banks and enterprises or between banks and supply-chain systems, with less emphasis on the role of blockchain technology in the internal mechanism of SCF and the behavior of financed enterprises. By incorporating the scenario of pre-guarantee of core enterprises, this paper aims to construct an evolutionary game model to analyze the strategic interactions within the ecosystem of SCF, focusing on the roles of core enterprises, SMEs, and financial institutions, and to examine how blockchain technology influences their strategic decisions and the stability of the system's dynamic evolution.

3. Problem Description and Assumption

In this section, the problem description, some model assumptions, terminologies, and symbols are given to construct the evolutionary game model.

3.1. Problem Description

Traditional game theory often assumes that the participants are completely rational and under the condition of complete information, but in a real economic life, it is very difficult to realize the conditions of complete rationality and complete information of the participants. In the cooperative competition of enterprises, there is a difference between the participants, and the problem of incomplete information and limited rationality of the participants caused by the complexity of the economic environment and the game problem itself is also obvious. Unlike traditional game theory, evolutionary game theory does not require the participants to be fully rational, nor does it require the condition of complete information. Evolutionary game theory is a theory that combines the analysis of game theory with the analysis of dynamic evolutionary processes. In terms of methodology, it differs from game theory in focusing on static equilibrium and comparative static equilibrium, emphasizing a dynamic equilibrium.

In the traditional SCF framework, there exists a notable information asymmetry among financial institutions, core enterprises, and SMEs. This discrepancy necessitates that financial institutions incur substantial costs in vetting the credentials of SMEs. Despite these efforts, there is no guarantee the information furnished by SMEs is authentic, which consequently elevates the barriers to secure financing for these small businesses.

Financial institutions adopt blockchain technology to manage their supply-chain financing operations; they could employ the blockchain's consensus mechanism to verify the credentials of SMEs. The integration significantly bolsters the efficiency of the supply-chain financing process. SMEs, aiming to optimize their gains, may strategically choose between defaulting on their obligations or adhering to the terms of their agreements.

Moreover, the role of core enterprises extends beyond mere participants. Their credit backing is pivotal within the supply chain. By offering guarantees for the financing endeavors of SMEs, core enterprises can substantially elevate the collective profitability of the supply chain. The application of blockchain technology endows the supply-chain financing process with enhanced transparency, security, and traceability, as depicted in Figure 1, which illustrates the streamlined and efficient financing process made possible by the integration of blockchain technology into the supply-chain management system. The blockchain platform eliminates the cumbersome auditing process, and after the contract is signed between the SME and the core business, the system is synchronized, as shown in Step 2 in Figure 1, speeding up the financing process and shortening the financing cycle significantly.

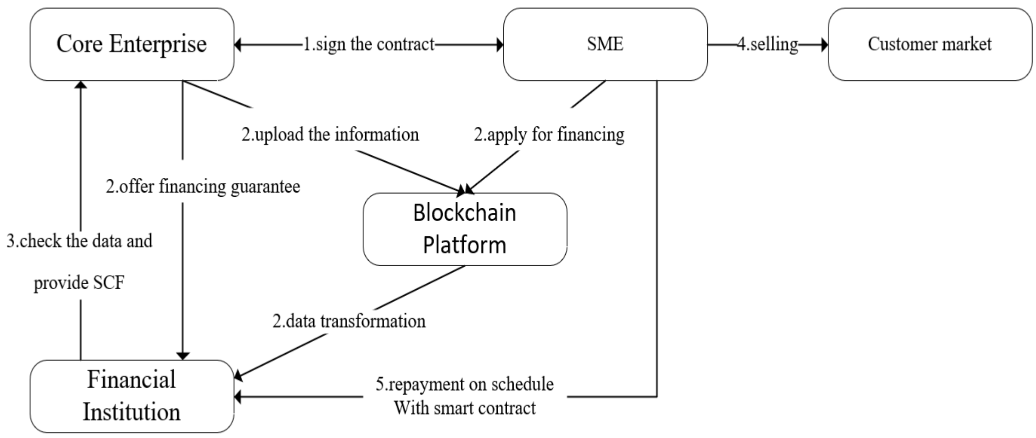

Figure 1. The financing process of blockchain-enabled SCF.

In this study, we consider a supply-chain financing system composed of core enterprises, SMEs, and financial institutions, all of which are characterized by bounded rationality. Financial institutions have two strategic behaviors at their disposal: adopting a blockchain model and adhering to a traditional model. The revenue derived from supply-chain financing operations by financial institutions is denoted as π_B.

Under the traditional model, financial institutions are tasked with assessing the creditworthiness of SMEs, incurring a supervisory cost c. In contrast, under the blockchain model, the institutions incur an initial deployment cost F to establish the blockchain infrastructure. This upfront investment, however, eliminates the need for subsequent regulatory costs associated with document review and verification. Additionally, the deployment of blockchain technology enhances the institutional reputation of the financial institutions, yielding an additional benefit U_B from the adoption of blockchain technology. In the event that SMEs honor their contractual obligations, financial institutions provide them with a compliance reward v. Conversely, should SMEs default on their agreements, financial institutions face a financial loss L_B due to their inability to recoup the loaned funds on schedule. Furthermore, financial institutions impose a penalty p_2 on SMEs for such breaches of contract.

Core enterprises within the supply-chain financing system have two strategic behaviors: providing a guarantee for SMEs' financing operations and opting not to provide such a guarantee. The revenue that core enterprises gain from engaging in supply-chain financing activities is represented by π_C. When a core enterprise elects to guarantee the financing of SMEs, it can earn a guarantee benefit denoted as π_n; however, in the event of an SME defaulting, the core enterprise is obligated to compensate for the losses L_C incurred by the bank and will also levy a penalty p_1 upon the SME. Upon the adoption of blockchain technology, core enterprises have the opportunity to upload their information onto the blockchain technology, which can lead to an information incentive benefit for them, signified by U. This inclusion enhances transparency and can potentially improve the core enterprise's credibility and access to financing within the supply-chain ecosystem.

SMEs within the financing system have two behavioral strategies at their disposal: defaulting on repayments and making timely repayments. The revenue that SMEs gain from engaging in supply-chain financing activities is designated as π_S. Should SMEs choose to default on their repayments, they may secure a default benefit represented by π_m, but they will also face penalties p_1 and p_2 imposed by the core enterprise and the financial institution, respectively. Additionally, under the blockchain model, where information is more transparent, the SMEs' default can lead to a loss of reputation and incur additional damages, denoted as t. Conversely, if SMEs adhere to the repayment schedule, the financial institution will provide them with a compliance reward v.

3.2. Model Assumption

Based on the dynamic game relationship analysis among the three parties involved, the following six assumptions were proposed and organized sequentially for the model's development:

(1) As the main entities in the game, the core enterprise, SMEs, and financial institutions all pursue the maximization of their own interests under conditions of incomplete information acquisition;
(2) Financial institutions, core enterprises, and SMEs all possess bounded rationality and have the capability to dynamically adjust their strategies over time and in response to the environment within the evolutionary game theory. Other entities may potentially influence any of the three parties are not considered in this game process;
(3) In the scenario where the blockchain model is utilized, it is assumed all information uploaded to the blockchain by the three parties is authentic and free from any malpractice;
(4) The revenue generated from the core enterprise's guarantee provision is less than the revenue derived from its own operations;
(5) All three parties involved in the game are considered to be risk-neutral;

(6) The probability that the core enterprise chooses to provide a guarantee is denoted as x, with a corresponding probability of $1 - x$ for not providing a guarantee. The probability that SMEs opt for compliance is denoted as y, and the probability of choosing to default is $1 - y$. The probability that financial institutions select the blockchain model is represented by z, with a probability of $1 - z$ for selecting the traditional model. The parameters and their corresponding symbols are shown in Table 1.

Table 1. The parameter symbol assignments and the meanings.

Symbol	Parameter Explanation
π_C	The revenue of the core enterprise
π_n	Revenue generated from the core enterprise's guarantee provision
L_C	Loss incurred by the core enterprise due to SME's default
π_B	The revenue of financial institution from financing operations
c	Supervision cost for the financial institution
π_S	Revenue obtained by SMEs after financing
v	Reward for SMEs when adhering to the contract
p_1	Penalty imposed by the core enterprise on SMEs for default
p_2	Penalty imposed by the financial institution on SMEs for default
L_B	Loss incurred by the financial institution due to SMEs' default
π_m	Benefit derived by SMEs from defaulting
U_B	Revenue generated by the financial institution through blockchain–SCF
U	Incentive for information uploading onto the blockchain platform
C	Cost of blockchain deployment
t	Additional loss incurred by SMEs for defaulting after information is uploading to the blockchain

4. The Model

By referring to the assumptions and parameter settings mentioned above, Figure 2 illustrates the tri-party game tree involving the core enterprise, SMEs, and financial institutions under different strategic choices. The payoff values of the three parties for each strategic combination are presented in Table 2.

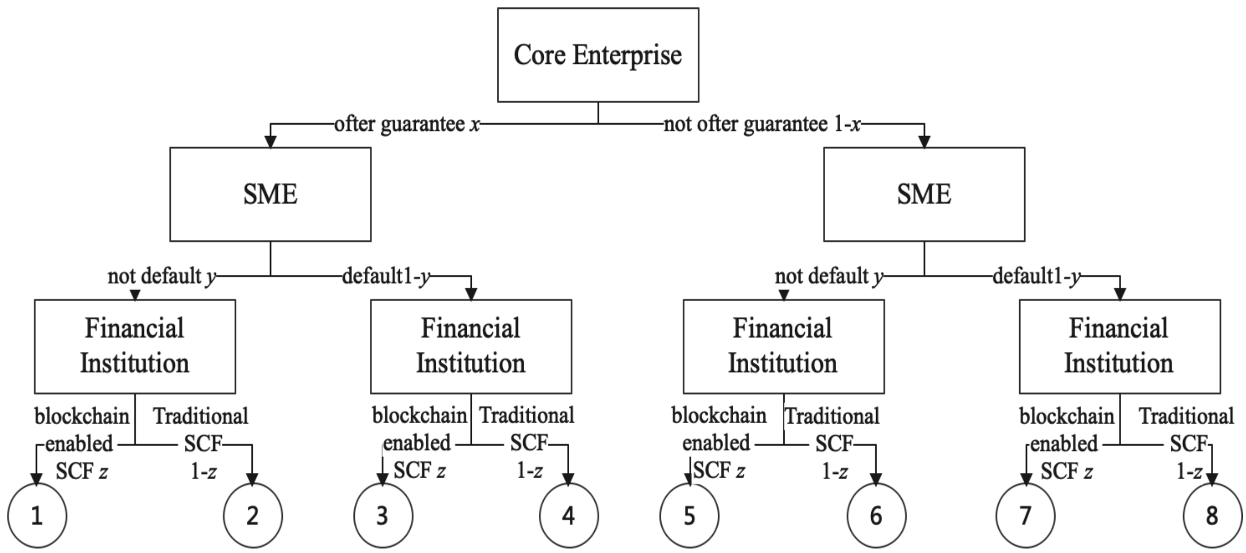

Figure 2. Tri-party game tree.

Table 2. Payoff matrix of interest game.

Strategy Combination	Each Party's Interest		
	Core Enterprise	**SMEs**	**Financial Institution**
(Guarantee, Compliance, Blockchain)	$\pi_C + \pi_n + U$	$\pi_S + v + U$	$\pi_B - C + U_B$
(Guarantee, Compliance, Traditional)	$\pi_C + \pi_n$	$\pi_S + v$	$\pi_B - c$
(Guarantee, Default, Blockchain)	$U - L_C + p_1$	$\pi_S + \pi_m - p_1 - t$	$\pi_B - C + U_B$
(Guarantee, Default, Traditional)	$-L_C + p_1$	$\pi_S + \pi_m - p_1$	$\pi_B - c$
(No Guarantee, Compliance, Blockchain)	$\pi_C + U$	$\pi_S + v + U$	$\pi_B - F + U_B$
(No Guarantee, Compliance, Traditional)	π_C	$\pi_S + v$	$\pi_B - c$
(No Guarantee, Default, Blockchain)	$\pi_C + U$	$\pi_S + \pi_m - p_2 - t$	$-C + U_B + p_2$
(No Guarantee, Default, Traditional)	π_C	$\pi_S + \pi_m - p_2$	$-c + p_2 - L_B$

Based on various strategic choices in Table 2, the evolutionary game payoff matrix for core enterprises, SMEs, and financial institutions is given in Table 3.

Table 3. Evolutionary game payoff matrix.

SME		Financial Institution	
		Blockchain-Enabled SCF z	**Traditional SCF $1-z$**
Guarantee x	Compliance y	$\pi_C + \pi_n + U$	$\pi_C + \pi_n$
		$\pi_S + v + U$	$\pi_S + v$
		$\pi_B - C + U_B$	$\pi_B - c$
	Default $1-y$	$U - L_C + p_1$	$-L_C + p_1$
		$\pi_S + \pi_m - p_1 - t$	$\pi_S + \pi_m - p_1$
		$\pi_B - C + U_B$	$\pi_B - c$
No Guarantee $1-x$	Compliance y	$\pi_C + U$	π_C
		$\pi_S + v + U$	$\pi_S + v$
		$\pi_B - F + U_B$	$\pi_B - c$
	Default $1-y$	$\pi_C + U$	π_C
		$\pi_S + \pi_m - p_2 - t$	$\pi_S + \pi_m - p_2$
		$-C + U_B + p_2$	$-c + p_2 - L_B$

In the case with complete information and full rationality, core enterprises would cooperate with SMEs, providing guarantees for their financing and enabling SMEs to repay on time, thus achieving a mutually beneficial outcome. However, in reality, the parties involved in the game are often not fully rational, and there is an inherent asymmetry of information. Core enterprises might refuse to provide financial guarantees for SMEs due to risk considerations, while SMEs might misrepresent information, delay repayments, or even default, causing irreparable losses to financial institutions. Consequently, financial institutions may increase their scrutiny over SMEs, which is detrimental to fostering a positive cooperative relationship and hinders the sustainable development of the supply chain. The method of evolutionary game theory overcomes the individualistic nature of traditional game theory and the assumptions of complete rationality and information inherent in Nash equilibrium. Participants in the game dynamically adjust their strategies based on the strategies of the other parties involved, ultimately achieving a balanced objective in the game. The following analysis employs the method of evolutionary game theory to investigate the strategic choices of core enterprises, SMEs, and financial institutions.

4.1. The Replication Dynamic Equation

4.1.1. The Evolutionary Equilibrium for the Core Enterprise

Table 3 shows the core enterprise's payoffs for adopting a strategy of guarantee and no guarantee are denoted as E_x and E_{1-x}, respectively:

$$E_x = y[z(\pi_C + \pi_n + U) + (1-z)(\pi_C + \pi_n)] + (1-y)[z(U - L_C + p_1) + (1-z)(-L_C + p_1)] \quad (1)$$

$$E_{1-x} = y[z(\pi_C + U) + (1-z)\pi_C] + (1-y)[z(\pi_C + U) + (1-z)\pi_C] \quad (2)$$

and the average profits in both cases are as follows:

$$\overline{E}_S = xE_x + (1-x)E_{1-x} \quad (3)$$

The replication dynamic equation of the core enterprise is as follows:

$$Fx = \frac{dx}{dt} = x(E_x - \overline{E}_R) = \left(x - x^2\right)[y\pi_n + (1-y)(p_1 - L_C - \pi_C)] \quad (4)$$

let $F(x) = 0$, then

$$x_1^* = 0, x_2^* = 1, y^* = \frac{L_C + \pi_C - p_1}{\pi_n - L_C - \pi_C + p_1} \quad (5)$$

Let $y_0 = \frac{L_C+\pi_C-p_1}{\pi_n-L_C-\pi_C+p_1}$, Equation (5) indicates that $\frac{\partial F(x)}{\partial x} = 0$ always holds when $y = y_0 = \frac{L_C+\pi_C-p_1}{\pi_n-L_C-\pi_C+p_1}$. Taking the first-order derivative with respect to x in $F(x)$, the following equation can be obtained:

$$\frac{dF(x)}{dx} = (1-2x)[y\pi_n + (1-y)(p_1 - L_C - \pi_C)]$$

Obviously, for the case of $y > y_0$, when $x = 0$, $\frac{dF(x)}{dx} > 0$; and when $x = 1$, $\frac{dF(x)}{dx} < 0$. Hence, $x = 1$ is the evolutionary stable strategy. For the case of $y < y_0$, the evolutionary stable strategy is $x = 0$. Figure 3 illustrates the evolutionary phase diagram of the core enterprise's strategy.

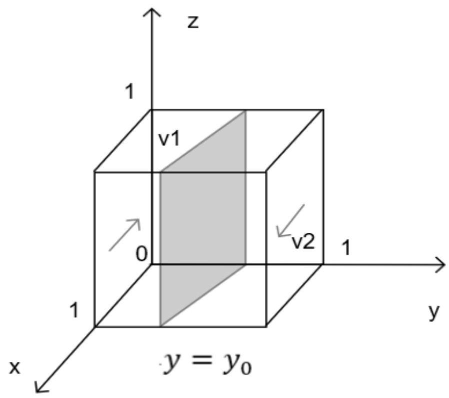

Figure 3. The phase diagram of the core enterprise's strategy evolution.

As depicted in Figure 3, when the initial state of the core enterprise's strategy is in space V_1, where $y < y_0$, $x = 0$ is the evolutionary strategy equilibrium point, indicating the core enterprise chooses to provide guarantees for the financing activities of SMEs. When the initial state of the core enterprise's strategy is in space V_2, where $y > y_0$, $x = 1$ is the evolutionary strategy equilibrium point, indicating the core enterprise opts not to provide guarantees.

The decision of core enterprises to provide guarantees for the financing activities is mainly impacted by the strategies of the SME. When the SME has a low intention to comply with their agreements, core enterprises do not offer financial guarantees. However, when the probability of the SME honoring its commitments is high, the core enterprise provides guarantees to the SME, which allows it to achieve higher earnings.

4.1.2. The Evolutionary Equilibrium for the SME

The payoffs for adhering to agreements and defaulting of the SME, respectively, denoted as E_y and $E_{(1-y)}$:

$$E_y = x[z(\pi_S + v + U) + (1-z)(\pi_S + v)] + (1-x)[z(\pi_S + v + U) + (1-z)(\pi_S + v)] \quad (6)$$

$$E_{(1-y)} = x[z(\pi_S + \pi_m - p_1 - t) + (1-z)(\pi_S + \pi_m - p_1)] + (1-x)[z(\pi_S + \pi_m - p_2 - t) + (1-z)(\pi_S + \pi_m - p_2)] \quad (7)$$

and the average profit in both cases is

$$\overline{E}_S = yE_y + (1-y)E_{1-y} \quad (8)$$

The replication dynamic equation of the SME is

$$G(y) = y(E_y - \overline{E}_S) = \left(y - y^2\right)[x(p_1 - p_2) + z(U+t) + v - \pi_m + p_2] \quad (9)$$

Let $G(y) = 0$, then

$$y_1^* = 0, y_2^* = 1, x^* = \frac{\pi_m - z(U+t) - v - p_2}{p_1 - p_2} \quad (10)$$

Let $x_0 = \frac{\pi_m - z(U+t) - v - p_2}{p_1 - p_2}$, Equation (10) indicates that $\frac{\partial G(y)}{\partial y} = 0$ always holds when $x = x_0 = \frac{\pi_m - z(U+t) - v - p_2}{p_1 - p_2}$. Taking the first-order derivative with respect to y in $G(y)$, then:

$$\frac{dG(y)}{dy} = (1-2y)[x(p_1 - p_2) + z(U+t) + v - \pi_m + p_2]$$

For the case of $x > x_0$, when $y = 0$, $\frac{dG(y)}{dy} > 0$; and when $y = 1$, $\frac{dG(y)}{dy} < 0$. Hence, $y = 1$ is the evolutionary stable strategy. For the case of $x < x_0$, the evolutionary stable strategy is $y = 0$. The evolutionary phase diagram of the SME's strategy is depicted in Figure 4.

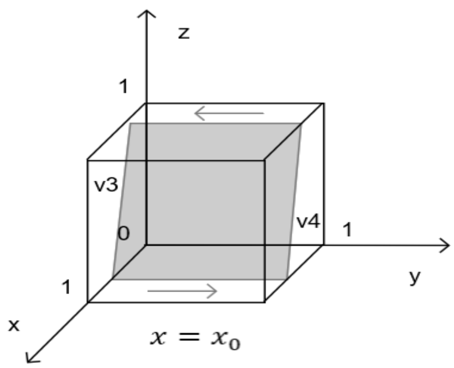

Figure 4. The phase diagram of the SME's strategy evolution.

Figure 4 illustrates when the initial state of the SME's strategy is in space V_3, where $x > x_0$ and $y = 1$, which constitutes an evolutionary strategy equilibrium; that is, the SME chooses to comply and repay their loans on time. Conversely, when the initial state of the SME's strategy is in space V_4, with $x < x_0$ and $y = 0$, this represents another evolutionary strategy equilibrium strategy. It means the SME may choose to default and not repay their loans. Therefore, the strategies of SMEs are simultaneously affected by the strategies of core enterprises and financial institutions. The evolution of SMEs' strategies is influenced by several key factors, as follows: the advantages SMEs gain from defaulting, the incentives offered by financial institutions to encourage SMEs' compliance, and the penalties levied by both financial institutions and core enterprises for instances of default.

4.1.3. The Evolutionary Equilibrium for the Financial Institution

The financial institution's payoff for adopting the traditional mode and the blockchain mode are denoted as E_z and E_{1-z}, respectively, as follows:

$$E_z = x[y(\pi_B - C + U_B) + (1-y)(\pi_B - C + U_B)] + (1-x)[y(\pi_B - C + U_B) + (1-y)(-C + U_B + p_2)] \quad (11)$$

$$E_{1-z} = x[y(\pi_B - c) + (1-y)(\pi_B - c)] + (1-x)[y(\pi_B - c) + (1-y)(-c + p_2 - L_B)] \quad (12)$$

the average profit in both cases is as follows:

$$\overline{E}_B = zE_z + (1-z)E_{1-z} \quad (13)$$

The replication dynamic equation of financial institution is as follows:

$$H(z) = z\left(E_z - \overline{E}_B\right) = \left(z - z^2\right)(-C + U_B + c + L_B - yL_B - xL_B + xyL_B) \quad (14)$$

Let $H(z) = 0$, then

$$z_1^* = 0, z_2^* = 1, y^* = \frac{C - U_B - L_B - c + xL_B}{xL_B - L_B} \quad (15)$$

Let $y_1 = \frac{C-U_B-L_B-c+xL_B}{xL_B-L_B}$, Equation (15) indicates that $\frac{\partial H(z)}{\partial z} = 0$ always holds when $y = y_1 = \frac{C-U_B-L_B-c+xL_B}{xL_B-L_B}$. Taking the first-order derivative with respect to z in $H(z)$, then:

$$\frac{dH(z)}{dz} = (1-2z)[-C + U_B + c + L_B - yL_B - xL_B + xyL_B]$$

For the case of $y > y_1$, when $z = 0$, $\frac{dH(z)}{dz} > 0$; and when $z = 1$, $\frac{dH(z)}{dz} < 0$. Hence, $z = 1$ is the evolutionary stable strategy. For the case of $y < y_1$, the evolutionary stable strategy is $z = 0$. The evolutionary phase diagram of the financial institution's strategy is depicted in Figure 5.

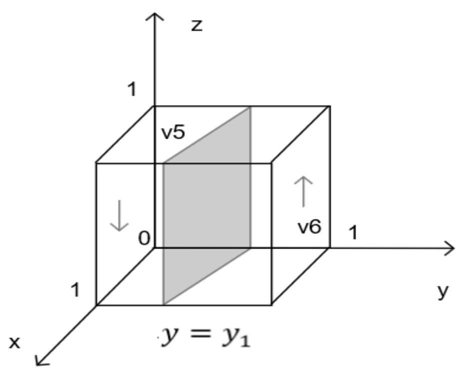

Figure 5. The phase diagram of financial institution's strategy evolution.

As illustrated in Figure 5, when the initial state of the financial institution's strategy is in space V_5, where $y < y_1$ and $z = 0$, which represents an evolutionary strategy equilibrium point. At this juncture, the financial institution opts to conduct financing operations using the traditional model. Conversely, when the initial state of the financial institution's strategy is in space V_6, with $y > y_1$ and $z = 1$, which signifies an evolutionary strategy equilibrium point. In this case, the financial institution chooses to engage in financing operations utilizing the blockchain model.

4.2. Analysis of System Evolutionary Stable Strategies

Integrating the replicator dynamic equations of the three parties involved in the supply-chain financing model, the overall replicator dynamic equation for the evolutionary game system is obtained as follows:

$$\begin{cases} F(x) = x\left(E_x - \overline{E}_R\right) = \left(x - x^2\right)[y\pi_n + (1-y)(p_1 - L_C - \pi_C)] \\ G(y) = y\left(E_y - \overline{E}_S\right) = \left(y - y^2\right)[x(p_1 - p_2) + z(U+t) + v - \pi_m + p_2] \\ H(z) = z\left(E_z - \overline{E}_B\right) = \left(z - z^2\right)(-C + U_B + c + L_B - yL_B - xL_B + xyL_B) \end{cases} \tag{16}$$

Based on the replicator dynamic equations mentioned earlier, the Jacobian matrix can be constructed as follows:

$$J = \begin{bmatrix} F_x'(x) & F_y'(x) & F_z'(x) \\ G_x'(y) & G_y'(y) & G_z'(y) \\ H_x'(z) & H_y'(z) & H_z'(z) \end{bmatrix} \tag{17}$$

where

$$F_x'(x) = (1-2x)[y\pi_n + (1-y)(p_1 - L_C - \pi_C)]$$

$$F_y'(x) = \left(x - x^2\right)[\pi_n + p_1 - L_C - \pi_C]$$

$$F_z'(x) = 0$$

$$G_x'(y) = \left(y - y^2\right)(p_1 - p_2)$$

$$G_y'(y) = (1-2y)[x(p_1 - p_2) + z(U+t) + v - \pi_m + p_2]$$

$$G_z'(y) = \left(y - y^2\right)(U+t)$$

$$H_x'(z) = \left(z - z^2\right)(yL_B - L_B)$$

$$H_y'(z) = \left(z - z^2\right)(xL_B - L_B)$$

$$H_z'(z) = (1-2z)(-C + U_B + c + L_B - yL_B - xL_B + xyL_B)$$

Let the replicator dynamic equation in Equation (17) be $F(x) = 0, G(y) = 0$ and $H(z) = 0$, eight combinations of strategies can be derived as $E_1(0,0,0), E_2(0,0,1), E_3(1,0,0), E_4(0,1,0), E_5(1,1,0), E_6(1,0,1), E_7(0,1,1), E_8(1,1,1)$.

According to the Lyapunov stability criterion, when all the eigenvalues of the Jacobian matrix J are negative, the equilibrium point is considered an evolutionary stability set (ESS). When all eigenvalues of the Jacobian matrix are positive, the equilibrium point is unstable. When the eigenvalues include both positive and negative values, the equilibrium point is a saddle point. By substituting the eight equilibrium points $E_1(0,0,0), E_2(0,0,1), E_3(1,0,0), (0,1,0), E_5(1,1,0), E_6(1,0,1), E_7(0,1,1), E_8(1,1,1)$ into the Jacobian matrix, the corresponding eigenvalues can be obtained, as shown in Table 4. The stability conditions for these eight local equilibrium points are presented in Table 5.

Table 4. The eigenvalues of equilibrium points.

Equilibrium Point	The Eigenvalues of Jacobian Matrix			Evolutionary Stability Condition
	λ_1	λ_2	λ_3	
$E_1(0,0,0)$	$p_1 - L_C - \pi_C$	$v - \pi_m + p_2$	$-C + U_B + c + L_B$	(1)
$E_2(0,0,1)$	$p_1 - L_C - \pi_C$	$U + t + v - \pi_m + p_2$	$C - U_B - L_B - c$	(2)
$E_3(1,0,0)$	$-p_1 + L_C + \pi_C$	$p_1 + v - \pi_m$	$-C + U_B + c$	(3)
$E_4(0,1,0)$	π_n	$-U - t - v + \pi_m - p_2$	$-C + U_B + c$	(4)
$E_5(1,1,0)$	$-\pi_n$	$-p_1 - v + \pi_m$	$-C + U_B + c$	(5)
$E_6(1,0,1)$	$-p_1 + L_C + \pi_C$	$p_1 + U + t + v - \pi_m$	$C - U_B - c$	(6)
$E_7(0,1,1)$	π_n	$-U - t - v + \pi_m - p_2$	$C - U_B - c$	(7)
$E_8(1,1,1)$	$-\pi_n$	$-p_1 - U - t - v + \pi_m$	$C - U_B - c$	(8)

Table 5. The evolutionary stability condition of the equilibrium point.

Equilibrium Point	Item Number	Evolutionary Stability Condition
$E_1(0,0,0)$	(1)	$p_1 - L_C - \pi_C < 0, v - \pi_m + p_2 < 0, -C + U_B + c + L_B < 0$
$E_2(0,0,1)$	(2)	$p_1 - L_C - \pi_C < 0, U + t + v - \pi_m + p_2 < 0, C - U_B - L_B - c < 0$
$E_3(1,0,0)$	(3)	$-p_1 + L_C + \pi_C < 0, p_1 + v - \pi_m < 0, -C + U_B + c < 0$
$E_4(0,1,0)$	(4)	$\pi_n < 0, -U - t - v + \pi_m - p_2 < 0, -C + U_B + c < 0$
$E_5(1,1,0)$	(5)	$-\pi_n < 0, -p_1 - v + \pi_m < 0, -C + U_B + c < 0$
$E_6(1,0,1)$	(6)	$-p_1 + L_C + \pi_C < 0, p_1 + U + t + v - \pi_m < 0, C - U_B - c < 0$
$E_7(0,1,1)$	(7)	$\pi_n < 0, -U - t - v + \pi_m - p_2 < 0, C - U_B - c < 0$
$E_8(1,1,1)$	(8)	$-\pi_n < 0, -p_1 - U - t - v + \pi_m < 0, C - U_B - c < 0$

4.3. Analysis of System Evolutionary Path

Based on the eight evolutionary stable strategies formed through the interactions between core enterprises, SMEs, and financial institutions, a viable evolutionary stable path can be delineated: evolving from the initial unstable state $E_1(0,0,0)$ to the intermediate state $E_5(1,1,0)$, and, ultimately, to the cooperative state $E_8(1,1,1)$. The evolutionary path of collaborative development among the three parties is presented in Table 6.

Table 6. Tripartite collaborative evolutionary path.

	Stage 1	Stage 2	Stage 3
Evolutionary path	$E_1(0,0,0)$	$E_5(1,1,0)$	$E_8(1,1,1)$

For Stage 1 ESS $E_1(0,0,0)$, the core enterprise does not provide a guarantee for the SME's financing activities, the SME defaults on the repayment, and the financial institution operates using traditional models. According to Table 5, the conditions for $E_1(0,0,0)$ to hold are given by condition (1): $p_1 - L_C - \pi_C < 0, v - \pi_m + p_2 < 0, -C + U_B + c + L_B < 0$. The penalty for default by the core enterprise is less than the loss incurred due to the SME's default and the revenue from the financing activities, leading the core enterprise to opt out of providing a guarantee. The SME finds it more beneficial to default rather than to adhere to the contract due to the higher gains from defaulting compared to the rewards for compliance and penalties for defaulting imposed by the financial institution. The financial institution chooses the traditional model over blockchain technology when the benefits from using the technology, combined with the supervision costs and losses from the SME's defaults, are less than the cost of deploying a blockchain system.

For Stage 2 ESS $E_5(1,1,0)$, the core enterprise provides a guarantee for the SME's financing activities, the SME adheres to the contract and repays on time, and the financial institution continues to use traditional models. The conditions for $E_5(1,1,0)$, as Table 5 are given by condition (5): $-\pi_n < 0, -p_1 - v + \pi_m < 0, -C + U_B + c < 0$. The core enterprise gains from providing a guarantee and chooses to do so. The penalties for defaulting imposed by the core enterprise are greater than the SME's gains from defaulting, prompting the SME to comply with the contract. The financial institution prefers the traditional model as the cost of deploying a blockchain system exceeds the regulatory costs under the traditional model.

For Stage 3 ESS $E_8(1,1,1)$, the core enterprise offers a guarantee for the SME's financing activities, the SME continues to honor the contract with timely repayments, and the financial institution adopts a blockchain model. The conditions for $E_8(1,1,1)$, as shown in Table 5, are given by the condition (8): $-\pi_n < 0, -p_1 - U - t - v + \pi_m < 0, C - U_B - c < 0$. The core enterprise still benefits from the guarantee and continues to provide it. The SME's gains from defaulting are significantly less than the penalties for defaulting and the incentives for compliance, leading the SME to choose to adhere to the contract. The financial institution opts for the blockchain model as the deployment cost of blockchain technology is lower than the regulatory costs under the traditional model and the additional benefits from using blockchain tip the balance in its favor.

5. Numerical Analysis

In this section, some numerical simulations are performed to analyze the evolutionary paths of three parties involved in the development of blockchain-enabled SCF at different stages, as well as the impact of the main parameters on evolutionary game strategies.

5.1. Analysis of Tripartite Evolutionary Path

In the initial phase of industry development, we assume that the core enterprise's guarantee provision, SMEs' loan repayment, and financial institutions' blockchain-based financing occur with a 0.5 probability. Other parameters are set as follows: $\pi_n = 140$, $\pi_C = 180$, $\pi_m = 160, p_1 = 40$, $p_2 = 40, v = 20$, $U_B = 20, U = 20, C = 80, c = 20$, $t = 40, L_C = 30, L_B = 30$. The evolutionary trajectory of the equilibrium point E_1 is illustrated in Figure 6. The core enterprise rapidly reaches equilibrium and opts not to provide guarantees for SMEs. SEMs achieve equilibrium at a relatively quicker pace and choose to default on their repayments. Financial institutions take the longest time to reach equilibrium and ultimately decide to conduct supply-chain financing services using traditional SCF models.

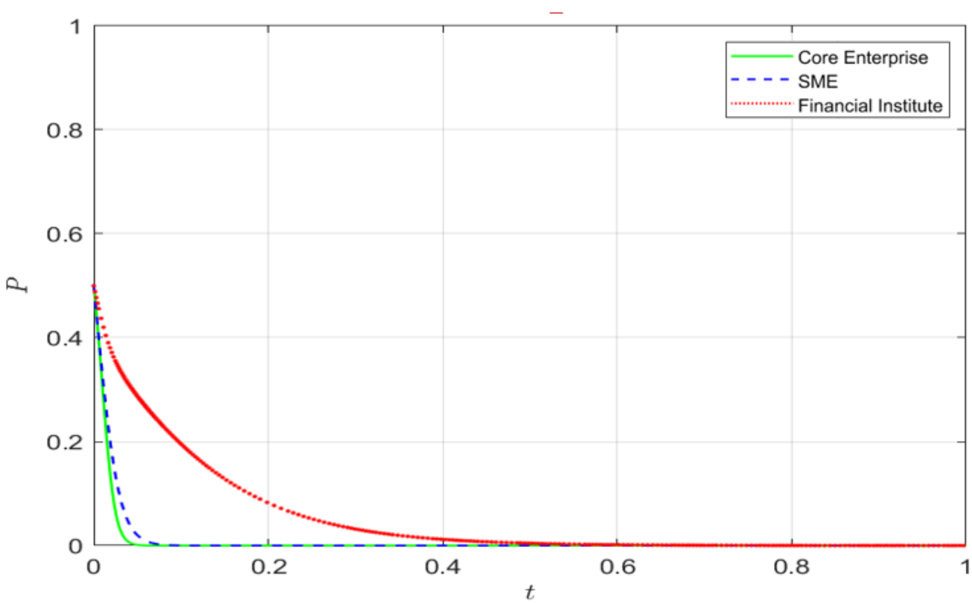

Figure 6. The evolutionary path of equilibrium point $E_1(0,0,0)$.

In the middle stage of industry development, set the strategy probabilities for the core enterprise providing guarantees to SMEs, SMEs to repay loans on time, and financial institutions conducting financing business using blockchain models are set to 0.5. Let $p_1 = 150$, other parameters are remained the same as in the previous section. The parameter settings ensure the local stability condition (5), and the evolutionary path of the stable point E_5 is illustrated in Figure 7. The core enterprise rapidly reaches equilibrium and chooses to provide guarantees to SMEs. SMEs achieve equilibrium at a relatively faster pace and choose to repay their loans on time. Financial institutions take the longest time to reach equilibrium and ultimately decide to provide financing service using traditional SCF models.

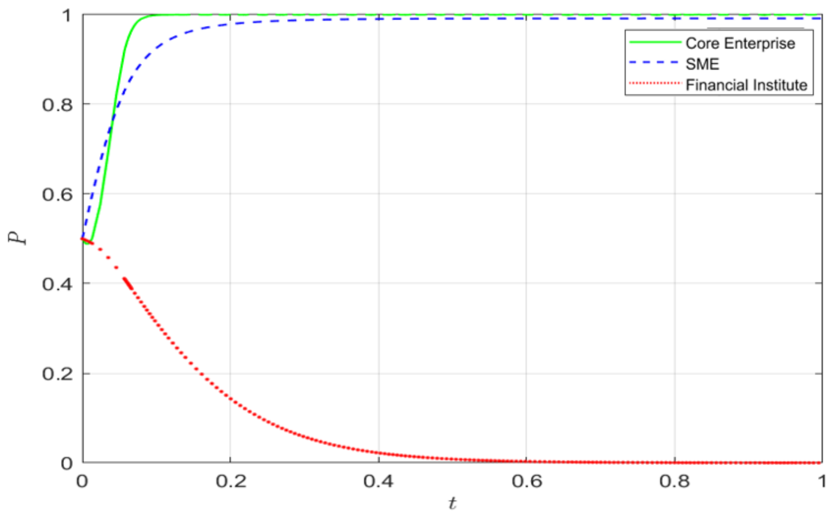

Figure 7. The evolutionary path of the equilibrium point $E_5(1,1,0)$.

In the maturity stage of industry development, similar to above sections, the probabilities of the core enterprise's providing guarantees to SMEs, the SME's repaying loans and the financial institution's conducting financing business using blockchain technology are all set to 0.5, let $C = 20$; other parameters remain the same with the above sections, which satisfies the local stability condition (8). Figure 8 illustrates the evolutionary path of the stable point E_8. The core enterprise rapidly reaches equilibrium and opts to provide guarantees for SMEs' financing operations. SMEs reach equilibrium at a relatively quick pace and choose to repay loans on time. The financial institution takes the longest time to reach equilibrium and ultimately decides to use blockchain technology to provide financing services.

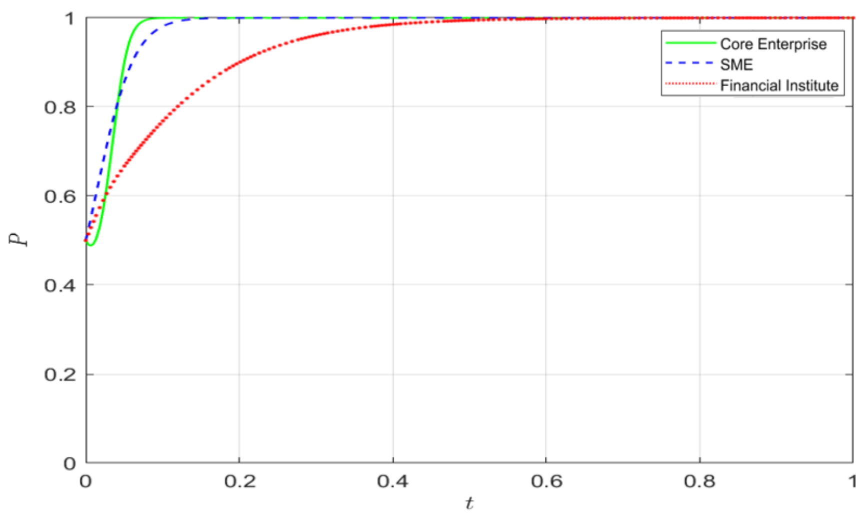

Figure 8. The evolutionary path of equilibrium point $E_8(1,1,1)$.

5.2. The Impact of Parameters on Evolutionary Game Strategies

5.2.1. The Impact of Blockchain Construction Cost

Set the blockchain construction cost to $C = 20, 30, 40, 50$, respectively, Figure 9 plots the impacts of blockchain construction cost on the evolutionary strategies with SCF system. When the deployment cost of the blockchain technology is at a low level, financial institutions are inclined to establish a blockchain platform to enhance the overall revenue of the supply chain, resulting in the system strategy $E_8(1, 1, 1)$. Conversely, when the deployment cost of the blockchain technology is at a high level, financial institutions will not opt for blockchain technology, leading to the system strategy $E_5(1, 1, 0)$.

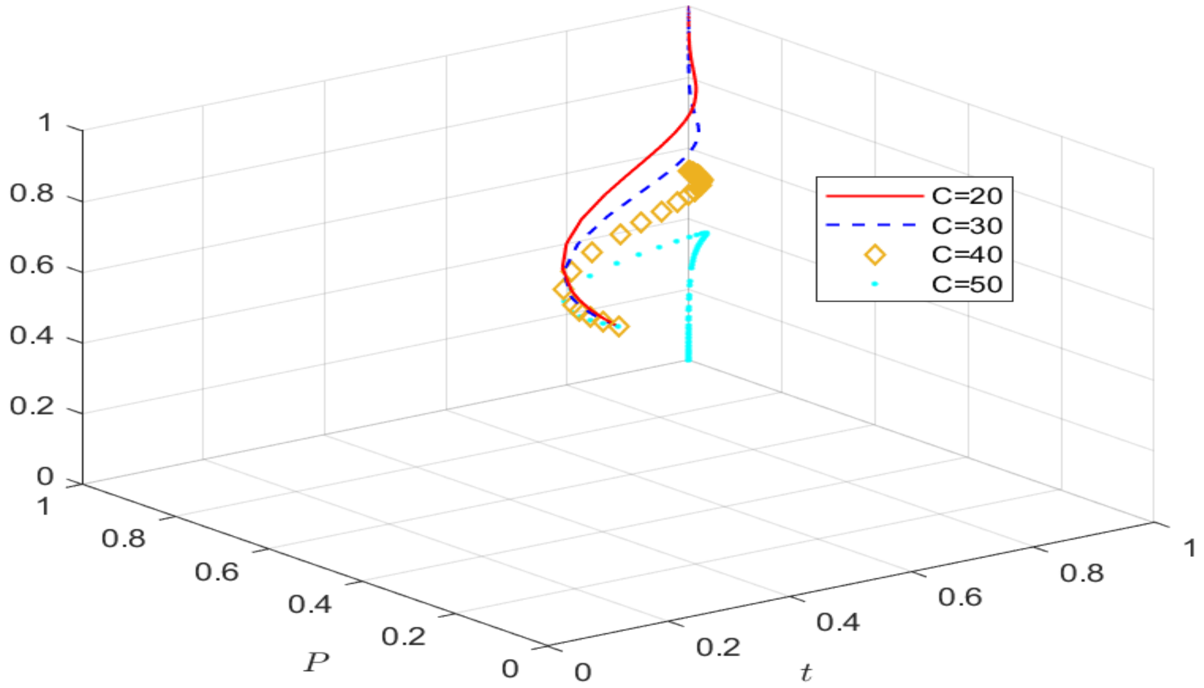

Figure 9. The impact of blockchain construction cost on evolutionary game strategies.

Blockchain technology can provide more authentic and tamper-proof traceability information, which aids financial institutions in verifying the authenticity of assets and transactions. If SMEs default, this will be recorded on the blockchain, causing a long-term impact on the enterprise's reputation, reducing its credit rating, and thereby making it more difficult or costly for the enterprise to secure financing in the future. Additionally, this can lead to other cooperative enterprises losing trust in the defaulting SME, potentially reducing, or terminating, cooperation with them. Due to the low probability of SMEs defaulting, core enterprises can offer guarantee services for them. This not only enhances the stability of the supply chain but also strengthens the collaboration between core enterprises and SMEs, increasing mutual trust. Providing guarantees for SMEs can also bolster the social image of core enterprises, thereby elevating their credibility in the market and society.

5.2.2. The Impact of SMEs' Default Benefits

Set $\pi_m = 30, 70, 110, 150$ to denote the default benefit for SMEs, respectively, and as the default benefit for SMEs increases, their strategies gradually evolve from compliance to default.

As shown in Figure 10, in the current financial market environment, SMEs face significant challenges when securing loan support. To obtain loans, some SMEs may provide inaccurate or false information to gain the trust of financial institutions. This strategy can enable SMEs to secure short-term financial support. However, this approach by SMEs reveals information asymmetry. In this scenario, SMEs have detailed knowledge of their financial status and operational capabilities, while financial institutions struggle to fully verify the authenticity of this information. As the loan maturity approaches, if SMEs choose to refuse loan repayment, this behavior not only demonstrates their ability to gain improper benefits from their informational advantage but also exposes the vulnerability of financial institutions in credit management. SMEs can achieve relatively high short-term benefits through this strategy, and the relatively minor default losses do not serve as sufficient punishment.

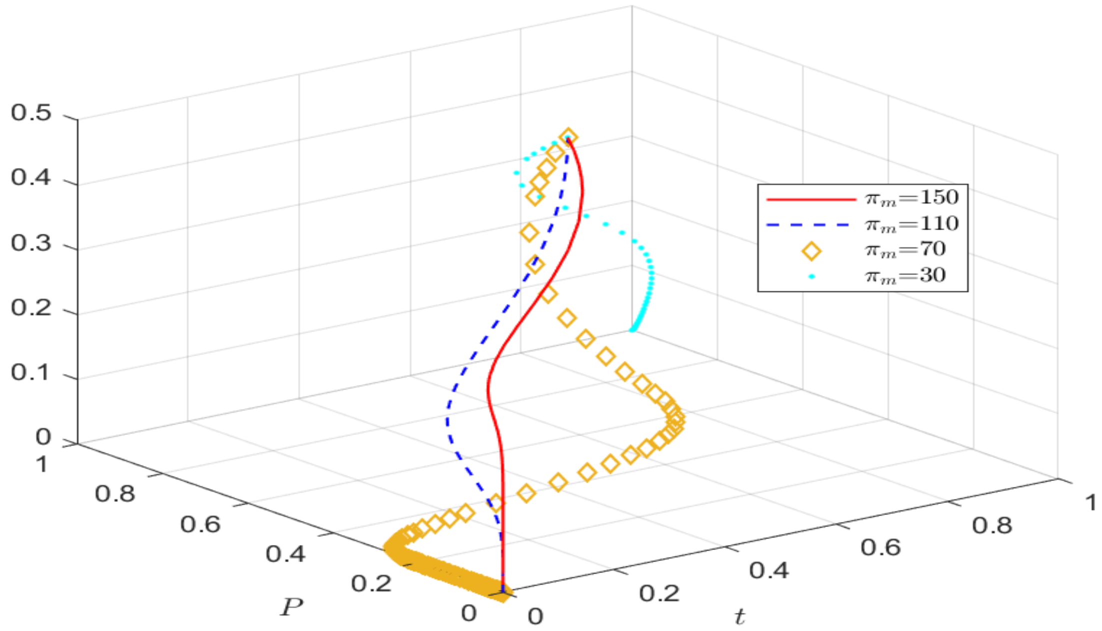

Figure 10. The impact of SME's default benefits on evolutionary game strategies.

Moreover, core enterprises, facing SMEs' loan guarantee requests, typically decline to provide them. This is due to the challenge in verifying the SMEs' information authenticity, leading to a self-protective decision to avoid potential risks. This phenomenon further exacerbates the difficulties SMEs in obtaining loans, as financial institutions will be more cautious and stringent in their loan approval processes in the absence of guarantees from core enterprises. Therefore, addressing the issue of information asymmetry is not only key to improving the efficiency of the financial market but also an important prerequisite for protecting the interests and sustainable development of SMEs. Financial institutions and core enterprises can appropriately increase the penalties for SMEs' defaults, making SMEs more wary of engaging in such behavior. It is also necessary for SMEs to share transaction information within the supply-chain financing system to collectively foster a healthier and more sustainable credit environment.

5.2.3. The Impact of Core Enterprises' Guarantee Benefits

Set $\pi_n = 90, 120, 150, 180$, the strategy of core enterprises evolves from not providing guarantees to providing them, as shown in Figure 11. Core enterprises play a pivotal role in the supply chain and by offering guarantees to SMEs, they can not only foster long-term cooperation with SMEs but also significantly enhance the stability of the entire supply-chain operations. This collaborative model brings mutual benefits to each party in the supply chain, reducing the risk of supply-chain disruption due to funding issues and ensuring the continuity of production and sales. In the current economic environment, the stability of the supply chain is crucial for maintaining corporate competitiveness and market share.

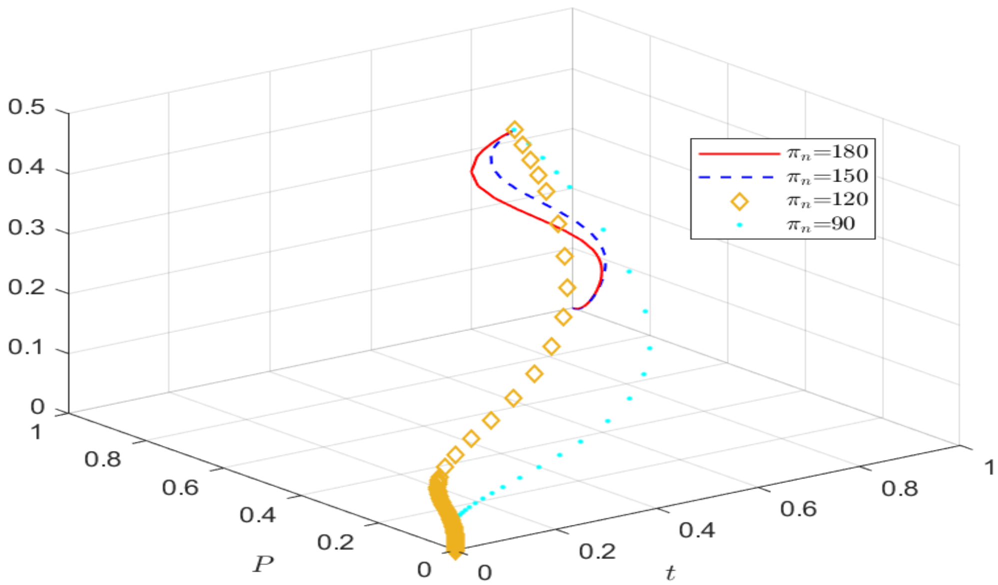

Figure 11. The impact of core enterprises' guarantee benefits on evolutionary game strategies.

When core enterprises choose to provide financing guarantees for SMEs within the supply chain, they form close economic interdependencies and, on a deeper level, a bond of social responsibility. Such actions reflect not only core enterprises' support for social and economic development but also their commitment to the overall sustainable development of the supply chain.

In reality, core enterprises stand to benefit in multiple ways by providing guarantees for SMEs. First, it strengthens the trust and cooperation among various enterprises in the supply chain, thereby improving operational efficiency and the ability to respond to market changes. Second, it alleviates the financial pressure faced by SMEs, helping them to develop steadily in an uncertain economic environment, which is vital for maintaining the overall health and flexibility of the supply chain. Third, by demonstrating support for SMEs and a sense of social responsibility, core enterprises can attract more consumers and partners, promoting continuous business growth. Therefore, by providing guarantees for SME financing, core enterprises support the growth of SMEs, enhance the stability of the supply chain, and elevate their own brand value and market competitiveness.

6. Conclusions

6.1. Main Findings

The current study has adopted an evolutionary game approach to analyze the strategic behaviors and decision-making processes within the SCF ecosystem, with a particular focus on core enterprises' guarantee role during blockchain-enabled SCF. The research developed a tripartite evolutionary game model comprising core enterprises, SMEs, and financial institutions, to examine their interactions and the impact of blockchain technology on their strategic choices and the system's evolutionary trajectory. The study showed that blockchain integration in SCF is able to lower regulatory and review expenses for financial institutions. In addition, blockchain technology is able to provide a more reliable platform for credit endorsement for SMEs, which is crucial for their ability to secure financing. This platform reduces the tendency of SMEs to default on their financial obligations and strengthens their motivation to comply with contracts. Moreover, the role of core enterprises in the supply chain is amplified with the support of blockchain technology. Their guarantee behavior becomes more effective, leading to the establishment of more solid financial cooperation relationships within the supply chain.

6.2. Research Contributions

The research has two main theoretical contributions. First, it extends the body of knowledge in terms of the integration of blockchain technology into SCF, especially for improving the operational efficiency of financial services provided to the supply chain, such as better clarity for evaluating credit risk [5] and reducing costs of supply-chain transactions [35]. The research has found numerical relationships of latent variables such as blockchain deployment cost, SMEs' default gain, SMEs' default compensation, and financial institution regulatory cost, which can affect the evolutionary stabilization strategy of the financing system through the application of blockchain technology. It could reduce costs for financial institutions and SMEs' likelihood of defaulting on financial obligations. The second theoretical contribution lies in its consideration of core enterprises' guarantee mechanism under the transactions with blockchain technology. This blockchain-backed guarantee can lead to more solid financial cooperation relationships within the supply chain, which is a significant advancement in understanding the strategic use of blockchain in supply-chain management. It promotes the virtuous cooperation cycle between SMEs and financial institutions. This has extended the preliminary finding, as presented by Su et al. (2022) [36], for securing loans for SMEs when they have core enterprises as guarantees with a good credit situation. Practically, the research also renders some managerial implications. Financial institutions and core enterprises can enhance the adoption of blockchain technology by increasing the incentives for information sharing on the blockchain. This strategy can reduce the credit management costs for enterprises and improve the willingness of core enterprises and SMEs to participate in blockchain-based SCF. For example, for SMEs who have poor credit status or lack appropriate credit records, financial institutions may choose to use blockchain technology to provide financing services. The research emphasizes the need for a dynamic incentive mechanism that considers the uncertainties of the economic environment and potential risks, fostering a more resilient and adaptive SCF ecosystem.

6.3. Implications for Future Research

While this research has demonstrated the benefits of blockchain in reducing costs and enhancing trust, further research could investigate the long-term effects of blockchain technology throughout operational processes of SCF in the entire green ecosystem. This should investigate how the sustainable relationships between stakeholders evolve over time, and any potential shifts in power dynamics within the green supply chain [37]. Second, as blockchain technology has become more popular in financial systems, it is vital to examine the regulatory landscape and ethical implications of its use in SCF. Future research could focus on how regulatory bodies are adapting to the new technology, especially for the development of new legal frameworks to govern the ethical considerations surrounding data privacy and security. Finally, the proposed model mainly focused on the role of core enterprises' guarantee mechanism for the transactions using blockchain technology. Future studies should integrate with other financial instruments, such as security tokens, derivates and so on, to improve data-informed decision-making, particularly through advanced data analytics and network modelling techniques [38].

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Abbreviations

SMEs	Small- and medium-sized enterprises
SCF	Supply-chain finance
ESS	Evolutionary stability set

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