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Research article

SEIR-diffusion modeling and stability analysis of supply chain finance based on blockchain technology

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ABSTRACT

Inadequate information sharing and difficult information diffusion are the main factors that cause upstream and downstream enterprises to default on supply chain finance. Blockchain technology, which exploits distributed storage and a consensus mechanism, can provide effective solutions to overcome these problems such as information sharing. When blockchain technology is adopted by the enterprises that comprise the supply chain finance business, this technology shows a diffusion trend. As a result, the decision pertaining to the application of novel technologies is affected. Therefore, to investigate the diffusion mechanism pertaining to the blockchain technology that is applied in supply chain finance, the study exploited the idea of a class of SEIR infectious disease models, and built a blockchain model that considers the supply chain financial system. Besides, the study verifies the stability of the model by constructing a Lyapunov function. The results indicate that the basic reproduction number determines the proliferation of the blockchain technology. When the basic reproduction number is less than 1, the proliferation of the blockchain technology that is applied in supply chain finance system would terminate. By contrast, when the basic reproduction number is greater than 1, during the average infection period, the number of non-adopting enterprises that accept the blockchain technology becomes greater than 1, which can maintain a continuous impact on supply chain finance system. Over time, the number of enterprises that accept blockchain technology tends to be stable. Through numerical simulations that consider the influencing parameters pertaining to the basic regeneration number, which has important effect on blockchain technology diffusion, we enlarge the diffusion efficiency and increase the transfer rate of potential on-chain enterprises or decrease the default exit rate. As a result, we facilitate the diffusion of blockchain technology in the system.

1. Introduction

Small and medium-sized enterprises (SMEs) effect an imperative role in the development of the national economy. However, due to low credit rating and high default risk, they are subject to financing constraints such as financing difficulties and expensive financing, thereby impeding their development [1]. To resolve the financing bottleneck that affects SMEs, the innovative “Supply Chain Finance (SCF)” mode, which integrates the industrial supply chain and financing behavior, is proposed [2,3]. SCF aims to integrate the

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financing process of upstream and downstream enterprises in the supply chain to induce additional value and optimize the capital flow of supply chain participants [4]. Moreover, due to the satisfactory credit of the core supply chain, SCF can support the financing credit that affects SMEs [5]. There are many participants in supply chain finance. However, information isolation exists among them [6], and the transaction information disclosure standard is not uniform. Consequently, the transaction data cannot be shared among the enterprises in time in SCF. Because information exchange is hindered, information asymmetry occurs. The information between financial institutions and small and medium-sized enterprises, or enterprises in the supply chain, is asymmetric in SCF [7].

In SCF, information asymmetry creates a scenario where it is impossible for enterprises to comprehensively understand the information sharing and transaction processes in a timely manner, therefore, the difficulty with which participants can control the occurrence of risks is increased [8]. Accordingly, the difficulty with which core enterprises and financial institutions can judge the information authenticity pertaining to SMEs in the supply chain is increased [9]. Because core enterprises cannot evaluate the authenticity of information, its credit is unable to trace the whole supply chain. Meanwhile, due to both the lack of credit guarantee from core enterprises and the difficulty in determining the risk level of financing enterprises, financial institutions reduce their willingness to invest. The realization of supply chain finance utility is hindered, and the financing dilemma of small and medium-sized enterprises cannot be alleviated. In addition, when there is a dispute between the parties in the SCF, a lack of evidence that can be shared throughout the chain is experienced, and the burden of proof and accountability consumes a lot of manpower, material resources, and time. If the information is maliciously hidden and tampered with, the financing relationship disintegrates [10]. With regard to SCF, if there is a robust information sharing platform [11], which enables each SCF participating enterprises to supervise the relevant transaction information and the flow of funds as well as to monitor the progress of business in real time, the occurrence of enterprise information asymmetry is reduced, thereby enhancing the trust between enterprises. Thus, the effectiveness of SCF is fully realized. Consequently, we apply blockchain technology to SCF and offer technical methods to solve the problems pertaining to information asymmetry and insufficient sharing among enterprises [12,13].

Blockchain (BCT) is a tamper-proof distributed storage database that is collaboratively maintained by multiple parties. The peer-to-peer transmission and access is secured by cryptographic algorithms. Furthermore, it is a public ledger that is applicable in all transaction scenarios [14,15]. Simultaneously, it provides a solution that can solve the problem of information barriers between SCF enterprises [16,17]. In accordance with the information asymmetry in the SCF credit system, a consensus mechanism performs verification on the exposed data from those on-chain enterprises, and subsequently records the data in the forming blocks to prevent a scenario where data is tampered with. Thus, access control and shared data management are realized [18]. As a shared and non-tamperable database, BCT not only guarantees the information security and avoids information asymmetry and information fraud in the supply chain [19], but also enhances the trust relationship between enterprises and financial institutions [20], thereby enhancing the operational efficiency and reducing transaction costs in SCF. Meanwhile, the enterprise utilizes the smart contract to integrate information flow, logistics, and capital flow [21], which can transparently visualize the business processes, and financing institutions can easily comprehend and monitor the business process as well as the related revenue that characterizes the financed SMEs in real time [22]. When a majority of enterprises in the supply chain enjoy the advantages occasioned by BCT, more enterprises are encouraged to adopt new financial technologies, through which they can enhance their own ability to obtain information channels, and formulate their development decisions more optimally. Consequently, a diffusion trend is observed in SCF. Thus, we analyze the diffusion mechanism of blockchain technology between upstream and downstream enterprises; the conditions that affect the blockchain technology diffusion are explored. It is better to promote the application of blockchain technology, solve the problem of information asymmetry, and enhance the effectiveness of supply chain finance.

Due to technical characteristics such as decentralization and non-tamperability, BCT can rapidly spread, and both SCF upstream and downstream enterprises are affected. An increasing number of enterprises in the supply chain accept the technology, which can immensely impact SCF development. Currently, research on the application of blockchain technology in the SCF scene dedicates more research attention to its impact on the society and economy, while ignoring the blockchain technology diffusion mechanism and diffusion trend. Technology innovation diffusion refers to the process where technology innovation directly affects potential adopters in a certain manner, and is adopted and disseminated by them [23]. First proposed in the ' contagion theory ' technology innovation diffusion is essentially a contagion process [24]. For blockchain technology diffusion in the SCF system, the core enterprises with a strong technological innovation ability lead the adaptation of blockchain technology and act as a 'source of infection' to influence the adoption decision of other enterprises in the supply chain through trading and financing channels. The influence of competition among enterprises in the chain further accelerates the adoption and dissemination of blockchain technology. Therefore, the diffusion process of blockchain technology in the supply chain financial system can be viewed like the spread process of infectious diseases. In addition, the technology innovation diffusion process can be divided into different phases according to the enterprises' adaptation process, which is similar to the compartment division in the infectious disease model. Therefore, this study utilizes the infectious disease model to analyze the blockchain technology diffusion mechanism in the SCF system.

Following a review of the previous research on blockchain technology in the SCF scenario, our research provides the following contributions to the literature. Scholars have mainly focused on studying the impact of blockchain technology on supply chain finance pricing, decision-making and economic benefits. However, this study focuses on the diffusion process of blockchain technology among SCF enterprises, and it also analyzes the conditions that affect technology diffusion, thereby laying a foundation for the subsequent formulation of incentive chaining measures. Moreover, it accelerates the landing of blockchain technology. Therefore, based on the diffusion theory that affects novel technology innovation as well as the contagion model that depicts the spread of diseases, this study demonstrates the blockchain technology diffusion mechanism that characterizes SCF and analyzes the stability of the diffusion model using the Lyapunov method. It was observed that the diffusion of blockchain technology eventually attains a stable state. Moreover, we analyzed the influence of relevant conditions on technology diffusion.

The rest of the study is organized as follows: the second section reviews the related literature; the third section constructs a blockchain technology diffusion model that considers SCF using the contagion model and analyzes and calculates the constructed model; the fourth section utilizes MATLAB software to numerically simulate the results of the analysis and the calculation that constitutes the third section; and the fifth section summarizes the article.

2. Literature review

This article utilizes technology innovation diffusion to investigate the mechanism pertaining to the blockchain technology proliferation that affected on-chain enterprises. Thus, we review three research fields: supply chain finance information asymmetry, blockchain technology applied in supply chain finance, and the technology innovation diffusion theory.

2.1. Supply chain finance information asymmetry

SCF can effectively coordinate with the flow of funds exhibited by the supply chain, and is a crucial method of solving the financing problems that affects SMEs. Information asymmetry between enterprises, which is increased by the large number of participants and the cumbersome business process in the SCF, also enlarges the difficulty of supply chain coordination [10]. Zheng et al. indicated that performance optimization is mainly dependent on the decision-making by core enterprises in traditional SCF. However, owing to the lack of a trust mechanism, the centralized network structure creates a scenario in which it is difficult to achieve information sharing among core enterprises, non-core enterprises and financial institutions [25]. Esmaeili and Zeephongsekul exploited the Stackelberg game to analyze the cost information asymmetry of core enterprises and the market demand information asymmetry of financing enterprises near the bottom of the supply chain [26]. Moreover, Reindorp et al. examined the impact of supplier credit and information transparency on order financing decisions and profits [27]. Wu et al. proposed that when the shared information is more accurate, the constraints on corporate behavior are greater, which also enhances the supply chain's visibility [20]. The existence of information asymmetry hinders the rapid development of supply chain finance. To overcome the potential adverse selection problem occasioned by information asymmetry, Ni et al. analyzed the process innovation and contract decision-making of the dynamic supply chain, and observed that investment in manufacturers with innovation efficiency can be significantly insufficient with information asymmetry [28]. Zheng and Chen, who aimed to mitigate the negative impact of information asymmetry, observed that companies such as Wal-Mart and Procter & Gamble have invested plenty of funds in information systems and technologies, collecting, analyzing and sharing product sales information with suppliers and retailers to alleviate the conflict between supply and demand [29].

The problems pertaining to information asymmetry and low information sharing widely pervade the SCF management. The member enterprises that constitute the supply chain exhibit different capabilities, and with respect to comprehending information, they exhibit different abilities. Furthermore, to maximize profits, enterprises conceal key information. Thus, the information systems between enterprises are disjointed, and the insufficient information exchange among the member enterprises, prevents them from controlling the revenue status and capital flow of financing enterprises in real time, and it also prevents them from forecasting the occurrence of enterprise default risk. Therefore, we introduce blockchain technology into the management of SCF, which exhibits distributed storage and a consensus mechanism. We provide a solution to the problem pertaining to inadequate information sharing in the process of supply chain enterprise financing and decrease the default risk that affects the enterprises that constitute the supply chain.

2.2. Blockchain technology and supply chain finance

Blockchain technology is a distributed database with non-tamperability, decentralization and traceability, as well as a smart contract and consensus mechanism. It can effectively break the information barriers between enterprises that constitute the supply chain, and it can enable enterprises to provide novel proposals that can prevent and solve problems pertaining to SCF risks. Data traceability can enhance the supervisory ability of lenders [30], and smart contracts can be designed to facilitate the automated execution of the contracts [31]. Blockchain technology facilitates information sharing and risk management. Wang et al. proposed that distrust, privacy issues, data misuse, or asymmetries that affect the sharing of data between entities often hinder data sharing, and they propose methods pertaining to the utilization of blockchain technology to overcome the data sharing barriers, thus, enterprises can create an efficient, fair, secure, and trustworthy data sharing mechanism [32]. Qin noted that blockchain enables the core enterprises to build an integrated platform for circulation mitigation, and that distributed ledger technology enhanced the transparency of the transaction process and decreased the operating costs of the financial market [33]. To address the problem pertaining to the large volume of credit data that characterizes supply chains, Zheng et al. proposed a blockchain-based model for access control and the management of shared transaction information, optimizing the existing credit system and improving the efficiency [18].

Blockchain technology solves the problem pertaining to opaque information by building a data sharing platform. Xu et al. constructed a game model of supply chain financial information sharing behavior based on blockchain technology with the differential game theory, and verified that blockchain technology can effectively alleviate the information island effect [34]. Chod et al. validated the role of information transparency in enhancing the ability of firms to obtain favorable financing terms that exhibits low information transfer costs [35]. With respect to information sharing, blockchain technology mitigates the default risk that characterizes SCF. Babich and Hilary stated that when blockchain technology is applied in SCF, it can overcome information asymmetry and reduce the cost pertaining to default risk, which is occasioned by moral issues [31]. Zheng, Zhang, & Jeffrey analyzed the SCF factoring business that is based on blockchain technology, verified whether the node enterprises would automatically follow the relevant agreements using the Byzantine theory, and demonstrated the optimization effect that smart contract technology exerts on the individual decision-making behavior that characterizes the supply chain using a three-party game, which can reduce the default probability of enterprises [36]. In regard to the risk of supply chain finance, Sun, He, & Su utilized the factoring of accounts receivable as the research object, compared the changes pertaining to evolutionary stabilization strategy before and after the introduction of blockchain technology using evolutionary game, and analyzed the blockchain technology mechanism to solve the risk pertaining to SCF [37]. The conclusion of the aforementioned study indicates that when a strict regulatory environment, which is formed by blockchain technology, is affected, the default risk that influences the SMEs and core enterprises increases, whereas on-chain companies are subjected to immense default fines. Therefore, SMEs will not choose to default regardless of foregone profit maximization. Blockchain technology provides a data sharing platform that can enhance information opacity, provide a safe and reliable trading platform for the on-chain enterprises, and effectively stop enterprises from defaulting on their contracts. Therefore, the blockchain technology that is applied in SCF can yield immense benefits, and enterprises that constitute the supply chain should be encouraged to accept the blockchain platform; thus, a safe and reliable environment, which can enable the coordinated development of SCF, can be created.

2.3. Technology innovation diffusion theory

Blockchain technology with decentralization, traceability, and asymmetric encryption provides a solution to the problem of information opacity and default in SCF. Thus, it can be a reliable technical support that can actualize coordinated SCF development. However, only when the novel technology forms the diffusion trend in the enterprise organization and is widely adopted can its economic value be realized. Rogers describes the diffusion of technology innovation based on communication theory [38], and postulates that the diffusion of technology innovation is a method for spreading technology to social system members through specific channels within a certain time period. Similar to the spread of infectious diseases, when the number of enterprises that adopt technology increases, the impact on enterprises becomes greater.

In recent years, scholars have conducted extensive research on technology innovation diffusion, considering the influencing factors of technology diffusion is one of the main studies. Based on evolutionary economy perspective, Zhong and He constructed the theoretical analysis framework driven by micro-enterprise technology innovation diffusion, and analyzed the interaction mechanism between micro-enterprise technology innovation diffusion and macro-regional industrial structure development [39]. Ma et al. analyzed the impact of industrial transfer and regional technological innovation diffusion using a complex network theory and threshold model [40]. Currently, research on the diffusion of blockchain technology has also focused on the influencing factors pertaining to the adoption of blockchain technology. They attempt to accelerate the proliferation of blockchain technology and enable it to affect its role in the economic society. Queiroz et al. developed a technology adoption model based on the network theory. By utilizing structural equation modeling, the factors affecting the adoption of blockchain technology in India and the United States were analyzed [41]. Zamani et al. analyzed the application of blockchain in the three industries, namely finance, logistics and medical care, and found that the inherent risks of technology, infrastructure compatibility and the support of leaders are the main factors that inhibit the adoption of blockchain technology [42]. To clarify the future development trend of blockchain technology, Cai and Ren constructed a system dynamics model of blockchain technology diffusion, simulated the blockchain technology diffusion mechanism using an empirical method, and analyzed the development trend of blockchain technology under different policy environments [43]. Zang et al. analyzed the global evolution process and diffusion characteristics of blockchain applied to the cultural and creative industry through quantitative data. Thus, they deeply reflected the trend of blockchain technology innovation in the global cultural and creative industry [44]. Boakye et al. utilized the partial least squares structural equation modeling method and the non-linear non-compensated PLS-ANN method. Thus, they examined the organization and environment-driven adoption of blockchain technology in supply chain finance by considering small and medium-sized enterprises in Ghana, and the need to promote the spread of technology among small and medium-sized enterprises through incentives [45].

Meanwhile, from the quantitative perspective, research on technology innovation diffusion has also achieved rich results. Mansfield creatively applied the ' contagion principle ' and the ' Logistic ' growth curve to the diffusion-related research. They noted that the technology adopters exhibited an ' S-shaped ' curve growth, which created the quantitative analysis of the diffusion problem [24]. Subsequently, by constructing differential equations, Bass et al. established a dynamics model. They analyzed the technology diffusion model, which facilitated subsequent studies on the technology diffusion mechanism [46]. To describe the diffusion process in a competitive state more vividly, the Lotka Volterra model is widely utilized in the evolution of a technology diffusion process based on a competitive relationship. Based on the Lotka Volterra model, Tian and Liu constructed a green technology diffusion model to analyze the impact of foreign-funded enterprises, domestic enterprises and governments on green technology diffusion technology in the green technology diffusion process [47]. In addition, the introduction of game theory also offers a more in-depth analysis of the internal technology diffusion mechanism. Dou et al. utilized evolutionary game to explore the formation process pertaining to decision-making process of assembly-type construction technology enterprises, and analyzed the micro-mechanism of its diffusion [48].

Meanwhile, because technology innovation diffusion is also essentially an infection process, the mechanism of technology innovation diffusion is also analyzed using an infectious disease model. Kermack and Mckendric studied the Black Death virus transmission pattern, recommended the SIR compartment model, and proposed the threshold theory that considers infectious disease diffusion as well as the equilibrium state [49], thereby facilitating the research on infectious disease dynamics. Previously, infectious disease models were mainly utilized for the prediction and control of infectious diseases. However, because the research on infectious disease models has advanced, scholars have realized that the spread of many negative social behaviors and emergencies also followed the infectious disease transmission pattern. Therefore, to solve the problems pertaining to the diffusion phenomena, the application of infectious disease models has become a renowned research topic. With respect to economic management, infectious disease models are usually applied in analysis pertaining to financial risk contagion and to that of the diffusion of management techniques. In response to the increasing financing risks that are occasioned by the development of internet finance, Mi and Qian established the SEIS contagion model that considers time delay to analyze the inherent internet finance contagion law [50]. The People's Bank of China (PBOC) utilizes the SIRS contagion model to analyze the cross-contagion mechanism pertaining to the risks that affect financial markets; thus, they addressed the increasing cross-contagion probability that affects financial risks [51]. Moreover, technology innovation diffusion is similar to disease transmission, and so the infectious disease model is also applicable. Ronggui and Jiang utilized the classical SIR contagion model to construct the model that analyzes the intra-organizational and inter-organizational technology diffusion, and they indicated the general laws that regulate the technology diffusion phenomenon [52]. Liao and Xu summarized the development process of the theorem analysis of the traditional technological innovation diffusion, and a horizontal diffusion model based on meta cellular automata technological innovations was established [53]. Ma et al. constructed the disruptive technology diffusion model that utilizes the SIRS epidemic model, and analyzed the diffusion mechanism and law of disruptive technology [54]. Deng and Yuan investigated the contagion relationship of blockchain technology between the subject and object of supply chain enterprises by constructing the SEI contagion model, and analyzed the effect of relevant influencing factors on the diffusion process of enterprises [55]. Therefore, in the SCF system, the diffusion of blockchain technology along with the channels of transaction and financing affects the decision of enterprises in the chain to adopt blockchain technology.

The existing literature fully proves that blockchain technology can provide technical support for the SCF-related problems. Nevertheless, there is a lack of research on the diffusion mechanism of blockchain technology, and on the change law and development trend of technology itself. Therefore, based on the perspective of the technology innovation theory, this study constructs a model, which analyzes the diffusion mechanism that affects blockchain technology. Using SEIR model that is prevalent in the biological field, it considers the small and medium-sized enterprises that characterize SCF. Due to the introduction of blockchain technology into SCF, enterprises gradually adopt the technology into the supply chain, and blockchain technology is successfully diffused into the SCF system.

3. Description and model

3.1. Description

In regard to SCF business, the degree of information sharing among enterprises that exhibit a financing business relationship is low, and with respect to financial enterprises, financial institutions cannot monitor the flow of funds in a timely manner, which increases the risk of non-repayment. Due to decentralization and asymmetric encryption as well as the distributed storage data, and consensus mechanism, blockchain technology is applied to the SCF financing mode. Thus, it strengthens the degree of information sharing among the enterprises that constitute the SCF business, which enables the members of SCF to supervise the flow of funds and other scenarios that affect enterprises in real time and to optimize the default risk pertaining to financing enterprises. Due to the transactions between enterprises in SCF, the attitude of enterprises, which influence their ability to accept technology, is affected. Eventually, it forms the diffusion trend in the SCF system.

In SCF, the blockchain technology innovation diffusion process is essentially a technology contagion process. In the disease transmission process pertaining to the population, the individuals who first come into contact with the pathogen are infected, and as the 'source of infection' for transmission to infect healthy individuals. The healthy population becomes susceptible when exposed to infected people. An infected individual does not exhibit symptoms until an incubation period, at which time an asymptomatic infected individual is referred to as exposed. When an infected individual exhibits symptom, they change from Exposed to Infected and become contagious. When the infected population is cured, the anti-bodies will not allow re-infection, and the population no longer infectious will be Removed. Similarly, when blockchain technology is introduced into SCF, core enterprises that exhibit a strong innovation ability and abundant capital, have the capacity to apply novel technology. Thus, they can be the first to initiate contact with blockchain technology, and be labelled as the 'source of infection' in the diffusion process. Core enterprises affect the acceptance of blockchain technology by non-core enterprises in SCF through trading and financing channels. In regard to the SCF business, the interplay between enterprises has led to the spread of blockchain technology. Meanwhile, non-core enterprises that come into contact with blockchain technology are 'Susceptible'. Before they finally decide to accept novel technologies, these enterprises should adopt a technology acceptance period to decide whether to adopt novel technologies, and to test whether the technology is beneficial to the development. 'Infected' denotes the enterprises that decided to accept blockchain technology and join the blockchain platform after the technology acceptance period. SCF enterprises that are violating smart contracts, are asked to withdraw from platforms and accept severe punishment, as "Removed".

Herein, the diffusion process that affects the blockchain technology, which is applied in the business model of SCF, is regarded as a contagion process, and the process is explained as follows.

(1) Source of the infection. In regard to the SCF network, enterprises are closely connected with each other. Due to the robust-capital base, innovation ability, and wide information channels that the core enterprises exhibit as well as their ability to accept novel technologies, they will prioritize the testing of novel technologies as a means of profit maximization. Therefore, in regard to the blockchain technology model that is applied to SCF, the core enterprises are assumed to be the source of contagion, and after the core enterprises have adopted blockchain technology, joined the blockchain platform, and become on-chain enterprises, they will spread the novel technology to their upstream and downstream enterprises in a phased manner.

(2) Transmission route. Assuming that the proliferation of blockchain technology characterizes the enterprises that constitute the SCF system. In regard to SCF, by virtue of their corporate credit ratings, core enterprises act as a guarantor that enables SMEs to obtain financing from banks. Before core enterprises guarantee SMEs, they should investigate the SMEs' creditworthiness, repayment ability, and capital liquidity. Due to the non-interlinked information systems, which leads to low information sharing, the emergence of the blockchain platform can address the information sharing which is exhibited by enterprises that constitute the supply chain, thus, the probability of enterprise default decreases. Furthermore, the core enterprises that utilize blockchain technology may require upstream SMEs to adopt the technology when guaranteeing to the downstream SMEs, or the up-downstream SMEs may actively choose to participate in the blockchain platform to obtain easier access to the transaction information. Consequently, blockchain technology proliferates among the SMEs that constitute the SCF.

(3) Direction of infection and environment. The transmission and diffusion of blockchain technology is non-directional and radial. When a certain enterprise becomes a part of the blockchain platform, it will be correlated with all the associated off-chain enterprise objects, and it does not exhibit a specific diffusion direction. Therefore, the diffusion of blockchain technology that affects the supply chain financial system is consistent with the disease transmission phenomenon. The environment that characterizes blockchain technology transmission and diffusion is comprised of multiple associated enterprise objects, and the contagion environment is characterized as an associated network.

(4) Assuming that the core enterprise has adopted blockchain technology, it becomes an on-chain enterprise, and as a "source of contagion" affects other enterprises which participate in SCF system. With respect to the SCF business, the off-chain enterprises are recorded as Susceptible (S). Enterprises that are adopting a novel technology should to be evaluated and examined by many parties. Therefore, after an enterprise is exposed to blockchain technology, it should undergo an examination period before it can decide whether to adopt the novel technology, and the enterprises that are undergoing the examination period are recorded as Exposed in the infectious disease model (E). Enterprises that decide to embrace blockchain technology after an inspection period and join the blockchain platform are recorded as Infectious in the infectious disease model (I). Enterprises that are in process of joining the blockchain platform should jointly fulfill the smart contract, and if they violate the contract, they will be subjected to immense losses, and they will be requested to withdraw from the blockchain platform. Therefore, the defaulting enterprises are regarded as Recovered in the infectious disease model (R). The symbolic description that illustrates the blockchain technology diffusion that characterizes SCF is depicted in Table 1.

Based on the division of the compartment model, the enterprises that are undergoing the blockchain technology diffusion phase are divided into four subjects, and the classification considers the state of their adoption, namely Not on-chain enterprises, Potential on-chain enterprises, On-chain enterprises, and Removed enterprises. According to the propagation principle that regulates the infectious disease model, we identify the diffusion mechanism of the blockchain technology that characterizes SCF. Through the transaction business and financing business paths, core enterprises proliferate blockchain technology into the SCF system. Not on-chain enterprises are exposed to blockchain technology in the course of their business dealings with core enterprises, thus, they become contact enterprises. Due to factors influencing the cost and benefits of adopting novel technologies, enterprises that have been exposed to blockchain technology and are undergoing the investigation period become potential on-chain enterprises. Enterprises that have decided to accept blockchain technology and to join the blockchain platform after an exploration period become on-chain enterprises. After the adopting blockchain platform, enterprises that are removed from the chain due to default become removed enterprise. The proliferation mechanism that affects the blockchain that characterizes the SCF system is depicted in Fig. 1.

3.2. The model

The diffusion process of blockchain technology in the SCF system is divided into four subjects according to the adoption stages, namely, Non-chain Enterprises, Potential on-chain Enterprises, On-chain enterprises and Removed Enterprises, corresponding to the Susceptible, Exposed, Infected and Removed in the disease model. The SEIR infectious disease model also divide the disease transmission in the population into four stages. Therefore, we utilize the SEIR model to construct a diffusion model of blockchain technology in the SCF system.

Table 1
Concept of BT proliferation in SCF.

	Notation	Description
Source	Diffusion source	Core enterprises that have adopted blockchain technology
Route	Diffusion route	Transaction business, Financing business
S	Non-chain enterprises	Enterprises that do not adopt blockchain technology
E	Potential on-chain enterprises	Enterprises that have been exposed to blockchain technology during the technology acceptance period
I	On-chain enterprises	Enterprises that join the blockchain platform
R	Removed enterprises	Enterprises that default and withdraw from the blockchain platform

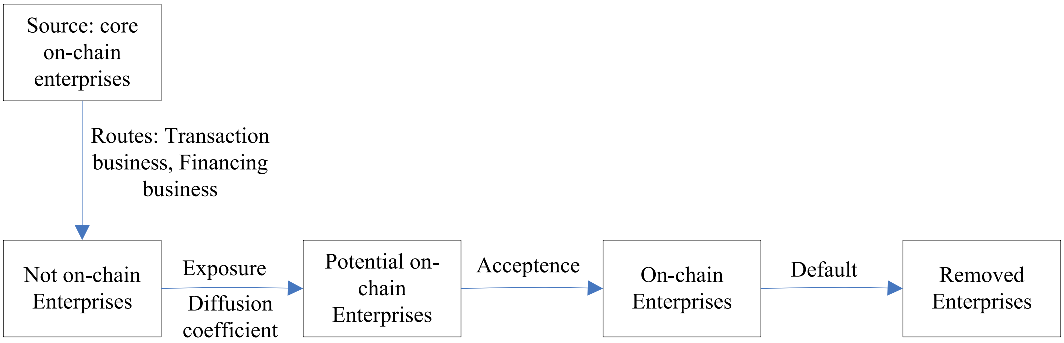

Fig. 1. Diffusion mechanism of blockchain technology in supply chain finance.

3.2.1. *Parameter and variable*

(1) In regard to the blockchain technology diffusion model that affects SCF, $S(t)$ denotes the number of enterprises, which participate in SCF business, at moment t that have been exposed to blockchain technology but have not yet implemented the technology. $E(t)$ denotes the number of enterprises at moment t that are investigating the technology but are likely to potentially accept it. $I(t)$ denotes the number of enterprises at moment t that accept blockchain technology and join the blockchain platform. $R(t)$ denotes the number of enterprises that are removed at time t due to defaulting on the platform's common contract. N denotes the number of enterprises that constitute the four subjects, $S(t) + E(t) + I(t) + R(t) = N$.
(2) We consider the SEIR contagion model with the contagion rate being bilinear, to construct the blockchain technology diffusion model. When blockchain technology is integrated into SCF, the number of enterprises that constitute the supply chain is in flux. Furthermore, novel enterprises are continually formed and bankrupt enterprises are removed. Therefore, the SEIR contagion model that considers the birth and death rates.
(3) Let β represent the diffusion efficiency of the enterprises that are in contact with the on-chain core enterprises that characterize the SCF, namely the successful on-chain probability that a core enterprise which adopted BCT affects the small and medium-sized enterprise in unit time. ε denotes the rate of transfer where the contacting enterprise decides to adopt blockchain technology after an inspection period. γ denotes the rate of enterprises exiting the blockchain platform. It indicates the probability that small and medium-sized enterprises in the supply chain are forced to withdraw from the blockchain in violation of smart contracts. b denotes the rate at which novel enterprises are formed within the supply chain. d denotes the probability that the firm will be bankrupt for internal reasons. We describe the notation in Table 2.

According to the state changes of the four subjects that constitute the proliferation of blockchain technology, with the number of enterprises "N" kept constant, the blockchain technology proliferation process is depicted in Fig. 2.

3.2.2. *The model*

According to the aforementioned blockchain technology diffusion mechanism, we construct the dynamics model (1) of the blockchain technology diffusion that is characterized by utilizing the basic principle (i.e., the infectious disease SEIR model).

Table 2
Notation and description.

Notation	Description
$S(t)$	Number of enterprises that are exposed to blockchain technology in the SCF at t moment.
$E(t)$	Number of enterprises in the stage of examining blockchain technology at t moment.
$I(t)$	Number of Enterprises on-chain to the Blockchain Platform at t moment.
$R(t)$	Number of companies exiting the platform at moment t.
N	Total number of enterprises in the four subjects.
β	Diffusion efficiency of enterprises in SCF system with core enterprises on the chain.
ε	The rate of transfer using blockchain technology.
γ	Percentage of enterprises are removed by blockchain platforms.
b	The rate of new enterprise generation.
d	Probability of the enterprise's own bankruptcy.
Ω	Positive invariant set.
R_0	Basic reproductive number, average contagion capacity of an on-chain enterprise.

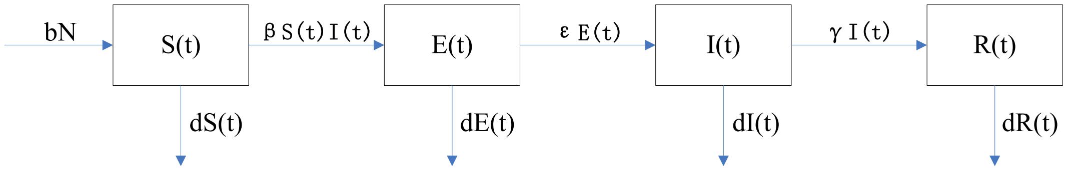

Fig. 2. Proliferation process of blockchain technology in SCF system.

$$\begin{cases} \frac{dS(t)}{dt} = bN - \beta SI - dS \\ \frac{dE(t)}{dt} = \beta SI - \varepsilon E - dE \\ \frac{dI(t)}{dt} = \varepsilon E - \gamma I - dI \\ \frac{dR(t)}{dt} = \gamma I - dR \end{cases} \tag{1}$$

At moment t, Model (1) respectively corresponds to the rate of change pertaining to the number of non-chain enterprises $S(t)$, potential on-chain enterprises $E(t)$, on-chain enterprises $I(t)$ and removed enterprises $R(t)$. At time t, βSI refers to the number from on-chain enterprises to not on-chain enterprises, which is transferred into exposed enterprises. New enterprises in the system are increasing at the rate of b, and the bankruptcy enterprises are decreasing at the rate of d, which jointly influence the change rate of $S(t)$. Through the technology acceptance period, potential on-chain enterprises at the proportion of ε decide to accept the novel technology, and become on-chain enterprises, while $E(t)$ is also affected by the cause of bankruptcy. On-chain enterprises exert an impact on the non-chain enterprises by the diffusion routes. Enterprises which breached the contract are asked to be removed from the platform, and change to the remover in rate γ. Meanwhile, the number of $I(t)$ is reduced at rate d because of bankruptcy. The change rate of $R(t)$ is affected by the number of exits and bankruptcies.

3.3. Analysis

3.3.1. Equilibrium points existence

The S, E, I equations in model (1) are all independent of R. Therefore, we consider the following subsystem (2).

$$\begin{cases} \frac{dS(t)}{dt} = bN - \beta SI - dS \\ \frac{dE(t)}{dt} = \beta SI - \varepsilon E - dE \\ \frac{dI(t)}{dt} = \varepsilon E - \gamma I - dI \end{cases} \tag{2}$$

As,

$$\frac{dS}{dt}|_{S=0} = bN > 0, \frac{dE}{dt}|_{E=0} = \beta SI \geq 0, \frac{dI}{dt}|_{I=0} = \varepsilon E \geq 0$$

The solution of the system in R_+^3 has non-negativity, summing system (2) in three equations.

$$\frac{d(S+E+I)}{dt} = \beta SI - \varepsilon E - dE + \varepsilon E - \gamma I - dI + bN - \beta SI - dS$$

$$= bN - d(S+E+I) - \gamma I \leq bN - d(S+E+I) \tag{3}$$

Then,

$$\limsup_{t\to\infty}(S+E+I) \leq \frac{bN}{d}$$

Therefore, we study system (1) in the closed set

$$\Omega = \left\{ (\mathrm{S}, \mathrm{E}, \mathrm{I}) \in \mathrm{R}_+^3 : \mathrm{S} + \mathrm{E} + \mathrm{I} \leq \frac{\mathrm{bN}}{\mathrm{d}} \right\}.$$

With respect to system (1), it is easy to see that the set Ω is positively invariant.

The following theorems study the equilibrium points existence.

Theorem 1. In regard to the blockchain diffusion model that is applied to SCF, when $R_0 = \frac{bN\beta\varepsilon}{d(\varepsilon+d)(\gamma+d)} < 1$, only the disease-free equilibrium point $P_0\left(\frac{bN}{d}, 0, 0\ , 0\right)$ exists in the System (2). When $R_0 > 1$, in addition to the disease-free equilibrium point P_0, a unique endemic equilibrium point $P^* = (S^*, E^*, I^*, R^*)$ for System (2) exists.

$$S^* = \frac{(\varepsilon+d)(\gamma+d)}{\beta\varepsilon}, E^* = \frac{\gamma+d}{\varepsilon}I^*, I^* = \frac{d(\varepsilon+d)(\gamma+d) - bN\beta\varepsilon}{\beta(\varepsilon+d)(\gamma+d)}, R^* = \frac{\gamma}{d}I^*$$

Proof. Obviously, there is always a disease-free equilibrium point $P_0\left(\frac{bN}{d}, 0, 0, 0\right)$ for System (2), by the regeneration matrix [56], we define the basic reproduction number R_0 as follows

$$R_0 = \frac{bN\beta\varepsilon}{d(\varepsilon+d)(\gamma+d)} \tag{4}$$

To find the endemic equilibrium point for the system (2), we let

$$bN - \beta SI - dS = 0,$$

$$\beta SI - \varepsilon E - dE = 0,$$

$$\varepsilon E - \gamma I - dI = 0.$$

By some calculation, we can get

$$S = \frac{(\varepsilon+d)(\gamma+d)}{\beta\varepsilon},$$

$$E = \frac{\gamma+d}{\varepsilon}I,$$

$$bN - \frac{(\varepsilon+d)(\gamma+d)}{\varepsilon}I - \frac{d(\varepsilon+d)(\gamma+d)}{\beta\varepsilon} = 0.$$

Let $F(I) = -\frac{(\varepsilon+d)(\gamma+d)}{\varepsilon}I + bN - \frac{d(\varepsilon+d)(\gamma+d)}{\beta\varepsilon}$, clearly, $F(I)$ is a monotonically decreasing function.

When $I = 0$, $F(0) = bN - \frac{d(\varepsilon+d)(\gamma+d)}{\beta\varepsilon} = \frac{bN\beta\varepsilon - d(\varepsilon+d)(\gamma+d)}{\beta\varepsilon}$.

According to the basic reproduction number $R_0 = \frac{bN\beta\varepsilon}{d(\varepsilon+d)(\gamma+d)}$, where $R_0 > 1$, $bN\beta\varepsilon - d(\varepsilon+d)(\gamma+d) > 0$. Thus, when $I = 0$, $F(0) > 0$.

Summing the system (2) first two equations, we can have

$$S = \frac{bN}{d} - \frac{(\varepsilon+d)(\gamma+d)}{\varepsilon d}I.$$

To guarantee $S > 0$, it is necessary to satisfy $0 < I < \frac{\varepsilon bN}{(\varepsilon+d)(\gamma+d)}$.

Where $I = \frac{\varepsilon bN}{(\varepsilon+d)(\gamma+d)}$, we have

$$F\left(\frac{\varepsilon bN}{(\varepsilon+d)(\gamma+d)}\right) = bN - \frac{(\varepsilon+d)(\gamma+d)}{\varepsilon} \cdot \frac{\varepsilon bN}{(\varepsilon+d)(\gamma+d)} - \frac{d(\varepsilon+d)(\gamma+d)}{\beta\varepsilon}$$

$$= -\frac{d(\varepsilon+d)(\gamma+d)}{\beta\varepsilon} < 0.$$

Due to the fact that $F(I)$ is monotonically decreasing, as well as satisfies $F(0) > 0$, $F\left(\frac{\varepsilon bN}{(\varepsilon+d)(\gamma+d)}\right)\langle 0$, and according to the zero-point existence theorem, a unique point I^* exists in the interval $\left(0, \frac{\varepsilon bN}{(\varepsilon+d)(\gamma+d)}\right)$; thus, we can get $F(I^*) = 0$.

Therefore, when $R_0 > 1$, there exists the unique endemic equilibrium point as well as the disease-free equilibrium point $P^*\left(\frac{(\varepsilon+d)(\gamma+d)}{\beta\varepsilon}, I^*, \frac{\gamma+d}{\varepsilon}I^*, \frac{\gamma}{d}I^*\right)$ in the system (2), where

$$I^* = \frac{d(\varepsilon+d)(\gamma+d) - bN\beta\varepsilon}{\beta(\varepsilon+d)(\gamma+d)} \tag{5}$$

By analyzing and calculating the blockchain technology diffusion model that characterizes SCF, the threshold value and two equilibrium points of the model are obtained. The basic regeneration number $R_0 = \frac{bN\beta\varepsilon}{d(\varepsilon+d)(\gamma+d)}$, which is calculated from the regeneration matrix, represents the threshold value pertaining to whether the blockchain technology can be proliferated. During the average diffusion period, which characterizes the beginning of the phase wherein the blockchain technology is introduced into the SCF mode, R_0 denotes the number of non-adopting enterprises that are impacted by enterprises that join the blockchain platform. When $R_0 < 1$, blockchain technology exhibits no apparent proliferation trend, and the proliferation is terminated. When $R_0 > 1$, blockchain technology exhibits a proliferation trend among enterprises, and it can continually proliferate the system.

When $R_0 < 1$, a unique positive equilibrium point $P_0\left(\frac{bN}{d}, 0, 0\ ,\ 0\right)$, which affects system (1), exists, the equilibrium point indicates the point at which the blockchain technology terminates the proliferation. At this point, there is no enterprise adopting blockchain technology in the SCF system, that is, blockchain technology fails to fully solve the problem like information asymmetry, and is not suitable for the system. When $R_0 > 1$, there is another positive equilibrium point $P^* = (S^*, E^*, I^*\ ,\ R^*)$ in addition to the equilibrium point $P_0\left(\frac{bN}{d}, 0, 0\ ,\ 0\right)$ that exists. This point refers to the number of enterprises that are reached at the stable diffusion phase, and it considers when the blockchain technology exhibits a SCF diffusion trend.

3.3.2. Model stability analysis

Theorem 2. In regard to the blockchain application proliferation model that considers SCF, when $R_0 < 1$, the unique disease-free equilibrium P_0 is asymptotically global stable in Ω, and when $R_0 > 1$, P_0 is unstable in Ω.

Proof. The Jacobian matrix of System (2) at P_0 is

$$J(P_0) = \begin{bmatrix} -\beta I - d & 0 & -\beta S \\ \beta I & -(\varepsilon + d) & \beta S \\ 0 & -\varepsilon & -(\gamma + d) \end{bmatrix}_{\left(\frac{bN}{d}, 0, 0\right)}$$

$$= \begin{bmatrix} -d & 0 & -\dfrac{\beta bN}{d} \\ 0 & -(\varepsilon + d) & \dfrac{\beta bN}{d} \\ 0 & \varepsilon & -(\gamma + d) \end{bmatrix}$$

Obviously, where $\lambda = -d$ is an eigenvalue of $J(P_0)$ and the other eigenvalues satisfy the following equation:

$$\lambda^2 + (\gamma + 2d + \varepsilon)\lambda + \frac{d(\varepsilon + d)(\gamma + d) - \varepsilon\beta bN}{d} = 0$$

Set the two roots of the above equation as λ_2, λ_3 respectively,

$$\lambda_2 + \lambda_3 = -(\gamma + 2d + \delta)$$

$$\lambda_2 \cdot \lambda_3 = \frac{d(\varepsilon + d)(\gamma + d) - \varepsilon\beta bN}{d}$$

According to Lyapunov method [57], when $R_0 < 1$, all the roots of the characteristic equation are negative real parts, and the disease-free equilibrium point P_0 is locally asymptotically stable on Ω. When $R_0 > 1$, there is a root of positive real parts in the characteristic equation, at this time, the disease-free equilibrium point P_0 is unstable on the positive indefinite set Ω.

Then, we prove the global stability [58] of the disease-free equilibrium point P_0 on Ω.

We consider the Lyapunov function:

$$V(S, E, I) = \varepsilon E + (\varepsilon + d)I \tag{6}$$

Derivation of t along System (2) :

$$V'(S, E, I) = \varepsilon \cdot \frac{dE}{dt} + (\varepsilon + d) \cdot \frac{dI}{dt}$$

$$= \varepsilon(\beta SI - (\varepsilon + d)E) + (\varepsilon + d)(\varepsilon E - (\gamma + d)I)$$

$$= I(\varepsilon\beta S - (\varepsilon + d)(\gamma + d))$$

$$= \frac{I}{(\varepsilon + d)(\gamma + d)}\left(\frac{\varepsilon\beta S}{(\varepsilon + d)(\gamma + d)} - 1\right)$$

$$\leq \frac{I}{(\varepsilon + d)(\gamma + d)}\left(\frac{\varepsilon\beta bN}{(\varepsilon + d)(\gamma + d)d} - 1\right)$$

$$= \frac{I}{(\varepsilon + d)(\gamma + d)}(R_0 - 1)$$

When $R_0 < 1$, $V'(S, E, I) \leq 0$, the full derivative of the Lyapunov function is semi-negative definite. Thus, judging from the Lyapunov second method, it is decided that the disease-free equilibrium point P_0 of the system (2) is globally stable.

When the blockchain proliferation model is introduced to SCF, the disease-free equilibrium point $P_0\left(\frac{bN}{d}, 0, 0, 0\right)$ is interpreted as follows: When the blockchain technology β stops spreading in the SCF system, the number of enterprises that are adopting blockchain technology gradually decrease, and they eventually form a stable state point $P_0\left(\frac{bN}{d}, 0, 0, 0\right)$. Meanwhile, no enterprises are adopting blockchain technology.

With respect to Theorem 2, in the average proliferation period, when the number of on-chain enterprises that influence enterprises that are not adopting blockchain technology (i.e., non-adopting) is less than 1, namely, when $R_0 < 1$, the blockchain technology proliferation among SCF companies ends, and the number of the four main companies gradually stabilizes at the equilibrium point $P_0\left(\frac{bN}{d}, 0, 0, 0\right)$. At the moment when the steady state is attained, there are no companies that are a part of the blockchain platform, which indicates that the blockchain technology is not adopted by the companies that constitute the SCF system, and that the proliferation of blockchain technology in the SCF system fails. Therefore, when the threshold value $R_0 > 1$, blockchain technology can proliferate the SCF scenario.

Theorem 3. When $R_0 > 1$, the unique endemic equilibrium is asymptotically global stable in for system (2).

Proof The System (2) Jacobian matrix in P^* can be obtained as

$$J(P^*) = \begin{bmatrix} -\beta I - d & 0 & -\beta S \\ \beta I & -(\varepsilon + d) & \beta S \\ 0 & -\varepsilon & -(\gamma + d) \end{bmatrix}_{(S^*, I^*, E^*)}$$

$$= \begin{bmatrix} -\beta I^* - d & 0 & -\beta S^* \\ \beta I^* & -(\varepsilon + d) & \beta S^* \\ 0 & -\varepsilon & -(\gamma + d) \end{bmatrix}$$

Then, the eigenvalue equation $\det(\lambda - J) = 0$ can be computed as

$$\lambda^3 + [(\varepsilon + d) + (\gamma + d) + (\beta I^* + d)]\lambda^2 + [2(\varepsilon + d)(\gamma + d) + (\varepsilon + d + d + \gamma)(\beta I^* + d)]\lambda + (\varepsilon + d)(\gamma + d)(\beta I^* + 2d) = 0.$$

With, $a_0 = 1$.

$$a_1 = (\varepsilon + d) + (\gamma + d) + (\beta I^* + d)$$

$$a_2 = 2(\varepsilon + d)(\gamma + d) + (\varepsilon + d + d + \gamma)(\beta I^* + d)$$

$$a_3 = (\varepsilon + d)(\gamma + d)(\beta I^* + 2d).$$

All coefficients are satisfied $a_0, a_1, a_2, a_3 > 0$, as well as satisfied

$$\triangle_2 = \begin{vmatrix} a_1 & a_0 \\ a_3 & a_2 \end{vmatrix}$$

$$= [(\varepsilon + d) + (\gamma + d) + (\beta I^* + d)][2(\varepsilon + d)(\gamma + d) + (\varepsilon + d + d + \gamma)(\beta I^* + d)] - 1 \cdot [(\varepsilon + d)(\gamma + d)(\beta I^* + 2d)]$$

$$= 2(\varepsilon + d)(\gamma + d)(\varepsilon + d + d + \gamma) + (\varepsilon + d)(\varepsilon + d + d + \gamma)(\beta I^* + d) + (\gamma + d)(\varepsilon + d + d + \gamma)(\beta I^* + d) + \beta I^*(\varepsilon + d)(\gamma + d) > 0$$

According to the Hurwitz criterion [58], it is known that the System (2) is locally asymptotically stable at the endemic equilibrium point P^*.

It is then indicated that, at that time, the only endemic equilibrium point P^* of the System (2) is globally stable within the Ω.

We set Lyapunov function [59,60] as

$$L = \int_{S^*}^{S} \frac{d - S^*}{d} d(d) + \int_{E^*}^{E} \frac{d - E^*}{d} d(d) + \int_{I^*}^{I} \frac{d - I^*}{d} d(d) \tag{7}$$

Calculating the full derivative of L along the solution of the system (2)

$$\frac{dL}{dt} = \frac{S - S^*}{S} \cdot \frac{dS}{dt} + \frac{E - E^*}{E} \cdot \frac{dE}{dt} + \frac{\varepsilon + d}{\varepsilon} \cdot \frac{I - I^*}{I} \cdot \frac{dI}{dt}$$

$$= \frac{S - S^*}{S}(bN - \beta SI - dS) + \frac{E - E^*}{E}(\beta SI - (\varepsilon + d)E) + \frac{\varepsilon + d}{\varepsilon} \cdot \frac{I - I^*}{I}(\varepsilon E - (\gamma + d)I)$$

By substitution, we can have

$$\frac{dL}{dt}=\frac{S-S^*}{S}(\beta S^*I^*+dS^*-\beta SI-dS)+\frac{E-E^*}{E}\left(\beta SI-\frac{\beta S^*I^*}{E^*}E\right)$$
$$+\frac{\varepsilon+d}{\varepsilon}\cdot\frac{I-I^*}{I}\left(\varepsilon E-\frac{\varepsilon E^*}{I^*}I\right)$$

For ease of calculation, note separately $x=\frac{S}{S^*}$, $y=\frac{E}{E^*}$, $z=\frac{I}{I^*}$.
Then,

$$\frac{dL}{dt}=\left(1-\frac{S}{S^*}\right)(\beta S^*I^*+dS^*-\beta SI-dS)+\left(1-\frac{E}{E^*}\right)\left(\beta SI-\frac{\beta S^*I^*}{E^*}E\right)$$
$$+\frac{\varepsilon+d}{\varepsilon}\left(1-\frac{I}{I^*}\right)\left(\varepsilon E-\frac{\varepsilon E^*}{I^*}I\right)$$
$$=\left(1-\frac{S}{S^*}\right)(\beta S^*I^*+dS^*-\beta xS^*\cdot zI^*-dxS^*)+\left(1-\frac{E}{E^*}\right)\left(\beta xS^*\cdot zI^*-\frac{\beta S^*I^*}{E^*}E\right)$$
$$+\frac{\varepsilon+d}{\varepsilon}\left(1-\frac{I}{I^*}\right)\left(\varepsilon yE^*-\frac{\varepsilon E^*}{I^*}I\right)$$
$$=\left(1-\frac{1}{x}\right)(\beta S^*I^*+dS^*-\beta xS^*\cdot zI^*-dxS^*)+\left(1-\frac{1}{y}\right)(\beta xS^*\cdot zI^*-\beta S^*I^*y)$$
$$+\frac{\varepsilon+d}{\varepsilon}\left(1-\frac{1}{z}\right)(\varepsilon yE^*-\varepsilon E^*z)$$
$$=dS^*\left(1-\frac{1}{x}\right)(1-x)+\beta S^*I^*\left(1-\frac{1}{x}\right)(1-xz)+\beta S^*I^*\left(1-\frac{1}{y}\right)(xz-y)$$
$$+(\varepsilon+d)E^*\left(1-\frac{1}{z}\right)(y-z)$$
$$=dS^*\left(2-x-\frac{1}{x}\right)+\beta S^*I^*\left(1-xz-\frac{1}{x}+z\right)+\beta S^*I^*\left(xz-y-\frac{xz}{y}+1\right)$$
$$+(\varepsilon+d)E^*\left(y-z-\frac{y}{z}+1\right)$$
$$=dS^*\left(2-x-\frac{1}{x}\right)+\beta S^*I^*\left(2-\frac{1}{x}+z-y-\frac{xz}{y}\right)+(\varepsilon+d)E^*\left(y-z-\frac{y}{z}+1\right).$$

By $\beta S^*I^*=(\varepsilon+d)E^*$, we can get

$$\frac{dL}{dt}=dS^*\left(2-x-\frac{1}{x}\right)+\beta S^*I^*\left(2-\frac{1}{x}+z-y-\frac{xz}{y}\right)+\beta S^*I^*\left(y-z-\frac{y}{z}+1\right)$$
$$=dS^*\left(2-x-\frac{1}{x}\right)+\beta S^*I^*\left(2-\frac{1}{x}+z-y-\frac{xz}{y}+y-z-\frac{y}{z}+1\right)$$
$$=dS^*\left(2-x-\frac{1}{x}\right)+\beta S^*I^*\left(3-\frac{1}{x}-\frac{xz}{y}-\frac{y}{z}\right)$$

Prove the positivity and negativity of $dS^*\left(2-x-\frac{1}{x}\right)$, $\beta S^*I^*\left(3-\frac{1}{x}-\frac{xz}{y}-\frac{y}{z}\right)$, respectively.

(1) $dS^*\left(2-x-\frac{1}{x}\right)=dS^*\left[2-\left(x+\frac{1}{x}\right)\right]$, since the value domain of the function $f(x)=x+\frac{1}{x}$ is $[2,+\infty)$, $dS^*\left(2-x-\frac{1}{x}\right)\leq 0$ holds.
(2) Based on the fact that the arithmetic mean of a number of positive numbers is greater than or equal to their geometric mean, it follows that

$$3-\frac{1}{x}-\frac{xz}{y}-\frac{y}{z}\leq 3+\left(-3\sqrt[3]{\frac{1}{x}\cdot\frac{xz}{y}\cdot\frac{y}{z}}\right)=3+\left(-3\sqrt[3]{1}\right)\leq 0$$

Therefore, it can be proved that $\beta S^*I^*\left(3-\frac{1}{x}-\frac{xz}{y}-\frac{y}{z}\right)\leq 0$ holds.

From the above proof, the derivative of the constructed Lyapunov function is negative definite. By Lyapunov direct method, when $R_0 > 1$, the unique endemic equilibrium is global asymptotically stable in System (2).

In the proliferation model of blockchain introduced to SCF, we interpret the endemic equilibrium point $P^* = (S^*, E^*, I^*, R^*)$ as: When the blockchain technology forms a proliferation trend in the SCF system, the number of enterprises that adopt blockchain technology increases, the number of off-chain enterprises, potential chain enterprises, on-chain enterprises and removed enterprises gradually attains a stable state, and the equilibrium point represents the point corresponding to the moment when the number pertaining to four types of enterprises attains a stable state.

Based on Theorem 3, when $R_0 > 1$, (i.e., in the average proliferation period), when the number of on-chain enterprises that influence enterprises that have not adopted blockchain technology is more than 1, blockchain technology is spread in the SCF system, and it is adopted by enterprises that constitute the supply chain. Thus, the blockchain technology is successfully proliferated in the SCF system, and the introduction of blockchain technology in SCF can effectively solve the problem of inadequate information sharing among enterprises and reduce the risk of enterprise default in financing business. Over time, the number of enterprises that join the blockchain platform gradually converges to the equilibrium point $P^* = (S^*, E^*, I^*, R^*)$, forming a stable state. The number of enterprises that utilize blockchain technology in the supply chain financial system attains a stable number, and blockchain technology is successfully accepted in supply chain finance and accepted by the enterprises in the system, which leads to the gradual formation of a symbiotic state that affects blockchain technology and SCF system.

4. Numerical simulation

4.1. Equilibrium point stability

This study constructs a blockchain technology diffusion model that considers SCF, and it utilizes a class of SEIR contagion models that exhibit standard linear incidence, analyzes the blockchain technology diffusion mechanism that characterizes the SCF model, utilizes the regeneration matrix to obtain the basic regeneration number, and calculates the two equilibrium points of the system. It utilizes the Lyapunov function to demonstrate that with the increase of time t, when $R_0 < 1$, the equilibrium point $P_0\left(\frac{bN}{d}, 0, 0, 0\right)$ is global asymptotically stable, and when $R_0 > 1$, the equilibrium point $P^* = (S^*, E^*, I^*, R^*)$ is global asymptotically stable. To verify the stability of the system, MATLAB software is applied, and numerical simulations are performed.

(1) Let $N = 1$, $b = 0.085$, $\beta = 0.15$, $d = 0.048$, $\varepsilon = 0.1$, $\gamma = 0.2$, calculated to have $R_0 = 0.7326 < 1$ [60,61]. We refer to the annual growth of small and medium-sized enterprises proportion as the value of b, and the proportion of annual bankruptcy of small and medium-sized enterprises as the proportion of bankruptcy d in the model. Four sets of initial values are taken as (0.75, 0,0.25,0), (0.5,0.18,0.3,0.02), (0.2,0.25,0.4,0.15), (0.1,0.28,0.5,0.12), and numerical simulations are performed. The number of subject enterprises of S, E, I, and R trajectories tend to the equilibrium point $P_0\left(\frac{bN}{d}, 0, 0, 0\right)$ (See Fig. 3(a)). Fig. 3(b) indicates that the S, E, I, and R change curves for four different initial values gradually converge to the equilibrium point at an equal rate. Meanwhile, with regard to the SCF system, there are no enterprises that utilize blockchain technology. Thus, the blockchain technology proliferation that affects the SCF model is insignificant, and that the introduction of blockchain technology has not solved the problem pertaining to inadequate information sharing, and the technology is gradually eliminated by the system.

(2) Let $N = 1$, $b = 0.085$, $\beta = 0.25$, $d = 0.048$, $\varepsilon = 0.3$, $\gamma = 0.1$, then the basic reproduction number $R_0 = 2.5789 > 1$ [60,61]. Four sets of initial values are taken as $(0.75, 0, 0.25, 0)$, $(0.5, 0.18, 0.3, 0.02)$, $(0.2, 0.25, 0.4, 0.15)$, $(0.1, 0.28, 0.5, 0.12)$, and numerical simulations are performed. When $R_0 > 1$, the four tracks of S, E, I and R subject enterprises gradually converge to the equilibrium point

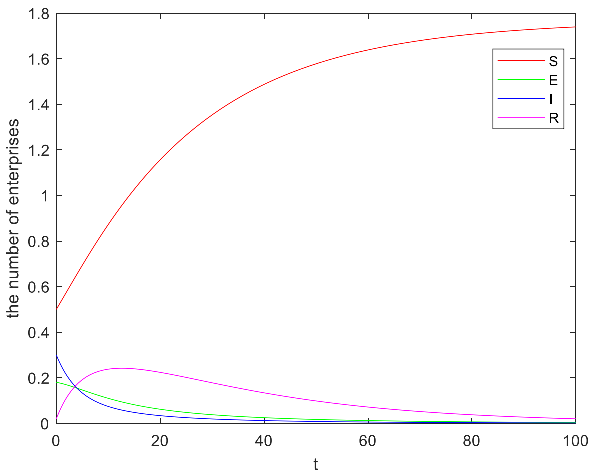

Fig. 3(a). $R_0 < 1$, global stability of the equilibrium point.

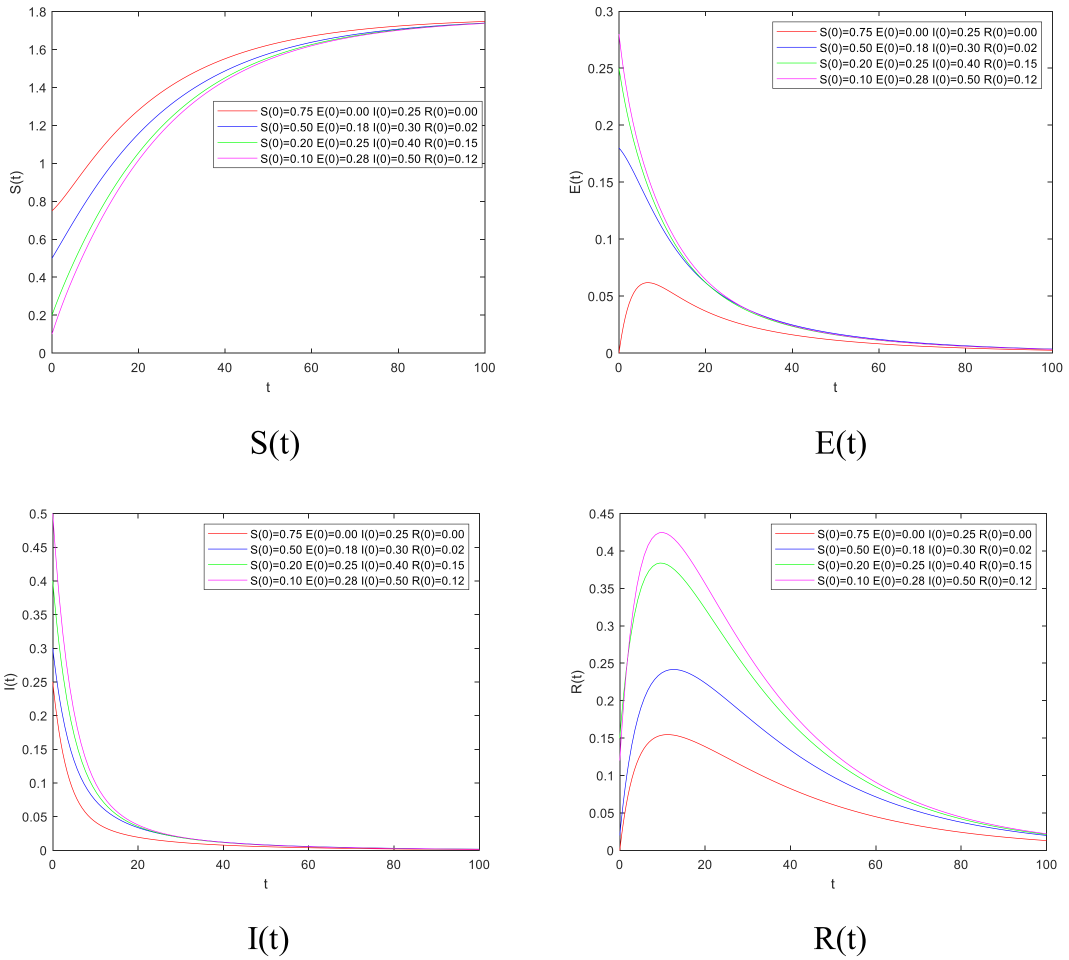

Fig. 3(b). S, E, I, R variation curves.

$P^* = (S^*, E^*, I^*, R^*)$, that attains a stable state in the system (See Fig. 4). It indicates that the blockchain technology effectively proliferates in the SCF model, the novel technology can be accepted by the system, and it can solve the problem pertaining to default risk. Finally, the blockchain technology and the enterprises that effect SCF attain a symbiotic state. Novel technology can continue to exist in the SCF system, which provide effective methods to solve the problems, to improve the financing difficulties of SMEs and promote

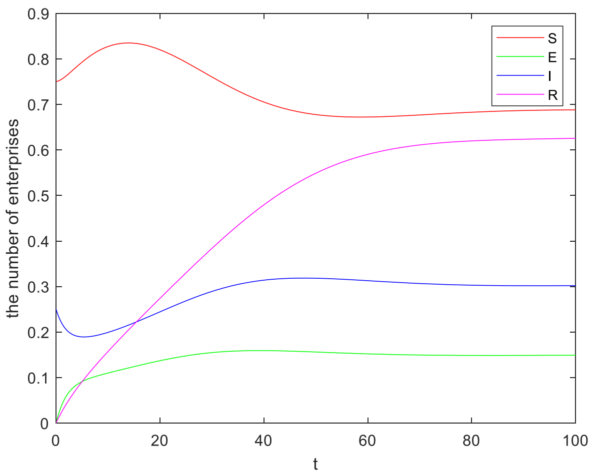

Fig. 4(a). $R_0 > 1$, global stability of the equilibrium point.

the coordinated development of the whole supply chain. Fig. 4(b) indicates that the S, E, I, and R change curves for four different initial values gradually converge to the equilibrium point $P^* = (S^*, E^*, I^*, R^*)$ at an equal rate. The R–S, R-E, and R–I change plots pertaining to the four sets of initial values indicate that the equilibrium point is asymptotically stable (See Fig. 5).

4.2. *The basic reproduction number analysis*

Through the analysis, we noted that the conditions that facilitate the proliferation of blockchain technology in the SCF enterprises can be represented by the following formula: $R_0 = \frac{bN\beta\varepsilon}{d(\varepsilon+d)(\gamma+d)}$. Furthermore, blockchain technology adoption tends to spread to the contacted companies, and when the core enterprise is capable, the impact on the contacted enterprises increases. Therefore, when the basic regeneration number is increased, the proliferation of blockchain technology in SCF is accelerated. Based on the $R_0 = \frac{bN\beta\varepsilon}{d(\varepsilon+d)(\gamma+d)}$ equation, the threshold R_0 is influenced by the following factors: proliferation efficiency β, the transfer rate pertaining to the potential enterprises on-chain enterprises ε, the proportion of default exit platforms γ, the rate of novel enterprise generation b, and the probability of enterprises becoming bankrupt for their internal d. Because the rate of enterprise generation and the probability of bankruptcy are mainly influenced by the social environment (e.g., policies and laws), only the proliferation efficiency, the transfer rate, and the proportion of exit platforms are considered when analyzing their influence on the blockchain diffusion that affects the SCF system. Thus, simulations of the influencing factors that are associated with to the basic regeneration number are performed using MATLAB, which considers the initial conditions and the values of the relevant parameters.

(1) The proliferation efficiency is positively correlated with the basic regeneration number. According to $\frac{dE(t)}{dt} = \beta SI - (\varepsilon + d)E$ which regulates System (1), under the condition that other parameters remain invariant, when the proliferation efficiency is increased, the up-chain rate of potential enterprises increases (See Fig. 6).

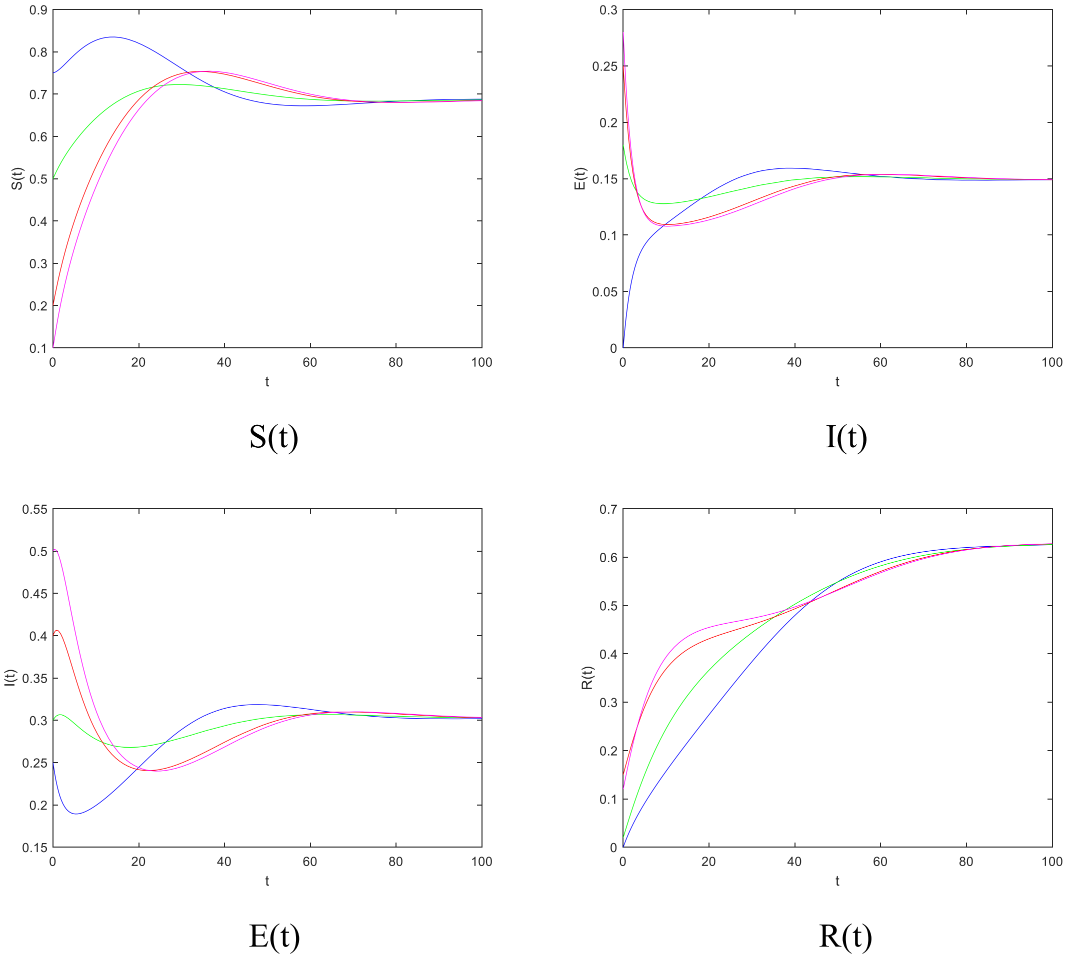

Fig. 4(b). S, E, I, R variation curves.

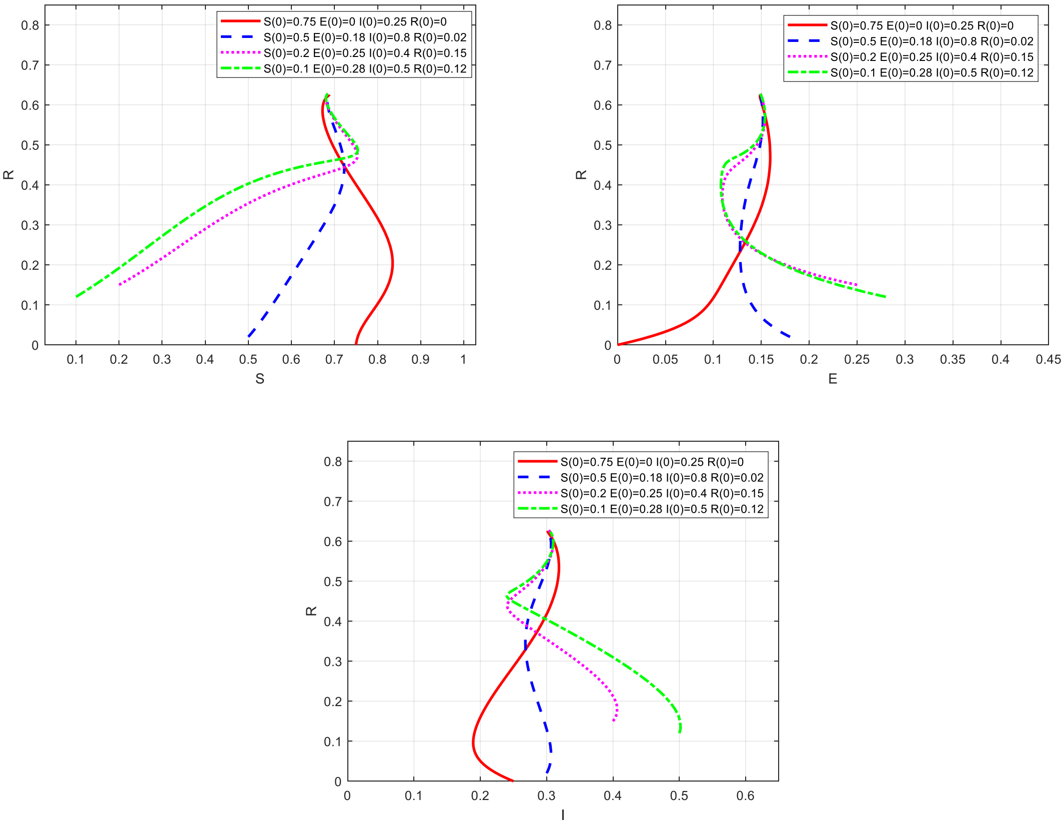

Fig. 5. $P^* = (S^*, E^*, I^*, R^*)$ is asymptotically stable.

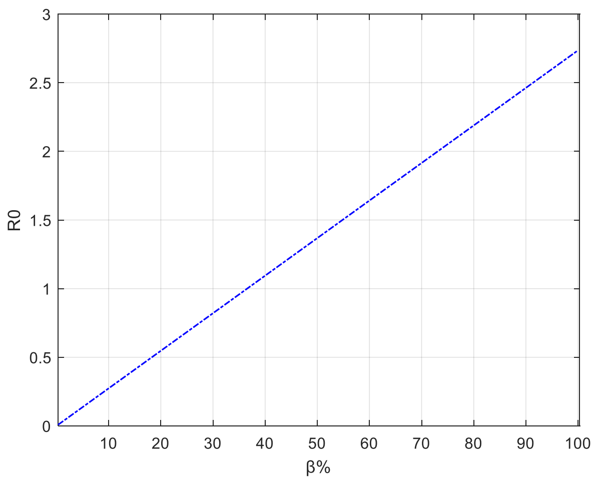

Fig. 6. Diffusion efficiency β on R_0.

- The proportion of potential enterprises that transit to on-chain enterprises have exhibited a positive trend about the basic regeneration number. With regard to $\frac{dI(t)}{dt} = \varepsilon E - (\gamma + d)I$ which regulates System (1), all other parameters remaining constant, when the transfer ratio is increased, the rate at which enterprises join the blockchain platform increases; thus, more enterprises adopt the novel technology (See Fig. 7).

Thus, by increasing the proliferation efficiency, increasing the transfer ratio of potential enterprises, and decreasing the default exit ratio, we can increase the number of on-chain enterprises that constitute the system. In regard to their business transaction, the on-chain enterprises implement technical propaganda, which influences the enterprises that do not accept the blockchain technology. Simultaneously, they reduce the cost pertaining to enterprise chaining, which encourages more financing enterprises to join the

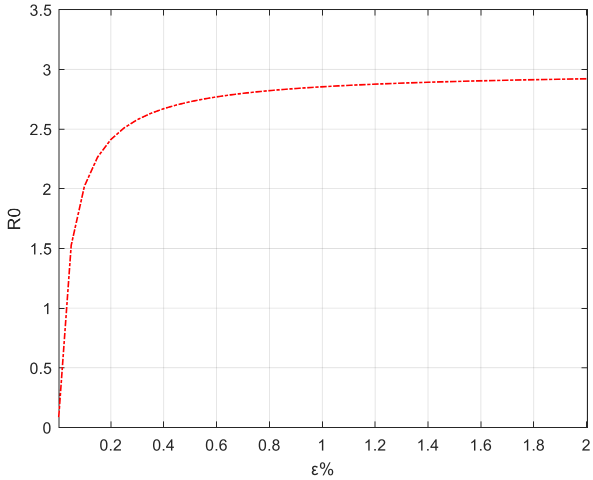

Fig. 7. the rate of transfer ε on R_0.

- The rate of being removed from a blockchain platform due to default can negatively affect the basic reproduction number. Based on $\frac{dI(t)}{dt} = \varepsilon E - (\gamma + d)I$, which regulates System (1), other parameters remaining constant, a smaller exit ratio can increase the rate pertaining to enterprise uptake, which can facilitate the proliferation of blockchain technology (See Fig. 8).

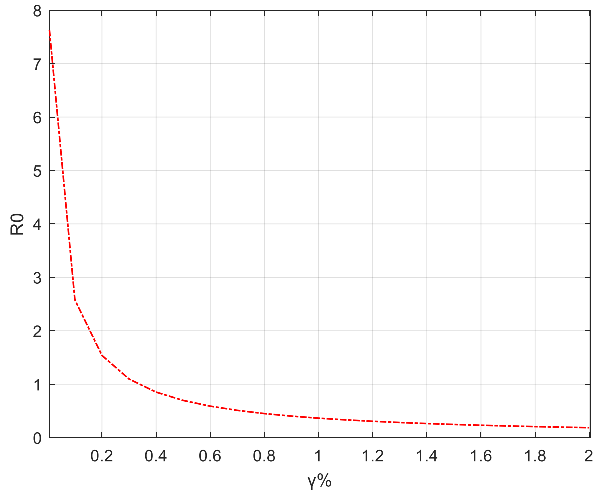

Fig. 8. the rate of removing γ on R_0.

blockchain platform. The information sharing that characterizes the supply chain is enhanced, simultaneously, with respect to the chained enterprises, they enhance the default penalty amount, reduce the probability of enterprise default, and realize collaborative decision-making that is based on blockchain technology.

5. Conclusions

The study analyzes the blockchain technology proliferation mechanism that affects the SCF scenario, and it utilizes an SEIR contagion model. We select the SEIR contagion model that considers the birth rate, mortality rate, and standard linear contagion rate, and the SCF enterprises are divided into four categories. Furthermore, we construct the blockchain technology diffusion model that affects SCF system. The regeneration matrix is utilized to obtain the basic regeneration number, which is the basic condition for the blockchain to be able to perform diffusion. Also, to verify the stability of the system, the reasonable Lyapunov function is constructed.

By examining the blockchain technology proliferation model, two equilibrium points are calculated, namely P_0 and P^*. When the basic reproduction number is set at $R_0 < 1$, the number of non-adopting technology enterprises that are influenced by an on-chain enterprise in the average diffusion period is less than one, which indicates that with respect to the SCF system, blockchain technology indicates a gradual extinction trend, and that when there are no more enterprises adopting blockchain technology in the system, the system gradually converges to the equilibrium point P_0.When the basic reproduction number is $R_0 > 1$, the number of non-adopting technology enterprises that are influenced by an uplinked enterprise during the average diffusion period is greater than 1. Meanwhile, blockchain technology can diffuse in the supply chain financial system, and the system gradually converges to the equilibrium point P^* . Furthermore, the system exhibits a global trend of gradual stability, which is consistent with the technology diffusion scenario, which indicates that blockchain technology has been accepted by the SCF system and that it gradually forms a symbiotic state. The basic regeneration number of the basic conditions that affect the blockchain technology proliferation is analyzed using numerical simulation. The proliferation efficiency, the transfer rate of potential on-chain companies, and the exit ratio can affect the size of the basic regeneration number.

By analyzing the blockchain technology diffusion mechanism, this study contributes to the research on the blockchain technology that is applied in SCF. We can see that the basic reproduction number is the key condition for the successful diffusion of blockchain technology. To enhance the impact of blockchain technology in the market and for more enterprises to understand the advantages of blockchain technology, the supply chain market can enhance the adoption efficiency of enterprises in SCF by effecting some incentive measures, such as reducing the cost of up-chaining platforms and implementing incentive measures. Currently, some companies such as Ant Financial and Suning Financial, utilize large-scale e-commerce platforms to build a ' Blockchain + Supply Chain Finance ' model, thereby realizing the visualization of supply chain finance, and reducing the financing costs of small and medium-sized enterprises on the basis of the safe sharing of information throughout the chain. With respect to on-chain companies, the default rate that leads enterprises to exit the platform can be reduced by amplifying the cost of default and other punitive measures. Blockchain technology with a distributed database can effectively solve the problem of low information sharing and reduce the probability of enterprise default in supply chain finance. Moreover, based on the technology innovation diffusion theory, we utilize the infectious disease model to analyze the blockchain technology diffusion mechanism, providing a novel quantitative method for the diffusion research of innovative technology.

Because the study exhibits some limitations, future studies can further expand on the topics discussed in this article. For the modeling, we consider only the ordinary differential infectious disease model SEIR. However, the influence of the time interval in the technology diffusion process is ignored. Future studies can consider building a class of differential equations with time delay to further analyze the diffusion mechanism of blockchain technology. In addition, the influence of random perturbation on technology diffusion can be increased in future study. Furthermore, subsequent researchers can study the diffusion mechanism of blockchain technology in online supply chain finance and offline supply chain finance. Currently, blockchain technology applied in supply chain finance is in the preliminary exploration stage. There is a lack of sufficient data sources in real scenarios, and the empirical analysis can be further enhanced.

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Data availability statement

No data was used for the research described in the article.

Ethics Declarations

Informed consent was not required for this study because this article does not include any studies involving humans and animals.

CRediT authorship contribution statement

Ying Teng: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Shujian Ma:** Writing – review & editing, Validation, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Qi Qian:** Software, Investigation. **Gang Wang:** Visualization, Validation, Supervision, Resources, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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