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EVOLUTIONARY GAME OF DIGITAL DECISION-MAKING IN SUPPLY CHAINS BASED ON SYSTEM DYNAMICS

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Abstract. This paper primarily focuses on whether supply chains enterprises adopt a digital strategy and the impact of various government measures on supply chain digital decision-making. The study develops a multi-agent decision-making evolutionary game model to examine the stability of decision-making among the government, suppliers, and manufacturers. Additionally, a system dynamics model is established to analyze the governing dynamics within the supply chain's digital decision-making process, identifying characteristic patterns and trends. The analytical results of this study illustrate the government's strength thresholds exist regardless of ex-part penalties or the mix of rewards and punishment. Once the government's strength exceeds these thresholds, the evolutionary game system undergoes abrupt changes. Suppliers and manufacturers who adopt digital strategies are more affected by government penalties than incentives. The stronger the mix of government incentives and penalties, the higher the incentives for the supplier and the manufacturer to adopt a digital strategy, but the lower the incentives for the government to choose a regulatory strategy. Low-intensity mixed rewards and punishments, as well as low-intensity government rewards, are effective mechanisms for promoting government decision-making and supervision. Conversely, high government penalties do not motivate governments to choose regulatory strategies. The unit cost of products to deploy digital strategies directly affects the final digital strategy choice of supply chain enterprises. To choose a digital strategy, supply chain companies must ensure that the unit cost of products remains within a reasonable range.

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1. Introduction

The global epidemic in 2020 had a significant impact on supply chains. According to the study by the Council of Supply Chain Management Professionals (CSCMP), only 3% of companies conducting business remained unaffected by the COVID-19 pandemic. Additionally, 42% of companies reported that the COVID-19 pandemic outbreak significantly accelerated their digitalization process. A digital supply chain allows a supply chain to become intelligent and resilient so that it can better respond to special situations such as epidemics or other disasters. In addition, with the booming digital economy, embracing digitalization presents a crucial opportunity

Keywords. Digital supply chain, multi-agent, evolutionary game, system dynamics.

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for the manufacturing industry to ascend to the middle and high end of the global value chain. A fundamental performance difference exists between traditional and digital supply chains. Traditional supply chains typically rely on a mix use of electronic and paper-based processes and documentation. The organizational structure is often characterized by functional and geographic silos that do not share information openly, leading to sub-optimal performance. However, digital supply chains could provide extensive information availability and enable superior collaboration and communication through digital platforms, improving reliability, agility, and effectiveness[1]. Supply Chain Institute (DSCI) believes that the Digital Supply Chain is a customer-centric platform model that can maximize the perception and utilization of real-time dynamic data from different sources and support demand-driven operational management for perception management to optimize performance and reduce risk[2]. Based on massive data processing performance and intelligent technology systems of digital hardware, software, network cooperation, and communication, the digital supply chain supports the connection and coordination between organizations by providing more valuable, accessible, and affordable services [10].

In addition, new technologies (big data, blockchain, 5G, and other digital technologies) are widely used to define the digital supply chain process. The digital supply chain process follows an "outside to inside" pattern. It always pays attention to supply chain market changes and risks, enabling a two-way perception, timely response, cooperation, and coordination between sales channels and supplier networks[3]. Ehie *et al.* [21] believe that supply chain digitalization refers to the extent to which key factories use emerging digital technologies when they connect businesses with suppliers and customers. Furthermore, supply chain digitalization pertains to the utilization of digital technologies to enhance supply chain operational efficiency and factory performance. Supply chain enterprises collaborate in the production and distribution of products to customers, with product information flowing through the digital supply chain. A digital supply chain system is composed of systems supporting the interaction between each supply chain node (*e.g.* Hardware, software, communication network, etc.), and a digital supply chain can coordinate the behaviors of node partners in the supply chain, including purchasing, manufacturing, storage, transportation, and sales of products [9]. In general, a digital supply chain is a demand-driven, network-structured supply chain with the help of digital technology, which mainly realizes the end-to-end visualization of the supply chain. However, the transformation from a traditional supply chain to a digital one is not accomplished overnight [34]. With the help of digital technology, the digital supply chain is bound to affect the management decisions of traditional supply chain enterprises. Plus, at the beginning of the new business mode development, it cannot leave the government regulation. Therefore, this article discussed the problem of digital supply chain decision-making behavior, namely whether suppliers and manufacturers use digital decision-making game tactics. Moreover, government involvement in regulation game strategy problems, finally it is concluded that government involvement impacts the supply chain enterprise's digital strategy.

The major economies worldwide have made efforts to improve their digital supply chain capabilities and levels, making the digital supply chain a key development task and encouraging the formation of policies to accelerate the development of supply chain digital transformation. In June 2021, the Biden White House published a 100-day review entitled "Building Resilient Supply Chains, Revitalizing American Manufacturing , and Fostering Broad-based Growth". At least US$50 billion was earmarked for semiconductor manufacturing and R&D, and US$50 billion was invested in establishing a supply chain resilience program for key products. In April 2020, China's top policy-making meeting explicitly called for improving digital supply chain capabilities and levels, identifying the digital supply chain as a key developmental task for China.

Policies and measures successively issued by national and local provinces and cities promote enterprises to carry out digital transformation, and digitalization has become a crucial way for enterprises to realize transformation and upgrading. According to the research report of Darry Consulting, 63% of enterprises believe that

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[1]Capgemini Research Institute, Digital Transformation of Supply Chains, `https://www.capgemini.com/resources/digital-transformation-of-supply-chains/`

[2]Digital Supply Chain Institute, Digital Supply Chains: A Frontside Flip, `https://www.dscinstitute.org/applied-research/frontside-flip`

[3]Supply Chain Shaman, Embracing the Digital Supply Chain, `https://www.supplychainshaman.com/demand/demanddriven/embracing-the-digital-supply-chain/`

the digitalization of the supply chain is the core competitiveness of enterprise development. Several well-known manufacturing enterprises, such as Huawei and Procter & Gamble, are actively promoting the implementation of supply chain digital projects. Huawei Intelligent Supply Chain Transformation (ISC+) project establishes digital connections with customers, suppliers, and industrial chains to realize the digital transformation of Huawei's internal supply chain[4]. P&G has built a digital supply chain from consumers to channels to production and procurement[5]. More than 300 digital tags are employed throughout the supply chain to provide timely insight about customer needs and real-time status. The dynamic digital supply chain management focuses on customers, relies on digital information technology to monitor production and orders in real-time, and improves the accuracy and precision of customers data through the data warehouse GDSN system. The digital transformation of the core supply chain enterprise further drives other enterprises to digital transformation. In this scenario, the government also assumes a guiding and regulatory role.

In addition to the government actively promoting enterprises to carry out the digital transformation of the supply chain, and enterprises are engaged in their digital transformation of the supply chain, end consumers are also forcing the supply chain to choose digital. With the development of the digital economy, the rapid response of the digital supply chain has become an important factor for sales enterprises to win the trust of consumers, which is also the core determinant of the enterprise business model. With the end consumer as the core, driven by the new retail channel and convenience stores, the production and circulation of commodities are the links of the supply chain that can not be ignored. The supply chain system, through digital means to realize the unity of the dual-flows (the full link logistics, node management information), makes the supply chain solutions and the actual business scenarios corresponding. However, supply chain digitalization is facing the restriction of the high cost of digital technology investment, as well as the problems of business process re-engineering and management mode innovation brought by the application of digital technology, which is bound to affect the decision of supply chain enterprises to invest in digitalization.

How do supply chain companies make digital decisions? What is the impact of different policy measures on digital supply chain decisions? The deep integration of digitalization and supply chains urgently needs the support of relevant theoretical research. The characteristic of an evolutionary game is to take the participant as the research object, analyze the dynamic evolution process of the participant's strategy, and explain why and how the participant achieves this state. To address these questions, this paper studies suppliers' and manufacturers' evolutionary game problems in making digital decisions in supply chains and government regulation. The paper proposes that suppliers and manufacturers "accept" digital strategy or "reject" digital strategy. Meanwhile, the government, as the decision-making participant, supervises the behavior of supply chain enterprises and studies the evolution trend of evolutionary stability strategy and the influencing factors of strategic change. This study provides a theoretical basis for supply chain enterprises to make digital decisions and promotes formulating supply chain digital policies.

It should be noted that other relevant concepts involved in this paper are cited and explained as follows:

First, the concept of digital strategy. Scholars classify digitalization strategies differently. In general, digitalization is defined as organizational change [24], which can traditionally be distinguished into more inwards-oriented digitalization strategies (*i.e.*, operations and structure) and more externally oriented digitalization strategies (*i.e.*, customers, suppliers, competitors). Through the literature analysis, external digitalization strategies are defined to strengthen external relationships, *i.e.*, cooperation with partners or customers [28]. The advantage is that customers can more actively increase the perceived value of the manufacturer's products, thus making it easier for enterprises to enter new market segments [26]. The internal digitalization strategy is defined as improving the efficiency of internal processes, including project management, product, or service development [27]. Internal digitalization pays more attention to enterprises' internal operations to reduce costs and enhence efficiency [42]. Based on the literature, this paper study holds that digital strategy refers to external digitalization strategy, which could promote the implementation of internal digitalization. The resources, knowledge,

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[4]How Huawei Transformed Its Supply Chain In the Digital Era - Huawei.

[5]P&G: End-to-end Supply Chain Model - Technology and Operations Management (harvard.edu).

and capabilities that suppliers and manufacturers gain through external digitalization enable them to better simplify internal processes by implementing digital tools.

Second, the concept of digital decision-making or digital decision.To maintain a supply chain enterprise's distinctive competitive edge, operations managers must possess a profound understanding of the competitive landscape, including the competition, enterprise, and industry organization within operations. This knowledge is essential for crafting effective strategies that enhance the enterprise's competitive position and advantages, ultimately achieving the flexibility required to adapt to market fluctuations. According to the literature analysis, many studies on decision tools describe the decision-tool implementation in a single company or setting [27]. Decision-making is defined as a decision-maker's choice in the face of an uncertain outcome [42]. Placing decision-makers at the center of behavioral decision-making is the most intuitive method to study behavioral decision-making in enterprises or industrial organizations [19]. In an organization, individuals are the recipients of automatic decisions or recommendations. For example, operational decision-makers who provide support for IT services [14]. A novel performance modeling system, based on Data Envelopment Analysis (DEA) and Artificial Neural Network (ANN) design, has emerged. This system not only predicts overall business efficiency performance but also provides a modeling framework for empirical testing. It presents a new model aimed at assisting managers in decision-making and bridging the gap between theory and practical application by promoting performance benchmarks and modeling research. Bennett *et al.* [8], Ahmed *et al.* [3] argue that harnessing digitally transformed data outcomes is now crucial for numerous organizations. Data-driven decision-making is increasingly becoming a cornerstone in the era of digital transformation, and a robust data framework is imperative for enterprises seeking to cultivate new competitive advantages in a dynamically evolving market. The primary objective of this paper is to translate the insights gained from digital transformation into actionable strategies.Therefore, the definition of digital decision-making or digital decision is the behavior choice of supply chain enterprises, and supply chain enterprises are the operational decision-makers of implementing digitalization in the digital transformation of the supply chain.

The remainder of this paper is organized as follows. Section 1 reviews the related literature. We introduce the model settings and describe the assumptions in Section 2. Section 3 presents the corresponding analysis. Section 4 concludes this paper and discusses future research directions.

2. Literature review

This paper is related to the research on digitalization supply chains. Integrating digital technology and the supply chain accelerates the innovation and remodeling of the supply chain. Digitalization stands as a prominent driving force in the contemporary economy and is poised to assume an even more pivotal role in the future economic landscape [15]. With digitalization, traditional linear supply chains have evolved into dynamic digital supply chains, which is conducive to improving the efficiency of business operations[6]. Zelbst *et al.* argue that high levels of information technology could lead to information sharing among supply chain companies [58]. Tokatli found that compared to the established apparel manufacturing leaders, Gap and H&M, ZARA, as latecomers, by adopting the latest information technology, they quickly acquire the production technology and R & D capability that the former needs to accumulate over a long period [54]. The ex-ante investment in innovation by the dominant firm necessitates ex-post compensation in the form of monopoly gains. In terms of innovation gains, the larger the scale of demand is, the greater the potential scope of profits, and the more likely to quickly obtain the innovation compensation, providing incentives for high levels of original innovation activity. Under technological proximity to the frontier, more competitive markets make firms generate ex-post-monopoly gains through the "competitive escape effect" of high-quality innovation [2]. In addition, Forghani *et al.* [22] believe that digital marketing strategies are sets of controllable E-marketing variables that organizations combine to achieve marketing goals and satisfy customers needs. They point out that, in digital marketing, brands could offer programs which are personalized based on customer behavior and their preferences. Sustainable operations

[6]McKinsey & Company. Supply Chain 4.0-Next generation digital supply chain. https://www.mckinsey.com/business-functions/operations/our-insights/supply-chain-40--the-next-generation-digital-supply-chain#

and strategic investment in green product development are significant issues in supply chain management, among other issues [48]. About the multi-echelon green supply chain model, Roy *et al.* [44] points out that investing in lower installation costs can reduce installation costs and total producer costs, which is a profitable strategy.

The booming development of a new generation of digital information technologies, such as big data, artificial intelligence and blockchain, has triggered changes in traditional supply chains and promoted significant improvements in the efficiency of business operations. Ardolino *et al.* [4] focus on the content of digital technology and divide digitalization into the Internet of Things, cloud computing and predictive analytics to discuss the impact of digital technology in the transformation of industrial enterprises. Digital technology drives the digital transformation of complex products [25] and improves product processing efficiency [6]. Regarding quantitative modeling research concerning supply chain digital operational decisions, a predominant focus lies in modeling and analyzing supply chain decisions and supply chain management performance within the context of blockchain technology.Lohmer *et al.* [35] established two models to discuss the impact of blockchain technology on supply chain elasticity, and demonstrate that efficient collaboration based on blockchain technology could significantly enhance supply chain elasticity. Giovanni [23] constructed a two-level supply chain game model and pointed out that supply chain enterprises could gain operational and economic advantages through the online platform management of blockchain. Niu *et al.* [40] constructed a two-level supply chain model composed of pharmaceutical manufacturers and retailers to discuss the impact of blockchain on the pharmaceutical supply chain. The results show that blockchain technology would produce the supply chain sales growth effect. BuyukOzkan *et al.* [12] proposed a fuzzy evaluation model based on the House of Quality to systematically integrate blockchain into the supply chain to achieve an effective digital supply chain. Their findings indicate that a blockchain-based digital supply chain (BC-DSC) could yield consistent financial benefits, enhance time utilization, and bolster support capacity. However, Choi *et al.* [18] established a supply chain model to study the impact of blockchain technology on data quality in a sustainable fashion supply chain, finding that blockchain would negatively impact the profitability of the supply chain.

Blockchain technology can improve the transparency and traceability of supply chain information, and reduce supply chain management costs and operational risks [1]. Radio frequency identification (RFID) is integrated into the licensed blockchain network supply chain and can be used for the traceability of supply chain products and services [50]. Combining the blockchain with technologies such as big data and cloud computing could significantly enhance the effectiveness of the blockchain in supply chain applications [20]. The digitalization of supply chains also facilitates the development of supply chain finance and the provision of finance for supply chains.

Omran *et al.* [41] discuss how blockchain technology enhances levels of transparency, automation, and trust in supply chain finance based on reverse factoring and dynamic discounting, thereby improving the inefficiencies of traditional supply chain finance instruments. Chod *et al.* [17] argue that blockchain technology has the potential to improve the authenticity and transparency of information verification in a supply chain, particularly concerning inventory, logistics, and capital flows. Through the transmission of signals to investors regarding a company's operational capabilities, blockchain can assist high-quality companies in securing financing advantages at reduced signaling costs. However, Bekmurzaev *et al.* [7] point out that implementing digital technology in supply chain systems is subject to risks such as mutual distrust of members and uneven factor development.

In the empirical study of the conceptual model of the supply chain, Nasiri *et al.* [39] established a digital concept model to research the digital smart technology intermediary effect in the supply chain. The result pointed out that when the enterprise combines intelligent technology and digital transformation, it will enhance the impact of supply chain relationship performance. Longo *et al.* [36] established a conceptual model of the supply chain to study the application potential of blockchain. The study pointed out that blockchain technology can promote collaboration and improve trust between supply chains. Recently, Liu *et al.* [33] employed four game models, examining the impact of monetary and symbolic incentives on supplier participation in the digital transformation of a two-echelon supply chain.

The studies theoretically define the development of supply chain digitalization in practice and digital technologies driving the digital transformation of upstream and downstream supply chain enterprises. However, no research has quantitatively analyzed the impact mechanisms of digital decision behaviour in supply chains, leading to a lack of theoretical understanding of supply chain digitalization.

In recent years, the big data discriminatory pricing behavior of the service platform has recurrently appeared in the platform service supply chain, Chen *et al.* [16] studied the emergence of hotel green behavior and green supply chain using the evolutionary game method. The results show that the green growth incentive mechanism does exist in most hotels. Hotels with green behavior are more profitable than hotels without green behavior. Liu *et al.* [32] used evolutionary game dynamics to promote and analyze the evolution of cooperation. Mai *et al.* [38] have established a dynamic pricing game model for the book supply chain, consisting of publishers and E-retailers. The primary focus is on examining the impact of agency rates and adjustment speeds on the intricacy of dynamic games. Furthermore, the study involves a comparative analysis of system stability and average returns between dynamic decentralized decision-making and dynamic centralized decision-making approaches. Sun *et al.* [51] developed an evolutionary game model of the green investment strategies of manufacturers and suppliers, studied the optimal investment strategy under government subsidies, and concluded the influence of game participants and government subsidies on the stable strategy of the game system. Zhu *et al.* [60] developed an evolutionary game model for the low-carbon investment strategy of suppliers and manufacturers, studied how the supply chain participants invested in low-carbon strategies, and discussed the factors affecting evolutionary stability.

While these studies delve into the evolutionary game dynamics among supply chain firms, they overlook the role of government intervention in the digital supply chain decision-making game. Economic theory suggests that government involvement has the potential to disrupt the optimal allocation of market resources. However, in the nascent stages of new business development, a lack of competition and inadequate market information disclosure can result in market mechanism failures. To address the issue of government participation in supply chain regulation and decision-making, scholars have analyzed the evolutionary behavioral characteristics of government participation in supply chain inter-firm games based on the system dynamics approach. Zhu *et al.* [61] used evolutionary game and system dynamics to conduct theoretical modelling and simulation analysis of behavioral strategy interaction among governments, restaurants, and waste management companies. The results show that the cost of restaurant waste disposal and the cost of supervision are the influencing factors for restaurants and government departments, respectively.

To some extent, the probability of exposure to informal supervision on behalf of the public and non-governmental organizations could improve the management of municipal food waste. Zhang *et al.* [59] established an evolutionary game model between the government and manufacturers, analyzing the influence of government policies on manufacturers' decisions and the dynamic trends of cap-and-trade markets. The influence of government policy on the carbon trading market under static and dynamic carbon trading prices is studied by previous research. It is found that the evolutionary game cannot achieve stability when the government implements a static carbon trading price. Under dynamic carbon trading price, an evolutionary game has evolutionary stability strategy and dynamic carbon trading pricing policy effectively accelerates carbon emission reduction. Lee *et al.* [29] designed a feedback model based on a socio-technological systems perspective to clarify the causal relationship between ICT innovation and regulation in the Korean mobile market and applied system dynamics simulation techniques to test three strategic scenarios. Research finds that R&D investment through shared mobile service subsidies in a taxi industry innovation can promote competitiveness and thus bring social benefits to users. Sana *et al.* [46] used a system dynamics model to discuss the operational and financial relationships among the channel members of a supply chain, which comprises a manufacturing company and a distributor.

The above study indicates the characteristics of the decision-making game of supply chain enterprises and the impact of government behaviour on game players. However, the introduction of government decision-making leads to many game players and complicated scenarios. Scholars have solved this problem by using the characteristics of system dynamics, such as "material flow and information flow", to describe the complex problem. As the market mechanism will fail in the initial stage of supply chain digital transformation, government regulation cannot be absent. Therefore, this paper develops an evolutionary game model of government participation in digital supply chain decisions and applies system dynamics methods to simulate and analyze the evolutionary stability strategies and to influence factors to reveal the mechanism of policy influence on a digital supply chain.

In addition, some scholars have also examined the game model analysis considering supply chain investment decisions. Sana [47] deals with a newsvendor inventory model in light of green product marketing of socially responsible corporate firms. In this model, a comparison between green and non-green marketing is analyzed, including subsidy and tax implementation by Government. It is government's responsibility to facilitate and manage the related issues, optimizing the diverse and competing interests of the actors in the environmental contest. Li *et al.* [30] applied a mathematical model to analyze the impact of sustainable development investment cost on supply chain performance, and found that investment cost is the key for enterprises to invest in sustainable development. Saberi *et al.* [45] conducted a model study on multi-stage supply chain sustainability investments that incorporate green technology. Their findings reveal that the timing and costs of these investments significantly impact a company's decision-making, profitability, and competitive advantages. In the short term, it may appear that the cost of investing in green technology is high; however, in the long term, these costs tend to be lower than the indirect and concealed liabilities associated with pollution, regulatory non-compliance, and health and safety issues. Yu *et al.* [56], established a supply chain network model to assess the short-term and long-term effects of sustainable supply chain competition management, strategic investment, and environmental policies. The study's results indicate that supply chain companies that are willing to invest in sustainability are likely to prosper. Such to Luo *et al.* [37], the four-game model is established to evaluate the impact of the carbon tax policy on manufacturing and re-manufacturing decisions. The study found that a carbon tax could effectively encourage manufacturers to invest in carbon reduction technology. Nonetheless, manufacturers might lack the incentive to engage in re-manufacturing activities in the absence of a well-designed carbon tax policy. This underscores the notion that government measures play a constructive role in shaping supply chain investment decisions.

In brief, the existing literature mainly studied the development of the digital supply chain theoretically or focused on the influence of digital technology on the digital supply chain. Moreover, most scholars pay attention to the game characteristics of supply chain enterprises. As far as we know, there are few works of literature on the model of supply chain digital decision-making with the participation of the government, suppliers, and manufacturers. Given our research objective, content, and methodology, the six most relevant research articles are compared with this study, as shown in Table 1. The main differences between this research and the extant literature are threefold: First, the behavior decision of suppliers and manufacturers in the digital transformation of the supply chain is concerned in this paper. Second, the government encourages suppliers and manufacturers to participate in decision-making when they choose digital strategies. Third, the supply chain decision-making behavior problems under different government supervision strategies are studied in this paper to reveal the influence of government supervision strategies on supply chain digitalization.

In summary, this paper constructs a game evolution model of multi-agent decision-making among governments, suppliers, and manufacturers, analyzes the evolutionary stability of each decision and mixed decisions, and further uses system dynamics simulation to reveal the operational mechanism of supply chain digitalization and the impact of government regulatory measures on supply chain digitalization decision-making. The primary innovation of this paper lies in the development of a game model for the evolutionary dynamics of multi-agent decision-making involving governments, suppliers, and manufacturers. Additionally, it establishes a comprehensive framework for the quantitative analysis of decision-making in the context of supply chain digitalization. The second innovation is that this paper builds a system dynamics model to simulate and analyze the behaviour of digital supply chain decision-making under different government regulatory strategies. Also, this paper reveals the mechanism of the effect of government regulatory strategies on digital supply chain decision-making. Additionally, it provides a basis for policy formulation to promote the development of digital supply chain transformation.

Table 1. Comparison between this paper and existing research.

Literature	Topics	Methods	Participants	Digital supply chain	Government	System dynamics
Ehie and Ferreira [21]	Conceptual Development of Supply Chain Digitalization Framework	Literature review	/	√		
Büyüközkan and Göer [11]	Digital Supply Chain: Literature review	Literature review	/	√		
Bhargava *et al.* [9]	Secure Information Sharing in Digital Supply Chains	Theoretical study	/	√		
Nasiri *et al.* [39]	Managing the digital supply chain: The role of smart technologies	Empirical modeling	/	√		
Zhang *et al.* [59]	The evolutionary game analysis and simulation with system dynamics of manufacturer's emissions abatement behavior	Theoretical modeling	Governments and manufacturers		√	√
Zhu *et al.* [61]	Urban food waste management with multi-agent participation	Theoretical modeling	Government departments, restaurants and waste disposal companies		√	√
This article	Evolutionary Game of Digital Decision-making in Supply Chains Based on System Dynamics	Theoretical modeling	suppliers, manufacturers, and government departments	√	√	√

3. Multi-agent evolutionary game model for supply chain digital decision-making

3.1. Model assumptions

The continuous innovation in digital technology significantly bolsters supply chain transformation capabilities. Supply chain digitalization facilitates the digitalization of supply and production processes, thereby enhancing the efficiency of supply chain operations and bolstering market performance [11]. However, it is imperative to determine the business strategy before making any investments. Leaders who aim to leverage digital technology for organizational improvement have a valuable tool at their disposal. Nonetheless, it's essential to ensure that digital transformation is aligned with a broader business strategy [52]. In general, digital transformation requires strong compatibility of digital technologies between upstream and downstream enterprises in the supply chain to create digital products and services. For example, JD.com has set up a digital platform to encourage suppliers to upgrade their digital systems for better interoperability and information exchange, which promotes a more efficient digitalization process of the entire supply chain. A Traditional method for the digital transformation of the supply chain, this paper starts with a digital strategy, and a digital operating model will set the direction for integrated execution. This will enable organizations to realize the untapped potential of existing capabilities, achieve higher performance, and ultimately create greater value. Supplier digitalization is digital technology research and development, raw material supply process digitalization, etc.; Manufacturer digitalization is digital procurement, digital production process, digital manufacturing, etc. Furthermore, the government sector stimulates and supervises the digitalization decisions of supply chain business entities, thus promoting the digital transformation of the supply chain.

Based on the analyses above, the game model of supply chain digitization is established under supplier, manufacturer, and government participation. Suppliers and manufacturers take the lead in digitalization, and the government, as a regulator, encourages suppliers and manufacturers to invest in digitalization. In this paper, we construct an evolutionary game model of suppliers (G), manufacturers (E), and government departments (D) involved in the digital decision-making of a supply chain. The symbols and descriptions of the model variables are shown in Table 2, and the basic assumptions are as follows.

Hypothesis 1: The set of actions for the supplier's digital decision is $(a_1, a_2) = ($ accept, reject$)$. The probability of "accept" for the supplier is x, and the probability of "reject" is $1-x$. The set of actions for a manufacturer's digital decision is $(b_1, b_2) =$ (accept, reject). The probability of "accept" for the manufacturer is y, and the probability of "reject" is $1-y$. The strategy of the government sector is to regulate or not to regulate, and the set of actions is $(c_1, c_2) =$ (regulate, not to regulate). The probability of the government sector "regulating" is z, the probability of "not regulating" is $1-z$, and $x, y, z \in [0, 1]$.

Hypothesis 2: When a supplier chooses to reject a digital strategy, the unit cost of the product is C_G^n, which is supplied to the downstream manufacturer at the wholesale price ^{w_n}. An organization's resource planning system uses four factors to select ERP, including implementation cost, seller, software quality, and software capabilities of functionality [57]. According to the research [5], supply chain digitalization will reduce the cost of supply chain management, including transportation costs, storage/distribution center operation costs, customer service operation costs, and direct procurement operation costs. However, when the supplier accepts a digital strategy, it increases the production costs, and the digital costs are incorporated into the product costs. The unit cost of the product is C_G^d, and the wholesale price is w_d, where $C_G^d > C_G^n, w_d > w_n$. The unit cost of the product when the manufacturer rejects the digital strategy is C_E^*, and the unit cost when the manufacturer accepts the digital strategy is C_E^d, where $C_E^d > C_E^n$.

Hypothesis 3: The selling price of the product when both the supplier and the manufacturer reject the digitalization strategy is P_{nn}, the selling price of the product when the supplier accepts the digitalization strategy but the manufacturer rejects the digitalization strategy is P_{dn}, the price of the product when the supplier rejects the digitalization strategy but the manufacturer accepts the digitalization strategy is P_{nd}, and the selling price of the product when both parties accept the digitalization strategy is P_{dd}. According to the literature [55], $P_{dd} > P_{nd} = P_{dn} > P_{nn}$.

Hypothesis 4: The marginal benefit of government regulation of suppliers' and manufacturers' digitalization behaviour is denoted as I_D, and the cost of regulation is denoted as C_D. In the case of regulation, government departments impose penalties on suppliers and manufacturers who reject digital strategies. (In practice, the government rarely uses penalties to promote the development of new industries. This paper aims to design penalties and incentives to conduct a comparative theoretical analysis of the effects of different policy levels.) The marginal penalties are recorded as ω_G, ω_E. For suppliers or manufacturers who accept digital strategies to provide incentives (such as financial incentives, etc.), the marginal incentives are recorded as R_G, R_E. The marginal incentives are denoted as bI_D. The marginal benefits when the government department does not regulate are denoted as $b(0 \leq b \leq 1)$, denoting the benefit discount factor under non-regulation. The government has accelerated the application exploration of blockchain and other digital technologies in supply chain management, built a scientific governance system by combining big data, Internet of Things and other technologies, provided government departments and industry institutions with accurate decision-making on social governance, and mobilized the enthusiasm and endogenous motivation of various subjects to participate in governance and improve the efficiency of social governance. For example, Shenzhen Longhua District uses blockchain and other digital technologies to launch a real estate full-chain supervision platform in Shenzhen, the objective is to enhance the application of blockchain technology, and gradually realize the on-chain of approval results, overturning records, and entity responsibilities. Addressing complex issues such as data islands and data privacy is crucial. It is essential to guarantee that the data across the entire real estate project chain, encompassing all links and entities, remains unmodifiable, non-repudiable, impartial, and trustworthy[7].

[7]CCID Report: 2022-2023 China Blockchain Development Annual Report (digitalelite.cn) https://www.digitalelite.cn/h-nd-6939.html

TABLE 2. Notations for the model.

Symbols	Description	Symbols	Description
x	The probability of "accept" for the supplier	P_{nn}	The selling price of the product both the supplier and the manufacturer reject the digitalization strategy
y	The probability of "accept" for the manufacturer	P_{dn}	The selling price of the supplier accepts the digitalization strategy
z	The probability of the government sector "regulating"	P_{nd}	The selling price of the manufacturer accepts the digitalization strategy
C_G^d	Product unit cost of supplier accepting digital strategy	P_{dd}	The selling price of the product both the supplier and the manufacturer accept the digitalization strategy
C_G^n	Product unit cost of supplier rejecting digital strategy	I_D	The marginal benefit of government regulation
C_E^d	Product unit cost of manufacturer accepting digital strategy	bI_D	The marginal benefit of government do not regulation
C_E^n	Product unit cost of manufacturer rejecting digital strategy	C_d	The cost of government regulation
w_d	The wholesale price of the supplier accepts digital strategy	R_E	The marginal incentives of suppliers to accept digital strategies
w_n	The wholesale price of the supplier rejects digital strategy		The marginal incentives of manufacturers to accept digital strategies
ω_G	Suppliers suffer marginal punishment without digitalization	ω_E	Manufacturers suffer marginal punishment without digitalization
d, n	Respectively represent acceptand rejectstrategies	G, E	Respectively represent suppliers and manufacturers

3.2. Model construction

The supplier-manufacturer-government tripartite evolutionary game of the supply chain digital decision model has eight strategy combinations: when the government chooses to regulate, the supplier action has two strategies to accept and reject, and when the supplier chooses to accept the strategy, the manufacturer action also has two strategies to accept and reject; and when the supplier chooses to reject the strategy, the manufacturer has two strategies to accept and reject. The situation is similar when the government chooses not to regulate. The payoff matrix of the three-party evolutionary game is shown in Table 3, where case 1 refers to the payoff matrix under the strategies of supplier taking (x), manufacturer taking (y), and government regulation (z); And the payoffs of the supplier, manufacturer, and government are $w_d - C_G^d + R_G, P_{dd} - w_d - C_E^d + R_E, I_D - R_G - R_E - C_D$, respectively. The remaining cases are similar.

Evolutionary game analysis is based on the theory of replication dynamic equations proposed by Taylor & Jonker [53]. The replication dynamic equation is a dynamic differential equation of the frequency of a particular strategy being adopted in a population. The equation can reflect the action behaviour and change trend of a finite population in a more reasonable and precise way. The following analysis examines the replication dynamic equations of suppliers, manufacturers, and governments to unveil and analyze the dynamic evolutionary characteristics and underlying causes of digital decision-making within a supply chain..

TABLE 3. The payoff matrix of the three-party evolutionary game.

Game subject		Manufacturer	Government: Regulate z	Government: Not regulate $1-z$
Supplier	accept x	accept y	①: $w_d - C_G^d + R_G$, $P_{dd} - w_d - C_E^d + R_E$, $I_D - R_G - R_E - C_D$	⑤: $w_d - C_G^d$, $P_{dd} - w_d - C_E^d$, bI_D
		reject $1-y$	②: $w_d - C_G^d + R_G$, $P_{dn} - w_d - C_E^n - \omega_E$, $I_D - R_G - C_D + \omega_E$	⑥: $w_d - C_G^d$, $P_{dn} - w_d - C_E^n$, bI_D
	reject $1-x$	accept y	③: $w_n - C_G^n - \omega_G$, $P_{nd} - w_n - C_E^d + R_E$, $I_D - R_E - C_D + \omega_G$	⑦: $w_n - C_G^n$, $P_{nd} - w_n - C_E^d$, bI_D
		reject $1-y$	④: $w_n - C_G^n - \omega_G$, $P_{nn} - w_n - C_E^n - \omega_E$, $I_D - C_D + \omega_G + \omega_E$	⑧: $w_n - C_G^n$, $P_{nn} - w_n - C_E^n$, bI_D

(1) The expected benefits for suppliers participating in the game to choose to accept digitalization are

$$W_{a_1} = zy(w_d - C_G^d + R_G) + y(1-z)(w_d - C_G^d) + (1-y)z(w_d - C_G^d + R_G) + (1-y)(1-z)(w_d - C_G^d).$$

The expected gains for suppliers participating in the game choosing to reject digitalization are

$$W_{a_2} = zy(w_n - C_G^n - \omega_G) + y(1-z)(w_n - C_G^n) + (1-y)z(w_n - C_G^n - \omega_G) + (1-y)(1-z)(w_n - C_G^n).$$

And the average expected returns to suppliers are $\bar{W}_a = xW_{a_1} + (1-x)W_{a_2}$.

(2) The expected benefits for manufacturers participating in the game to choose to accept digitalization are

$$W_{b_1} = xz(P_{dd} - w_d - C_E^d + R_E) + x(1-z)(P_{dd} - w_d - C_E^d) + (1-x)z(P_{nd} - w_n - C_E^d + R_E) + (1-x)(1-z)(P_{nd} - w_n - C_E^d).$$

The expected benefits for manufacturers participating in the game to choose to reject digitalization are

$$W_{b_2} = xz(P_{dn} - w_d - C_E^n - \omega_E) + x(1-z)(P_{dn} - w_d - C_E^n) + (1-x)z(P_{nn} - w_n - C_E^n - \omega_E) + (1-x)(1-z)(P_{nn} - w_n - C_E^n).$$

And the average expected returns to manufacturers are $\bar{W}_b = yW_{b_1} + (1-y)W_{b_2}$.

(3) The expected benefits for government participating in the game to choose to regulate the behaviour is

$$W_{c_1} = xy(I_D - R_G - R_E - C_D) + x(1-y)(I_D - R_G - C_D + \omega_E) + (1-x)y(I_D - R_E - C_D + \omega_G) + (1-x)(1-y)(I_D - C_D + \omega_G + \omega_E).$$

The expected benefits for government participating in the game to choose not to regulate the behaviour is

$$W_{c_2} = xybI_D + x(1-y)bI_D + (1-x)ybI_D + (1-x)(1-y)bI_D.$$

And the average expected return to government is $\bar{W}_c = zW_{c_1} + (1-z)W_{c_2}$

Based on the preceding analysis, the replication dynamic equation for the supplier participation game can be derived as follows.

$$F(x) = \frac{dx}{dt} = x(W_{a_1} - \bar{W}_a) = x(1-x) [-2(w_n - C_G^n - \omega_G)zy + (R_G - \omega_G)z + w_d - C_G^d + w_n - C_G^n]. \tag{1}$$

The replication dynamic equation of the manufacturer's participation game is obtained as follows.

$$F(y) = \frac{dy}{dt} = y(W_{b_1} - \bar{W}_b) = y(1-y) [2(\omega_E + w_d + C_E^n - P_{dn})zx + (P_{dd} - P_{nn})x + 2(w_n - w_d)x + (R_E - \omega_E)z - 2w_n + P_{nd} - C_E^d + P_{nn} - C_E^n). \tag{2}$$

The replication dynamic equation of the government's participation game is obtained as follows.

$$\begin{aligned} &F(z) = \tfrac{dz}{dt} = z(W_{c_1} - \bar{W}_c) = z(1-z) \\ &[I_D[(-3b+1)yx + (b-1)x + 2 + (b-1)y] \\ &+x(-R_G - \omega_G) + y(-R_E - \omega_E) - C_D + \omega_G + \omega_E]. \end{aligned} \tag{3}$$

3.3. Model analysis

Firstly, we analyze the stability of the decision of a single game subject of a supplier, manufacturer and government, and reveal the influencing factors of the optimal strategy of a single subject. The evolutionary game can reach the Nash equilibrium only after several games, and the stable solution of the Jacobian Matrix imitates the stable solution of the system after several decisions. Given that the decisions made within the evolutionary game involving suppliers, manufacturers, and governments are mutually influenced, the examination of the overall stability of the evolutionary game system is conducted as a secondary step.

(1) Evolutionary stability analysis of supplier single-subject decision-making
The evolutionary stability of supplier decision-making is analysed based on the supplier replication dynamic equation model. The derivation of equation (1) yields:

$$\begin{aligned} &F'(x) = (1-2x) \\ &[(2(-w_n + C_G^n + \omega_G)y + R_G - \omega_G)z + w_d - C_G^d + w_n - C_G^n]. \end{aligned} \tag{4}$$

According to the principle of the stability of differential equations, the solution when satisfying equations $F(x) = 0$ and $F'(x) < 0$ is the supplier evolutionary stability strategy. At this point, there are the following cases.

1) When $\mathrm{z} = \mathrm{z}^* = \frac{-\left(w_d - \mathrm{C}_G^d + w_n - C_G^*\right)}{2\left(-w_n + C_G^n + \omega_G\right)y + R_G - \omega_G}$ for any, there exists $x(0 \le x \le 1)$, that is, $F(x) = 0$; And the supplier choosing to accept or reject the strategy is a stable strategy.
2) When $z \neq z^*$, let $F(x) = 0$. Then, we obtain $x = 0, x = 1$. This is analyzed as follows:
If $z^* < 0$, then $F'(x)|_{x=0} > 0, F'(x)|_{x=1} < 0$, and $x = 1$ is the evolutionary stability point of the supplier.
If $z^* > 1$, then $F'(x)|_{x=0} < 0, F'(x)|_{x=1} > 0$, and $x = 0$ is the evolutionary stability point of the supplier.
If $0 < z^* < 1$ and $z > z^*$, then $F'(x)|_{x=0} > 0, F'(x)|_{x=1} < 0$, and $x = 1$ is the evolutionary stability point of the supplier. If $0 < z^* < 1$ and $z < z^*$, then $F'(x)|_{x=0} < 0, F'(x)|_{x=1} > 0$, and $x = 0$ is the evolutionary stability point of the supplier. The acceptance of digital decisions by the supplier in this case is influenced by the government regulatory strategy.

(2) Evolutionary stability analysis of a manufacturer's single subject decision-making
Based on the manufacturer replication dynamic equation model, the evolutionary stability of the manufacturer's decision is analyzed. The derivation of equation (2) yields:

$$\begin{aligned} &F'(y) = (1-2y)[[2(\omega_E + w_d + C_E^n - P_{dn})x + R_E - \omega_E]z \\ &+(P_{dd} - P_{nn})x + 2(w_n - w_d)x - 2w_n + P_{nd} - C_E^d + P_{nn} - C_E^n]. \end{aligned} \tag{5}$$

1) When $z = z^* = \frac{-[(P_{dd} - P_{nn})x + 2(w_n - w_d)x - 2w_n + P_{nd} - C_E^d + P_{nn} - C_E^n]}{2(\omega_E + w_d + C_E^n - P_{dn})x + R_E - \omega_E}$, at this time, $y(0 \le y \le 1)$ for any $F(y) = 0$. That is, the manufacturer chooses to accept or reject the strategy is a stable strategy.
2) When $z \neq z^*$, let $F(y) = 0$, where $y = 0, y = 1$. Then. The analysis is obtained as follows.
If $z' < 0$, then $F'(y)|_{y=0} > 0, F'(y)|_{y=1} < 0$. That is, $y = 1$ is the evolutionary stability point of the manufacturer.
If $z^* > 1$, then $F'(y)|_{y=0} < 0, F'(y)|_{y=1} > 0$. That is, $y = 0$ is the evolutionary stability point of the manufacturer.

If $0 < z^* < 1$ and $z > z^*$, when $F'(y)|_{y=0} > 0$, $F'(y)|_{y=1} < 0$, then $y = 1$ is the evolutionary stability point of the manufacturer.

If $0 < z^* < 1$ and $z < z^*$, when $F'(y)|_{y=0} < 0$, $F'(y)|_{y=1} > 0$, then $y = 0$ is the evolutionary stability point of the manufacturer. This implies that the manufacturer's acceptance of digital decisions is also influenced by the government's regulatory strategy during this period.

(3) Analysis of the evolutionary stability of government single-subject decision-making

Based on the dynamic equation model of government replication, the evolutionary stability of governmental decision-making is analyzed. The derivation of equation (3) yields:

$$\begin{aligned} &F'(z) = (1-2z)[(I_D(-3b+1)y + b - 1) - R_G - \omega_G)x \\ &+2I_D + I_D(b-1)y + y(-R_E - \omega_E) - C_D + \omega_G + \omega_E]. \end{aligned} \tag{6}$$

1) When $x = x^* = \frac{2I_D+(b-I)yI_D+y(-R_E-\omega_E)-C_D+\omega_D+\omega_E}{-[I_D(-3b+1)y+b-1-R_G-\omega_D]}$, at this time, for any $z(0 \leq z \leq 1)$, $F(z) = 0$. That is, the government chooses to regulate or not to regulate strategy is a stable strategy.

2) When $x \neq x^*$, let $F(z) = 0$, where $z = 0, z = 1$. Then. The analysis is obtained as follows.

If $x^* < 0$, then $F'(z)|_{z=0} > 0, F'(z)|_{z=1} < 0$. That is, $z = 1$ is the evolutionary stability point of the government.

If $x^* > 1$, then $F'(z)|_{z=0} < 0, F'(z)|_{z=1} > 0$. That is, $z = 0$ is the evolutionary stability point of the government.

If $0 < x^* < 1$ and $x > x^*$, when $F'(z)|_{z=0} < 0$, $F'(z)|_{z=1} > 0$, then $z = 0$ is the evolutionary stability point of the government.

If $0 < x^* < 1$ and $x < x^*$, $F'(z)|_{z=0} > 0, F'(z)|_{z=1} < 0$ when $z = 1$ is the evolutionary stability point of the government. The greater the probability that the supplier (manufacturer) chooses to accept the digital strategy, the greater the benefits of not regulating the government compared to the benefits of regulation. Finally, the government tends to choose the non-regulation strategy. The smaller the probability that the supplier (manufacturer) chooses to accept the digital strategy, the greater the benefits of government regulation compared to non-regulation, the government tends to choose the regulation strategy.

(4) Evolutionary stability analysis of the multi-agent decision-making of suppliers, manufacturers, and governments

By associating equations (1), (2), and (3), a system of replicated dynamic equations for the three-party game between suppliers, manufacturers, and governments is obtained.

$$\begin{aligned} &F(x) = \frac{dx}{dt} = x(W_{a_1} - \bar{W}_a) = x(1-x) \\ &[-2(w_n - C_G^n - \omega_G)zy + (R_G - \omega_G)z + w_d - C_G^d + w_n - C_G^n] \\ &F(y) = \frac{dy}{dt} = y(W_{b_1} - \bar{W}_b) \\ &= y(1-y)[[2(\omega_E + w_d + C_E^n - P_{dn})x + R_E - \omega_E]z \\ &+(P_{dd} - P_{nn})x + 2(w_n - w_d)x - 2w_n + P_{nd} - C_E^d + P_{nn} - C_E^n] \\ &F(z) = \frac{dz}{dt} = z(W_{c_1} - \bar{W}_c) \\ &= z(1-z)[I_D[(-3b+1)yx + (b-1)x + 2 + (b-1)y] \\ &+x(-R_G - \omega_G) + y(-R_E - \omega_E) - C_D + \omega_G + \omega_E]. \end{aligned} \tag{7}$$

Let $F(x) = F(y) = F(z) = 0$. Then, we find the strategy combination $(0,0,0), (0,0,1), (0,1,0)$, $(0,1,1), (1,0,0)$, $(1,0,1), (1,1,0)$, or $(1,1,1)$ is the equilibrium point of the system. According to Lyapunov's second law, the equilibrium point that satisfies the eigenvalues of the corresponding Jacobi matrices being all less than 0 is the evolutionary stable strategy (ESS) of the system, *i.e.*, the point is in the evolutionary stable strategy state.

The Jacobi matrix of this system is obtained from equation (7) as

$$J = \begin{bmatrix} \frac{\partial^3 F(x)}{\partial t \partial x} & \frac{\partial^3 F(x)}{\partial t \partial y} & \frac{\partial^3 F(x)}{\partial t \partial z} \\ \frac{\partial^3 F(\mathrm{y})}{\partial t \partial x} & \frac{\partial^3 F(\mathrm{y})}{\partial t \partial y} & \frac{\partial^3 F(\mathrm{y})}{\partial t \partial z} \\ \frac{\partial^3 F(\mathrm{z})}{\partial t \partial x} & \frac{\partial^3 F(\mathrm{z})}{\partial t \partial y} & \frac{\partial^3 F(\mathrm{z})}{\partial t \partial z} \end{bmatrix}.$$

TABLE 4. Eigenvalues of the equilibrium points of the multi-agent evolutionary game.

Equilibrium point	Eigenvalue λ_1	Eigenvalue λ_2	Eigenvalue λ_3
$(0,0,0)$	$w_d - \mathrm{C}_G^d + w_n - C_G^n$	$-2w_n + P_{nd} - C_E^d + P_{nn} - C_E^n$	$2I_D - C_D + \omega_G + \omega_E$
$(0, 1, 0)$	$w_d - C_G^d + w_n - C_G^n$	$-(-2w_n + P_{nd} - C_E^d + P_{nn} - C_E^n])$	$I_D b + I_D - R_E - C_D + \omega_G$
$(0, 0, 1)$	$R_G - \omega_G + w_d - C_G^d + w_n - C_G^n$	$R_E - \omega_E - 2w_n + P_{nd} - C_E^d + P_{nn} - C_E^n$	$-(2I_D - C_D + \omega_G + \omega_E)$
$(0, 1, 1)$	$\omega_G + R_G + w_d - w_n - C_G^d + C_G^n$	$-(R_E - \omega_E - 2w_n + P_{nd} - C_E^d + P_{nn} - C_E^n)$	$-(I_D b - I_D - R_E - C_D + \omega_G)$
$(1, 0, 0)$	$-(w_d - C_G^d + w_n - C_G^n)$	$P_{dd} - 2w_d + P_{nd} - C_E^d - C_E^n$	$I_D(b-1) + 2I_D - R_G - C_D + \omega_E$
$(1, 0, 1)$	$R_G - \omega_G + w_d - C_G^d + w_n - C_G^n$	$\omega_E + C_E^n - P_{dn} + R_E + P_{dd} - C_E^d$	$I_D(b-1) + 2I_D - R_G - C_D + \omega_E$
$(1, 1, 0)$	$-(w_d - C_G^d + w_n - C_G^n)$	$-(P_{dd} - 2w_d + P_{nd} - C_E^d - C_E^n)$	$I_D(-b+1) - R_G - R_E - C_D$
$(1, 1, 1)$	$-(-w_n + C_G^n + \omega_G + R_G + w_d - C_G^d)$	$-(\omega_E + C_E^n - P_{dn} + R_E + P_{dd} - C_E^d)$	$-[I_D(1-b) - R_G - R_E - C_D]$

Where $\frac{\partial^3 F(x)}{\partial t \partial x} = (1-2x)\left[-2\left(w_n - C_G^n - \omega_G\right) zy + \left(R_G - \omega_G\right) z + w_d - C_G^d + w_n - C_G^n\right]$,

$$
\begin{aligned}
\frac{\partial^3 F(x)}{\partial t \partial y} &= x(1-x)\left[\left(-2w_n + 2C_G^n + 2\omega_G\right) z\right], \\
\frac{\partial^3 F(x)}{\partial t \partial z} &= x(1-x)\left[-2\left(w_n - C_G^n - \omega_G\right) y + R_G - \omega_G\right], \\
\frac{\partial^3 F(\mathrm{y})}{\partial t \partial x} &= y(1-y)\left[2\left(\omega_E + w_d + C_E^n - P_{dh}\right) z + P_{dd} - P_{nn} + 2\left(w_n - w_d\right)\right], \\
\frac{\partial^3 F(\mathrm{y})}{\partial t \hat{\partial} y} &= (1-2y)\left[\left[2\left(\omega_E + w_d + C_E^n - P_{dh}\right) x + R_E - \omega_E\right] z + \left(P_{dd} - P_{nn}\right) x \right. \\
&\quad \left. +2\left(w_n - w_d\right) x - 2w_n + P_{nd} - C_E^d + P_{nn} - C_E^n\right], \\
\frac{\partial^3 F(\mathrm{y})}{\partial t \partial z} &= y(1-y)\left[2\left(\omega_E + w_d + C_E^n - P_{dn}\right) x + R_E - \omega_E\right], \\
\frac{\partial^3 F(\mathrm{z})}{\partial t \partial x} &= z(1-z)\left[I_D(-3b+1)y + I_D(b-1) - R_G - \omega_G\right], \\
\frac{\partial^3 F(\mathrm{z})}{\partial t \partial y} &= z(1-z)\left[I_D(-3b+1)x + I_D(b-I) - R_E - \omega_E\right], \\
\frac{\partial^3 F(\mathrm{z})}{\partial t \partial z} &= (1-2z)\left[I_D[(-3b+1)yx + (b-1)x + 2 + (b-I)y] + x\left(-R_G - \omega_G\right)\right. \\
&\quad \left. +y\left(-R_E - \omega_E\right) - C_D + \omega_G + \omega_E\right].
\end{aligned}
$$

At this point, the equilibrium points are brought into the Jacobi matrix, and the eigenvalues corresponding to each equilibrium point are obtained separately, as shown in Table 4.

The eigenvalues corresponding to the equilibrium point of the game $\lambda_1, \lambda_2, \lambda_3$ depend on the w_d, w_n, $C_G^n, \mathrm{C}_G^d, C_E^d, C_E^n, P_{dd}, P_{nd}, P_{nn}, P_{dn}, I_D, C_D, R_G, R_E, \omega_E$, and ω_G of the parameter. However, it is difficult to precisely determine the stability of an equilibrium point theoretically due to a large number of game subjects and complex model parameter relationships. Drawing on the studies in the literatures [49][50][51], the following establishes the dynamic model of the multi-agent evolutionary game system of supply chain digital decision-making under government participation. And then, this paper simulates and analyses the stability of the equilibrium point of the system under government reward and punishment regulatory measures.

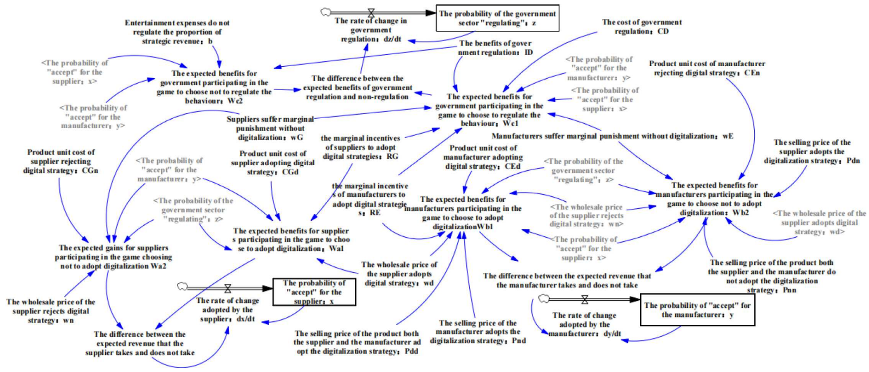


FIGURE 1. Evolutionary game system dynamics model for digital decision-making in the supply chain.

4. SYSTEM DYNAMICS ANALYSIS FOR SUPPLY CHAIN DIGITAL DECISION-MAKING

4.1. System dynamics model building

The system dynamics model is the simulation of the structure and function of the system. It analyzes and models the system according to its internal mechanism and micro-structure and deals with the complex system by qualitative and quantitative methods. System dynamics is a very effective method for dynamic simulation analysis such as supply chain decision problems. According to Tables 2 and 3, combined with the principle of system dynamics, the Vensim PLE software is used to establish the system dynamics simulation model of the multi-agent evolutionary game of supply chain digital decision-making under government participation.

As shown in Figure 1, the model consists of 3 state variables (the probability that suppliers accept digital strategies x, the probability that manufacturers accept digital strategies y, and the probability that governments enact regulation z), 3 rate variables $\left(\frac{dx}{dt}, \frac{dy}{dt}, \frac{dz}{dt}\right)$, and 9 auxiliary variables ($W_{a_1}, W_{a_2}, W_{a_1} - W_{a_2}, W_{b_1}, W_{b_2}, W_{b_1} - W_{b_2}, W_{c_1}, W_{c_2}, W_{c_1} - W_{c_2}$). The 17 external variables and their interrelationships are composed, and the arrows in the figure indicate the causal flow diagram between the variables. A detailed description of the SD model, variables, and formulas is attached Appendix.

INITIAL TIME is the initial time of the model simulation, FINAL TIME is the final time of the model operations, and TIME STEP is the time step. The larger the step value is, the larger the model simulation error; therefore, with reference to a previous study, this paper sets the model's INITIAL TIME = 0, FINAL TIME = 100, and TIME STEP = 1.

Refer to relevant literature [31, 55, 59], an initial probability of 0.2 is set for suppliers, manufacturers, and governments; and the 17 external variables in the model are assigned the values $C_G^d = 0.2, C_G^n = 0.1, w_d = 0.3, w_n = 0.2, C_E^n = 0.1, C_E^d = 0.2, P_{nn} = 0.3, P_{dn} = 0.4, P_{nd} = 0.4, P_{dd} = 0.5, I_D = 0.9, \quad b = 0.5, C_D = 0.2$. The parameter assignments meet the basic logical requirements of the model after several debugging sessions, and can be used for simulation analysis.

4.2. System dynamics simulation analysis

The subsequent simulation analysis elucidates the effects of varying government regulatory incentives and penalties on supply chain digitalization decisions. It also sheds light on how government regulatory probabilities influence the likelihood of supply chain digitalization decisions. Table 5 demonstrates the six simulation scenarios.

TABLE 5. Six scenarios for government incentives and penalties.

Incentives/Penalties	Scenarios
Government incentives	Scenario 1 (the government gives incentives to suppliers and manufacturers)
	Scenario 2 (the government only rewards suppliers)
	Scenario 3 (government incentives only for manufacturers)
Government penalties	Scenario 4 (government simultaneously penalizes suppliers and manufacturers)
	Scenario 5 (the government only penalizes suppliers)
	Scenario 6 (the government only penalizes manufacturers)

TABLE 6. Figure 2 through Figure 4 illustration of the legend.

Government reward intensity	Legend	Figure 2 through Figure 4 illustration of the legend Illustration
Low rewards	RG&RE1	The low-level incentive on behalf of the government is 0.1
	RG&RE2	The low-level incentive on behalf of the government is 0.2
	RG&RE3	The low-level incentive on behalf of the government is 0.3
Medium rewards	RG&RE4	The medium-level incentive on behalf of the government is 0.55
	RG&RE5	The medium-level incentive on behalf of the government is 0.6
	RG&RE6	The medium-level incentive on behalf of the government is 0.7
High rewards	RG&RE7	The high-level incentive on behalf of the government is 0.85
	RG&RE8	The high-level incentive on behalf of the government is 0.9
	RG&RE9	The high-level incentive on behalf of the government is 1

4.2.1. Government incentives

In this section, we focus on the impact of government incentives on digital decision-making in a supply chain.

Government penalties are set as $\omega_G = \omega_E = 0$, and only the impact of government rewards R_G, R_E on the probability of digital decision-making of suppliers and manufacturers is considered. As shown in Figures 2–4, nine curves represent government reward intensity (low, medium, and high). Here, 0.1, 0.2, and 0.3 are set as low rewards; 0.55, 0.6, and 0.7 are set as medium rewards; and 0.85, 0.9, and 1 are set as high rewards.

3.2.1.1. Scenario 1 (the government also gives incentives to suppliers and manufacturers)

Given the complexity of this simulation and the large number of legends. Therefore, in order to facilitate readers to have a better reading experience, Table 6 lists the description of the legend.

The results claims that the level of government rewards affects the probability of suppliers and manufacturers to the same extent; and the higher the level of rewards is, the faster the probability of convergence of the suppliers and manufacturer's choice to take.

The simulation found that the critical values of R_G, R_E are approximately 0.2. When the low government reward is greater than 0.2, the final game strategy of suppliers and manufacturers is in an unstable state, and the probability that they choose to take digital strategies gradually decreases, such as with curve 2 and curve 3 in Figures 2 and 3. When time > 30, the probability of suppliers and manufacturers taking digital strategies at 0.9 and 0.75, respectively, tends to smooth out. This results in an unstable evolutionary game state. When the government gives a high level of incentives, as with curves 7–9 in Figures 2 and 3, the probability that both suppliers and manufacturers choose to accept the digital strategy smooths out at approximately 0.3, *i.e.*, both eventually evolve into unstable strategies.

As in Figure 4, there is a negative relationship between the strength of government incentives and their regulatory probability, and the critical value of government incentives is approximately 0.1. When $R_G = R_E = 0.2$, the initial trend of the government decision probability tends to converge towards the regulatory strategy,

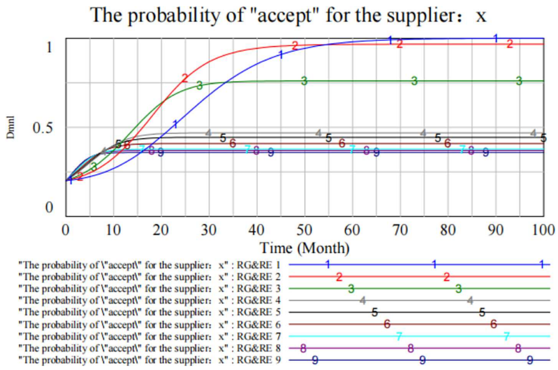


Figure 2. R_G and R_E Effect of change on x.

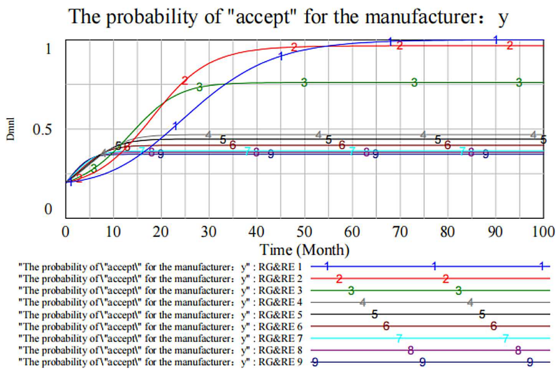


Figure 3. R_G and R_E Effect of change on y.

but the government tends to choose the non-regulatory strategy over time. When R_G, R_E are sufficiently large (as in Curve 4-Curve 6 in Fig. 4), the government implements a medium level of incentives for supply chain enterprise regulation, *i.e.*, the cost expenditures are higher, the convergence of the probability of the government choosing the no regulation strategy is faster, and eventually the government will evolve to the no regulation strategy. When the government gives a high level of incentives (as in curves 7–9 in Fig. 4), the simulation finds that the greater the government incentives are, the faster the convergence of the probability of government regulation Z to 1. At this point, the stable point of the evolutionary game system exists in one cases: (1, 1, 1) .

3.2.1.2. Scenario 2 (the government only rewards suppliers)

In order to facilitate readers to have a better reading experience, Table 7 lists the description of the legend. (Figs. 7 and 8 in Sect. 3.2.1.3 have similar legends, representing the 9 lines of The low(/medium/high)-level incentive on behalf of the government only rewards manufacturers, respectively.)

The results show that the higher the level of rewards is, within a certain range, the faster the probability of convergence of the supplier's choice to take. However, beyond a certain range, the supplier's final game strategy is in an unstable state and the probability of choosing digitalization gradually decreases, such as with curve 4, curve 5 and curve 6 in Figure 5. When time > 30, the probability of suppliers choosing to take digital strategies at 0.8, 0.79 and 0.75, respectively, tends to smooth out. This results in an unstable evolutionary game state. When the government gives a high level of incentives, as with curves 7–9 in Figure 5, the probability that suppliers choose to accept the digital strategy smooths out at 0.7, eventually evolving into unstable strategies. Currently, the government does not carry out any incentive or punishment measures for the manufacturer, and

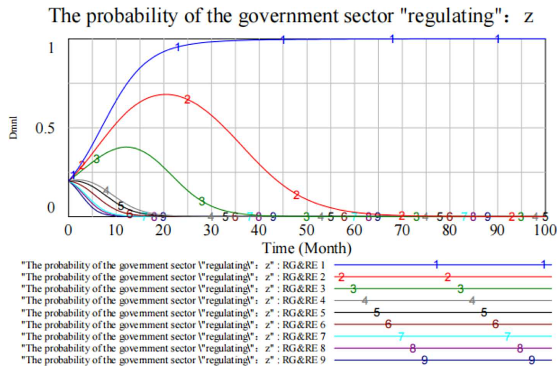


FIGURE 4. R_G and R_E Effect of change on z.

TABLE 7. Figure 5 through Figure 6 illustration of the legend.

Government reward intensity	Legend	Figure 5 through Figure 6 illustration of the legend Illustration
Low rewards	RG1	The low-level incentive on behalf of the government only rewards suppliers is 0.1
	RG2	The low-level incentive on behalf of the government only rewards suppliers is 0.2
	RG3	The low-level incentive on behalf of the government only rewards suppliers is 0.3
Medium rewards	RG4	The medium-level incentive on behalf of the government only rewards suppliers is 0.55
	RG5	The medium-level incentive on behalf of the government only rewards suppliers is 0.6
	RG6	The medium-level incentive on behalf of the government only rewards suppliers is 0.7
High rewards	RG7	The high-level incentive on behalf of the government only rewards suppliers is 0.85
	RG8	The high-level incentive on behalf of the government only rewards suppliers is 0.9
	RG9	The high-level incentive on behalf of the government only rewards suppliers is 1

the manufacturer does not have a strong willingness to accept digitalization and tends to reject digitalization strategy.

As in Figure 6, there is a negative relationship between the strength of government incentives and their regulatory probability, and the critical value of government incentives is approximately 0.2. When $R_G > 0.2$, the government tends to choose the non-regulatory strategy over time. When R_G is sufficiently large (as in Curve 4-Curve 9 in Fig. 6), the government implements a medium or high level of incentives for supply chain enterprise regulation, *i.e.*, the cost expenditures are higher, however, suppliers do not choose to follow the strategy at this time, which has input loss for the government, that is, government incentives do not work. At this point, the faster the convergence speed of the probability of the government choosing the non-regulatory strategy, the government will eventually evolve into the non-regulatory strategy.

The evolutionary stability strategy of the evolutionary game system in scenario 2 is (1,0,1).

3.2.1.3. Scenario 3 (government incentives only for manufacturers)

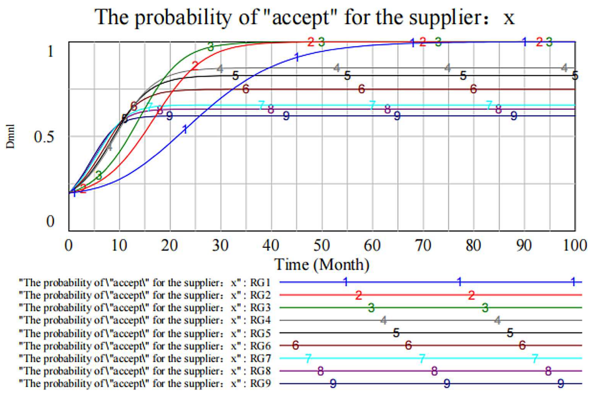


FIGURE 5. R_G and R_E Effect of change on x.

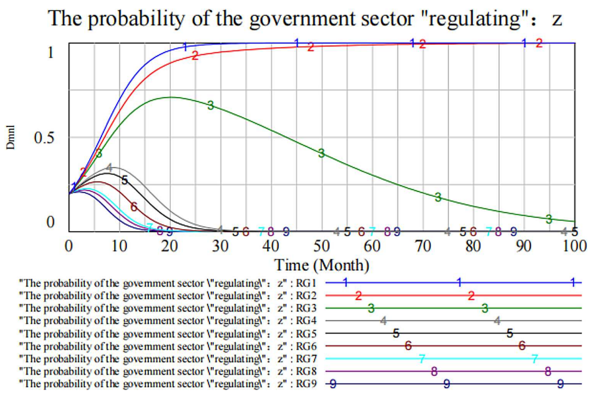


FIGURE 6. R_G and R_E Effect of change on z.

The analysis shows that the evolutionary game trend of the manufacturer in scenario 3 is similar to that of the supplier in scenario 2. The evolutionary stability strategy of the evolutionary game system in scenario 3 is (0,1,1).

4.2.2. Government penalties

In this section, we focuses on the impact of government penalties on digital decision-making in a supply chain. Government incentives are set as $R_G = R_E = 0$, and only the impact of government penalties ω_G, ω_E on the probability of digital decisions of suppliers and manufacturers is considered. As shown in Figure 9–11, the nine curves represent the government penalty strength. Here, 0.1, 0.2, and 0.3 represent low penalties; 0.55, 0.6, and 0.7 represent medium penalties; and 0.85, 0.9, and 1 represent high penalties.

3.2.2.1. Scenario 4 (government simultaneously penalizes supplier and manufacturer)

The figures show that the higher the government penalty is, the faster the probability of suppliers and manufacturers accepting digital strategies converges to 1. Over time, the probability of supply chain firms accepting digital technology eventually evolves to a steady state of 1. The greater the punishment is, the faster the probability of government choosing a regulatory strategy converges to 1. The simulation finds that when the government adopts a high level of punishment (as in curves 7, 8, and 9 in Fig. 11b), the probability of government regulation changes abruptly to greater than 1 in the initial time ($0 < \text{time} < 4$), which is inconsistent with the

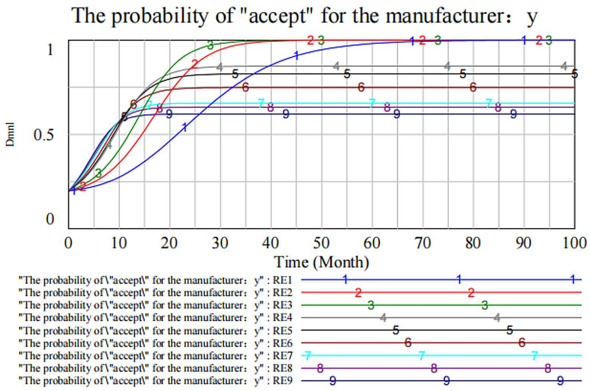


FIGURE 7. R_G and R_E Effect of change on y.

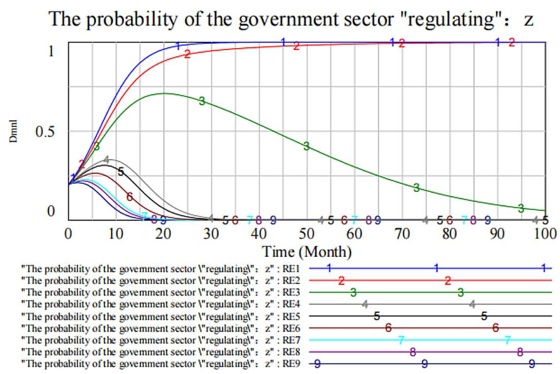


FIGURE 8. R_G and R_E Effect of change on z.

evolutionary game system setting, but the probability of regulation eventually evolves to a stable state of 1 over time. At this point, the stable point of the evolutionary game system is (1, 1, 1).

3.2.2.2. Scenario 5 (the government only penalizes suppliers)

The figures show that the higher the government penalty is, the faster the probability of suppliers accepting digital strategies converges to 1. Over time, the probability of supply chain firms accepting digital technology eventually evolves to a steady state of 1. The probability of government regulation also increases with the increase of ω_G, and the speed of convergence and probability 1 is also faster and faster.

The system stability strategy of the evolutionary game in scenario 5 is (1,0,1).

3.2.2.3. Scenario 6 (the government only penalizes manufacturers)

The analysis shows that the evolutionary game trend of manufacturers in scenario 6 is similar to that of suppliers in scenario 5. The stability strategy of scenario 6 occurs at (0,1,1).

4.2.3. Mixed government incentives and penalties

In this section, we focuses on the impact of mixed government incentives and penalties on supply chain digitalization decisions.

Consider $R_G, R_E, \omega_G, \omega_E$. The effect of different values on the probability of suppliers and manufacturers accepting digitalization. As shown in Figures 16–18, Cases 1 9 represent nine different values of the mixed reward and punishment parameters $(R_G, R_E, \omega_G, \omega_E)$, which are set to 0.1, 0.2, and 0.3 for low mixed reward and punishment; 0.55, 0.6, and 0.7 for medium mixed reward and punishment; and 0.85, 0.9, and 1 for high

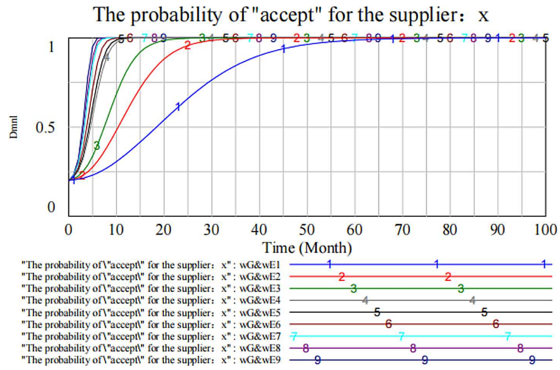


FIGURE 9. ω_G and ω_E Effect of change on x.

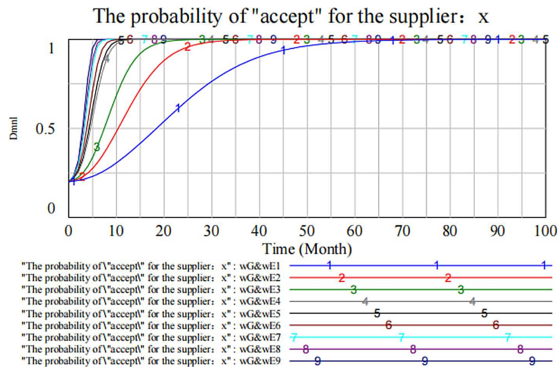


FIGURE 10. ω_G and ω_E Effect of change on y.

mixed reward and punishment. The results show that as government rewards and penalties increase, the probability of suppliers and manufacturers accepting digitalization strategy converges to 1 faster. The mixed government rewards and penalties measures significantly positively impact supply chain digitalization. The simulation finds that when the mixed measures of government rewards and punishments are high (as with curves 7–8 in Figs. 16b and 17b), the probability of acceptance by suppliers x, and the probability of acception by manufacturers y will change abruptly to greater than 1 in the initial time period $(0 < \text{time} < 6)$, which is inconsistent with the evolutionary game model setting. As we can see, Curves 9 has been unstable, illustrating that high levels of rewards and punishments are not a good option for governments. That is, there is a certain threshold of mixed government measures in the initial time of supply chain digital transformation, but as time passes, the probability that supply chain firms accept digitalization eventually evolves to a steady state of 1. Figure 18 shows that the threshold value of mixed government incentives and penalties is approximately 0.1; and once the mixed government incentives and penalties increase, the regulatory costs borne by the government are correspondingly larger; and when government regulation is sufficiently large (as in curve 6 in Fig. 18), the strategy eventually evolves to no regulation. The simulation finds that when the government implements a high level of mixed incentives and penalties, the probability of government regulation will suddenly change to a negative value in the initial period $(6 < \text{Time} < 15)$, which is not in line with the evolutionary game model setting; however, the probability of government regulation eventually evolves to a stable state of 0 over time, and the government's final decision will evolve to no regulation. When the government implements a high level of mixed rewards and punishments, each subject of the evolutionary game system suddenly changes, indicating a certain threshold of

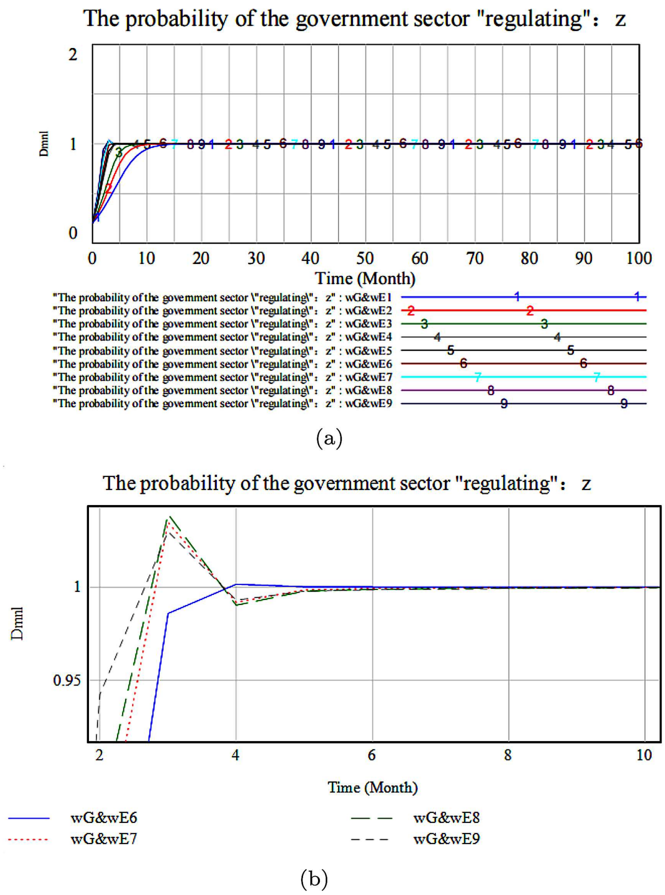


FIGURE 11. ω_G, ω_E the effect of change on z. (a) ω_G, ω_E the effect of change on z. (b) Partially enlarged version.

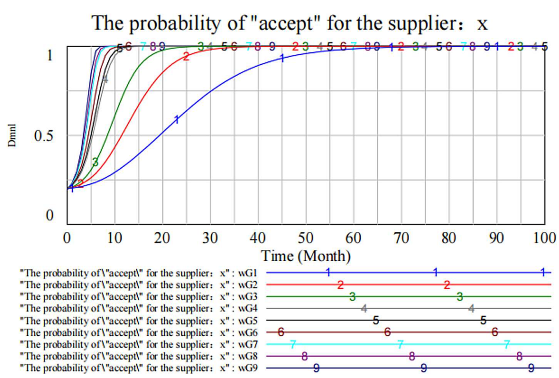


FIGURE 12. ω_G and $\omega_E = 0$ Effect of change on x.

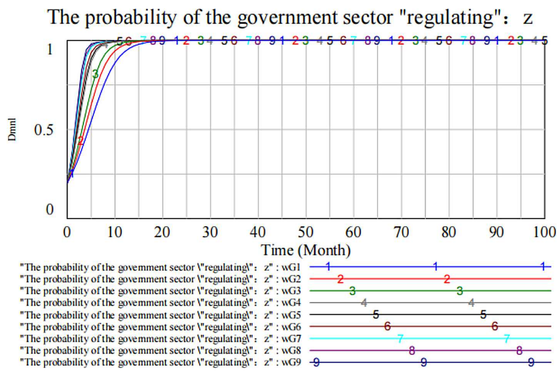


FIGURE 13. ω_G and $\omega_E = 0$ Effect of change on z.

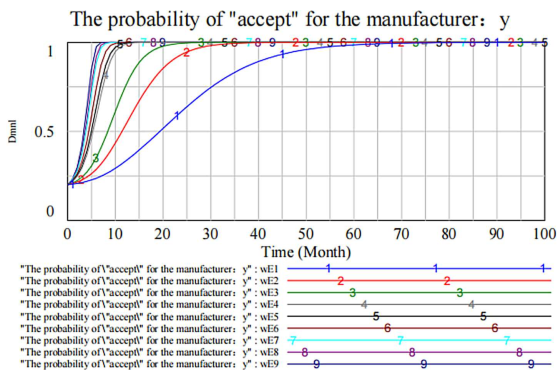


FIGURE 14. ω_E and $\omega_G = 0$ Effect of change on x.

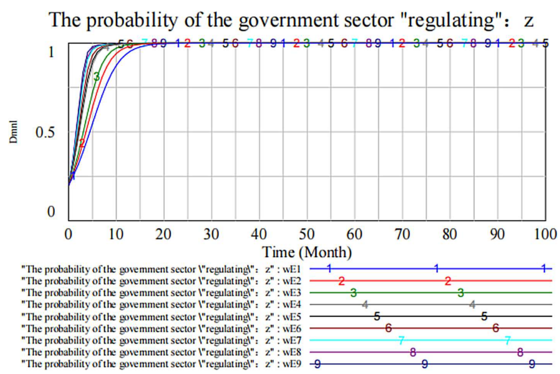
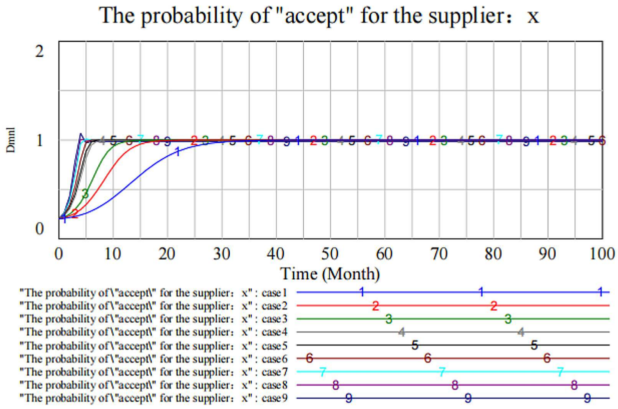
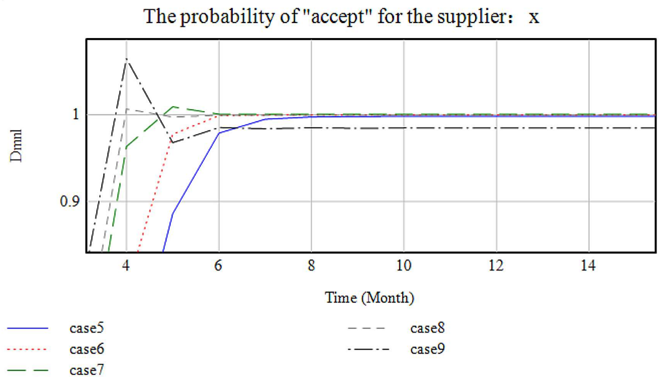


FIGURE 15. ω_E and $\omega_G = 0$ Effect of change on z.



(a)

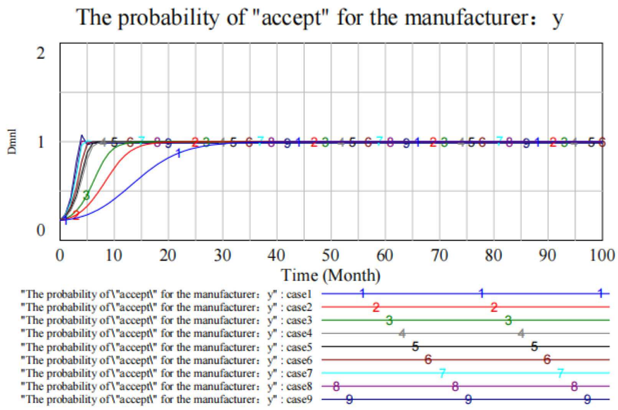


(b)

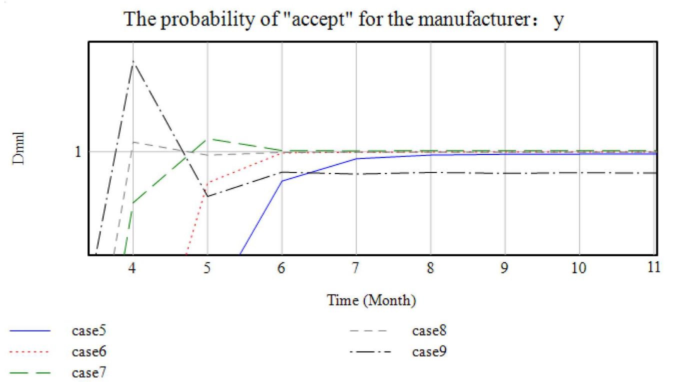
FIGURE 16. Effect of mixed measures on x. (a) Effect of mixed measures on x. (b) Partially enlarged version.

mixed government rewards and punishments. Currently, there are two stable points of the evolutionary game system at (1, 1, 1) and (1, 1, 0).

A comparative study is conducted to elucidate similarities and differences in the efficacy of single-government incentives, single-government penalties, and mixed-government incentives and penalties for supply chain digitalization decision-making. First, all three government measures have a stable point in the evolutionary game system (1, 1, 1), *i.e.*, the stable strategy of "supplier takes, the manufacturer takes, and the government regulates". Second, there is a certain threshold value of government punishment and mixed reward and punishment measures. Once the threshold value is exceeded, the evolutionary game system dynamics model will have a sudden change in probability. Third, as government single incentive measures increase, supply chain enterprises eventually become unstable. As the government single punishment or mixed reward and punishment measures increase, supply chain enterprises eventually evolve to accept digital strategies, that is, a stable state. Fourth, the effect of a government's single punishment and mixed reward and punishment measures on the supply chain enterprises' choice of accepting digital strategies is larger than the effect of a single incentive measure, which can stimulate the supply chain enterprises to choose to accept digital strategies. In addition, we can conclude that low levels of mixed rewards and punishments are an effective mechanism to promote government choice of regulation.



(a)



(b)

FIGURE 17. Effect of mixed measures on y. (a) Effect of mixed measures on y. (b) Partially enlarged version.

4.3. The impact of initial probabilistic changes on system stability

As mentioned aboved, we noticed that in the case of government strategies RG&RE1, wG&wE1-6, and Case 1, the dynamic system of the evolutionary game system can reach a stable state at (1, 1, 1). Case 2–5 case (1, 1, 0) is a stable strategy. Therefore, let's discuss the influence of the expected probability changes of game participants (suppliers, manufacturers and governments) on the existence of game system stability strategies (1,1,1) and (1,1,0). In this section, we set up the evolutionary game system change trend to observe the initial probability change of suppliers and manufacturers choosing to accept digitalization and government choice regulation under different circumstances.

4.3.1. Mixed government incentives and penalties (Case 1–5)

The stable strategy of the evolutionary game system in the case of Case 1 is (1,1,1). Programme 1, 2, 3, 4 in Figures 19a and b are evolutionary trends when the initial probability of evolution of suppliers, manufacturers, and governments is 0.2, 0.5, 0.8, and 1, respectively. See the Figures 19a, b and c, we can observe that regardless of the initial probability changes of suppliers, manufacturers, and governments, the stable strategy of the final evolutionary game system is (1,1,1), that is, suppliers and manufacturers choose digital strategies, and

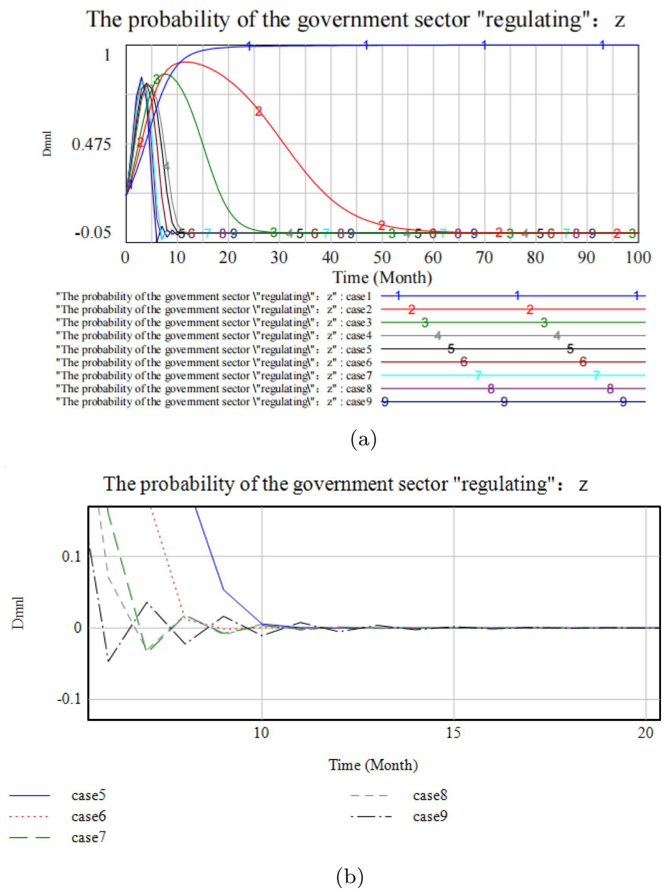
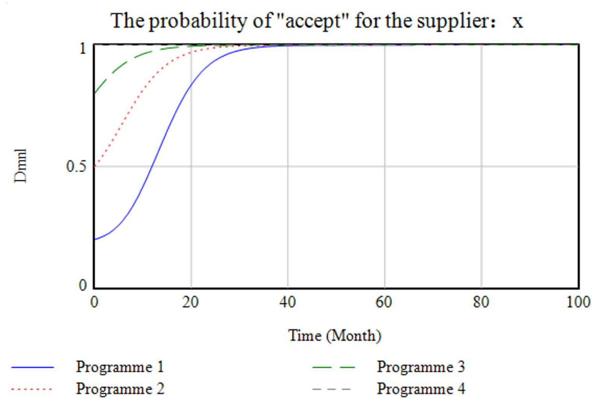


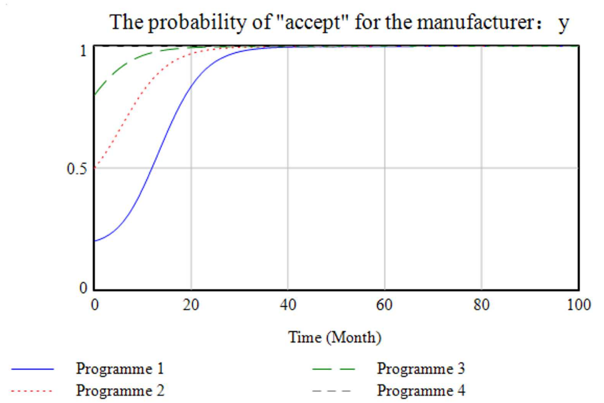
FIGURE 18. Effect of mixed measures on z. (a) Effect of mixed measures on z. (b) Mixed measures (Partially enlarged version).

governments choose regulatory strategies. And, as the initial probability gets closer to 1, the trend of suppliers, manufacturers, and governments evolving into stabilizing strategies is accelerating.

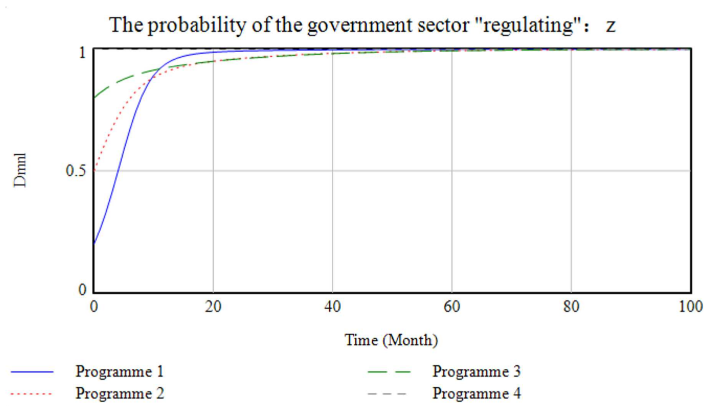
As can be seen earlier, the stability strategy of the evolutionary game system in the case of Case 2–5 is (1,1,0). Programme A1, A2, A3 and A4 are the evolution trends when the initial probability of supplier, manufacturer and government evolution is 0.2, 0.5, 0.8, and 1 in the case of Case 2. Programme B1, B2, B3 and B4 are the evolution trends when the initial probability of supplier, manufacturer and government evolution is 0.2, 0.5, 0.8, and 1 under Case 3. We did the same simulation on Cases 4 and 5, and found that the result was the same, again without showing specific images. See the Figures 20a, b and c, we conclude that although the stability strategy of Cases 2–5 in the previous article is (1,1,0), when the initial probability of supplier manufacturers and governments is 1, no matter how the government rewards and punishments change, suppliers and manufacturers will always choose digital strategies, and governments will always choose regulatory strategies. As the initial probability moves closer to 1, the trend of suppliers, manufacturers, and governments evolving into stabilizing strategies is getting faster and faster.



(a)



(b)



(c)

FIGURE 19. Case 1. (a) Evolutionary trend of x initial probability change. (b) Evolutionary trend of y initial probability change. (c) Evolutionary trend of z initial probability change.

4.3.2. The government simultaneously Low incentives or penalizes to suppliers and manufacturers(RG&RE1, wG&wE1)

As the results shown above, the stability strategy of the evolutionary game system in the RG&RE1 and wG&wE1 cases is (1,1,1). Programme 111, 222, 333, 444 is the evolution trend when the initial probability of supplier, manufacturer and government evolution is 0.2, 0.5, 0.8,1 in the RG&RE1 case. Programme 11, 22, 33, 44 are the evolutionary trends when the initial probability of supplier, manufacturer and government evolution is 0.2, 0.5, 0.8, 1 under wG&WE1. It is clear from Figures 21a, b and c that the evolutionary stable convergence trend under punishment is faster than the trend under reward. And the higher the initial probability, the faster the stable strategy choices of suppliers, manufacturers, and governments converge with 1.

4.4. The impact of product unit cost changes on system stability

The choice of digital decision-making by supply chain enterprises is often related to the cost of digital technology [34, 43, 49], and this section discusses the impact of digital technology cost changes on the choice of digital strategy by supply chain enterprises.The figure below depicts the impact of changes in product unit cost (1,1,1) in Case 1 (stabilization strategy (1,1,1)) and RG&RE1 (stabilization strategy (1,1,1)) on stabilization strategy (1,1,1) as digital technology is invested. Among them, Legend "CASE0.2-case1" represents the case when the unit cost of the product is 0.2 in the case of Case 1. Legend "CASE0.4-case1" indicates the case of Case 1 when the unit cost of the product is 0.4. Legend "CASE0.6-case1" indicates the case of Case 1 when the unit cost of the product is 0.6. Legend "CASE0.8-case1" indicates the case of Case 1 when the unit cost of the product is 0.8. Legend "CASE0.2-RG&RE1" is the same. (Note that we have simulated the impact of product unit cost changes on the strategy of game participants in the case of wG&wE1 and found that the conclusions reached are the same as those reached by Case 1 and RG&RE1, and will not be repeated here.).

As can be seen in Figures 22a and b, when the unit cost of a product increases, the digital strategy of both suppliers and manufacturers shows a shift from 1 to 0, that is, from choosing a digital strategy to not choosing a digital strategy. We can conclude that the unit cost of a product that deploys a digital strategy directly affects the final digital strategy choice of the supply chain enterprise. If supply chain companies want to choose a digital strategy, they need to control the unit cost of products within a reasonable range. However, it can be found that the government's regulatory strategy has not changed (Fig. 22c). It can be seen that changes in the unit cost of suppliers and manufacturers do not affect the government's decision to regulate or not.

5. Concluding remarks, insights, and future research

5.1. Summary the results

Digitalization is regarded as the future development trend in supply chain management and has become the industry consensus. Therefore, this paper constructs an evolutionary game model to analyze the evolutionary process of digitalized multi-agent decision-making in a supply chain. It further uses the system dynamics method to analyze the behavioral evolution law of government regulation, suppliers' and manufacturers' digitalized decision-making, and their influencing factors.

The results show the following: (1) Regarding the system stabilization policy: there are two stable strategies in the evolutionary game system: "suppliers and manufacturers choose to accept digitalization, and the government chooses to regulate" and "suppliers and manufacturers choose to accept digitalization, and the government chooses not to regulate". (2) Product unit cost: The unit cost of products directly impacts the ultimate decision of supply chain enterprises regarding the adoption of a digital strategy. To choose a digital strategy, supply chain companies must ensure that the unit cost of products remains within a reasonable range. (3) Government single reward or penalty threshold: There exists a threshold value for a single government reward strategy, and its impact on both suppliers and manufacturers is identical. Once the government reward exceeds this threshold value, suppliers and manufacturers eventually decide not to accept digital strategies and evolve into an unstable

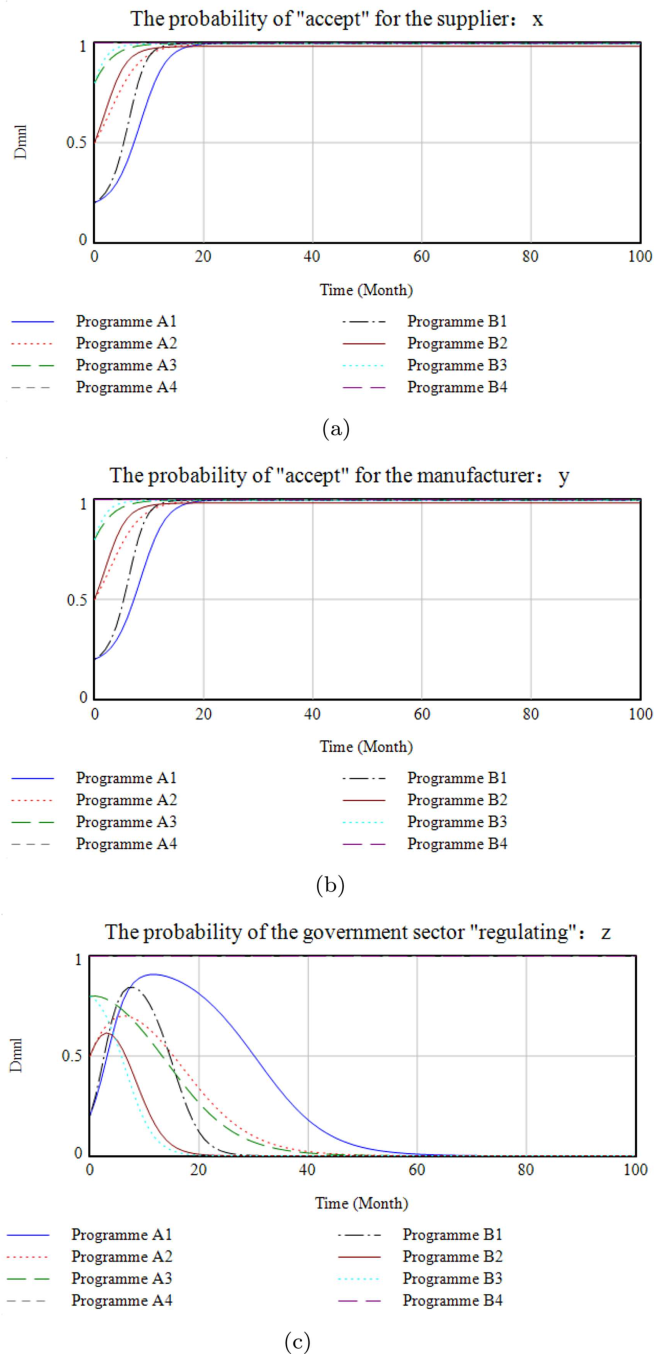
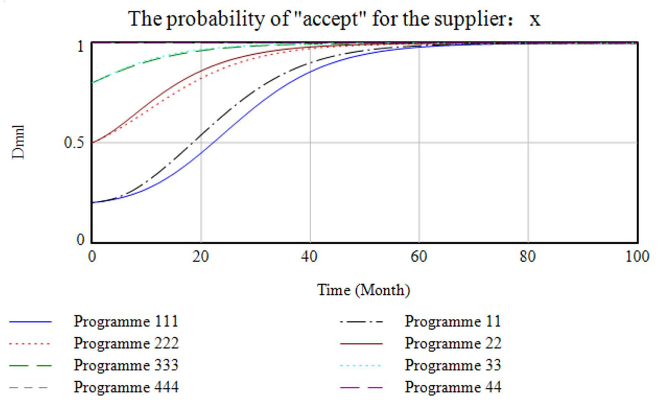
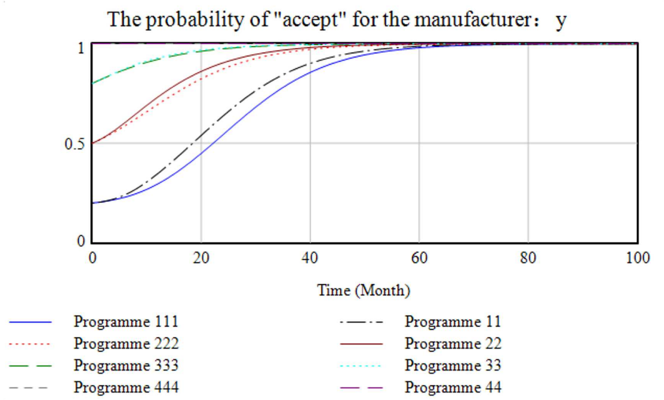


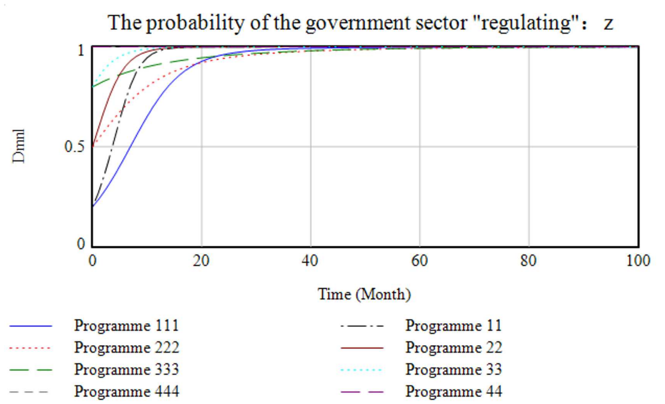
FIGURE 20. Case 2 and 3. (a) evolutionary trend of x initial probability change. (b) evolutionary trend of y initial probability change. (c) evolutionary trend of z initial probability change.



(a)



(b)



(c)

FIGURE 21. RG&RE1, wG&wE1. (a) Evolutionary trend of x initial probability change. (b) Evolutionary trend of y initial probability change. (c) Evolutionary trend of z initial probability change.

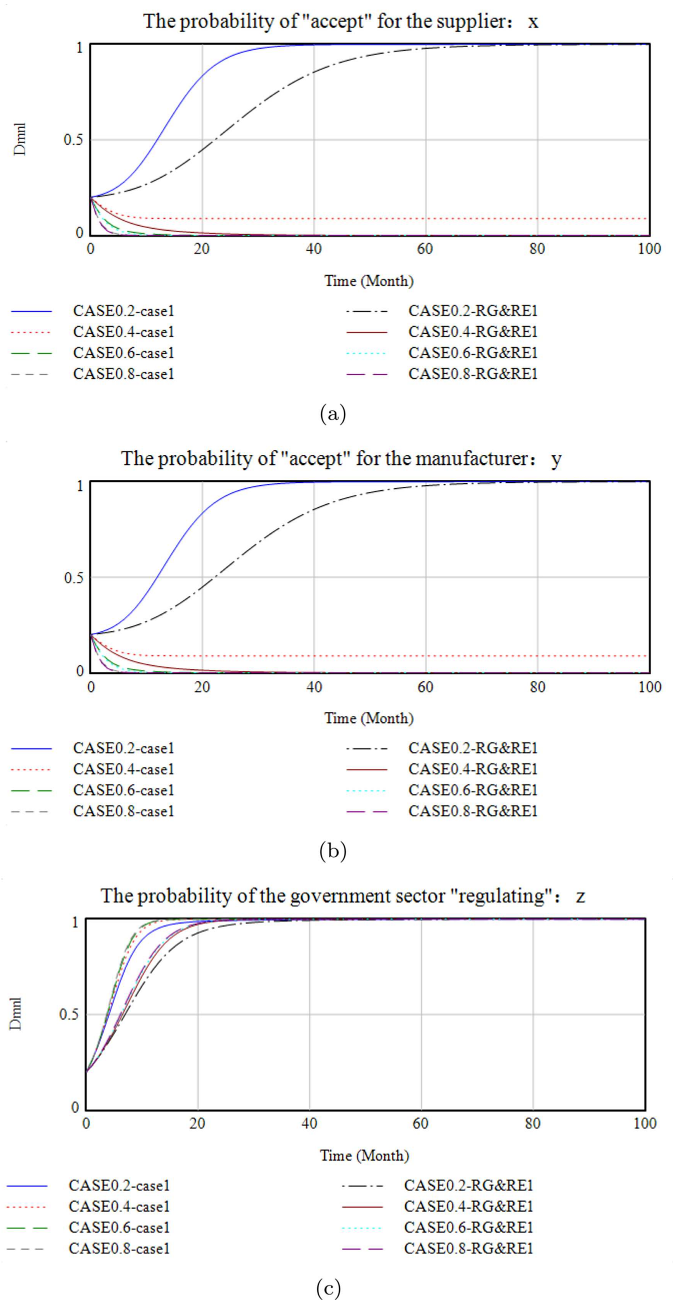


FIGURE 22. Case 1 and RG&RE1 cases, the impact of product unit cost changes on supplier, manufacturer, and government decisions. (a), (b) and (c).

situation.The greater the single government punishment, the greater the probability that suppliers and manufacturers will accept a digital strategy. (4) Mixed rewards and punishments: the stronger government effort of the mixed reward and punishment, the greater the probability that suppliers and manufacturers choose to accept digitalization and eventually evolve into a digital strategy. Furthermore, once the rewards and punishments exceed a certain threshold, the government's initial regulatory strategy eventually evolves into a non-regulatory strategy state over time. (5) The Impact of a Single Government Reward or Penalty on Government Regulatory Strategy: the greater the single government reward is, the more the government tends to choose not to regulate. The greater the single government penalty is, the more the government tends to choose the regulation strategy. The greater the probability of government regulation, the greater the probability that the supplier manufacturer will accept digital strategies. (6) Effective mechanisms to facilitate government regulatory strategies and the impact of initial probabilistic changes: In addition, low-level mixed rewards and punishments are an effective mechanism that promotes the government's decision to adopt regulatory strategies. A low level of government single incentives can also be effective in promoting government choice of regulation. Conversely, high levels of single government penalties do not motivate governments to choose regulatory strategies. As the initial probability moves closer to 1, the trend of suppliers, manufacturers, and governments evolving into stable points is getting faster and faster. (7) These conclusions provide useful references for supply chain node enterprises and related practitioners. They can effectively align the interests of different supply chain collaborators, thus building solid strategic alliances to improve profitability for all stakeholders.

5.2. Managerial insights

Based on the research findings, the paper proposes three policy managerial insights recommendations to promote the digital development of a supply chain.

5.2.1. For government

(1) In the early stage of supply chain digital development, the government should play a leading role in promoting the market mechanism to push supply chain enterprises to accept digital decision-making. Market-oriented means will allow the government to build an important platform for the digital transformation of supply chains. The market agglomeration effect will drive the agglomeration of supply chain digitalization and digital talents to form a good market environment for the digital development of supply chains. (2) The government should strengthen the targeting and relevance of supply chain digitalization policy design. The government can establish a mixed regulatory mechanism of rewards and punishments, and formulate reward and punishment policies in a targeted manner to stimulate the endogenous motivation and enthusiasm of supply chain enterprises to make digital decisions. (3) Governments should focus on strengthening supervision and optimizing services, introduce relevant support policies and measure to promote digital supply chain concepts and technologies, and create a favorable environment for digital supply chain innovation and application. Furthermore, governments should actively build a digital supply chain service platform, study the establishment of a digital supply chain investment fund, build a digital supply chain science and technology innovation centre, and support the research and promotion of supply chain digital technology and advanced models. In real cases, blockchain as the most critical digital technology. Based on incomplete statistics, over 1,200 blockchain-related policies have been issued by various cities, encompassing first, second, and third-tier cities such as Beijing, Shanghai, Chengdu, and Chongqing. These policies are designed to expedite the digital transformation of smart cities and smart manufacturing through blockchain technology. The objective is to establish an efficient and convenient digital government, ultimately creating a model city for the innovation and advancement of the digital economy.

5.2.2. For manufacturers

In practice, since supply chain digitalization would promote supply chain efficiency, it has become increasingly prevalent for supply chain enterprises to undergo digital transformations. Based on the conclusions of this paper, several policy suggestions are put forward for the digital transformation of manufacturers of core enterprises in the supply chain: First, when deploying digital strategies, do not forget to pay attention to the unit cost of products. This paper points out that unit cost control within a reasonable range is beneficial for enterprises to deploy digital strategies. Therefore, manufacturers should focus on building a demonstration workspace for digital transformation within manufacturing enterprises, cultivate new formats and new models for the development of manufacturers' digital economy, promote key technologies and product research and development for digital transformation within manufacturers, and lay a solid foundation for reducing product unit costs. The second is to accelerate the construction of digital transformation infrastructure construction centers for manufacturers, and provide comprehensive digital transformation services such as technical support, equipment services, and talent training. The third is always to pay attention to government policy support and accelerate the docking of construction and government policies. Further open up the data of manufacturers' digital transformation stages and share it with the government to obtain government policy support. In addition, Cañas *et al.* [13] provide a conceptual framework for planning control systems in Industry 4.0, including business, functional, information, communication, integration, assect levels. These levels include product, field device, control device, station, work centre, enterprise, connected world. For manufacturers, it is particularly important to design a conceptual framework for deploying a digital supply chain by drawing on the conceptual framework of planning control systems in Industry 4.0, which can provide guidance for supply chain enterprises to deploy digitalization.

5.2.3. For suppliers

Supply chain digitalization is the trend of the times. This paper studies the evolution trend of digital strategy selection of supply chain node enterprises under government regulatory measures. As a raw material supplier for most products in the supply chain, what are the measures for digitalization? For example, JD.com's "Wan Jia" system is for offline stores, upstream suppliers, and ultimately serves the consumer digital ecosystem and the supply chain through the analysis of the large data capacity. The realization of data interconnection and scene interconnection makes services more accurate, the supply chain more transparent, flexible, and agile, and the functions of each supply chain node more coordinated. Digital system in the whole supply chain links supply chain solutions in various fields and the seller's actual business scenarios in supply chain Platform vendors are actively engaged in digital transformation, and this paper points out that government regulatory mechanisms can effectively select digital strategies for suppliers. Under the background of countries actively promoting digital development, major platform suppliers, raw material suppliers and other product suppliers should seize this policy opportunity and actively explore the construction standards and paths for the digitalization of suppliers in the future.

5.3. Limit and future research

This paper addresses the issue of supply chain digital decision-making in the context of government participation by employing a combination of an evolutionary game model and a system dynamics approach. However, in this paper, the model did not consider the evolutionary game characteristics of supply chain digital decision-making at different stages. The mechanism of supply chain enterprises' active or passive acception of digital decision-making has not been analyzed. Further research can explore the evolutionary game problem of supply chain digital decision-making under different power structures. A Stackelberg game model is established to analyze the digital decision characteristics of supply chain from a static perspective, and then an evolutionary game model is combined to analyze the digital decision characteristics from a dynamic perspective. In doing so, we can reveal the mechanism of the role of supply chain power structures in influencing supply chain digital decision-making and provide an insightful understanding of the motives of supply chain digital development from supply chain structure design. In addition, this study ignores the phased characteristics of supply chain digital development. Establish a development stage model to evaluate the digital maturity of the supply chain so that supply chain enterprises can identify their own digital stage. Then, the digital collaboration of supply chain node enterprises can be studied from an empirical perspective. That is, an empirical model can be established to study the digital collaborative transformation and development of the supply chain. By doing so, industry-specific insights can be obtained for operations managers, which hold significant practical guidance value.

This study has limitations despite its meaningful results and insights. First, The present model has many limitations, such as static values of the parameters and no consumer preference parameters. The immediate extension of this model may include random character of the cost parameters and consumer preference parameters. Second, the model can be further extended by considering the static values of market capacity as an uncertain variable. Third, in our model, the digital investment game model of supply chain enterprises is established, and the supply chain enterprises decide whether to invest in digitalization. In the future, it is worthwhile to consider the case when supply chain enterprises complete digital transformation through digital platforms.

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