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The Enabling Mechanism of Supply Chain Digital Transformation Based on Evolutionary Game Modeling

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Abstract. With the development of various digital technologies such as the Internet of Things, big data, and cloud computing, digitalization of the supply chain has become an important strategy to enhance supply chain resilience and improve its efficiency in China. However, as the leader of digitalization, manufacturers are mostly in the very initial stage of digital transformation and they lack experience, thus they need to actively cooperate with upstream and downstream supply chain nodes to achieve the overall digital transformation. In the process of digital transformation, how the leading manufacturers collaborate with upstream and downstream nodes of the supply chain so as to improve the efficiency of supply chain digitalization is a problem that needs to be solved urgently both in theory and in practice. Therefore, this paper establishes a three-party evolutionary game model focusing on the supply chain digital transformation activities, trying to explore the influencing factors of collaborative digital transformation of the supply chain. Besides the model formulation and mechanism discussion, we further conducted a Matlab numerical simulation to illustrate the dynamic evolutionary trend. The findings in this research provide certain insights towards the cooperative digital transformation of the supply chain under the market mechanism, which will be beneficial to the sustainability of the digital transformation of the supply chain.

Keyword: Supply chain; digital transformation; evolutionary game; cooperation

1. Introduction

Along with the continuous progress of various digital technologies such as the Internet of Things, artificial intelligence, cloud computing and so on, more and more enterprises are beginning to integrate and fuse these digital technologies with their supply chains. In this way, they can improve the flexible scheduling and control ability of each link in the supply chain, and enhance the risk resistance and sustainability of the supply chain. The Digital Transformation Index for Chinese Enterprises 2023 report shows that 9% of leading enterprises in China have successfully achieved high business growth using digital transformation in 2023, compared to 7% in 2018.Under the turbulent external environment of accelerated iterations of technological innovation, climate change, changing consumer demands, supply chain challenges and talent shortages, more and more Chinese enterprises are realizing that Digital transformation is no longer simply a technical concept or technology choice, but has evolved into an overall strategy for the survival of enterprises. The 2023 Manufacturing Enterprise Supply Chain Development Research and Analysis Report shows that about 38% of enterprises have already formulated segmented digital supply chain strategies. And digital transformation of supply chain has become an important support for enterprise optimization and upgrading and sustainable development.

In the face of the wave of development of digital economy, China's Party Central Committee and the State Council have attached great importance to it. in March 2021, the Ministry of Commerce and other units pointed out that ‘strengthening supply chain innovation leadership, accelerating the integration and application of new supply chain technologies such as the Internet of Things, big data, edge computing, blockchain, 5G, artificial intelligence, augmented reality/virtual reality, etc., and promoting the accelerated development of digital supply chain. ‘The report of China's 20th National Congress in 2022 pointed out that it is necessary to ‘accelerate the development of the digital economy, promote the in-depth integration of the digital economy and the real economy, and build an internationally competitive digital industry cluster’; the Fourteenth Five-Year Plan for the Development of the Digital Economy issued by the State Council of China The ‘14th Five-Year Plan for the Development of Digital Economy’ issued by the State Council of China points out that it accelerates the digital transformation and upgrading of enterprises, guides enterprises to strengthen their digital mindset, encourages and supports industry leaders to open up their digital resources and capabilities, and helps traditional enterprises and small and medium-sized enterprises to realize their digital transformation, which provides the basis of the path of the development of industry leaders.

However, with the deepening of economic integration, the uncertainty and complexity of the supply chain is also increasing, such as public health emergencies, natural disasters, terrorism, military or political conflicts and other uncertain events have significantly increased the external environmental risks of the supply chain[1]. In order to achieve supply chain sustainability, data plays an important role in creating value by analyzing data to intervene in potential risks and improve the ability of companies to cope with unknown risks [2]. Emerging smart and innovative technologies such as AI, IoT, blockchain, and cloud computing, as key tools for data analysis, are also getting more and more attention in solving supply chain digital transformation issues. For example, Oracle launched a blockchain application cloud to support seamless connection to the SCM cloud, ERP cloud, etc., to build a variety of supply chain data traceability applications so that enterprises can more easily conduct cause analysis and faster dispute resolution, and execute targeted product recalls, reduce counterfeit products, prevent fraud, etc.; Midea, at the initial stage of digital supply chain construction, built a supplier collaboration platform to support suppliers to adopt account number In the early stage of digital supply chain construction, Midea built a supplier collaboration platform, which supports suppliers to fill in online reports by logging in to share information, and launched SaaS applications such as quality cloud, logistics cloud, and inventory cloud to realise real-time sharing of quality data, inventory data and delivery information in the production process of the suppliers, so that upstream and downstream collaboration can be more timely and reliable.

The Enabling Mechanism of Supply Chain Digital Transformation Based on Evolutionary Game Modeling

In the face of the era of digital transformation, many small and medium-sized enterprises (SMEs) in the supply chain face the problem of 'not being able to turn, not daring to turn' due to technical and financial reasons, etc. 2022 Chinese Tencent Research Institute pointed out in the 'SMEs Digital Transformation Development Research Report' that the application rate of supply chain management digital technology in SMEs is only 10-20%. 10-20%, 10% of SMEs believe that digital transformation will not bring profits to the enterprise, and nearly 30% of SMEs believe that digital transformation brings general benefits to the enterprise [3]. The OECD found that the uptake of digital technologies by SMEs is still particularly low, even in the face of technologies relevant to SMEs such as cloud computing. Verhoef C P et. al argue that digital transformation is the most pervasive and complex phase, but that the vast majority of resource-constrained SMEs do not have the capacity to cope with this level of complexity[4]. The lack of collaboration and information transfer between upstream and downstream firms constrains the innovation spillover of digital transformation in the supply chain[3,5]. Although some previous studies have explored the definition of digital transformation, its necessity, and the challenges faced by SMEs in the transformation process [6], these studies have done little research on how to facilitate sustainable digital transformation in SMEs. In this context, based on the perspective of supply chain digital transformation, it is of great practical significance and social value to explore in depth the synergy and incentive mechanism of digitisation of upstream and downstream enterprises, to enhance the willingness of each enterprise in the supply chain to digitally transform, and to promote the degree of overall sustainable digital transformation of the supply chain. Based on this, this paper will explore the incentive mechanism of supply chain digital transformation by constructing an evolutionary game model, which will provide reference for the digital transformation of each subject in the supply chain under the market mechanism.

The possible innovations and contributions of this paper are as follows:

First, the high-quality development of manufacturing industry can be achieved by incentivising the digital transformation of supply chain enterprises, a result that has been agreed by many scholars. In this research field, other scholars' perspectives are highly focused on government intervention, however, this paper argues that the digital transformation of enterprises needs to rely more on market mechanisms to carry out in order to obtain spontaneity and continuity. Therefore, this paper positions the research context as a study of coordination strategies between enterprise subjects in the supply chain in the market mechanism, assuming that the supply chain structure is composed of a leading manufacturing enterprise and a number of small and medium-sized upstream and downstream supporting enterprises with relatively weak resource capacity. Among them, the leading enterprise plays a leading role and provides certain transformation assistance to upstream and downstream enterprises to achieve the digital transformation of the supply chain as a whole. This paper will study the key influencing factors and synergistic mechanism of the joint digital transformation of each subject of the supply chain to provide theoretical support for the digital transformation of the supply chain under the market mechanism.

Second, the digital transformation model of China's manufacturing industry can be summarized into two main types from the perspective of practical experience: first, government intervention, which mainly provides financial and policy support to large-scale leading enterprises; and second, inter-firm co-operation, which means that various forms of joint actions are carried out between enterprise subjects with stakeholder relationships in the transformation process. Among them, the latter should be carried out as the main mechanism, for example, Sany Heavy Industry 2021 relies on the cloud platform to achieve the interconnection of more than 1,000 pieces of equipment from more than 200 suppliers, which enhances the digital synergy efficiency of the supply chain; Midea, in order to cope with the challenges of the epidemic and other uncertain factors, establishes an intelligent and digital supply chain system, pulls through the upstream and downstream information of the supply chain, and achieves the transparency of the source-seeking and price-checking business. Accurately guide suppliers to ship, improve operational efficiency and reduce enterprise costs. The digital transformation of the supply chain involves cooperation and information sharing among multiple enterprises, and requires a market mechanism to guide and promote the participation and collaboration of all parties to achieve efficient operation and optimization of the supply chain. This paper analyses the incentives, interventions, and management countermeasures of mechanisms to promote the implementation of collaborative digital transformation among supply chain actors, which can help to achieve the sustainable digital transformation of the supply chain as a whole.

The rest of the paper is as follows: Section 2 provides a review of the literature on supply chain digitisation, evolutionary game theory and evolutionary games in supply chain digital transformation. Section 3 establishes the enabling mechanism diagram of this paper. Section 4 gives the assumptions of the model and establishes the evolutionary game model. Section 5 analyses the effect of different parameters on the evolutionary outcome. Finally section 6 gives the main conclusions and implications of this study.

2. Literature review

This paper focuses on the enabling mechanism of supply chain digital transformation based on evolutionary game models. This section reviews and summarizes the literature on supply chain digital transformation and evolutionary game models.

2.1. Supply chain digital transformation

IBM proposed the concept of ‘intelligent future supply chain’ in 2009, which summarizes the future development direction of supply chain from three aspects: advanced, interconnected and intelligent, which is very close to the characteristics of digital transformation of supply chain, so this study believes that the digital change of supply chain begins from this. With the rapid development of the global digital economy and the high-speed evolution of digital technologies such as the Internet of Things (IoT), Big Data, and Artificial Intelligence (AI), the concept of smart supply chain is gradually replaced by digital supply chain. As this concept is still under development, it has not yet been defined uniformly in academia, and most of the definitions of it in the existing literature come from industry perspectives, with significant differences based on research perspectives. Academics and industries study digital transformation of supply chains based on two different levels: the technical level and the management level. The technical level refers to the addition of various digital technologies in supply chain management, such as the application of information collection, storage and transmission devices, to help enterprises establish a big data-based supply chain management model at the technical level. The deep integration of a large number of advanced digital technologies and supply chains will inevitably have an impact on the organizational form and resource structure of enterprises, and stimulate Schumpeterian 'destructive creation'.

Some scholars focus on the digital technology perspective, emphasizing the importance of digital technology in digital supply chains, i.e., the need to introduce a large number of new digital technologies into traditional supply chains to transform processes and create new value. Kinnett defines digital transformation of supply chains as a value-driven, intelligent network that leverages new technologies and methods to create new revenues and business opportunities through one central platform that captures and maximises real-time information from a variety of sources[7]. Wu et al. emphasise that all phases of supply chain digitisation are interconnected, which enables robust data collection as well as intelligent decision-making based on real-time communication[8]. Büyüközkan and Göçer define supply chain digitisation as a system of intelligent optimisation technologies, which with the help of digital hardware and software performing functions such as massive data processing and excellent collaboration and communication that synchronise and support interactions between organizations[9]. Bhargava et al. argue that digital supply chains mediate the activities of partners in the supply chain through hardware, software, and communication networks to support interactions in the processes of purchasing, producing, storing, transporting, and selling goods between organizations around the world[10]. The above studies have demonstrated that advanced digital technologies can have a positive impact on supply chain flexibility by enabling data connectivity between firms across organizational boundaries, thereby significantly improving supply chain efficiency. In supply chain management, improving supply chain flexibility is conducive to increasing the risk resistance of the supply chain, thus promoting the continuous use of the supply chain and achieving sustainable development [11].

In addition to the technological perspective, some scholars focus on the managerial perspective, emphasizing that the spread of digital technologies is accompanied by further advances in operations management to improve supply chain agility, succession, and resilience, etc. Frederico et al. refer to the digitization of the supply chain as 'Supply Chain 5.0', whereby firms are supply chain development in terms of transparency, predictability, scalability, adaptability, collaboration, integration, and customer centricity [12]. Garay-Rondero et al. emphasizes that digital transformation of the supply chain requires firms to move from stability to adaptability, standardization to customization, policy-driven to judgement-driven, and siloed to collaborative [13]. Organizations such as the Centre for Global Enterprise and the Digital Supply Chain Institute in the US define supply chain digitization as a customer-centric platform that takes real-time information from a variety of sources and maximizes its use, and optimizes performance through demand stimulation, matching, detection and management to minimize risk. Ivanov et al. combine the digital supply chain with the SCOR model and define it as a system that includes functions such as plan execution, traceability, manufacturing and delivery, based on emerging digital technologies such as big data analytics, CPS networks and additive manufacturing [144]. Calatayud et al. define supply chain digitization as a self-thinking supply chain that predicts and detects risks by analyzing large amounts of data collected from a variety of sources and proactively takes preventive measures before risks occur, allowing for performance to be continuous monitoring [155].

Previously, scholars have proposed different understandings of the connotation of supply chain digitization based on their respective research purposes and perspectives. However, it is not difficult to see that the existing literature generally believes that supply chain digitization is not only the simple application of digital technology in the supply chain domain. It is more about the integration of internal and external resources, opportunities and capabilities to stabilize operations, improve efficiency and enhance supply chain agility. This study combines previous research to define sustainable supply chain digitization as follows: a supply chain is an open, self-generating and evolving intelligent network. It is an information and data-driven supply chain management model that is customer-centric. By using digital technology to record and analyze the entire process of a product from component procurement to delivery, it continuously optimizes product development, warehouse management, logistics visibility, quality traceability, etc., and achieves flexible supply chain management. This means that the supply chain as a whole can not only adapt to challenges and restore normalcy, but also improve the intelligent supply chain network to self-improve and generate, and try to find a new and innovative way to flexibly cope with difficulties, and realize sustainable supply chain management level improvement.

2.2. Supply chain digitization and sustainability

Supply chain sustainability is about having a favourable impact on the environment, society and the economy[16]. A large body of literature suggests that sustainability is the future of organizations and the importance of establishing a sustainability programme has been recognized by supply chains [17,18]. In today's market competition where uncertainty is increasing dramatically, cross-functional and cross-organizational supply chain collaboration through various digital technologies will enhance supply chain flexibility and achieve supply chain sustainability. In recent years, many scholars have argued that the digital transformation of supply chains facilitates the development of dynamic capabilities for each organization to cope with supply chain risks. The digital transformation of supply chains improves the efficiency and transparency of supply chains, which are key requirements for sustainable supply chains. Digital technology enables enterprises to cross organizational boundaries and gain access to more information resources, thereby improving the efficiency of the supply chain. Collaboration among firms in the supply chain through various digital technologies can enable them to create new knowledge and practices in manufacturing, inventory, and marketing to effectively respond to market changes and uncertainty.

In addition, many scholars have demonstrated through their research that advanced digital technologies increase the flexibility of the firms in the supply chain. For example, Wenqian Li et.al suggest that technological innovation can improve supply chain flexibility by improving management accuracy[1919]; Hao Jiao et.al suggest that technological flexibility can promote the transformation and upgrading of enterprises, thus improving supply chain flexibility[20]. Digital supply chain can break down the barriers of geography and information silos, and provide ubiquitous information, collaboration and superior communication through digital platforms, thus improving the reliability, agility and effectiveness of supply chain collaboration[21,22]. In reality, technology is constantly evolving and supply chains can only be innovative and sustainable if they embrace digitalization.

2.3. Evolutionary game theory

It is generally agreed that the formation and development of evolutionary game theory has gone through three stages: the first is the application of game theory in biology. The idea of economic evolution has existed in economic theory for a long time, and Van Buren first proposed the term ‘evolutionary economics’ based on Darwin's idea of evolution. Marshall conducted a large number of economic theory research is based on mechanical analogy, equilibrium, stability, and determinism, this is because the concept of evolution is more complex than static concepts; ALchian proposed a dynamic selection mechanism to determine the existence of various institutional forms. He suggested that in economic analysis to use the concept of natural selection to replace the profit maximization concept. Under the mechanism of natural selection, even if the actors are not regarded as rational, the evolutionary pressures of society will prompt each actor to take the action that is best suited to his or her survival, thus making the evolutionary equilibrium a Nash equilibrium. Taking a cue from this, biologists have attempted to apply game-theoretic ideas to construct a variety of evolutionary models of biological competition, including animal competition, sex allocation, and plant growth and development [23].

The second stage is the formalization of evolutionary games. In this stage, biologists modified the traditional game theory according to the laws of biological evolution, including transforming the payoff function in the traditional game theory into the biological fitness function, introducing the mutation mechanism to refine the traditional Nash equilibrium into the evolutionarily stable equilibrium (evolutionarily stable equilibrium), and The introduction of a selection mechanism to construct a replication dynamics model.

With the expansion of evolutionary games to traditional games, economists in turn borrowed the ideas of biologists and applied evolutionary games to economics, which further promoted the development of evolutionary games, including the development from evolutionarily stable equilibrium to stochastically stable equilibrium, and the development from deterministic replication dynamics equations to randomized individual learning dynamics models.

The idea of evolutionary games can be traced back to John Nash's explanation of the concept of equilibrium. There are two ways of interpreting Nash's concept of equilibrium: one is the classical game theory way of interpreting (rationalism), and the other is the evolutionary game way of interpreting (mass action interpretation). Nash believes that the realization of equilibrium does not necessarily assume that the participants have full knowledge of the game structure, as well as the individual possesses complex reasoning ability, as long as it is assumed that the participants in the decision-making are able to accumulate relevant empirical information from a variety of pure strategies that have a comparative advantage (e.g., learning strategies with high payoffs), and that the equilibrium can be reached after a period of strategy adjustment. Smith and Price put forward the evolutionary game theory in the basic concept of Evolutionary Stable Strategy (Evolutionary Stable Strategy) so that the theory of evolutionary games in various different fields has been greatly developed. [24,25]Smith and Price freed people's attention from the rationality trap of game theory and found a possible outlet for game theory research from another angle. Since then, evolutionary game theory has developed rapidly, and in the 1980s, with the in-depth study of evolutionary game theory, many economists introduced evolutionary game theory into the field of economics, which was used to analyze social system change, industrial evolution and stock market, etc. At the same time, the study of evolutionary game theory began to go deeper from symmetric to asymmetric games, and achieved certain results [26,27]. Since the 1990s, the development of evolutionary game theory has entered a new stage. Weibull summarized the evolutionary game theory in a more systematic and complete way, which contains some of the latest theoretical results [28]. Some other theoretical results include the works of Cressman [29] and Samuelson [30].

Although the present evolutionary game theoretical system has not been fully developed, it has made great contributions to the study of game problems, and the ideas of evolutionary games have been widely applied in many fields. Since supply chain digital transformation is a dynamic process, the evolutionary game method can simulate the decision-making choices and behavioral changes of all parties at different stages, which helps to understand the dynamic changes and evolutionary laws in the process of digital transformation, and provides theoretical support for the formulation of effective supply chain digital transformation strategies from the fact that it can more comprehensively and dynamically analyze the mechanism of supply chain digital transformation.

2.4. Application of evolutionary game theory to digital transformation

In real life, due to the asymmetry of information, each subject in the supply chain, based on limited rationality, makes decisions that are often constrained by their own interests and goals [31]. In order to solve this problem, some scholars have now analyzed the behavioral strategies of supply chain participants through evolutionary game theory. For example, the strategy choices between two parties are analyzed, including suppliers and manufacturers [32], manufacturers and retailers [31,33] and so on. In order to promote the digital transformation of supply chains, governments often adopt a series of fiscal policies and regulatory measures [34]. For example, rewards and penalties and subsidies [35], tax incentives [36] and so on. However, in reality, relying on government investment alone can easily cause financial risk, which is not conducive to the spontaneity and sustainability of enterprises [37]. Therefore, this paper will establish a three-party evolutionary game model from the perspective of market mechanism to reveal the behavioral characteristics and strategic choices of manufacturers and supply chain upstream (suppliers) and downstream (sellers). At the same time, we introduce the benefit coefficient, cost coefficient, and risk coefficient, as well as the incentive and penalty coefficients of the manufacturer to the upstream and downstream, and explore the influence of the external coefficients on the benefits of digital transformation of the supply chain, to provide a reference for guiding the supply chain's sustainable digital transformation and empowerment.

3. The design of the enabling mechanism for the digital transformation of the supply Chain

The digital transformation of every topic in the supply chain, followed by company growth and enterprise development, has become fundamentally dependent on data as a new element of production, with strategic direction from both the central government and diverse locations. According to the statistics published by the China Academy of Communication and Information Sciences Research, from January to August 2023, 5-plus data trading organizations were newly established in China. At present, the country has successively set up 53 data trading organizations, of which the active data trading organizations have shelved more than 12,000 kinds of data products. In order to encourage the entry and sharing of data components between all businesses in the supply chain, Ruihan Liu et al. suggested a Q-Learning algorithm-based dynamic incentive system [38]. One obvious aspect of the supply chain's digital transformation is the movement of data pieces throughout the chain. Since digital transformation relies on the flow of data components across the supply chain, this article will address the degree to which each firm in the chain has undergone digital transformation by analyzing the data elements that they have input. It is believed that data components are passed around among the three supply chain participants, and that each participant has a "free-rider" impact when it comes to handling data and information elements. The leading manufacturer will subsidize the upstream and downstream enterprises that carry out digital transformation and sanction the firms who fail to implement digital transformation. The three entities in the supply chain are influenced by the risks, expenses, and advantages associated with digital transformation. The schematic illustrating the enabling mechanism of chain of supply digitization is shown in Figure 1.

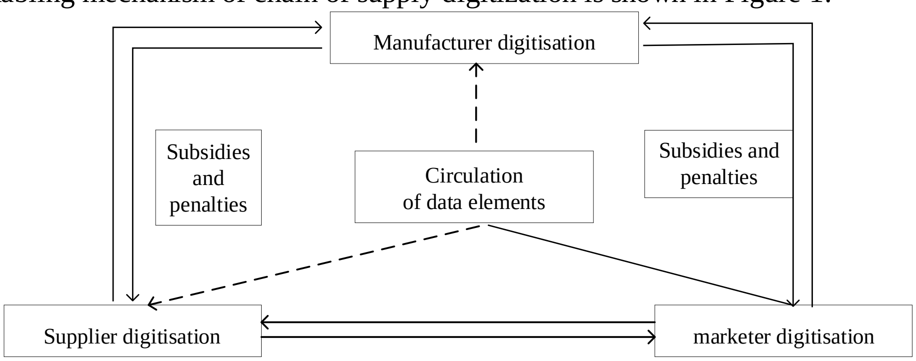


Figure 1: Enabling mechanisms chart

Core manufacturers exhibit the highest level of digital advancement within the supply chain, while incentivizing and imposing penalties on suppliers and sellers for their digital transformation efforts. Both upstream and downstream entities that undergo digital transformation will confer advantages onto the core manufacturers.

A supplier can take advantage of the subsidies offered by the core manufacturer to transform digitally, with additional costs and risks to capture the corresponding benefits. Alternatively, it can choose a "no digital transformation" strategy, where it will be penalized by the leading manufacturer. Still, it can maintain its initial benefits and generate additional revenue by "free-riding" on the data elements invested by the upstream and downstream manufacturers. The supplier can also choose a "no digital transformation" strategy, in which case it will be penalized by the leading manufacturer. Still, it can maintain its initial revenue by "free-riding" on the data elements invested in digital transformation by the rest of the supply chain, generating additional revenue without incurring additional risks and costs.

Sellers, similarly, can take advantage of the subsidies provided by the manufacturer to implement digital transformation while managing the associated risks and expenses to achieve digital advantages; in the event that the manufacturer imposes penalties, they may also opt to forgo digital transformation, additional advantages may be generated by using the data components of the other subjects' digital transformation inputs.

If the strategy is [digital shifts, non-digital shifts], then x, y, and z are the probabilities that the three groups will go with the "digital transformation" option.

Given the strategy of [Digital Transformation, Non-Digital Transformation], the probabilities of the three parties selecting the strategy of "Digital Transformation" (DT) are x, y, and z. Each of the three components in the supply chain has the option of pursuing either "Digital Transformation" (DT) or "Non-Digital Transformation" (N-DT).There are two possible techniques that the three supply chain participants might adopt: digital transformation (DT) and non-digital transformation (N-DT). The probability that a core manufacturer selects DT is x, while the probability that it selects N-DT is 1-x;a supplier's likelihood of selecting DT is y, and the likelihood of selecting N-DT is 1-y; the likelihood of a seller selecting DT is z, whereas the likelihood of a seller selecting N-DT is 1-z.When all three parties in a supply chain decide against using digital technology to make collaborative choices, the enabling impact of digital transformation does not take place; at this point, all three parties' initial revenue is Ei (where i = 1, 2, 3).

4. Evolutionary game model

4.1. Model assumptions and parameterization

Assumption 1: Assumption of benefits of collaborative authorization

Each subject can produce a clustered digital-driven effect through the collaborative participation of digital technology in supply chain tripartite decision-making. This effect can enhance the innovation and competitiveness of suppliers and assist them in better managing and protecting their intellectual property rights; help manufacturers efficiently develop and utilize the technology and resources of suppliers in order to achieve productivity improvements and cost reductions, manufacturers are also more easily able to comprehend and satisfy consumers' requirements, as well as enhance the quality of what they offer; and it helps sellers to better access and utilize manufacturers' products and services, and promotes cooperation and sharing between them and manufacturers to strengthen the synergy effect of the whole sales channel. Where Qi (i=1, 2, 3) denotes the empowering benefits obtained from the three-party synergistic decision, assume that each subject's contribution to the data and information resource components is represented by di(i=1,2,3). The subject's choice of "non-digital transformation" approach results in di=0.The digital drive's intelligent creation impact varies between topics due to differences in data mining capabilities, information processing levels, and methods of integrating and using digital intelligence technologies. Denote each subject's enabling benefit coefficient under digital technology as Ri. By using digital technology, each topic may facilitate data integration and resource exchange, leading to the realization of dynamic coordination. Consequently, the facilitating benefit that each subject derives is not solely linked to the information elements of resources that it invests in, but also to the inputs of other subjects. Taking the automobile manufacturing industry as an example, suppliers can adopt digital technologies such as intelligent manufacturing systems and automated production lines to enable automobile manufacturers to obtain more competitive parts and components, and sellers can help manufacturers carry out product innovation and improvement and conduct more accurate marketing and sales activities through social media, e-commerce platforms and other digital technology platforms. Generally speaking, manufacturers will have a higher level of digital technology application and informationization. Their digital enablement benefit coefficient will also be relatively high, which can be expressed by Q1=r1(d1+ d2+ d3).

Assumption 2: Collaboration-driven cost assumption

While fostering collaboration and cooperation in the supply chain via the use of next-gen digital information technologies, the use of information technology, infrastructure, and other equipment, as well as the production of software, platforms, and systems, all contribute to the rising cost of scientific research, digital system building, information and communication, and other related endeavors. The aforementioned price encapsulates the essential cost associated with the cooperative decision-making procedure of each subject. Ci (i=1, 2, 3) represents the motivational cost coefficient for each subject, while Cidi indicates the driving cost associated with each subject's implementation of digital technology to enhance supply chain collaboration.

Assumption 3: Potential risk assumption

In the process of digital technology-enabled supply chain cooperation, there are some potential risks, including information asymmetry, fluctuating trust levels, opportunistic behavior, and external market and policy changes. In addition to this, potential risks could arise from various factors, including technology, personnel, essential information, and critical boundaries during the negotiation process. These risks may affect the synergistic cooperation and efficiency of the whole value chain, which could result in the diminishing of the subject's fundamental strengths. Mi (i=1, 2, 3) represents the potential risk coefficient associated with each subject's involvement in digital-enabled supply chain teamwork. Midi indicates the potential risks associated with each subject's involvement in supply chain cooperation facilitated by digital transformation.

Assumption 4: Synergistic incentive mechanism hypothesis

In this model, manufacturers who are leading in digital transformation will subsidize suppliers and sellers who are actively engaged in digital transformation and let Pi (i=2, 3) be the incentive compensation coefficient.

Assumption 5: Synergistic Penalty Mechanism Assumption

In this model, manufacturers will penalize suppliers and sellers who do not carry out digital transformation, denoted by Si (i=2, 3) as the penalty coefficient. Table 1 presents the acronyms and fundamental parameters.

Table 1: Definitions and specifications of the model components

Parameters	Description
MF	Manufacturers
SP	Suppliers
MK	Marketers
DT	Digital Transformation
N-DT	Non-digital transformation
X	The probability that a manufacturer chooses to digitise
Y	The likelihood of a supplier opting for digitization
Z	The likelihood of a marketer choosing to digitize
di	Inputs of data elements
Ei	Selection of non-digitalized tripartite initial returns
Ri	return factor
Ci	cost factor
mi	Potential risk factor

Pi	Manufacturers' subsidy factor for digital transformation upstream and downstream
Si	Penalty factor for manufacturers for not digitally transforming upstream and downstream
I2	Advantages of supplier DT for manufacturers
I3	Benefits of DT for Marketers to manufacturers

4.2. Construction and solution of replicated dynamic equations

The gain matrix has been constructed as illustrated in
Table **2**.

Table 2: Matrix of evolutionary game outcomes with three possible outcomes

decision making				MK	
				DT	N-DT
MF	DT	SP	DT	$E_1 + r_1(d_1 + d_2 + d_3) - c_1d_1 - m_1d_1 - p_2d_2 - p_3d_3 - I_2 - I_3$ $E_2 + r_2(d_1 + d_2 + d_3) - c_2d_2 - m_2d_2 + p_2d_2$ $E_3 + r_3(d_1 + d_2 + d_3) - c_3d_3 - m_3d_3 + p_3d_3$	$E_1 + r_1(d_1 + d_2) - c_1d_1 - m_1d_1 - p_2d_2 - S_3d_3 + I_2$ $E_2 + r_2(d_1 + d_2) - c_2d_2 - m_2d_2 + p_2d_2$ $E_3 + r_3(d_1 + d_2) - s_3d_3$
MF	DT	SP	N-DT	$E_1 + r_1(d_1 + d_3) - c_1d_1 - m_1d_1 + s_2d_2 - p_3d_3 + I_3$ $E_2 + r_2(d_1 + d_3) - s_2d_2$ $E_3 + r_3(d_1 + d_3) - c_3d_3 - m_3d_3 + p_3d_3$	$E_1 + r_1d_1 - c_1d_1 - m_1d_1 + s_2d_2 + s_3d_3$ $E_2 + r_2d_1 - s_2d_2$ $E_3 + r_3d_1 - s_3d_3$
MF	N-DT	SP	DT	$E_1 + r_1(d_2 + d_3) - p_2d_2 - p_3d_3 + I_2 + I_3$ $E_2 + r_2(d_2 + d_3) - c_2d_2 - m_2d_2 + p_2d_2$ $E_3 + r_3(d_2 + d_3) - c_3d_3 - m_3d_3 + p_3d_3$	$E_1 + r_1d_2 - p_2d_2 + s_3d_3 + I_2$ $E_2 + r_2d_2 - c_2d_2 - m_2d_2 + p_2d_2$ $E_3 + r_3d_2 - s_3d_3$
MF	N-DT	SP	N-DT	$E_1 + r_1d_3 + s_2d_2 - p_3d_3 + I_3$ $E_2 + r_2d_3 - s_2d_2$ $E_3 + r_3d_3 - c_3d_3 - m_3d_3 + p_3d_3$	$E_1 + s_2d_2 + s_3d_3$ $E_2 - s_2d_2$ $E_3 - s_3d_3$

Let the expected return when the core manufacturing company chooses the digital transformation strategy be U_1, the expected return when it decides the non-digital transformation be denoted by U_1', and the average return be denoted by letter $\overline{U}1$;here are the three sets of replication dynamic equations:

$$F(x) = \frac{dx}{dt} = x(1\text{-}x)\left(U_1\text{-}U_1'\right) = x(1\text{-}x)(r_1d_1\text{-}c_1d_1\text{-}m_1d_1) \quad (1)$$

$$F(y)=\frac{dy}{dt}=y(1-y)(U_2-U_2')=y(1-y)(r_2d_2-c_2d_2-m_2d_2+p_2d_2+s_2d_2) \quad (2)$$

$$F(z)=\frac{dz}{dt}=z(1-z)(U_3-U_3')=z(1-z)(r_3d_3-c_3d_3-m_3d_3+p_3d_3+s_3d_3) \quad (3)$$

The association yields a tripartite system of replicated dynamic equations:

$$\begin{cases} F(x)=\frac{dx}{dt}=x(1-x)(U_1-U_1')=x(1-x)(r_1d_1-c_1d_1-m_1d_1) \\ F(y)=\frac{dy}{dt}=y(1-y)(U_2-U_2')=y(1-y)(r_2d_2-c_2d_2-m_2d_2+p_2d_2+s_2d_2) \\ F(z)=\frac{dz}{dt}=z(1-z)(U_3-U_3')=z(1-z)(r_3d_3-c_3d_3-m_3d_3+p_3d_3+s_3d_3) \end{cases} \quad (4)$$

Differential equations are formulated as follows: dx/dt=0, dy/dt=0, dz/dt=0. E1(0，0，0),E2(0，1，0),E3(0，1，1),E4(0，0，1),E5(1，0，0),E6(1，0，1),E7(1，1，0),E8(1，1，1)and E9(x^*，y^*，z^*) are solutions to the system of equations. The variables (x^*，y^*，z^*) denote the answer to equation (5).

$$\begin{cases} r_1d_1-c_1d_1-m_1d_1=0 \\ r_2d_2-c_2d_2-m_2d_2+p_2d_2+s_2d_2=0 \\ r_3d_3-c_3d_3-m_3d_3+p_3d_3+s_3d_3=0 \end{cases} \quad (5)$$

Since E9 is not strictly a Nash equilibrium solution, the next step in the analysis below is only for E1-E8.

4.3. Model assumptions and parameterization

The Jacobi matrix obtained from the three replicated dynamic equations is presented as follows:

$$=\begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix}$$

$$=\begin{bmatrix} (1-2x)(r_1d_1-c_1d_1-m_1d_1) & 0 & 0 \\ 0 & (1-2y)(r_2d_2-c_2d_2-m_2d_2+p_2d_2+s_2d_2) & 0 \\ 0 & 0 & (1-2z)(r_3d_3-c_3d_3-m_3d_3+p_3d_3+s_3d_3) \end{bmatrix}$$

When all eigenvalues in the Jacobi matrix are negative, the equilibrium point serves as the stabilization point, i.e., the three main parties, i.e., the manufacturer, the supplier and the seller, are adopting the stabilization strategy. Let α=$r_1d_1-c_1d_1-m_1d_1$， β=$r_2d_2-c_2d_2-m_2d_2+p_2d_2+s_2d_2$， and γ=$r_3d_3-c_3d_3-m_3d_3+p_3d_3+s_3d_3$. The eigen-values and equilibrium points can be seen in Table 3.

Table 3: Equilibrium points along with their corresponding eigenvalues

Equilibrium points	λ_1	λ_2	λ_3
E1(0，0，0)	α	β	γ
E2(0，1，0)	α	$-\beta$	γ
E3(0，1，1)	α	$-\beta$	$-\gamma$
E4(0，0，1)	α	β	$-\gamma$
E5(1，0，0)	$-\alpha$	β	γ

E6(1，0，1)	$-\alpha$	β	$-\gamma$
E7(1，1，0)	$-\alpha$	$-\beta$	γ
E8(1，1，1)	$-\alpha$	$-\beta$	$-\gamma$

Taking E8 (1，1，1) as an example, the equilibrium point E8(1, 1, 1) is the equilibrium stabilization point of the model when the following three conditions are satisfied: $r_1d_1 - c_1d_1 - m_1d_1 > 0$, $r_2d_2 - c_2d_2 - m_2d_2 + p_2d_2 + s_2d_2 > 0$, and $r_3d_3 - c_3d_3 - m_3d_3 + p_3d_3 + s_3d_3 > 0$. The equilibrium point E8(1，1，1) serves as the stabilization point of the model.

4.4. Analysis of equilibrium in evolutionary stabilization strategies

a) Asymptotic Stability of Manufacturers

When $r_1d_1 - c_1d_1 - m_1d_1 = 0$, the manufacturer's strategy is in a steady state, it does not change over time.

When $r_1d_1 - c_1d_1 - m_1d_1 > 0$, we have $F_1'(1) < 0$, indicating that the manufacturer's "digital transformation strategy" seems to be a solid option.

When $r_1d_1 - c_1d_1 - m_1d_1 < 0$, we have $F_1'(0) < 0$, indicating the manufacturer's decision to adopt a "no digital transformation" strategy demonstrates stability.

b) Asymptotic stability of the supplier

When $r_2d_2 - c_2d_2 - m_2d_2 + p_2d_2 + s_2d_2 = 0$, the supplier's strategy remains constant and does not evolve over time.

When $r_2d_2 - c_2d_2 - m_2d_2 + p_2d_2 + s_2d_2$ <0, we have $F_2'(0) < 0$, indicating that the supplier's choice of "no digital transformation" strategy is stable.

When $r_2d_2 - c_2d_2 - m_2d_2 + p_2d_2 + s_2d_2 > 0$, we have $F_2'(1) < 0$, indicating that the vendor is stable in choosing the "digital transformation" strategy.

c) Asymptotic Stability of Vendors

When $r_3d_3 - c_3d_3 - m_3d_3 + p_3d_3 + s_3d_3 = 0$, the vendor's strategy is stable and does not change over time.

When $r_3d_3 - c_3d_3 - m_3d_3 + p_3d_3 + s_3d_3 < 0$, we have $F_3'(0) < 0$, indicating that the seller's choice of "no digital transformation" strategy is stable.

When $r_3d_3 - c_3d_3 - m_3d_3 + p_3d_3 + s_3d_3 > 0$, we have $F_3'(1) < 0$, indicating that the seller's choice of "digital transformation" strategy is stable.

5. Numerical simulation

In order to clearly and intuitively demonstrate the effect of parameter changes on the evolutionary path of the system, this paper uses MATLAB to carry out simulations. In the research scenario of this paper, the manufacturer is in the leading position of digital transformation and the input of data elements is much larger than the other two enterprises. Therefore the input of data elements is larger than the other two enterprises, and the driving cost and risk will be relatively higher. Therefore in most cases, d1> d2 ,d1> d3, r1> r2, r1> r3, c1> c2, c1> c3.

Take a real situation in a supply chain for example, where a supply chain alliance consisting of a manufacturer, supplier, and seller in China. After negotiation, the number of information resources invested by the three subjects is 30, 20, and 10 respectively. The empowerment revenues obtained by the three parties from each unit of information resources are \$80,000, \$40,000, and \$35,000 respectively. The driving costs per unit of information resources are \$50,000, \$40,000, and \$30,000, respectively. The risk costs per unit of information resources are \$80,000, \$40,000, and \$35,000, respectively. The subsidy and penalty coefficients for manufacturers are set with reference to policies introduced in Shandong Province and Xiamen City in Fujian Province (assuming that the subsidy coefficients s2=8, s3=7, p2=6,p3=4.5).Other parameters are drawn from the research of other scholars and combined with the actual situation and objective facts. The initial assignment of each parameter is as follows：d1=30, d2=20, d3=10, c1=5, c2=4, c3= 3, r1= 8, r2=4, r3=3.5 (set r1> r3), m1= 2, m2=1.5, m3=1, p2=6, p3=4.5, s2=8, s3=7.

5.1. Effect of initial parameters on evolutionary results

It is clear by looking at the game system's development roadmap in Figure 2 under various beginning strategy ratios that the strategy of (1, 1, 1) produces stable evolution, which the Pareto ideal condition of the three-player game conforms. And the speed of suppliers and sellers converging to 1 is always greater than that of manufacturers. The simulation results show that the higher the initial inclination of the three parties to adopt digital transformation, the more rapidly the game system attains a stable state; when the initial willingness to undergo digital transformation is identical, the manufacturer often needs to spend more time and energy to reach a stable state. Therefore, in the actual situation, manufacturers often need to carry out digital transformation faster and earlier than sellers and suppliers to realize the equilibrium of the game system.

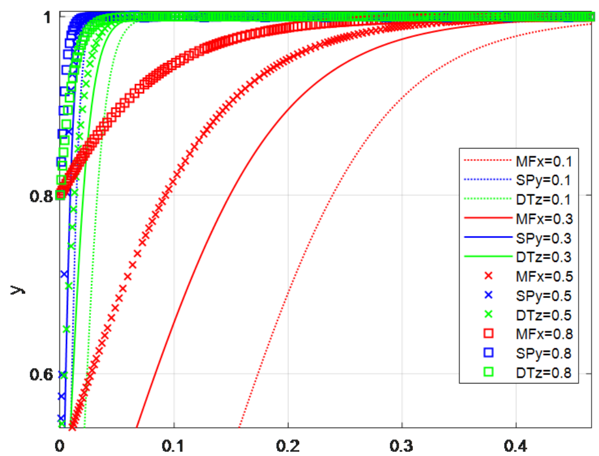
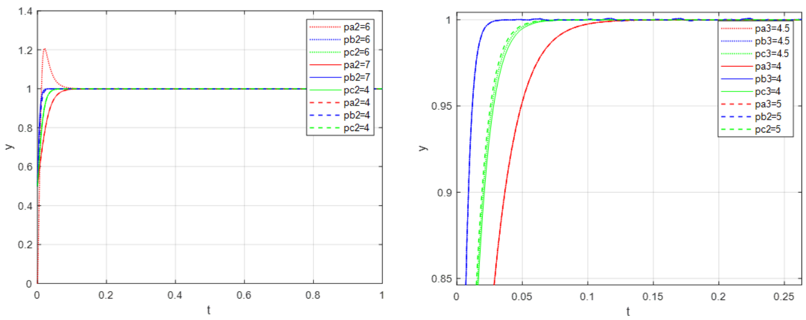


Figure 2: Effect of initial strategy on evolutionary outcomes

5.2. Effect of initial parameters on evolutionary results

Figure 3 illustrates the influence of the manufacturer subsidy coefficient on the evolution results. As can be seen from the figure, the stabilization point is (1, 1, 1) regardless of how p2 and p3 change. It can be seen from Figure (a) that the larger the manufacturer's subsidy coefficient to the supplier, the faster the supplier evolves to the stabilization point. From Figure (b), it can be seen that the larger the manufacturer's subsidy coefficient to the seller, the faster the rate at which the seller evolves to the stable point.

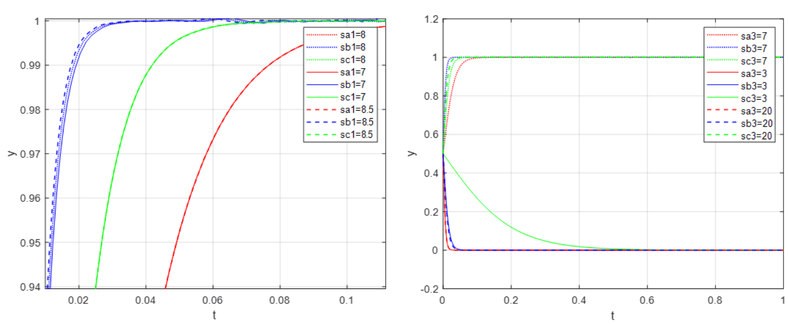


(a)Effect of p2 changes on evolutionary outcomes. (b)Effect of p3 changes on evolutionary outcomes.

Figure 3: Effect of p2 /p3changes on evolutionary outcomes

5.3. Impact of manufacturer's penalty coefficients for non-digital transformation on evolutionary outcomes

Figure 4 shows the various evolutionary results produced by the manufacturer's penalty coefficient for non-digital transformation. From Fig. (a), we can see that the more the manufacturer punishes the supplier, the faster the system evolves to the stabilization point. From Figure (b), we find that the manufacturer's punishment of sellers affects the evolutionary speed of all three parties of the supply chain at the same time. When the manufacturer penalizes the seller at a low level, it chooses a negative strategy, while when the penalty reaches a threshold, the seller turns to a positive strategy. And the stronger the punishment, the faster it reaches the steady state. Manufacturers‘ and suppliers’ strategy choices show the same variation as sellers. This may be due to the fact that sellers are closest to users, and the higher their degree of digital transformation, the more favorable it is for suppliers and manufacturers to produce products that are more in line with market demands.



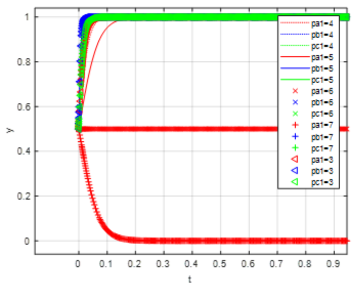
(a)Effect of s2 changes on evolutionary outcomes. (b)Effect of s3 changes on evolutionary outcomes.

Figure 4: Effect of s2/s3 changes on evolutionary outcomes

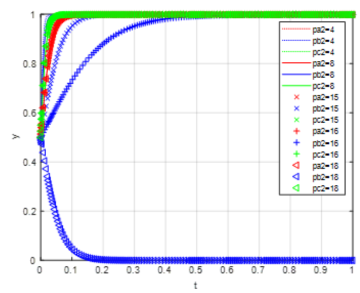
5.4. Impact of digital transformation costs on evolutionary outcomes

Figure 5 illustrates the influence of expenses related to digital transformation on evolutionary results. Where: (a) illustrates the impact of manufacturers' digital transformation costs on evolutionary outcomes; (b) illustrates how the expenses of suppliers' digital transformation affect the results of evolution; and (c) illustrates how the expenses of digital transformation for sellers affect the results of evolution. The Figures shows that the C1 threshold is between 5 and 7, the rate of convergence increases as the cost decreases below the threshold; C2 threshold is between 16 and 18, additionally, the rate of convergence increases when the cost below the threshold decreases; the C3 threshold is between 8 and 15, and the smaller the cost is below the threshold, the faster the speed of convergence

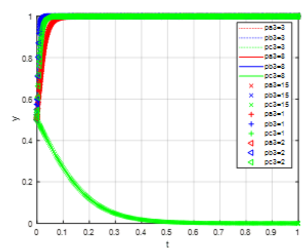
The findings indicate that the cost coefficient of digital transformation is of critical importance. When the cost is excessive, the three parties involved in the game will abandon the positive strategy and opt for the negative strategy; a lower cost causes the game system to converge to the equilibrium point more quickly when it is below the threshold (1, 1, 1).



(a)Effect of c1 changes on evolutionary outcomes.



(b)Effect of c2 changes on evolutionary outcomes.



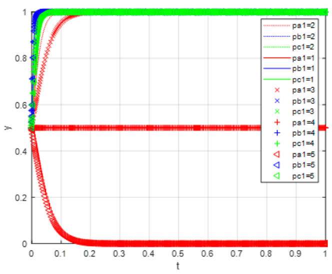
(b)Effect of c3 changes on evolutionary outcomes.

Figure 5: Effect of C1/C2/C3 change on evolutionary outcomes

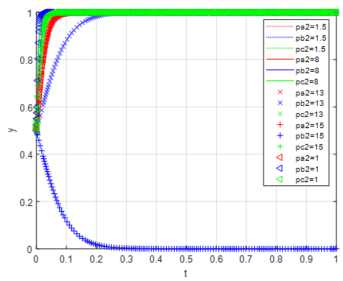
5.5. Effects of potential risks from digital revolution on evolutionary results

Figure 6 illustrates the effects of risk factors associated with digital transition on evolutionary results. Figure (a) displays the effects on evolutionary outcomes of digital transformation risks on manufacturers, Figure (b) shows the effects on evolutionary outcomes on suppliers, and Figure (c) shows the effects on evolutionary outcomes on sellers. The Figures show that the m1 threshold is between 3 and 5, and when m1 is smaller than the threshold, the smaller the risk, the faster the convergence; as m1 grows over the threshold, the stabilization method moves towards (0, 1, 1), and the manufacturer's convergence to 0 happens more quickly as m1 becomes bigger. The M2 threshold is between 13 and 15, and when m2 is smaller than the threshold, the smaller the risk, the faster the convergence; when m2 exceeds the threshold, the stabilization strategy approaches (0, 1, 1), and as m2 increases, the supplier converges to 0 more rapidly. M3 thresholds are between 13-15 and when m3 is smaller than the threshold, the smaller the risk is, the faster the convergence; when m3 exceeds the threshold, the stabilization strategy tends to (0, 1, 1), and as m3 increases, the manufacturer converges to 0 more rapidly.

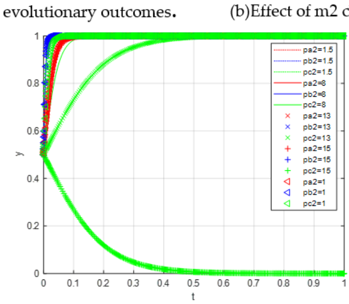
The results of the study show that: there exists a pivotal threshold regarding the risks associated with digital transformation. When these risks become excessively high, all three parties involved in the game will abandon the "digital transformation" strategy in favor of a more negative approach; the game system achieves the pace of stable strategy quicker when the danger of digital transformation is reduced, provided that the crucial value is within range.



(a)Effect of m1 changes on evolutionary outcomes.



(b)Effect of m2 changes on evolutionary outcomes.

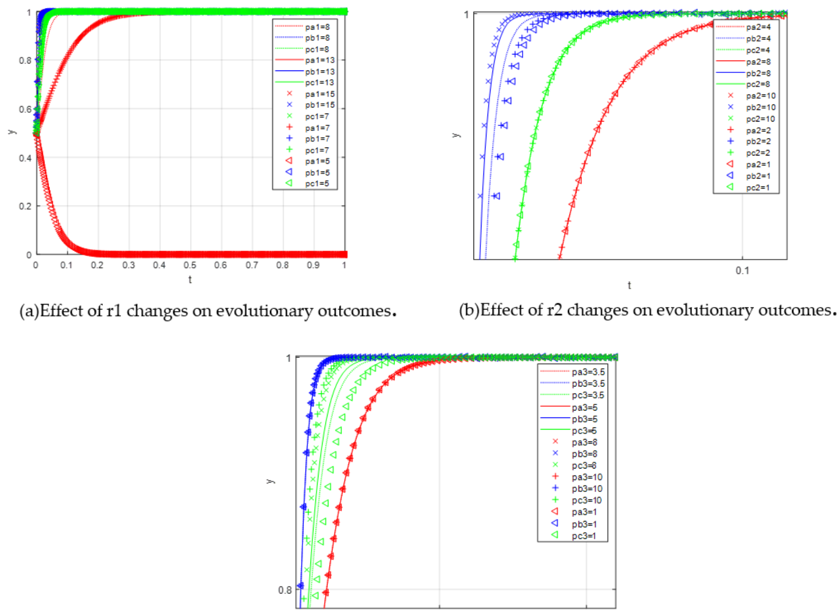


(b)Effect of m3 changes on evolutionary outcomes.

Figure 6: Effect of m1/m2/m3 change on evolutionary outcomes

5.6. Effects of advancements in digital transformation on the results of evolution

The results of evolution as a result of digital transformation are shown in Figure 7. Figure (a) illustrates how manufacturers' profits from DT affect the course of development. Figure (b) illustrates how suppliers' profits from DT affect the course of development. Figure (c) illustrates how retailers' profits from DT affect the course of development. From Fig. (a), the r1 threshold is between 5-7,when r1 is smaller than the threshold, the stable strategy of the three-party evolution is (0, 1, 1), and the smaller r1 is, the faster the manufacturer converges to 0. When r1 is larger than the threshold, the stable strategy tends to be (1, 1, 1), and the larger r1 is, the faster the three-party converges to (1, 1, 1). From Fig. (b), when $r2 > 0$, the supplier will always choose the digital transformation strategy, and the larger r2 is, the faster the convergence to 1. From Figure (c), when $r3 > 0$, the seller will always choose the digital transformation strategy, and the larger r3 is, the faster the convergence to 1 is.



(a)Effect of r1 changes on evolutionary outcomes. (b)Effect of r2 changes on evolutionary outcomes.

(b)Effect of r3 changes on evolutionary outcomes.

Figure 7: Effect of r1/r2/r3 changes on evolutionary outcomes

6. Main conclusion and policy implications

6.1. Main conclusion

Firstly, this study investigates the evolutionary stabilization strategies of supply chain tripartite from the perspective of market mechanisms, which few studies have examined from the perspective of market mechanisms. Therefore this study extends the study of supply chain sustainable digital transformation mechanism from a new perspective. It is found that the initial willingness of the three parties of the supply chain to choose digital transformation affects the speed of the game system to reach a stable state, and the larger the initial willingness, the faster the system converges to 1.

Secondly, this study identifies the impact of manufacturer's subsidy and penalty coefficients on digital transformation upstream and downstream of the supply chain. It is found that manufacturer subsidy coefficients and penalties play an active role in the operation of the enabling mechanism of supply chain digital transformation. The increase of subsidies and penalties can promote the convergence speed of the game system and accelerate the evolution of the Pareto-optimal state in the three directions of the game.

Third, supply chain digital transformation is affected by digitalization costs, risks as well as benefits. Reducing the transformation costs and risks of the participating subjects will help the three parties to choose the 'digital transformation' strategy, and promote the speed of convergence of the game system to the Pareto optimal state. Increasing the benefits of transformation will help the three parties to choose the 'digital transformation' strategy and promote the speed of convergence of the game system to the Pareto optimal state. Moreover, manufacturers are more sensitive to the revenue coefficient, when the revenue is low, manufacturers will abandon the 'digital transformation' strategy, while suppliers and sellers will not. Therefore, in the real supply chain sustainable digital transformation, we can take various measures from this perspective to reduce the cost and risk of digital transformation, and improve the benefits of transformation.

6.2. Policy implications

(1) Increase the readiness of organizations to embrace digital change

In the process of digital transformation of the supply chain, the willingness of manufacturers, suppliers and sellers to actively participate in digital transformation affects the speed of the enabling mechanism. The desire of DT of manufacturers, suppliers, and sellers in supply chain influences the velocity of the enabling mechanism. If one of the parties lacks enthusiasm or support, it may lead to a slowdown in the overall digital transformation empowerment stabilization and affect the speed of the gaming system stabilization. Therefore, the three parties in the supply chain can improve each party's willingness to engage in digital transformation by establishing incentive mechanisms and win-win cooperation.

(2) Manufacturers should develop reasonable subsidies and penalties policy

Manufacturer's subsidy and penalty policy is an important influence on the supply chain digital transformation empowerment mechanism. Manufacturers who are at the forefront of DT in the chain of supply should be proactive in the development of a multi-level subsidy and penalty mechanism. Since the sellers are more sensitive to the manufacturer's subsidies, they should pay attention to the implementation of a certain degree of subsidies for the sellers, reduce the transformation pressure of the partners through subsidies for the upstream and downstream, and technological and information help, and facilitate the comprehensive DT of the supply chain with an appropriate punishment policy.

(3) Decrease the risk and cost of DT for all parties

The cost and risk of digital transformation are important influencing factors that affect the enabling mechanism of supply chain digital transformation. The rapid development of blockchain technology can help supply chains achieve a higher degree of information sharing. Each enterprise in the supply chain needs to continuously optimize the information management mechanism to ensure that the participating entities actively share information. In addition, the three parties in the supply chain can use big data, machine learning and other digital technologies to conduct deep mining of relevant information, so as to carry out early warning and prevention and control of potential risks and crises. Acquire more information through the establishment of a data center and other means to establish a close cooperative relationship. Select appropriate digital technologies and solutions according to the actual situation and needs of all parties to avoid investing too much unnecessary resources.

(4) Enhance the advantages of DT for all stakeholders

The benefits of digital transformation are an important influence on the enabling mechanism of supply chain digital transformation. Based on the theory of supply chain management, the individual quality improvement and efficiency within the enterprise has little effect compared to the improvement of the overall supply chain efficiency. In the supply chain digital transformation, all the participants need to apply digital technology to interact with each other, as well as to make use of data generated during collaborative actions. Therefore, it becomes particularly important to improve the digitization level of cooperative enterprises. On the one hand, information sharing and data interoperability among all parties in the supply chain can be achieved through the establishment of a digital platform to enhance the transparency of data in the supply chain as well as the efficiency of collaborative cooperation among the various subjects, and to achieve the reduction of communication costs; on the other hand, a close digital partnership can be established among the three parties to jointly formulate the strategies and objectives of digital transformation, share the benefits of digital transformation, and collect the feedbacks through the regular evaluation of the On the other hand, the three parties can establish a close digital partnership to jointly formulate digital transformation strategies and goals, jointly share the benefits of digital transformation, and collect feedback by regularly assessing the effects of digital transformation to continuously optimize the digitalization and improve the digitalization process, so as to ensure that the digital transformation continuously brings benefits.

6.3. Limitations of the study and future research directions

Due to the limitations of research conditions and capabilities, this study has the following shortcomings: firstly, this study explores the evolution trend of supply chain sustainable digital transformation and the influence of various influencing factors on the evolution stability point, but due to the limitations of scientific research capabilities and time, it only takes the manufacturing enterprises and upstream and downstream in China as the research object, and does not carry out a more specific industry segmentation, since the sustainable digital transformation of enterprises in the supply chain is a long-term and dynamic process, there may be some differences in the transformation of different subsectors. Since the digital transformation of each enterprise in the supply chain is a long-term and dynamic process, there may be some differences in the transformation of different sub-industries, so future research can try to be more detailed in the division of sub-industries, and according to the different industries in which the enterprises are located, to further clarify the differentiated role of supply chain sustainable digital transformation in different industries.

Secondly, this thesis mainly focuses on the enabling theory of supply chain sustainable digital transformation, without empirical testing. The external influencing factors in this paper are based on the combing of the conclusions of previous studies in the industry and the synthesis of relevant expert opinions, which may not cover all the influencing factors, and the subsequent studies can comb the literature more comprehensively and use more scientific methods to verify the reasonableness of the influencing factors.

Finally, this paper explores the issue of the supply chain digital empowerment mechanism by considering the impact of various external factors on supply chain transformation and upgrading under the pure market mechanism. In the future, we can consider the impact of government policies and market mechanisms on supply chain transformation and upgrading. Although this paper proposes the enabling mechanism of supply chain sustainable digital transformation, it does not carry out in-depth research on the actual application scenarios of specific industries. Related issues can be further expanded in the future.

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